October 17, 2003

Exposure Analysis for Dioxins, Dibenzofurans, and Coplanar Polychlorinated Biphenyls in Sewage Sludge

Technical Background Document

Prepared for

ICF Consulting, Inc.
The Office of Water, U.S. Environmental Protection Agency
401M Street, SW (5307W)
Washington, DC 20460

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401 M Street, SW (5307W)
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Prepared by

Center for Environmental Analysis
RTI
Research Triangle Park, NC 27709

Table of Contents

Section **Page**

Table of Contents (continued)

Section **Page**

Table of Contents (continued)

Section **Page**

Table of Contents (continued)

Section **Page**

List of Figures

Number **Page**

List of Tables

Number **Page**

List of Tables (continued)

Number **Page**

Acronyms and Abbreviations

ADD	Average daily dose
Ah	Aryl hydrocarbon
AhR	Ah receptor
AHF	Altered hepatocellular foci
AML	Arc Macro Language
BAF	Bioaccumulation factor
BEF	Bioaccumulation equivalence factor
BSAF	Biota-sediment accumulation factor
CI	Confidence intervals
CSF	Cancer slope factor
CV	Coefficients of variation
CWA	Clean Water Act
DW	Dry weight
ED	Effective dose
EFH	Exposure factors handbook
EGF	Epidermal growth factor
EPA	U.S. Environmental Protection Agency
ER	Estrogen receptor
FC	Field capacity
foc	Fraction organic carbon
GIRAS	Geographic retrieval and analysis system
GIS	Geographic information systems
GSCM	Generic soil column model
HQ	Hazard quotient
HUC	Hydrological unit code
I-P	Initiation-promotion
IARC	International agency for research on cancer
ISCST3	Industrial source complex, short-term model, version 3
IUPAC	International Union of Pure and Applied Chemists
LADD	Lifetime average daily dose
LOAEL	Lowest observed adverse effects level
LOEC	Lowest observed effects concentration
MAF	Moisture adjustment factor
MATC	Maximum allowable toxicant concentration
NOAEL	No observed adverse effects level

Acronyms and Abbreviations (continued)

NIOSH	National Institute of Occupational Safety and Health
NSSS	National sewage sludge survey
PCB	Polychlorinated biphenyl
PCDD	Polychlorinated dibenzo-p-dioxin
PCDF	Polychlorinated dibenzofuran
POTW	Publicly owned treatment works
QC	Quality control
RSD	Relative standard deviations
SAMSON	Solar and meteorological surface observation network
SCRAM	Support center for regulatory air models
SCS	Soil conservation service
SERA	Screening ecological risk assessment
SMR	Standardized mortality ratio
STATSGO	State soil geographic
T3	Trophic level 3
T4	Trophic level 4
TCDD	Tetrachlorodibenzo-p-dioxin
TEF	Toxic equivalency factor
TEQ	Toxic equivalency quotient
UAC	Unit air concentration
UDPGT	Uridine diphosphate-glucuronyltransferases
USDA	U.S. Department of Agricultural
USGS	U.S. Geological Survey
USLE	Universal soil loss equation
WHO	World health organization
WP	Wilting point
WW	Wet weight
WWTP	Wastewater treatment plant

1.0 Introduction

1.1 Background

In February 1993, the U.S. Environmental Protection Agency (EPA) published the Standards for the Use or Disposal of Sewage Sludge (40 CFR Part 503). This regulation lists management practices and pollutant limits that protect public health and the environment from the reasonably anticipated adverse effects of pollutants in municipal biosolids (formerly referred to as "sewage sludge") when the biosolids are land-applied, placed on a surface disposal site, or fired in a biosolids incinerator. The Part 503 rule published in February 1993 is known as the Round One Biosolids Regulation. Section 405 of the Clean Water Act (CWA) requires EPA to publish a Round Two Biosolids Regulation, which will contain limits for pollutants not regulated in Round One.

Pollutants considered but not regulated under Round One were again considered under Round Two for potential regulation. Subsequently, EPA conducted preliminary exposure analyses in a comprehensive hazard identification exercise to determine which of the 31 pollutants should be on the final pollutant list for potential regulation under Round Two (U.S. EPA, 1996). Based on the results of those analyses, three groups of pollutants were placed on the pollutant list for Round Two: polychlorinated dibenzo-p-dioxins (PCDDs, or dioxins), polychlorinated dibenzofurans (PCDFs, or furans), and coplanar polychlorinated biphenyls (PCBs).

This document describes the risk assessment conducted to determine the concentrations of dioxins, furans, and PCBs that can be present in biosolids and remain "protective" (below a specified level of risk) of human health. This risk-based concentration limit was generated by evaluating cancer risks for individuals (receptors) who may be exposed to these constituents if biosolids are applied to agricultural fields. The goal of this risk assessment was to estimate a national distribution of the incremental increase in individual lifetime risk of developing cancer due to exposure to dioxins, furans, and PCBs potentially present in the biosolids for farm families who apply biosolids as fertilizer or soil conditioner.

1.2 Summary of the Risk Assessment Process

For risk assessments, human health risks are generally assessed using a four-step process, as outlined in NRC (1994):

1. Hazard Identification. Identify the hazard posed by a pollutant by determining whether a pollutant may cause health hazards, quantifying environmental concentrations of the pollutant, describing the toxicity that may be caused by the

pollutant, and evaluating the conditions under which toxicity might be expressed in humans. Sources for this information include environmental monitoring data, as well as epidemiologic and animal studies.

2. **Dose-Response Assessment.** Establish the relationship between pollutant doses and the health effects in humans through data analysis (most often data from animal studies and occasionally from human studies) and modeling. Mathematical models may help determine the quantitative relationship between the dose of the pollutant and toxic responses; in particular, the potencies of suspected carcinogens have frequently been evaluated using such models.

3. **Exposure Assessment.** Use available data on constituent concentrations in materials of concern to estimate concentrations of constituents in environmental media and human contact with those media. Exposure assessments should consider fate and transport of material in the environment, routes of exposure, and pharmacokinetics of material once in the body. Data limitations on the environmental concentrations of interest often require the use of environmental modeling to provide relevant estimates of exposure, as they did in this risk assessment.

4. **Risk Characterization.** Integrate information from Steps 1, 2, and 3 to estimate the likelihood that any of the hazards associated with the pollutant will be manifested in exposed persons. In addition, EPA emphasizes the importance of clearly describing uncertainties in the risk assessment when characterizing risks.

The *Draft Exposure and Human Health Reassessment of 2,3,7,8-Tetrachlorodibenzo-p-Dioxin (TCDD) and Related Compounds* (U.S. EPA, 2000) describes Steps 1 and 2 of the process for this risk assessment. This document is referred to here as the Draft Dioxin Reassessment Document. The current document focuses on the last two steps of the process—exposure assessment and risk characterization.

1.3 Overview of Risk Assessment Methodology

The purpose of this analysis was to estimate the total concentrations of dioxins, furans, and PCBs that can be present in biosolids and remain protective of human health when biosolids are applied to agricultural land. The two final steps of the risk assessment process—exposure assessment and risk characterization—were conducted to arrive at the estimates.

Steps in the exposure assessment included

- Characterizing the management practices associated with the agricultural uses of biosolids,

- Describing the environmental settings where agricultural uses of biosolids may occur,

- Identifying scenarios under which contaminants in biosolids may be transported through the environment and/or the food chain to a human receptor, and

- Quantifying an individual's exposure to the contaminants resulting from the agricultural use of biosolids in the environment.

Steps in the risk characterization phase included

- Describing the individual's predicted risk from exposure to concentrations of constituents in environmental media, and

- Determining the risk-based concentrations for dioxins in biosolids that are protective of individual health when biosolids are applied to agricultural land.

EPA estimated protective constituent concentrations using a probabilistic analysis. A probabilistic risk analysis produces a distribution of risks for each receptor by allowing some of the parameters in the analysis to have more than one value. This type of analysis was ideal for this risk assessment because biosolids are generated nationwide and, therefore, may be used on agricultural fields anywhere in the United States. The probabilistic analysis not only captures the nationwide variability in biosolid application practices, it also captures the differences in the environmental settings (e.g., soils, meteorology) in which biosolids may be land-applied.

1.4 Document Organization

This document is organized into the following sections:

- Section 2, Hazard Identification/Dose-Response Assessment, summarizes the toxicological data supporting the health benchmark used in this analysis and the toxic equivalency factors (TEFs) used for the congeners evaluated in this risk assessment. These data are based on the Draft Dioxin Reassessment Document (U.S. EPA, 2000).

- Section 3, Risk Assessment Overview, describes the conceptual framework for the biosolids risk assessment. This section presents the conceptual framework for the human health risk assessment, including a description of biosolids and biosolids management practices, fate and transport modeling, exposure assessment, and calculation of protective biosolids concentrations, as well as a detailed explanation of the framework for the probabilistic analysis.

- Section 4, Input Data Characterization, presents the methodologies used to characterize the environmental setting, including delineation of the site layout and environmental setting (e.g., meteorology, climate, and soils). It also describes how the agricultural fields were characterized.

- Section 5, Estimating Exposure Point Concentrations, describes the models and methods used for source partition modeling, air dispersion and deposition

modeling, watershed and waterbody modeling, terrestrial food chain modeling, and aquatic food chain modeling.

- Section 6, Human Exposure Assessment, presents an overview of the human receptors, selected exposure pathways, and exposure scenarios considered for this assessment. It also presents exposure factors (i.e., values needed to calculate human exposure) used in the analysis and methods used to estimate dose, including lifetime average daily dose (LADD).

- Section 7, Human Health Risk Results, presents the methods used to characterize the risk posed to an individual. It describes the calculation methods used to generate risk-based constituent concentrations that are protective of human health.

- Section 8, Analysis of Variability and Uncertainty, discusses the methods that were used to account for variability and uncertainty in the risk assessment.

- Section 9, Screening Ecological Risk Assessment of Dioxins in Land-Applied Biosolids, describes the screening ecological risk assessment that was performed to investigate the potential for adverse ecological effects from dioxins in land-applied biosolids.

The following appendices provide supplemental technical information and supporting data:

- Appendix A, 2001 National Sewage Sludge Survey—Congener Concentration Data

- Appendix B, 2001 National Sewage Sludge Survey—Sample Selection Strategy

- Appendix C, Agricultural Parameters

- Appendix D, Congener-Specific Parameters for Source Partitioning and Fate and Transport Models

- Appendix E, Site Data

- Appendix F, Source Model for Land Application Units

- Appendix G, Air Dispersion and Deposition Modeling Input Files

- Appendix H, Direct and Indirect Exposure Equations

- Appendix I, Variables for Aboveground Fate and Transport

- Appendix J, Human Exposure Factors

- Appendix K, Sensitivity Analysis

- Appendix L, Ecological Assessment
- Appendix M, Climate Region Selections

1.5 References

NRC (National Research Council). 1994. *Science and Judgement in Risk Assessment*. National Research Council, Committee on Risk Assessment of Hazardous Air Pollutants. Washington, DC: National Academy Press.

U.S. EPA (Environmental Protection Agency). 1996. *Technical Support Document for the Round Two Sewage Sludge Pollutants*. EPA-822-R-96-003. Washington, DC: U.S. Government Printing Office.

U.S. EPA (Environmental Protection Agency). 2000. *Exposure and Human Health Reassessment of 2,3,7,8-Tetrachlorodibenzo-p-Dioxin (TCDD) and Related Compounds*. EPA/600/P-00/001Bg. Washington, DC: National Center for Environmental Assessment, Office of Research and Development. September.

2.0 Hazard Identification/Dose-Response Assessment[1]

The constituents evaluated in this risk assessment are dioxins, furans, and PCBs contained in biosolids managed as a beneficial use on agricultural fields. All of these constituents were evaluated in the Draft Dioxin Reassessment Document (U.S. EPA, 2000), which concluded that "based on all available information, dioxins are potent animal toxicants with potential to produce a broad spectrum of adverse effects in humans." This risk assessment focuses on the potential of these biosolid constituents to act as human carcinogens. EPA characterizes 2,3,7,8-tetrachlorodibenzo-p-dioxin (TCDD) as a human carcinogen based on weight of evidence and characterizes other dioxins, furans, and PCBs as likely human carcinogens. The toxicity of all of the dioxin, furan, and PCB congeners considered in this analysis is based on the toxicity of the most highly characterized congener, 2,3,7,8-TCDD (U.S. EPA, 2000).

The cancer slope factor (CSF) for 2,3,7,8-TCDD used by EPA in this risk assessment is 1.56×10^5 $(mg/kg\text{-}d)^{-1}$ (U.S. EPA, 1997). The CSF is defined as the upper bound on the slope of the dose-response curve in the low-dose region and is generally assumed to be linear. It is expressed as a lifetime excess cancer risk per unit exposure. The same slope factor is used to estimate cancer risks for both child and adult resident receptors. However, significant uncertainties exist concerning the estimation of lifetime cancer risks in children. This factor differs from the more recent CSF for TCDD proposed in the Draft Dioxin Reassessment Document (U.S. EPA, 2000). At the time this risk assessment was conducted, the decision was made to use the older value until a consensus was reached on a new value.

2.1 Adverse Effects in Humans and Animals

2,3,7,8-TCDD and related compounds have been reported to produce a wide variety of adverse effects in humans and animals, including cancer, reproductive and developmental effects, immunotoxicity, chloracne, diabetes, and several other less common health effects. This assessment will evaluate risk based only on the cancer endpoint because this is the only endpoint for which there are sufficient data to adequately support the assessment for all the dioxin-like congeners (U.S. EPA, 2000).

[1] This section summarizes and draws heavily from the material presented in *Part II: Health Assessment for 2,3,7,8-Tetrachlorodibenzo-p-dioxin (TCDD) and Related Compounds* (U.S. EPA, 2000).

2.1.1 Mechanism of Action

The mechanisms of toxicity for dioxins are not completely understood but have been studied extensively, particularly for 2,3,7,8-TCDD. Many dioxins, furans, coplanar PCBs, and other structurally related halogenated aromatic hydrocarbons are believed to share a common mechanism of action related to similarities in their structures. The extraordinary potency of 2,3,7,8-TCDD in evoking a dose-related induction response, and the tissue specificity of enzyme induction led Poland and Glover (U.S. EPA, 2000, citing Poland and Glover, 1973) to postulate the existence of an induction receptor. This receptor, the Ah receptor (Ah for aromatic hydrocarbon), was identified in the cytosol of mouse liver cells (U.S. EPA, 2000, citing Poland et al., 1976) and in hepatic and extrahepatic tissues of a variety of laboratory animals, mammalian cell cultures, human organs and cell cultures, and tissues of nonmammalian species (U.S. EPA, 2000, citing Okey et al., 1994). 2,3,7,8-TCDD and structurally related compounds induce a wide range of biological responses, including alterations in metabolic pathways, body weight loss, thymic atrophy, impaired immune responses, hepatotoxicity, chloracne and related skin lesions, developmental and reproductive effects, and neoplasia. These responses are thought to be initiated by the binding of individual congeners (or ligands) with the aryl hydrocarbon (Ah) receptor. Of the many adverse responses observed both in humans and experimental animals after exposure to 2,3,7,8-TCDD, the ones that appear at the lowest dose (more sensitive) are developmental and reproductive effects, alterations in the immune response, and neoplasia.

Much evidence indicates that 2,3,7,8-TCDD acts via the intracellular protein, AhR, that functions in partnership with a second protein (known as the Ah receptor nuclear translocator, Arnt) to alter gene expression. In addition, receptor binding may result in release of cytoplasmic proteins, which alter the activity of cell regulatory proteins. Comparative data from animal and human cells and tissues suggest a strong similarity in response to dioxin-like chemicals across species. Biochemical and biological responses to dioxin exposure are sometimes considered adaptive, or reflective, of exposure but are within normal homeostatic limits and thus may not be considered adverse. However, many of these biochemical changes are potentially on a continuum of dose-response relationships, which leads to adverse responses. Given the possible mechanism of action, there are constraints on the possible models that account for dioxin's biological effects and on the assumptions used during the risk assessment. The linear relationship expected between ligand concentration and receptor binding may or may not be reflective of dose-response relationships for downstream events that require complex interactions. Biochemical and genetic analyses of these mechanisms suggest a novel regulatory system whereby a chemical signal can alter cellular regulatory processes.

The ability of 2,3,7,8-TCDD and other dioxin-like compounds to modulate a number of biochemical parameters is well recognized. Despite the ever-expanding list of these responses over the past 20 years and the work on the molecular mechanisms mediating some of these, there is still a considerable gap between our knowledge of the biochemical changes and the degree to which they are related to the more complex biological and toxicological endpoints.

TCDD-elicited activation of the Ah receptor has been clearly shown to mediate altered transcription oncogenes (cancer genes) and genes encoding growth factors, receptors, hormones, and drug-metabolizing enzymes. Based on the cumulative evidence available, it is presumed that

all of these processes are mediated by the binding of 2,3,7,8-TCDD to the AhR. The dioxin induces certain drug-metabolizing enzymes, such as CYP1A1, CYP1A2, and CYP1B1, in different animal species, including humans, at body burdens as low as 1 to 10 ng TCDD/kg. These and other enzymes are responsible for the metabolism of a variety of exogenous and endogenous compounds. Several lines of experimental evidence suggest that these enzymes may be responsible for either enhancing or protecting against the toxic effects of a variety of agents, including known carcinogens, as well as endogenous substrates such as hormones. These effects are dependent upon the compounds and the experimental system examined. Several reports (U.S. EPA, 2000, citing Kadlubar et al., 1992; Esteller et al., 1997; Ambrosone et al., 1995; Kawajiri et al., 1993) provide evidence that higher levels of enzyme activity are associated with increased susceptibility to colorectal, endometrial, breast, and lung tumors. Changes in these enzymes by dioxin may play a role in chemical carcinogenesis. However, the exact relationship between the induction of these enzymes and any toxic endpoint observed following dioxin exposure has not been clearly established. Animal evidence supports the understanding that AhR plays a key role in tumor production.

The role of the epidermal growth factor (EGF) receptor in 2,3,7,8-TCDD-induced carcinogenicity has also been examined. EGF is a mitogen that stimulates the generation of mitotic signals in both normal and neoplastic cells, and its receptor and ligands have a variety of functions involved in cell transformation and tumorigenesis. It has been shown that 2,3,7,8-TCDD decreases the binding capacity of the plasma membrane EGF receptor for its ligand without changing the affinity constant (U.S. EPA, 2000, citing Abbott and Birnbaum, 1990; Hudson et al., 1985; Lin et al., 1991; Madhukar et al., 1984). The effects of 2,3,7,8-TCDD on the EGF receptor have been shown to require the Ah receptor (U.S. EPA, 2000, citing Lin et al., 1991).

The possible role of uridine diphosphate-glucuronyltransferases (UDPGTs) on the carcinogenicity of 2,3,7,8-TCDD has also been studied. UDPGTs are thought to be a deactivation pathway for many environmental chemicals by increasing their water solubility, thereby facilitating excretion. 2,3,7,8-TCDD induces synthesis of at least one UDPGT isozyme (U.S. EPA, 2000, citing Lucier et al., 1986) by an Ah receptor-mediated mechanism (U.S. EPA, 2000, citing Bock, 1991). The results of Kohn et al. (1996) (U.S. EPA, 2000, citing Kohn et al., 1996) provide further support to the hypothesis that induction of UDPGT is an early event in the generation of thyroid tumors by 2,3,7,8-TCDD in the rat.

There is evidence that some carcinogenic responses to 2,3,7,8-TCDD are related to effects of 2,3,7,8-TCDD on the estrogen receptor (ER) and on estrogen metabolism. The responses appear to be tissue-specific. In rats, 2,3,7,8-TCDD increases liver tumor incidence, but decreases tumor incidence in mammary glands, the uterus, and the pituitary gland (U.S. EPA, 2000, citing Kociba et al., 1978a).

2.1.2 Epidemiologic Studies—Cancer Endpoint

Numerous studies have provided support for an association between exposure to dioxin and dioxin-like compounds and several types of cancer. Since the last formal EPA review of the human database relating to the carcinogenicity of TCDD and related compounds in 1988, a

number of new follow-up mortality studies have been completed. Among the most important of these are

- Studies of 5,172 U.S. chemical manufacturing workers by Fingerhut et al. (U.S. EPA, 2000, citing Fingerhut et al., 1991a) and Steenland et al. (U.S. EPA, 2000, citing Steenland et al., 1999) from the National Institute of Occupational Safety and Health (NIOSH) and an independent study by Aylward et al. (U.S. EPA, 2000, citing Aylward et al., 1996)

- A study of 2,479 German workers involved in the production of phenoxy herbicides and chlorophenols by Becher et al. (U.S. EPA, 2000, citing Becher et al., 1996, 1998) and by others in separate publications (U.S. EPA, 2000, citing Manz et al., 1991; Nagel et al., 1994; Flesch-Janys et al., 1995, 1998)

- A study of more than 2,000 Dutch workers in two plants involved in the synthesis and formulation of phenoxy herbicides and chlorophenols (U.S. EPA, 2000, citing Bueno de Mesquita et al., 1993) and subsequent follow-up and expansion by Hooiveld et al. (U.S. EPA, 2000, citing Hooiveld et al., 1998)

- A smaller study of 247 workers involved in a chemical accident cleanup by Zober et al. (U.S. EPA, 2000, citing Zober et al., 1990) and subsequent follow-up (U.S. EPA, 2000, citing Ott and Zober, 1996b)

- An international study of more than 18,000 workers exposed to phenoxy herbicides and chlorophenols by Saracci et al. (U.S. EPA, 2000, citing Saracci et al., 1991), with subsequent follow-up and expansion by Kogevinas et al. (U.S. EPA, 2000, citing Kogevinas et al., 1997).

Although uncertainty remains in interpreting these studies, because not all potential confounders have been ruled out, all indicate a potential association between exposure to dioxin and related compounds and increased cancer mortality. One of the strengths of these studies is that each has some exposure information that permits an assessment of dose response (U.S. EPA, 2000).

Results from several epidemiologic studies are summarized in Table 2-1. Observed numbers of cases, standardized mortality ratios (SMRs), and 95 percent confidence intervals (CI) are given for all cancers and for lung cancer, specifically. Although uncertainty remains concerning potential confounders in the studies, there is a strong inference regarding the carcinogenic potential of these constituents and the increased cancer mortality. Some of these studies have been judged adequate for use for fitting the dose-response models in the dioxin reassessment (U.S. EPA, 2000). In studies reviewed for the International Agency for Research on Cancer (IARC) monograph (U.S. EPA, 2000, citing IARC, 1997), the working group focused on the most exposed subcohorts with adequate latency and found that the most exposed groups had the highest incidence for all cancers combined and for lung cancer mortality. Although the increase was generally low (20 to 50 percent), it was highest in subcohorts with presumed

Table 2-1. Summary of Combined Cohort and Selected Industrial Cohort Studies with High Exposure Levels[a]

Reference[a]	All Cancers			Lung Cancer		
	Obs.	SMR	95% CI	Obs.	SMR	95% CI
International cohort						
Kogevinas et al. (1997) [b]	394	1.2	1.1–1.3	127	1.2	1.0–1.4
Industrial populations (high-exposure subcohorts)						
Fingerhut et al. (1991a) [c] (USA)	114	1.5	1.2–1.8	40	1.4	1.0–1.9
Becher et al. (1996) [d] (Germany)	105	[1.3]	[1.0–1.5]	33	[1.4]	[1.0–2.0]
Hooiveld et al. (1998) [e] (Netherlands)	51	1.5	1.1–1.9	14	1	0.5–1.7
Ott and Zober (1996b) [f] (BASF accident)	18	1.9	1.1–3.0	7	2.4	1.0–5.0
Total [g]	288	[1.4]	[1.2–1.6]	[94]	[1.4]	[1.1–1.7]
p value	<0.001			<0.01		

CI = Confidence intervals.
Obs = Observed number of cases.
SMR = Standardized mortality ratios.
Adapted from IARC; Table 38 (U.S. EPA, 2000, citing IARC; Table 38, 1997); non-Hodgkin's lymphoma, soft tissue sarcoma, and gastrointestinal results not shown.

[a] All references are as cited in U.S. EPA (2000).
[b] U.S. EPA, 2000, citing Kogevinas et al. (1997): men and women >20 years since first exposure. These data include the cohorts of Fingerhut et al. (1991a,b), Becher et al. (1996), Hooiveld et al., (1998), the original IARC cohort (Saracci et al., 1991), and other cohorts.
[c] Fingerhut et al. (1991a): men ≥20 years latency and ≥1 year exposure.
[d] Becher et al. (1996): men, Cohort I and II, summed (Boehringer-Ingelheim, Bayer-Uerdingen cohorts).
[e] Hooiveld et al. (1998): men and women, Factory A.
[f] Ott and Zober (1996b): men, chloracne subgroup, ≥20 years latency. Data presented for lung cancer are all respiratory tract cancers combined.
[g] Totals in square brackets are those calculated by the IARC Working Group.

heaviest exposure. This outcome is unlikely due to chance, and the increase in lung cancer is not explained by confounding exposure due to smoking. Positive dose-response trends in the German studies and increased risk in the longer-duration U.S. subcohort and the most heavily exposed Dutch workers support this view. These results are further substantiated by the increased mortality found in the Japanese rice oil poisoning accident where high levels of exposure to furans and PCBs were observed and were associated with increased incidence of lung and liver cancers. Although increases in cancer incidence at other sites (e.g., non-Hodgkin's lymphoma, soft tissue sarcoma, gastrointestinal cancer) have been reported, the data to associate them with exposure to dioxin-like chemicals are less compelling because of the limited numbers of observed tumors at any specific site (U.S. EPA, 2000).

2,3,7,8-TCDD and, by inference from more limited data, other dioxin-like compounds are potentially multisite carcinogens in the more highly exposed human populations that have been studied, primarily in adult males. 2,3,7,8-TCDD cancer experience for women may differ from that for men. Animal and mechanistic studies suggest different responses in males and females, but there are no data to adequately support this. Although the epidemiologic data are not sufficient by themselves to infer a causal association between exposure to TCDD and other dioxin-like chemicals and increased cancer in humans (U.S. EPA, 2000, citing IARC, 1997; ATSDR, 1998) and although uncertainty remains, the epidemiologic data are generally consistent with results from studies of multiple laboratory animal species where dioxin-like compounds have clearly been identified as multisite carcinogens and tumor promoters. In addition, the findings of increased cancer incidence at multiple sites in occupationally exposed workers appear to be plausible given what is known about mechanisms of dioxin action. The epidemiological data, however, are insufficient to establish the shape of the dose-response curve below the range of observation in these occupationally exposed populations.

2.1.3 Animal Studies—Cancer Endpoint

Many animal studies have shown that 2,3,7,8-TCDD is a carcinogen; these studies include long-term bioassays conducted in numerous species, including both sexes of rats and mice. According to the Draft Dioxin Reassessment Document, "TCDD is a nongenotoxic carcinogen because it is negative in most assays for DNA damage; however, it is a potent "promoter" and a weak initiator or noninitiator in two-stage initiation-promotion (I-P) models for liver and skin" (U.S. EPA, 2000). Multiple I-P studies show that induction of altered hepatocellular foci (AHF) is dose-dependent, exposure duration-dependent, and partially reversible. AHF induction is associated with liver cancer in rodents.

In addition to liver effects, TCDD is a potent cancer promoter in mouse skin (source of the CSF used). It is also characterized as a multisite carcinogen because it increases the incidence of tumors at sites distant from treatment sites. This association is substantiated by the fact that all long-term cancer bioassays have been positive in both sexes of both rats and mice.

2.2 Risk Characterization

Characterization of dioxin risks is based on an extensive amount of data. Characterization of the health hazard, modes of action, dose-response, and exposure all

contribute to the dioxin risk. Subpopulations and developmental stages are included in this characterization.

EPA drew several solid conclusions regarding carcinogenicity based on its analysis (U.S. EPA, 2000):

- "Dioxin and related compounds can produce a wide variety of effects in animals and might produce many of the same effects in humans"
- "Dioxin and related compounds are structurally related and elicit their effects through a common mode of action"
- "EPA and the international scientific community have adopted toxic equivalency of dioxin and related compounds as prudent science policy"
- "Complex mixtures of dioxin and related compounds are highly potent, likely carcinogens."

Adequate evidence supports the belief that humans are likely to respond to exposure to dioxin with a broad spectrum of effects. These effects appear to begin with biochemical changes at or near background levels of exposure (concentrations measured in the ambient environment), increasing in severity as body burdens increase. Enzyme induction, changes in hormone levels, and altered cellular function may represent effects of unknown significance at the lowest exposure levels. Adverse effects, including cancer, may not be detectable until exposure reaches 10 to 100 times background levels. Humans most likely fall into the middle of the range of sensitivity among mammals, neither extremely sensitive nor extremely insensitive to the effects of dioxin.

Currently, there have been few cohorts with dioxin exposure high enough to raise body burdens significantly over background levels. In those studies, few clinically significant noncancer effects were detected.

Most, if not all, observed effects of dioxin can be described in a series of common biological steps. The initial step and the single largest determinant of toxicity, including tumor development, is binding of dioxin and related compounds to the AhR. Dioxin and dioxin-related compounds exist as complex mixtures in nature, and the biological activity of the mixture can be estimated using relative potency values, coupled with an assumption of dose additivity. This exposure has evolved to the use of toxic equivalency quotients (TEQs) in risk assessment. With this approach, cumulative exposures of AhR-mediated chemicals can be translated with increasing confidence to human responses.

A weight-of-evidence evaluation concluded that mixtures of dioxin and related compounds are strong cancer promoters and likely pose a cancer hazard to humans. The data for complex mixtures of dioxins, furans, and coplanar PCBs constitute "strong evidence" of carcinogenicity (U.S. EPA, 2000) and include epidemiological cancer observations and unequivocal positive responses in both sexes, multiple species, multiple sites, and different routes. Laboratory evidence supports the epidemiological results, suggesting dioxin exposure

contributes to carcinogenic response, but it is insufficient to confirm a causal relationship. Human studies alone cannot demonstrate this causal relationship.

2.3 Dose-Response and Slope Factors

Current knowledge of the mechanisms of action of dioxin, receptor theory, and the available dose-response data are insufficient to establish a nonlinear procedure for estimating cancer potency. Both cancer and noncancer effects appear to result from qualitatively similar modes of action; thus, the potential for either type of effect is considered equal. A common metric for comparison is the effective dose (ED). In the observable range of 1 percent excess response, quantitative differences between cancer and noncancer EDs are relatively small.

2.3.1 Human and Animal Studies

Dioxins and other xenobiotics that operate through receptor-binding mechanisms will, according to theory, follow a linear dose-response binding. This theory is supported by empirical findings. The biochemical and transcription reactions for dioxins may also follow linear dose-response kinetics. More distal toxic effects could be linear or threshold (sublinear) depending on (1) the toxic mechanism, (2) the location on the dose-response curve, and (3) interactions with other processes. Too much data variability exists to clearly distinguish statistically between dose-response curve options and to determine whether dose-response follows linear, supra/sublinear, power curve, or threshold kinetics. Toxic effects at higher doses may be more likely to result from multiple cellular changes and thus be less likely to follow linear relationships. Empirical dose-response data from cancer studies—both epidemiological and bioassays—do not provide consistent or compelling support to either threshold or supralinear models. Thus, the default linear extrapolation policy is used.

Current human body burdens are already relatively high on the dose-response curve. Margins of exposure between population levels of background exposure and the empirical 1 percent effect levels due to additional exposure for a number of biochemical and toxic effects are on the order of less than 1 to 2 orders of magnitude. Therefore, the extrapolation between observed effects and background levels is not large.

Because human data were available for cancer dose-response analysis and because EPA wanted to stay within the estimated range of responses, EPA chose a 1 percent excess risk as a point of departure (U.S. EPA, 2000). Restricting the analysis to log-linear models, human cancer effective doses at the 1 percent excess risk level *($ED_{01}s$)* were estimated to range from 5.7 to 250 ng/kg. In similar estimates based on animal studies, most $ED_{01}s$ ranged from 14 to 500 ng/kg.

Calculations of a CSF based on the extrapolation of lower ED_{01} to background response rates based on human data yielded a CSF estimate of approximately 1×10^{-3} per pg TCDD/kgBW/d. Based on animal data, a similar CSF of 1.4×10^{-3} per pg TCDD/kgBW/d was estimated (U.S. EPA, 2000). "The Agency, although fully recognizing the range and the public health conservative nature of slope factors that make up the range, suggests the use of the 1×10^{-3} per pg TEQ/kgBW/d as an estimator of upper bound cancer risk for both background intakes and incremental intakes above background" (U.S. EPA, 2000).

For this risk assessment, however, the current EPA-sanctioned CSF was used because of the draft nature of the most recent dioxin risk assessment document. EPA has used a CSF for 2,3,7,8-TCDD of 1.56×10^{-1} $(pg/kg\text{-}d)^{-1}$ and unit risk estimates of 3.3×10^{-5} $(pg/m^3)^{-1}$ for inhalation exposure and 4.4×10^{-3} $(pg/L)^{-1}$ for drinking water exposure. These values are now under review and are subject to change; they are based on an oral study in which rats were exposed to 2,3,7,8-TCDD in their diet for 720 days, resulting in tumors of the respiratory system and liver (U.S. EPA, 2000; U.S. EPA, 2000, citing Kociba et al., 1978). The inhalation unit risk estimate was based on route-to-route extrapolation from the oral CSF, assuming 75 percent absorption (U.S. EPA, 1997, 2000).

2.3.2 Toxicity Equivalency Factors

Over the past decade, the scientific community, led by the World Health Organization (WHO), has developed a system of TEFs that relate the toxicity of each dioxin, furan, and PCB congener to the toxicity of 2,3,7,8-TCDD. The TEFs used in this analysis are those developed by the WHO in 1998 (U.S. EPA, 2000, citing Van den Berg et al., 1998) and recommended in the Draft Dioxin Reassessment Document (U.S. EPA, 2000).

These TEFs, presented in Table 2-2, were multiplied by the CSF of 1.56×10^{5} $(mg/kg\text{-}d)^{-1}$ currently recommended by EPA to determine the congener-specific CSF that was used to estimate congener-specific risks.

Table 2-2. Toxic Equivalency Factors

Congener	TEF (U.S. EPA, 2000)
Polychlorinated dibenzodioxins	
2,3,7,8-TCDD	1
1,2,3,7,8- PeCDD	1
1,2,3,4,7,8-HxCDD	0.1
1,2,3,7,8,9-HxCDD	0.1
1,2,3,6,7,8-HxCDD	0.1
1,2,3,4,6,7,8-HpCDD	0.01
1,2,3,4,6,7,8,9-OCDD	0.0001
Polychlorinated dibenzofurans	
2,3,7,8-TCDF	0.1
1,2,3,7,8-PeCDF	0.05
2,3,4,7,8-PeCDF	0.5
1,2,3,4,7,8-HxCDF	0.1

(continued)

Table 2-2. (continued)

Polychlorinated dibenzofurans		
1,2,3,7,8,9-HxCDF		0.1
1,2,3,6,7,8-HxCDF		0.1
2,3,4,6,7,8-HxCDF		0.1
1,2,3,4,6,7,8-HpCDF		0.01
1,2,3,4,7,8,9-HpCDF		0.01
1,2,3,4,6,7,8,9-OCDD		0.0001
Polychlorinated biphenyls		**TEF (U.S. EPA, 2000)**
IUPAC #[1]	**Structure**	
77	3,3',4,4'-TCB	0.0001
81	3,4,4',5-TCB	0.0001
105	2,3,3',4,4'-PeCB	0.0001
114	2,3,4,4',5-PeCB	0.0005
118	2,3',4,4',5-PeCB	0.0001
123	2',3,4,4',5-PeCB	0.0001
126	3,3',4,4',5-PeCB	0.1
156	2,3,3',4,4',5-HxCB	0.0005
157	2,3,3',4,4',5'-HxCB	0.0005
167	2,3',4,4',5,5'-HxCB	0.00001
169	3,3',4,4',5,5'-HxCB	0.01
170	2,2',3,3',4,4',5-HpCB	-
180	2,2',3,,4,4',5,5'-HpCB	-
189	2,3,3',4,4',5,5'-HpCB	0.0001

[1] International Union of Pure and Applied Chemists number.

2.4 References

ATSDR (Agency for Toxic Substances and Disease Registry). 1998. *Toxicological Profile for Chlorinated Dibenzo-p-dioxins*. Agency for Toxic Substances and Disease Registry, Department of Human and Health Services. Atlanta, GA.

U.S. EPA (Environmental Protection Agency). 1997. Chapter 8. Dose-response modeling for 2,3,7,8-TCDD. January 1997 Workshop Review Draft. EPA/600/P-92/001C8.

U.S. EPA (Environmental Protection Agency). 2000. *Exposure and Human Health Reassessment of 2,3,7,8-Tetrachlorodibenzo-p-Dioxin (TCDD) and Related Compounds*. EPA/600/P-00/001Bg. Washington, DC: National Center for Environmental Assessment, Office of Research and Development. September.

3.0 Risk Assessment Overview

This section describes the conceptual framework for the risk assessment conducted for dioxins, furans, and coplanar PCBs in biosolids applied to agricultural land. Section 3.1 presents the conceptual framework for the human health risk assessment. This includes a description of biosolids and the agricultural practices, fate and transport modeling, exposure assessment, and calculation of risk-based concentrations of these constituents in biosolids. Section 3.2 describes the framework for the probabilistic analysis.

3.1 Human Health Risk Assessment

The human health risk assessment for the evaluation of dioxins, furans, and coplanar PCBs was intended to evaluate nationwide risk to farmers and the children of farmers who apply biosolids to their croplands and pastures and consume home-produced foods. The concentrations of the 29 dioxin, furan, and PCB congeners used in this risk assessment were derived from the 2001 National Sewage Sludge Survey (NSSS, see Appendix A).

Biosolids are solid, semisolid, or liquid residue generated during the treatment of domestic sewage in municipal wastewater treatment works. When biosolids are land-applied, surface-disposed, or fired in a biosolids incinerator, the applicable requirements in Part 503 of the CWA must be met. Part 503 contains both risk-based requirements and technology-based requirements. The EPA risk assessment approach used in this analysis was designed to produce a scientifically defensible evaluation of the concentrations of dioxins in biosolids that are protective of human health when biosolids are applied to agricultural land.

3.1.1 Application of Biosolids to Agricultural Land

Biosolids may be applied to agricultural land that may be used as cropland or as pasture for cattle. These applications occur nationwide; therefore, a probabilistic risk assessment was structured to capture the variability in climate, soil, and agricultural practices throughout the United States. The 48 contiguous states were subdivided into 41 climatic regions assumed to be sufficiently uniform to be represented adequately by climate data from any reporting meteorologic station within the bounds of the region. These geographic regions were also used as the basis for identifying a representative farm size and a distribution of soil types on the farms.

The data sources for characterizing the distribution of agricultural field sizes are

- U.S. DOC (Department of Commerce). 1989. *1987 Census of Agriculture, Volume 1, Geographic Area Series State and County Data*.

- U.S. DOC (Department of Commerce). 1994. *1992 Census of Agriculture Volume 1, Geographic Area Series State and County Data*. Bureau of the Census, Washington, DC.

3.1.2 Constituents of Concern

Constituents of concern for the Round Two Biosolids Regulation are dioxins, furans, and coplanar PCBs. These pollutants are similar in many respects, including fate and transport and toxicology. The human health benchmarks for these constituents are related by a system of TEFs to the health benchmark for the most well-characterized of these compounds: 2,3,7,8-TCDD. Table 2-2 presents the constituents of concern evaluated in this risk assessment.

3.1.3 Site Configuration and Environmental Setting

A single conceptual site layout was used to define the relationship between the agricultural site and the human receptors evaluated in this risk assessment. The same site layout was used for the 41 geographical regions. The environmental characteristics of the regions provide the data used for the environmental characteristics of the sites.

3.1.3.1 Conceptual Site Layout. Figure 3-1 depicts the conceptual site layout for the agricultural application of biosolids. Farmers are assumed to apply biosolids to cropland where exposed fruits, vegetables, and root crops are produced and pastureland where beef and dairy cattle are grazed. The farmers are assumed to live on a small strip of land (the buffer area) between the cropland or pastureland and the stream. The farmer raises free-range chickens in a yard that is also located in the buffer area. Beyond the buffer area is a third-order stream.[1] This order-size stream was chosen because it is the smallest size stream that is assumed to be fishable. EPA chose to model an adjacent stream and did not include a farm pond in this scenario because the adjacent stream scenario is a realistic and defensible scenario. A farm pond may or may not be more or less protective than the adjacent stream, because the amount of land draining into the pond may include only a fraction of the farmland amended with biosolids. In the stream scenario, all of the biosolids-amended fields drain into the stream. The stream is diluted because of the inflow of clean water; however, this scenario is realistic and defensible in a fish ingestion scenario. The farm pond scenario, although ponds may exist on many farms, may not be as realistic as an adjacent stream for the catching of edible fish.

The farmer, his lactating wife, their infant, and older children may come in contact with dioxin congeners via several routes of exposure. The hypothetical farm scenario was developed to represent all potential routes of exposure to the farm family. The biosolids were assumed to be applied to the whole farm. There were no data available to estimate sizes of fields where biosolids may be applied. EPA constructed the layout of the hypothetical farm to provide a protective scenario for the farm family that applies biosolids to its own cropland and pasture and consumes food items grown on the biosolids-amended land. Two elements of the exposure scenario depend on the location of the residence: the concentration of constituents in the soil

[1] A third-order stream is defined as the joining of two second-order channels. Second-order channels are formed from the joining of two first-order channels. First-order channels are the smallest finger-tip tributaries in a watershed. Thus, the actual dimensions of streams of each order may vary.

ingested by the resident and the concentration of constituents in the air inhaled at the residential buffer. Neither of these pathways was a driving pathway in this risk assessment. Therefore, the location of the residence on the buffer, although potentially unrealistic, did not have a significant impact on the results of the risk assessment.

In the modeled scenario, routes of exposure to the farm family could be considered either individually or in any group of exposure pathways desired by the decision maker or the public. The modeling of all pathways (e.g., fishing) made possible the estimation of risk for various groups of pathways. Exposure to any desired group of pathways could be estimated by simply adding the exposure from the desired pathways and omitting the other pathways on an iteration by iteration basis. Although it was appropriate to develop a distribution of risk for each pathway, it was not appropriate to add, for example, the 90th percentile risks for one pathway to the 90th percentile risks for other pathways to estimate the 90th percentile risk for specific groups of pathways. Residential or home gardening scenarios were not addressed; however, these scenarios include lower exposures of individuals to the constituents in biosolids than the farmer scenario. Thus, if exposure levels are protective of the most exposed individuals, the farm family, the same levels will be protective of individuals who apply biosolids to their lawns and/or home gardens.

The multipathway risk assessment approach used for this assessment provided flexibility in interpreting the results. The pathways assessed in this risk assessment could be considered either combined or individually. Because all pathways were based on the same assumptions, the exposures and risks could be added together; however, it was equally justified to consider each pathway independently. For example, an individual may be exposed only to homegrown, aboveground vegetables. In that case, it would be appropriate to consider the risks from only that pathway and to disregard the risks from any other pathway. However, if all pathways had not been calculated originally using the same assumptions for each iteration, it would not be possible to add the pathways together to obtain a total risk from multiple pathways, and all pathways would have to be considered independently.

3.1.3.2 Regional Environmental Setting. Biosolids are produced and managed in all states in the contiguous 48 states; therefore, environmental settings used in this risk assessment were developed to be representative of each geographical region in the United States. The primary objective in characterizing a regional environmental setting was to represent the variation in environmental conditions that results from the geographic diversity in the United States. Within each of the 41 representative climatic regions, a meteorological station was identified to represent the climatic and meteorological conditions for that geographic area. The 41 climatic regions used for modeling are shown in Figure 3-2.

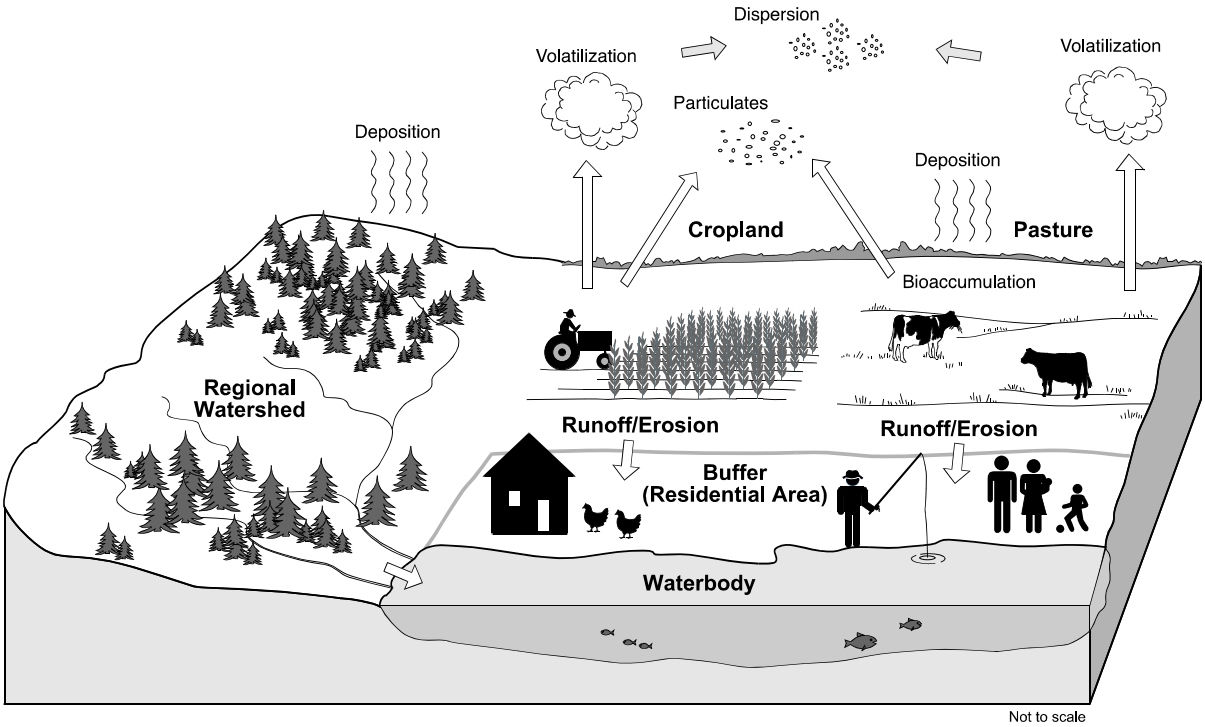

Figure 3-1. Agricultural application conceptual site model.

Figure 3-2. Map of 41 climatic regions.

The following characteristics are assumed to be associated with the 41 regions:

- Soil characteristics for land having agricultural use (crops or pasture)
- Representative meteorological and climatic data
- Agricultural field sizes (median farm size for the region).

3.1.4 Exposure Point Estimates

A series of models was used to estimate concentrations of congeners in the environment with which individuals may come into contact. A source partition model was used to estimate environmental releases of each congener from the cropland, or pasture, where biosolids are applied. These estimated environmental releases provide input to the fate and transport models to estimate media concentrations for dioxins, furans, and coplanar PCBs in air, soil, above- and belowground produce, and surface water. A farm food chain model was used to estimate environmental concentrations of these congeners in home-produced produce, poultry, eggs, beef, and dairy products. These models are discussed in detail in Section 5.0. Aquatic bioconcentration factors were used to estimate concentrations in home-caught fish. All concentrations were estimated as congener-specific concentrations and TEQ concentrations (both congener-specific and total).

3.1.4.1 Source Partition Modeling. Biosolids application to pastures is assumed to differ from biosolids application to cropland, and the differences affect the behavior of constituents in the environment. The source partition model requires information on farm area, biosolids characteristics (e.g., moisture content, congener concentrations), and environmental setting (e.g., precipitation, temperature, soil characteristics) to estimate environmental releases.

Cropland. Biosolids applied to cropland are tilled into the soil; thus, the dioxins are thoroughly mixed with the top 20 cm of soil. The congeners are released to the air from the soil as vapors and particulates; the crops take the congeners in through the air; and congeners bound to the soil particles are eroded onto and through the residential property and chicken yard and into the nearby stream.

Pasture. Biosolids applied to the pasture are not tilled and, thus, are not actively mixed with the soil. However, over time the congeners penetrate into the soil and are assumed to be mixed in the top 2 cm of soil. The congeners are released to the air from the soil surface; grasses take up the congeners through air-to-plant transfer. The congeners bound to the biosolids and to the soil are eroded onto and through the residential property and chicken yard and into the nearby stream (where they are mixed with the soil estimated to be eroded from the adjacent cropland).

3.1.4.2 Fate and Transport Modeling. Fate and transport algorithms describe the mechanism by which the congeners move from the source through the environment. As described above, a source partition model was used to determine the amount and nature of congener released from the agricultural field. A multimedia approach was used to characterize the movement of the dioxins through the environment. This approach considered atmospheric concentrations, atmospheric deposition, soil concentrations, and sediment concentrations in the waterbody.

3.1.4.3 Farm Food Chain Model. A farm food chain model was used to estimate the concentration of congeners in aboveground produce, belowground produce, poultry, eggs, beef, and dairy products. Aboveground produce is affected via vapor transfer and deposition of dioxins in the air. Belowground produce is affected only by uptake of dioxins from tilled soil. The concentration of dioxins was also estimated for the forage and silage consumed by cattle. Forage is assumed to be grown on the untilled pasture, whereas silage is assumed to be harvested from the tilled crop fields. Agricultural field size was estimated as the median agricultural farm size for each of the 41 climatic regions modeled, and it varied among the climatic regions. Dioxins that are ingested by animals were partitioned to the lipid fraction of each animal product.

3.1.4.4 Aquatic Food Chain Model. An aquatic food chain model was used to estimate the concentration of dioxins, furans, and coplanar PCBs in fish populations. These congeners are eroded from the agricultural fields where they are managed into the sediment of the adjacent stream where they can contaminate fish. The uptake into fish from the sediment is represented by congener-specific bioaccumulation constants called biota sediment accumulation factors (BSAFs). Trophic level 3 (T3) and 4 (T4) fish were considered in this analysis. Trophic level 3 fish are those that consume invertebrates and plankton. Trophic level 4 fish are those that consume other fish. Most of the fish that humans consume are T4 fish (e.g., salmon, trout, walleye, bass) and medium to large T3 fish (e.g., carp, smelt, perch, catfish, sucker bullhead, sauger).

3.1.5 Assessing Human Exposures

Individuals may come into contact with dioxins in biosolids applied to agricultural fields through a variety of pathways.

3.1.5.1 Human Receptors. Four individual receptors were evaluated in this assessment:

- Adult farmer (members of the farm family who begin exposure as adults)
- Child of farmer (members of the farm family who begin exposure in childhood)
- Infant of farmer (infant born to the farm family during the exposure period)
- Fisher (adult member of the farm family who fishes in the stream adjacent to the farm where biosolids are applied).

These receptors reflect the range of possible individual exposures for direct and indirect exposure pathways. Child exposures were evaluated based on an initial start age of 1 to 6 years. This age range was selected because this represents the highest consumption rate (intake/body weight) for most of the exposure pathways evaluated in this risk assessment. The child was assumed to age through a selected exposure duration; thus, because consumption rates vary over time, childhood exposures reflect a time-weighted consumption rate for the selected exposure duration.

3.1.5.2 Exposure Pathways. Environmental media and exposure pathways were modeled in this assessment for agricultural and fisher scenarios. Exposure pathways are either direct, such as inhalation of ambient air, or indirect, such as the farm food chain pathways. The exposure pathways considered in this assessment were

- Inhalation of ambient air
- Incidental ingestion of soil in the buffer
- Ingestion of above- and belowground produce grown on the cropland
- Ingestion of beef and dairy products from the pasture
- Ingestion of home-produced poultry and eggs from the buffer
- Ingestion of fish from the nearby waterbody.

3.1.6 Toxicity Assessment and Risk Characterization

The single risk characterization endpoint used in this risk assessment was the incremental individual lifetime risk of developing cancer. To characterize this risk from human exposure to dioxins, furans, and PCBs, TEFs were used with the CSFs developed for 2,3,7,8-TCDD and the congener-specific exposure assessment results. The toxicity of all other dioxin, furan, and PCB congeners was determined based on the relationship of each congener to the toxicity of 2,3,7,8-TCDD. The TEFs used in this analysis were developed by WHO and published in 1998 and are recommended for use by the Draft Dioxin Reassessment Document (U.S. EPA, 2000). These TEFs are applied to the CSF for TCDD (1.56×10^5) to determine the congener-specific health benchmarks used in this risk analysis. The congener-specific health benchmark values were linked to this single CSF because all congeners are assumed to act by the same mechanism and, therefore, can be evaluated using the TEF convention. The TEF scheme to calculate the TEQ of mixtures is currently the worldwide accepted procedure for evaluating exposure and potential health risk for dioxin-like compounds. As such, the CSF, which was developed mostly, if not solely, based on data from 2,3,7,8-TCDD, is appropriately applied using TEFs. In addition, dioxin-like congeners occur as a suite of congeners and are thus best addressed as a mixture and not as individual congeners.

3.2 Probabilistic Method for Determining Exposure Point Concentrations

The primary objective of this assessment was to estimate risk using a probabilistic (Monte Carlo) approach. The probabilistic analysis produces a nationwide distribution of risk for each receptor type by varying parameter values over multiple iterations of the model.

An overview of the probabilistic analysis follows, and this analysis method is discussed in greater detail throughout this document. The results of this analysis are presented in Section 7.0.

The probabilistic analysis was performed using a Monte Carlo simulation. In a Monte Carlo simulation, the models are run for a fixed number of iterations, each producing a single result (e.g., a single estimate of cancer risk). For this assessment, 3,000 iterations were run in the Monte Carlo simulation; therefore, the output of the probabilistic analysis was a distribution of 3,000 values. This distribution represents the distribution of possible outcomes, which

reflects the underlying variability in the data used in the analysis. These results were then used to identify risk at various percentile levels (e.g., 90^{th} percentile risk value).

Some model input parameters used in the Monte Carlo simulation were drawn from statistical distributions. For others, variability was associated with variable locations; thus, location variability was explicitly considered in the setup of the data used for the probabilistic analysis. For location-dependent parameters, locations were first selected at random with equal probability of occurrence based on the 41 climatic regions. These regions defined a set of related environmental conditions (e.g., soil type, hydrogeologic environment) that characterized the environmental setting. All location-specific parameters (e.g., rainfall) thus remained correlated while allowing variability within and among locations. Location-dependent parameters are discussed in Section 4.3.

3.3 References

U.S. DOC (Department of Commerce). 1989. *1987 Census of Agriculture, Volume 1, Geographic Area Series State and County Data*. Bureau of Census, Washington, DC.

U.S. DOC (Department of Commerce). 1994. *1992 Census of Agriculture Volume 1, Geographic Area Series State and County Data*. Bureau of the Census, Washington, DC.

U.S. EPA (Environmental Protection Agency). 2000. *Exposure and Human Health Reassessment of 2,3,7,8-Tetrachlorodibenzo-p-Dioxin (TCDD) and Related Compounds.* EPA/600/P-00/001Bg. National Center for Environmental Assessment, Office of Research and Development, Washington, DC. September.

4.0 Input Data Characterization

This risk assessment provides a national characterization of biosolids applied to agricultural fields. How this practice is characterized in terms of the physical dimensions of the farms, agricultural application practices, and climatic region is fundamental to the construction of scenarios for modeling.

The foundation for the Monte Carlo simulation is the data describing the scenario that defines each of the Monte Carlo iterations. Specifically for this analysis, 3,000 iterations were completed to define a distribution of risk for each pathway in the agricultural application scenario. Compiling the source data for this analysis required characterizing the environmental setting in which biosolids application to agricultural fields is likely to occur.

Section 4.1 presents an overview of the source data development procedure. Section 4.2 summarizes development of the biosolids management scenarios evaluated in this risk assessment. Section 4.3 presents the methodologies used to characterize the environmental setting, including delineation of the environmental setting (e.g., meteorology, climate, and soils).

4.1 Input Data Development Procedure

To capture the national variation in agricultural practices for the Monte Carlo analysis, a database of representations of agricultural practices was developed that contains all of the parameters needed to describe the application of biosolids to cropland or pasture. These source data, which provide the input data for the fate and transport modeling, are organized into two source data files, one for pastures and one for croplands. The source data files contain information on climatic region and biosolid characteristics and descriptions of agricultural practices. Agricultural application rates, frequencies, and duration for the use of biosolids on cropland and pastures were selected to be consistent with common agronomic practices.

4.2 Characterization of Biosolids

Biosolids in this risk assessment were assumed to be characterized by a single set of physical and chemical parameter values. Thus, the physical characteristics of biosolids (e.g., bulk density, percent solids, and fraction organic carbon) required to estimate emissions using the source models used the biosolids characteristics provided by EPA. If biosolid-specific physical characteristics were not available from EPA for a specific parameter, silt soil parameters were used to represent biosolids. Table 4-1 provides the biosolids characteristics used in this analysis.

Table 4-1. Physical Characteristics of Biosolids

Characteristic	Parameter Value	Units	Source
Dry bulk density (BD)	1.6	g/cm^3	*Technical Support Document for Land Application of Sewage Sludge* (U.S. EPA, 1992)
Fraction organic carbon (foc)	0.4	Unitless	
Percent solid	Variable	Volume percent	2001 NSSS (U.S. EPA, 2001)
Porosity	0.4	Unitless	Based on Carsel and Parrish (1988)
Silt content	2.2 to 21 Uniform distribution	Mass percent	Table 13.2.2-1 AP-42 (U.S. EPA, 1995a)

These characteristics, including fraction organic carbon (foc) for biosolids, remained the same for the final rule because no additional data were submitted during the comment period. No data were available to provide a variable distribution of values for the organic matter content of biosolids. If distributional data had been available for use in the analysis, the foc of biosolids could have been included as a variable parameter in the Monte Carlo analysis. Because there were no data, a single constant value was selected by EPA for use in this analysis based on best professional judgment.

Availability of dioxin-like constituents in biosolids was considered in the analysis. A high foc was assumed for biosolids (0.4); however, the foc of the soil is also important in the modeling of dioxins in biosolids applied to agricultural land. When the biosolids are applied to the land, they are assumed to be totally mixed with the soil, and the dioxins are assumed to be part of the biosolids/soil mixture. The foc of soil varied from 0.000661 to 0.249 in this analysis; this great variability was more important in the modeling of the environmental fate and transport of dioxins in biosolids than the assumed high foc of only the biosolids component of the mixture.

4.2.1 Concentrations of Dioxin and Furan Congeners

The concentrations of dioxin and furan congeners in biosolids were obtained from the NSSS 2001 (U.S. EPA, 2001). This survey analyzed more than 100 samples of biosolids for the 17 dioxin and furan congeners and 12 PCBs of concern in this risk assessment. These analytical results are presented in Appendix A of this document. The biosolids samples were obtained from 94 municipal wastewater treatment facilities. The following steps outline how the variable concentrations were selected for use in the variable concentration Monte Carlo risk analysis:

1. **Identify one representative sample for each wastewater treatment plant (WWTP) in the NSSS.** The 100 analyzed samples in the NSSS represented 94 WWTPs. For the facilities with multiple types of biosolids, multiple samples were taken and analyzed. These multiple samples were combined, based on the percentage of the total biosolids volume represented by each sample, to produce a

single weighted average concentration for each congener. This process produced a single representative sample for each congener for each facility.

2. **Select samples from the distribution.** The frequency with which a facility was selected from the distribution of sample data was weighted according to the quantity of biosolids produced by the facility. The facilities were placed into one of four strata depending on the quantity of biosolids produced at that facility. The strata were given weights of 0.0035, 0.03902, 0.23027, or 0.71921. The weighting method is the same as that used for the 1988 NSSS samples and is described in detail in Appendix B.

3. **Use the concentrations in sample selected for all congeners in the sample.** When a facility was selected, that facility's sample was used. The concentrations for each congener in the sample were thus kept correlated throughout the analysis.

4. **For congener concentrations below the analytical detection limit, use a value of one-half the analytical detection limit.** When the congener concentrations were below the minimum detection limit, a concentration equal to one-half of the detection limit was assumed.

Each iteration of the Monte Carlo analysis evaluated one sample from a single facility from the distribution of dioxin, furan, and PCB samples. Thus, each total TEQ risk result represents the total risk from all 29 congeners (17 dioxin and furan congeners and 12 PCBs). For each iteration, the concentration of dioxins in the biosolids was assumed to remain constant for the entire period of application. Thus, some iterations in this analysis represented the repeated application to agricultural land of biosolids containing up to 700 ng/kg of dioxin TEQ. Comparisons of samples for the same facility from the EPA 1988 NSSS and the EPA 2001 NSSS indicate that high dioxin TEQ concentrations in biosolids (i.e., > 100 ppt TEQ) do not appear to remain constant over time. This variability is not reflected by varying the concentration over time but is represented by varying the sample applied to the land for the duration from iteration to iteration. Thus, different concentrations are assumed applied to the same site during the risk analysis, and this addresses the variation in biosolids concentration in the risk analysis. The model does not allow the variation in the concentration from year to year during a single simulation (iteration). For this reason, the use of a constant high or very low dioxin TEQ concentration in biosolids may somewhat underestimate or overestimate the risk for those iterations.

4.2.2 Agricultural Application of Biosolids

Biosolids were assumed to be applied to agricultural land at appropriate agronomic rates. Agronomic rates vary according to soil type, crop type, biosolid characteristics, and climatic conditions. Currently, Section 503 rules limit application of biosolids based on loading of metals to the soil. For this risk assessment, the following assumptions were made about the application of biosolids. These assumptions reflect a distribution of agricultural practices common throughout the United States:

- Biosolids are applied at a rate of 5 to 10 metric tons per hectare per application (uniform distribution).
- Applications occur once every 2 years.
- Application continues for up to 40 years (20 applications).
- Cropland is tilled to a depth of 20 cm multiple times during the year.
- Pastureland is not tilled; thus, biosolids are assumed to be incorporated into only the top 2 of soil.

The application frequency of biosolids to the soil is considered constant. In this analysis, biosolids were assumed applied to the soil once every other year for variable periods of up to 40 years. The period of biosolids application, the rate of application, and the exposure duration for the farm family were variable and were assumed to be independent; however, the exposure period was constrained to begin during the period of application of biosolids to the agricultural land. The farm family was assumed either to begin exposure any time from the time of the first application of biosolids, or to move to a farm where biosolids have been applied by a previous owner and to be present only for the last application of biosolids. All farmers were assumed to continue to live on the farm after biosolids applications ceased and continue the same land use patterns for the duration of their exposure period. These are realistic but protective assumptions. The farm family's diet was assumed to be composed to a significant extent of items that were home produced on the family's own biosolids-amended fields. Therefore, when average values were selected for certain parameters in the assessment of this high-end scenario, the risk assessment itself remained conservative. In cases where distributions of parameters could be justified, distributions were used for those parameters. It was only when no distributions were available that single average or representative values were selected for use.

The predicted concentrations in food products were compared to background levels reported in the Draft Dioxin Reassessment Document (U.S. EPA, 2000) to facilitate comparison of levels of exposure with background levels.

Application rates for biosolids were not varied with location in this analysis and were assumed to be uniform nationwide. No data were available on the variation in biosolids application rates for specific crops or regions. If these data had been available, they would have been considered in the analysis. The assumptions regarding application rates are assumed to represent the range of realistic agronomic practices; thus, this is not a worst-case scenario but represents a reasonable high-end exposure scenario on the farm where biosolids are applied.

4.3 Site Characterization

The site characteristics used in this analysis were based on one conceptual site layout and regional characterization of environmental parameters. The conceptual site layout defines the area in the immediate vicinity of the farm applying biosolids and defines the geographic relationship among important features, such as the cropland, pasture, residence, chicken yard,

and stream. A single conceptual site layout was evaluated at each of the 41 climatic regions in the analysis.

4.3.1 Conceptual Site Layouts

This risk assessment was based on a conceptual site layout rather than on site-specific layouts. The conceptual site layout was designed to capture possible relationships between management practices for biosolids and individual receptors.

The conceptual or general site layouts are shown in Figure 3-1, which shows the agricultural field, the buffer area (i.e., an area between the agricultural field and the stream or the monofill), and the residence.

The agricultural field area was assumed to be the median area for farms in each climatic region. The agricultural field sizes were taken from the county-level data provided in the Census of Agriculture. The Census of Agriculture (U.S. DOC, 1989, 1994) provides periodic and comprehensive statistics about agricultural operations, production, operators, and land use. It is conducted every 5 years for years ending in 2 and 7. Its coverage includes all operators of U.S. farms or ranches (Division A, SIC 01-02) that sold or normally would have sold at least $1,000 worth of agricultural products during the census year. In 1992, approximately 1.9 million operators produced $162 billion in crops and livestock. Data for 1987 and 1992 were averaged. The median farm size was determined for all counties in each of the 41 climatic regions. From this distribution, the median farm size for each climatic region was determined. No data on field size were available. The agricultural field sizes used in this analysis are presented in Table 4-2. The farm size was important in this analysis for the air dispersion and deposition and soil erosion pathways. The larger the source, the greater the off-site concentrations due to air deposition and erosion.

Adjacent to the farm is a waterbody that is assumed to be 5.5 m wide and 0.21 m deep. These values are typical of a third-order stream (van der Leeden et al., 1990). The stream length is determined by the width of the agricultural field. Surface area of the stream is, therefore, determined by the fixed width (5.5 m) and the size of the farm, which varies by climatic region as described above. The fishing scenario estimated risks to adult fishers who caught and consumed fish on a recreational basis from this waterbody.

4.3.2 Regional Environmental Setting

The regional environmental setting approach was developed as a way to include the variability associated with geographic locations throughout the United States. The boundaries of the climatic regions used in this analysis were drawn to circumscribe areas that could be represented by a single set of climatic data. The boundaries considered geographic boundaries, such as mountains, and other parameters that differentiate meteorological conditions (rainfall, temperature, windspeed). A description of the selection of the climatic regions and the representative meteorological stations is presented in Appendix M. However, once the boundaries of the climatic regions were drawn, other data associated with geographic location were linked to the climatic region designations. For example, soil characteristics also vary by

Table 4-2. Median Farm Size for Each Climatic Region

Climatic Region Name (Selected Met. Station)	Median Farm Size (Acres)
Seattle	40.10
Boise	194.40
Billings	1241.70
Burlington	159.20
Portland	98.20
Bismarck	923.80
Minneapolis	208.60
Salem	44.60
Muskegon	117.10
Chicago	177.60
Cleveland	109.20
Winnemucca	162.30
Casper	829.60
Hartford	50.00
San Francisco	39.80
Williamsport	127.10
Salt Lake City	143.50
Fresno	46.80
Lincoln	282.20
Philadelphia	39.00
Denver	738.00
Harrisburg	102.80
Norfolk	97.50
Huntington	86.70
Raleigh-Durham	85.40
Nashville	94.40
Asheville	55.40
Las Vegas	97.60
Little Rock	159.10
Tulsa	184.00
Albuquerque	464.30
Los Angeles	24.20
Charleston	80.40
Atlanta	105.90
Phoenix	339.70
Meridian	123.00
Shreveport	110.90
New Orleans	90.90
Houston	123.50
Miami	39.60
Tampa	67.00

geographic location, and this variability is reflected using a regional environmental setting approach. Another variable that is associated with location, but not directly linked to climate or soil conditions, is farm size. Farms in the more densely populated eastern part of the United States are much smaller than farms and ranches in the less densely populated western portion of the country. This variation was also included by using the regional environmental setting approach, which keeps correlated the conditions that are likely to occur together and prevents implausible combinations from being chosen during a random selection process. Using this approach, the climatic region was randomly selected, but all other data were selected to be consistent with conditions in that geographic location.

A meteorological station was selected to represent each of the 41 climatic regions. All meteorological stations within each climatic region were assumed to be representative of the entire region. The selected meteorological stations are listed in Table 4-2. Each climatic region was equally weighted in the probabilistic analysis.

4.3.2.1 Meteorological Data. Five years of representative meteorological data were processed for this analysis. The data gathered included surface data, upper-air data, and precipitation data. These observational data were used as Industrial Source Complex, Short-Term Model, version 3 (ISCST3), inputs.

Surface Data. Hourly surface meteorological data used in air dispersion modeling were processed from the Solar and Meteorological Surface Observation Network (SAMSON) CD-ROM (U.S. DOC and U.S. DOE, 1993). Variables included

- Temperature
- Pressure
- Wind direction
- Windspeed
- Opaque cloud cover
- Ceiling height
- Current weather
- Hourly precipitation.

Upper-Air Data. Twice-daily mixing-height data were calculated from upper-air data contained in the radiosonde data of the North America CD-ROM set (NCDC, 1997). This set contains upper-air data from 1946 through 1996 for most upper-air stations in the United States. The upper-air data were combined with the SAMSON data to create the mixing-height files. EPA's Support Center for Regulatory Air Models (SCRAM) bulletin board was also used to obtain mixing-height data (if available) when mixing-height data could not be successfully calculated from the radiosonde data. The mixing heights used in this risk assessment, however, were not fixed at a low level, but were variable based on hourly meteorologic observations used in the ISCST3 air model. Mixing heights based on the observed ceiling were well above the height of any fruit tree.

Filling in Missing Data. Missing surface data were identified using a program called SQAQC, which searched for incidents of missing data on the observation indicator, opaque cloud cover, temperature, station pressure, wind direction and speed, and ceiling height. Years

that were missing 10 percent or more of the data were discarded (Atkinson and Lee, 1992). Verification (quality control or QC) checks were performed on the SQAQC program by applying it to station data where the missing data were known and by intentionally degrading surface meteorological files and then running SQAQC to detect the missing values.

Missing surface data were filled in by a program called METFIX. This program fills in up to 5 consecutive hours of data for cloud cover, ceiling height, temperature, pressure, wind direction, and windspeed. For single missing values, the program follows the objective procedures developed by Atkinson and Lee (1992). For two to five consecutive missing values, other rules were developed because the subjective methods provided by Atkinson and Lee (1992) rely on professional judgment and could not be programmed. The METFIX program flagged files where missing data exceeded five consecutive values. In the few cases where this occurred and the missing data did not constitute 10 percent of the file, they were filled in manually according to procedures set forth in Atkinson and Lee (1992). If more than 10 percent of the data were missing, the station was discarded and another station in the climatic region was selected.

All upper-air files were checked for missing data using a program called QAQC. QAQC produces a log file containing occurrences of missing mixing height. Verification (QC) checks were performed on the QAQC program by applying it to station data where the missing data were known and by intentionally degrading existing mixing height files and then running QAQC to detect the missing values.

Missing mixing heights were filled in by running the files through another program written to interpolate one to five consecutive missing values. According to Atkinson and Lee (1992), if there are one to five consecutive missing values, the values should be filled in subjectively using professional judgment. Again, programming these subjective procedures was not feasible, and the program used simple linear interpolation to fill in these values automatically. Information from Atkinson and Lee (1992) was used to determine which files should be discarded (i.e., files missing more than five consecutive missing values or missing 10 percent or more of the data). After the missing mixing heights were filled in for all upper-air files, they were checked once more for missing data using the QAQC program.

Other Meteorological Data. In addition to the surface and upper-air data, air modeling requires the input of the following meteorological parameters (U.S. EPA, 1995b):

- Minimum Monin-Obukhov length (m)
- Anemometer height (m)
- Roughness length (m), surface meteorological station
- Roughness length (m), area around facility
- Noontime albedo
- Bowen ratio
- Anthropogenic heat flux (W/m^2)
- Fraction net radiation absorbed by the ground.

Anemometer height was collected from local climatic data summaries (NOAA, 1983). When anemometer height was not available, the station was assigned the most common anemometer height from the other stations. This value was 6.1 m.

Land use information is required for determining a number of inputs. To obtain this information, a geographic information system (GIS) was used to determine the land use within a 3 km radius around each meteorological station by using Geographic Retrieval and Analysis System (GIRAS) spatial data with Anderson land use codes (Anderson et al., 1976). Table 4-3 shows how the Anderson land use codes were related to PCRAMMET land use codes.

A weighted average, based on the land use percentages for a 3 km radius around each meteorological station, was used to estimate the Bowen ratio, minimum Monin-Obukhov length, the noontime albedo, the roughness height at the meteorological station, and the fraction of net radiation absorbed by the ground.

The Bowen ratio is a measure of the amount of moisture at the surface around a meteorological station. The wetness of a location was determined based on the annual average precipitation amount. The range of values is provided in Table 4-4 as a function of land use type, season, and moisture condition. For this analysis, the annual average values were applied.

The minimum Monin-Obukhov length, a measure of the atmospheric stability at a meteorological station, was correlated with the land use classification, as shown in Table 4-5.

Noontime albedo values also were correlated with land use around a meteorological station, as shown in Table 4-6.

The surface roughness length is a measure of the height of obstacles to the wind flow. It is not equal to the physical dimensions of the obstacles but is generally proportional to them. Surface roughness length data are shown in Table 4-7 along with their corresponding land use. The roughness height was assumed to be the same at the meteorological station and at the farm site.

Table 4-3. Relation between Anderson Land Use Codes and PCRAMMET Land Use Codes

Anderson Code and Description[a]		PCRAMMET Type and Description[b]	
51	Streams and canals	1	Water surface
52	Lakes	1	Water surface
53	Reservoirs	1	Water surface
54	Bays and estuaries	1	Water surface
41	Deciduous forest land	2	Deciduous forest
61	Forested wetland	2	Deciduous forest
42	Evergreen forest land	3	Coniferous forest

(continued)

Table 4-3. (continued)

Anderson Code and Description[a]		RAMMET Type and Description[b]	
43	Mixed forest land	4	Mixed forest
62	Nonforested wetland	5	Swamp (nonforested)
84	Wet tundra	5	Swamp (nonforested)
21	Cropland and pasture	6	Agricultural
22	Orchards-groves-vineyards-nurseries-ornamental	6	Agricultural
23	Confined feeding operations	6	Agricultural
24	Other agricultural land	6	Agricultural
31	Herbaceous rangeland	7	Rangeland (grassland)
32	Shrub and brush rangeland	7	Rangeland (grassland)
33	Mixed rangeland	7	Rangeland (grassland)
11	Residential	9	Urban
12	Commercial and services	9	Urban
13	Industrial	9	Urban
14	Transportation-communication-utilities	9	Urban
15	Industrial and commercial complexes	9	Urban
16	Mixed urban or built-up land	9	Urban
17	Other urban or built-up land	9	Urban
71	Dry salt flats	10	Desert shrubland
72	Beaches	10	Desert shrubland
73	Sandy areas not beaches	10	Desert shrubland
74	Bare exposed rock	10	Desert shrubland
75	Strip mines-quarries-gravel pits	10	Desert shrubland
76	Transitional areas	10	Desert shrubland
81	Shrub and brush tundra	10	Desert shrubland
82	Herbaceous tundra	10	Desert shrubland
83	Bare ground	10	Desert shrubland
85	Mixed tundra	10	Desert shrubland
91	Perennial snowfields	10	Desert shrubland
92	Glaciers	10	Desert shrubland

[a] Anderson codes from Anderson et al. (1976).
[b] PCRAMMET codes from U.S. EPA (1995b).

Table 4-4. Daytime Bowen Ratio by Land Use and Season

	Spring			Summer			Autumn			Winter			Annual Average		
Land Use Type	**Dry**	**Wet**	**Avg.**	**Dry**	**Wet**	**Avg.**	**Dry**	**Wet**	**Avg.**	**Dry**	**Wet**	**Avg.**	**Dry**	**Wet**	**Avg.**
Water surface	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	2.0	0.3	1.5	0.575	0.15	0.45
Deciduous forest	1.5	0.3	0.7	0.6	0.2	0.3	2.0	0.4	1.0	2.0	0.5	1.5	1.53	0.35	0.875
Coniferous forest	1.5	0.3	0.7	0.6	0.2	0.3	1.5	0.3	0.8	2.0	0.3	1.5	1.4	0.275	0.825
Swamp	0.2	0.1	0.1	0.2	0.1	0.1	0.2	0.1	0.1	2.0	0.5	1.5	0.65	0.2	0.45
Cultivated land (agricultural)	1.0	0.2	0.3	1.5	0.3	0.5	2.0	0.4	0.7	2.0	0.5	1.5	1.63	0.35	0.75
Grassland	1.0	0.3	0.4	2.0	0.4	0.8	2.0	0.5	1.0	2.0	0.5	1.5	1.75	0.425	0.825
Urban	2.0	0.5	1.0	4.0	1.0	2.0	4.0	1.0	2.0	2.0	0.5	1.5	3.0	0.75	1.6
Desert shrubland	5.0	1.0	3.0	6.0	5.0	4.0	10.0	2.0	6.0	10.0	2.0	6.0	7.75	2.5	4.75

Source: U.S. EPA (1995b). Averages were computed for this effort.

Table 4-5. Minimum Monin-Obukhov Length (Stable Conditions)

Urban Land Use Classification	Length (m)
Agriculture (open)	2
Residential	25
Compact residential/industrial	50
Commercial (19–40 story buildings) (> 40 story buildings)	100 150

Source: U.S. EPA (1995b).

Table 4-6. Albedo Values of Natural Ground Covers for Land Use Types and Seasons

Land Use Type	Spring	Summer	Autumn	Winter	Annual Average
Water surface	0.12	0.1	0.14	0.2	0.14
Deciduous forest	0.12	0.12	0.12	0.5	0.22
Coniferous forest	0.12	0.12	0.12	0.35	0.18
Swamp	0.12	0.14	0.16	0.3	0.18
Cultivated land (agricultural)	0.14	0.2	0.18	0.6	0.28
Grassland	0.18	0.18	0.20	0.6	0.29
Urban	0.14	0.16	0.18	0.35	0.21
Desert shrubland	0.3	0.28	0.28	0.45	0.33

Source: U.S. EPA (1995b). Average values were computed for this analysis.

Table 4-7. Surface Roughness Length for Land Use Types and Seasons (meters)

Land Use Type	Spring	Summer	Autumn	Winter	Annual Average
Water surface	0.0001	0.0001	0.0001	0.0001	0.0001
Deciduous forest	1.0	1.3	0.8	0.5	0.9
Coniferous forest	1.3	1.3	1.3	1.3	1.3
Swamp	0.2	0.2	0.2	0.05	0.16
Cultivated land (agricultural)	0.03	0.2	0.05	0.01	0.07
Grassland	0.05	0.2	0.01	0.001	0.04
Urban	1.0	1.0	1.0	1.0	1.0
Desert shrubland	0.3	0.3	0.3	0.15	0.26

Source: U.S. EPA (1995b). Average values were computed for this analysis.

During daytime hours, the heat flux into the ground is parameterized as a fraction of the net radiation incident on the ground. This fraction varies based on land use. A value of 0.15 was used for rural locations. Suburban and urban locations were given values of 0.22 and 0.27, respectively (U.S. EPA, 1995b).

Anthropogenic heat flux for a meteorological station can usually be neglected in areas outside of highly urbanized locations; however, in areas with high population densities or energy use, such as an industrial facility, this flux may not always be negligible (U.S. EPA, 1995b). For this analysis, anthropogenic heat flux was assumed to be zero for all meteorological stations.

4.3.2.2 Meteorological Data. Meteorological stations selected for purposes of air dispersion modeling also provided long-term climatic data that were necessary for fate and transport modeling. For each of the 41 stations, the following data were compiled:

- Mean annual wind direction
- Mean annual windspeed
- Average temperature
- Average annual runoff
- Universal Soil Loss Equation (USLE) rainfall/erosivity factor.

4.3.2.3 Soil Characterization. The fate and transport models used in the biosolids risk assessment require surface soil properties to model erosion and overland transport and properties of the entire soil column. A regional approach was also used to compile soil data for these modeling requirements. All land with agricultural use was used to characterize the soils within the 41 climatic regions. This regional characterization of soil types captured variability in soils in a manner that is generally representative of agricultural lands across the United States. A GIS was used to compile soil texture and other soil data within each climatic region. Then, database programs processed these data to create a distribution of input variables required by the models.

Data Sources. The primary data source for soil properties is the State Soil Geographic (STATSGO) database. STATSGO is a repository of nationwide soil properties primarily compiled by the U.S. Department of Agriculture (USDA) from county soil survey data (USDA, 1994). STATSGO includes a 1:250,000-scale GIS coverage that delineates soil map units, and an associated database containing soil data for each STATSGO map unit. (Map units are areas used to spatially represent soils in the database.)

In addition, two compilations of STATSGO data, each keyed to the STATSGO map unit GIS coverage, were used in the analysis as a convenient source of average soil properties:

- **USSOILS.** USSOILS (Schwarz and Alexander, 1995) averages STATSGO data over the entire soil column for each map unit.

- **CONUS.** CONUS (Miller and White, 1998) provides average STATSGO data by map unit and a set of 11 standardized soil layers.

- **GIRAS.** The GIRAS land use database (U.S. EPA, 1994) provides comprehensive land use data, in digital GIS format, for the contiguous 48 states.

Soil properties derived directly from STATSGO, CONUS, or USSOILS data include organic matter content, USLE *K* (erodibility) and *S* (slope) factors, and pH. A complete set of

hydrologic soil properties[1] was not available from STATSGO. To ensure consistent and realistic values, it was necessary to rely on established, nationwide relationships between hydrologic properties and soil texture or hydrologic soil group, both of which are available from STATSGO. Sources for these relationships include Carsel and Parrish (1988), Carsel et al. (1988), and Clapp and Hornberger (1978). These peer-reviewed references provide a consistent set of correlated hydrologic properties for each soil texture or hydrologic group.

Finally, two parameters—root zone depth and Soil Conservation Service (SCS) curve number (used for recharge calculations)—required site-based land use data, as well as soil texture or hydrologic soil group. The land use data were obtained for each of the 41 climatic regions from the GIRAS land use database (U.S. EPA, 1994). GIRAS provides comprehensive land use data, in digital GIS format, for the contiguous 48 states. Land use/land cover information in GIRAS was mapped and coded using the Anderson classification system (Anderson et al., 1976), which is a hierarchical system of land use characterizations. This nationwide coverage is based on late-1970s to early-1980s satellite images and aerial photography. The relationships used to convert the land use and soil data were obtained from Dunne and Leopold (1978) for root zone depth and USDA (1986) for the SCS curve number.

Methodology. The soil data collection methodology begins with GIS programs (in Arc Macro Language (AML)) that overlay the boundaries of the 41 climatic regions on the STATSGO map unit coverage to determine the STATSGO map units and their area within the regions. These data are then passed to data processing programs that derive predominant soil properties within each climatic region, either through direct calculations or by applying established relationships in lookup tables. In deriving soil model inputs, the biosolids soil data processing effort bases all collected soil properties on the predominant soil type (texture and hydrologic group) for the STATSGO map units having agricultural land use within each climatic region. Depending on modeling requirements, soil properties were derived for surface soils (top 20 cm), the entire soil column (to represent the vadose zone), or both, as shown in Table 4-8.

To ensure consistent, realistic properties, the soil data processing effort bases all collected soil properties on the predominant soil texture for each STATSGO map unit. For each STATSGO map unit within a meteorological station region, predominant texture was determined both for surface soils (top 20 cm) and the entire soil column (to represent the vadose zone) from CONUS data. For surface soils, the predominant texture is the thickest, weighted by depth, soil texture for the top three CONUS layers (20 cm). Where there was a tie, the texture of the top two layers was used as the predominant soil texture for that map unit. Twelve common soil textures were collected to develop hydrologic properties (Table 4-9). Map units that did not have one of the 12 common soil textures (e.g., those with water or organic matter) were excluded from the analysis. Soil column texture was obtained in a similar manner, except that all CONUS layers were used.

[1] Hydrologic soil properties required for modeling include bulk density, saturated water content, residual water content, field moisture content, wilting point, saturated hydraulic conductivity, soil moisture coefficient *b*, and soil moisture retention parameters alpha and beta.

Table 4-8. Summary of Soil Properties Collected for Biosolids Risk Analysis

Soil Variable	Units	Data Source
Properties Derived from Soil Texture		
USDA soil texture	Unitless	CONUS/STATSGO
Saturated hydraulic conductivity	cm/h	Relationship from Carsel and Parrish (1988)
Saturated water content	L/L	Relationship from Carsel and Parrish (1988)
Soil moisture coefficient *b*	Unitless	Relationship from Clapp and Hornberger (1988)
Soil bulk density	mg/L	Calculated from saturated water content
Root zone depth	cm	Relationship (with land use) from Dunne and Leopold (1978)
Properties Derived from Soil Hydrologic Class		
SCS hydrologic class	Unitless	CONUS/STATSGO
Field capacity	% (vol.)	Relationship from Carsel et al. (1988)
Wilting point	% (vol.)	Relationship from Carsel et al. (1988)
SCS curve number	Unitless	Relationship (with land use) from USDA (1986)
Properties Obtained Directly from STATSGO		
Fraction organic carbon	g/g	STATSGO
Silt content	% (wt.)	STATSGO
USLE erodibility factor (*K*)	kg/m^2	STATSGO
USLE slope (*S*)	Degrees	STATSGO
Properties Derived from Slope		
USLE slope length (*L*)	m	Relationship from Lightle and Weesies (1998)
USLE length/slope factor (*LS*)	Unitless	Calculated from *L* and *S* per Williams and Berndt (1977)

To limit data collection to agricultural soils, GIS programs (in AML) were used to overlay the STATSGO map unit GIS coverage with the GIRAS land use GIS coverage and then determine the map units (and their respective areas) that occur in cropland use and pastureland use (i.e., Anderson land use code 21) within each meteorological region. These data were then processed to create a set of the 12 soil textures, ranked by percentage of cropland and pastureland with each texture, for each region. These textures were used to derive soil properties for this analysis for each region/texture combination as described in the next section. These properties were then passed on to the model in Access database tables indexed by meteorological station and soil texture.

Because certain soil properties were derived from SCS hydrologic soil groups, it was necessary to develop a hydrologic soil group that would be consistent with the soils of each

texture within a region. To do so, a table of hydrologic soil groups by STATSGO map unit was created using STATSGO data for hydrologic soil groups by the component soils within the map unit. Based on the predominant texture for each map unit, hydrologic soil groups for the component soils with the same texture were averaged across each map unit (weighted by component percent) using the numeric conversion: group A = 1, group B = 2, group C = 3, and group D = 4. These values were then averaged again (weighted by map unit area) for each soil texture occurring in a region. After this regional average by texture was calculated, the numbers were converted back to letters using the same conversion, resulting in a hydrologic soil group for each texture occurring within a meteorologic region. Note that hydrologic soil group applies to the entire soil column and is not layer-specific.

Development of Soil Properties. Once the distribution of soil textures and their related hydrologic class was determined for each meteorological region, average soil properties were determined for each soil texture present in a region by relationships with soil texture or hydrologic class or by extracting the data for soils of each texture directly from STATSGO.

Soil Properties Based on Relationship with Predominant Texture—Several soil hydrologic properties were derived directly from the predominant texture using database lookup tables relating mean properties to texture class (see Table 4-9). Tables 4-9 through 4-11 summarize the relationships used, which are described below.

- **Saturated hydraulic conductivity (cm/h)** was determined for both surface soil (*Ksat_top20*) and the entire soil column (*VadSATK*) using a national relationship from Carsel and Parrish (1988) (Table 4-9).

- **Saturated water content (unitless)** was determined for both surface soil (*WCS_top20*) and the entire soil column (*VadWCS*) using a relationship from Carsel and Parrish (1988) (Table 4-9).

- **Bulk density (g/cm^3)** was calculated for surface soil (*BD_top20)* from saturated water content using the equation

$$\rho_b = 2.65(1 - \phi) \qquad (4\text{-}1)$$

where

ρ_b = bulk density of the soil (U.S. EPA, 1997)
2.65 = particle density in g/cm^3 (assumed to be quartz)
ϕ = saturated water content.

- **Soil moisture coefficient (unitless)** was determined for both the surface soil (*SMb_top20*) and the entire soil column (*SMb_sub*) using a relationship from Clapp and Hornberger (1978) (Table 4-9).

Table 4-9. Hydrological Soil Parameters Correlated to Soil Texture

Soil Texture	Saturated Hydralic Conductivity *Ksat*[a] (cm/h)	Storated Water Content *WCS*[a] (L/L)	Bulk Density ρB[b] (g/cm^3)	Soil Moisture Coefficient *b* *SMb*[c]
Clay (C)	0.20	0.38	1.643	11.4
Clay loam (CL)	0.26	0.41	1.5635	8.52
Loam (L)	1.04	0.43	1.5105	5.39
Loamy sand (LS)	14.59	0.41	1.5635	4.38
Silt (SI)	0.25	0.46	1.431	--
Silt loam (SIL)	0.45	0.45	1.4575	5.30
Silty clay (SIC)	0.02	0.36	1.696	10.4
Silty clay loam (SICL)	0.07	0.43	1.5105	7.75
Sand (S)	29.70	0.43	1.5105	4.05
Sandy clay (SC)	0.12	0.38	1.643	10.4
Sandy clay loam (SCL)	1.31	0.39	1.6165	7.12
Sandy loam (SL)	4.42	0.41	1.5635	4.90

[a] Carsel and Parrish (1988).
[b] Calculated from *WCS* using equation from U.S. EPA (1997).
[c] Clapp and Hornberger (1978).

Depth to root zone (cm) was determined using a Dunne and Leopold (1978) table of rooting depth by vegetation type and soil texture (Table 4-10). For each soil texture, a minimum and a maximum root zone depth (for shallow and deep-rooted crops) were used to represent the range across cropland and pastureland use. Because Dunne and Leopold included only five soil textures, these five textures were mapped across the 12 basic textures used in this analysis as shown in Table 4-10.

Soil Parameters Based on Relationship with Hydrologic Group—The following soil parameters are all based on the average hydrologic soil group for each texture within a meteorological region. Mean values by hydrologic group were obtained using the following relationships:

- **Soil moisture field capacity (volume %).** A single field capacity value (*SMFC*) was obtained by hydrologic soil group by averaging the layered property values from Carsel et al. (1988). Table 4-11 presents the mean value for field capacity by hydrologic soil group and layer, as well as the average values used in this analysis.

- **Soil moisture wilting point (volume %).** A single wilting point value (*SMWP*) was obtained by hydrologic soil group by averaging the layered property values from Carsel et al. (1988). Table 4-11 lists the mean value for wilting point by hydrologic soil group and layer, as well as the average values used in this analysis.

Table 4-10. Depth to Root Zone Values

USDA Soil Texture	Dunne and Leopold Texture	Shallow-Rooted Crops (*DRZ_Min*, cm)	Deep-Rooted Crops (*DRZ_Max*, cm)
Sand	Fine sand	50	100
Loamy sand	Fine sandy loam	50	100
Sandy loam			
Silt	Silt loam	62	125
Silt loam			
Loam			
Sandy clay loam	Clay loam	40	100
Silty clay loam			
Clay loam			
Sandy clay	Clay	25	67
Silty clay			
Clay			

Source: Dunne and Leopold (1978).

Table 4-11. Field Capacity (FC) and Wilting Point (WP) Values

Hydrologic Group	Layer	FC	WP
A	1	9.4	3.1
	2	8.1	2.3
	3	5.9	2.1
	4	5.8	1.9
	Avg.	*7.3*	*2.4*
B	1	19.1	8.7
	2	18.8	9.3
	3	18.7	8.9
	4	17.5	8.4
	Avg.	*18.5*	*8.8*

(continued)

Table 4-11. (continued)

Hydrologic Group	Layer	FC	WP
C	1	22.5	10.4
	2	23.2	12.1
	3	22.9	11.9
	4	21.3	11.5
	Avg.	*22.5*	*11.5*
D	1	24.2	13.8
	2	26.3	17.0
	3	25.6	16.3
	4	24.4	15.1
	Avg.	*25.1*	*15.6*

Source: Carsel et al. (1988).

- **SCS curve number (unitless).** Minimum and maximum SCS curve number values (*CN_min* and *CN_max*) were determined for each regional soil texture based on a USDA (1986) table of curve numbers by cover type and hydrologic soil group, assuming a good condition pastureland use for *CN_min* and poor condition cropland use for *CN_max*. A lookup table (Table 4-12) with minimum and maximum SCS curve numbers by hydrologic soil group was used to assign the appropriate value for each regional soil texture according to its hydrologic soil group.

Table 4-12. SCS Curve Number Values by SCS Hydrologic Soil Group

SCS Hydrologic Soil Group	SCS Curve Number	
	CN_Min (Pasture)	CN_Max (Cropland)
A	39	72
B	61	81
C	74	88
D	80	91

Source: Derived from USDA (1986).

Parameters Collected Directly from STATSGO-Based Data Sources—Several variables were obtained directly from STATSGO (Schwarz and Alexander, 1995). Although they are not derived from soil texture, they were extracted and averaged based only on soil map units with the predominant texture to ensure consistent soil properties.

- **USLE erodibility factor—top 20 cm** (ton/acre). An area-weighted average erodibility factor for the top 20 cm of soil (*K_top20*) was calculated from STATSGO data by layer and component. STATSGO layer data were translated into *K* values using standardized CONUS layers and calculating a depth-weighted average value. Further, a component percent-weighted average *K* was calculated for each CONUS layer across all components contained in each map unit. The resulting table contains *K* values by map unit and standardized CONUS layer. To get one value for *K* by map unit for the top 20 cm of soil, a depth-weighted average for the top three CONUS layers was calculated. The final *K* value by meteorological region and soil texture was obtained by averaging the map units for each surface soil texture present within the meteorological region.

- **Fraction organic carbon—top 20 cm** (mass fraction). An area-weighted average foc for surface soils (*foc_top20*) was calculated for each region and soil texture using only the map units with the predominant surface soil texture of interest within the region. Percent organic matter for the top 20 cm of soil was obtained from STATSGO organic matter data by layer and component (Schwarz and Alexander, 1995) and converted to foc by dividing by 174 (100 × 1.74 g organic matter/g organic carbon) (U.S. EPA, 1997). Percent organic matter values were translated from STATSGO layer and component into standardized CONUS layers using the same methodology described for the USLE erodibility factor *K*. Then, a depth-weighted average percent organic matter was calculated for the top three CONUS layers (top 20 cm of soil).

- **Silt content—top 20 cm** (weight percent). An area-weighted average silt content for surface soils (*Ss_top20*) was derived from STATSGO data for each region and soil texture in the same manner described for USLE erodibility factor.

The USLE's length slope factor (*LS*) was derived from STATSGO slope data. Percent slope (*Theta*) was obtained by region and soil texture by using only the map units with the predominant texture of interest. An area-weighted average slope was calculated for each texture occurring in a region. Length (*Length*, ft) was then obtained from a Lightle and Weesies (1998) lookup table of default flow lengths by slope, using slope values rounded to the nearest integer (Table 4-13). All slopes less than 0.5 were given the length corresponding to 0.5 and all slopes greater than 24 were given the length corresponding to 24. The USLE length/slope factor *LS* (unitless) was then calculated using the equation from Williams and Berndt (1977):

$$LS = (L/72.6)^{m}(0.065 + 0.0454S + 0.0065S^{2}) \quad (4\text{-}2)$$

where

L = flow length
S = slope in percent

and

m = 0.2 for slope <1 percent
m = 0.3 for slope ≥1 percent and <3 percent
m = 0.4 for slope ≥3 percent and <5 percent
m = 0.5 for slope ≥5 percent.

One basic type of source was evaluated in this assessment: land application of biosolids to cropland or pastures. It was necessary to determine the physical characteristics of the farm where biosolids were assumed to be applied and the operating parameters used for that application for the air dispersion modeling and source partition modeling. First, representative agricultural field sizes were identified. To identify a representative farm size for each climatic region, the median farm size in each county within a climatic region was determined from the Census of Agriculture (U.S. DOC, 1989, 1994). Then, the median farm sizes for each county within each of the 41 climatic regions were ranked and the median farm size for each climate region was selected. The farm was assumed to devote one-half of its area to raising crops and one-half to pasturing cattle. In the hypothetical farm scenario used as the basis for modeling, the proportion of land devoted to crops or pastures was not intended to reflect the actual percentage of land used for each purpose. It was intended to ensure that both pastureland and cropland are adequately assessed in each geographical region. The crop scenario and the pasture scenario may be considered independently or together in this risk assessment. This assessment was an assessment of individual risk and was not intended to be used as the basis for calculating risk to a population of receptors.

Table 4-13. Default Flow Lengths by Slope

Slope	Length (ft)	Slope	Length (ft)
≤0.5	100	13	90
1	200	14	80
2	300	15	70
3	200	16	60
4	180	17	60
5	160	18	50
6	150	19	50
7	140	20	50
8	130	21	50
9	125	22	50
10	120	23	50
11	110	≥24	50
12	100		

Source: Lightle and Weesies (1998).

Next, 3,000-record source data files were constructed for use in the probabilistic analysis. These files were constructed by combining the environmental setting data, agricultural practice data, and the biosolids characterization data using the following steps:

- Select one of the 41 climatic regions (each region was assumed to be equally likely)
- Select data associated with the selected climatic region (farm size, soil data, meteorologic data)
- Select agricultural practice data independent of climatic region (application rate, frequency, and number of applications)
- Select biosolids characteristics (independent of climatic region and agricultural practice).

Two source data files were generated in this manner: one for cropland and one for pastures. Each of the 3,000 records in each of the source data files was identified by a model run identification number.

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5.0 Estimating Exposure Point Concentrations

Exposure point concentrations are constituent concentrations at the location in the environment at which an individual may be exposed. To determine constituent concentrations in environmental media (e.g., air or soil) with which a receptor comes in contact, several computer-based models and sets of equations are used:

- Source partition models
- Fate and transport models
- Farm food chain equations
- Aquatic food chain equations.

The agricultural application of biosolids evaluated in this risk assessment is described in Section 4.0. Dioxins, furans, and coplanar PCBs found in biosolids are released from these agricultural applications into the environment. Releases to the atmosphere occur through volatilization or wind erosion of particles. Releases from the agricultural field may also occur through erosion of soil particles onto the residential plot and, subsequently, into a nearby stream. The constituents may move into the human food chain by contaminating fruits, vegetables, poultry, eggs, beef, milk, and fish consumed by humans.

This risk analysis was performed in a probabilistic format. Section 3.0 explains the risk assessment framework, including the structure of the probabilistic analysis. The current section describes the models and algorithms used for the risk analysis. In the probabilistic analysis, specified model input parameter values were varied in each of 3,000 iterations to generate a distribution of media concentrations.

The following subsections describe the models and equations used in this risk assessment and their application. Section 5.1 describes the source partition models used to predict environmental releases of constituents from the biosolids. Section 5.2 discusses the air dispersion and deposition modeling and methodologies used to estimate concentrations of constituent releases used in the human health risk analysis. Section 5.3 discusses the methodology for calculating food chain concentrations based on air, soil, and water concentrations. Section 5.4 discusses infant exposure to contaminants through breast milk.

Greater detail on the modeling performed for this risk analysis is provided in appendices to this document:

- Appendix F, Source Model for Land Application Unit. This appendix explains the source partition model used in this risk assessment.

- Appendix G, Air Dispersion and Deposition Modeling. This appendix provides details, including all input data files, used in the air dispersion and deposition modeling for this risk assessment.

- Appendix H, Direct and Indirect Exposure Equations. This appendix documents the algorithms used to calculate exposure point concentrations for the surface water sediment, terrestrial food chain, and aquatic food chain.

- Appendix I, Variables for Aboveground Fate and Transport. This appendix presents and references the input values or distributions used in the algorithms presented in Appendix H.

5.1 Source Partition Modeling of Constituent Releases

5.1.1 Land Application Unit Partitioning Model Used for Agricultural Fields

Fate and transport of chemicals within the agricultural fields and chemical emissions from these fields to surrounding media were simulated using adaptations of the Land Application Unit (LAU) model. The LAU model was used in two slightly different versions for this biosolids risk assessment—one version representing the crop agricultural field, and the second representing the pasture agricultural field. An overview of the LAU model is presented in the following sections, including a description of the LAU's "local watershed" concept, the important assumptions inherent in the LAU methodology, its fundamental fate and transport algorithmic "engine"—the Generic Soil Column Model (GSCM), its hydrology and soil erosion methodologies, its particulate emissions to the atmosphere estimation methods, and the differences between the LAU (crop) and LAU (pasture) versions and other modifications required to execute the LAU model for purposes of this analysis. The LAU model is described in Appendix F.

A complete listing of input parameters for both the crop and pasture source partition models is provided in Appendix C.

Figure 5-1 shows the data flow into and out of the source model.

5.1.1.1 Local Watershed. The agricultural land where biosolids are applied, whether cropland or pastureland, is considered an integral part of a "local watershed," as illustrated in Figure 5-2. A local watershed is defined here as that drainage area that contains only the agricultural field and its downslope contiguous land areas in which runoff occurs as overland flow (sheet flow) only. Thus, a local watershed extends downslope only to the point that runoff flows and eroded soil loads would enter a well-defined drainage channel, e.g., a ditch, stream, lake, or some other waterbody. The sheet-flow-only restriction is based on the assumption that any area downstream of the agricultural field is subject to contamination from the application of biosolids through overland runoff and soil erosion.

The "buffer" illustrated in Figure 5-2 shows the area where the farm family is assumed to live. For simplicity, it is assumed that the agricultural field extends from the drainage divide of the local watershed downslope to the boundary with the buffer (where the family resides). The

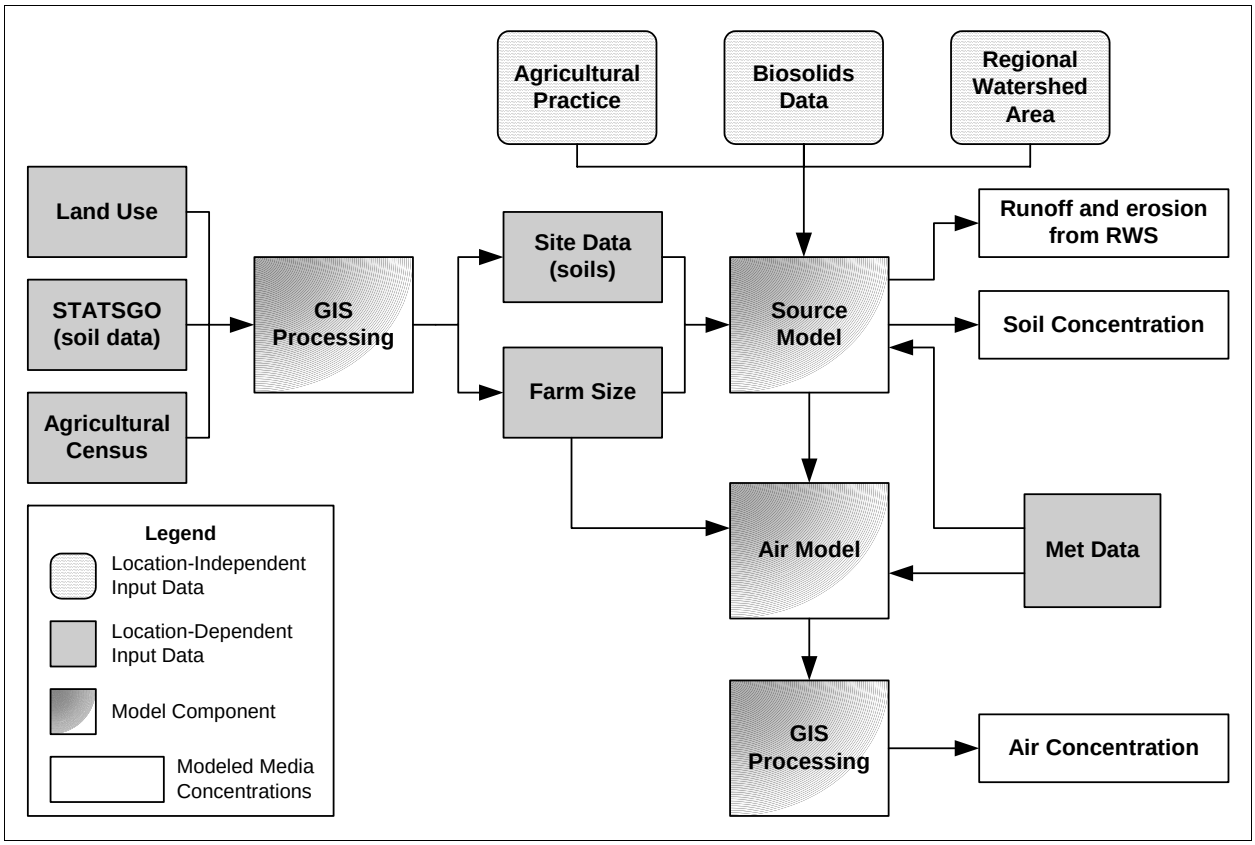

Figure 5-1. Biosolids application to agricultural field source module.

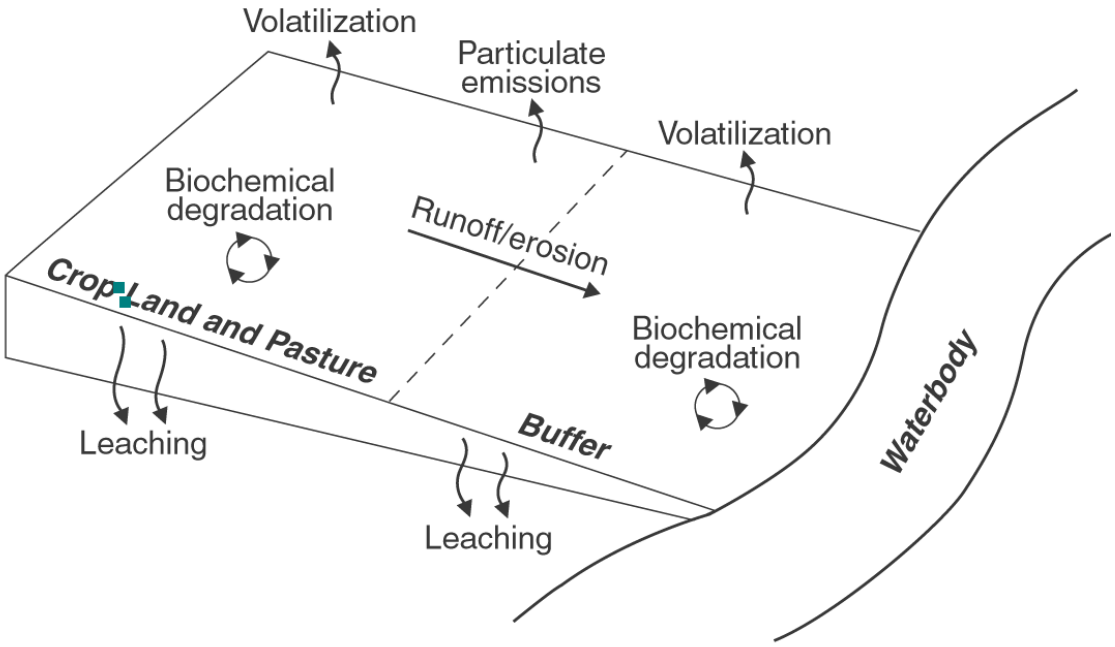

Figure 5-2. Emissions mechanisms in the local watershed.

buffer, which is part of the local watershed, is also simulated by the LAU model; that is, the LAU model simulates the dynamic fate and transport of constituents within the agricultural field, from the agricultural field to the buffer, within the buffer, and from the buffer to the waterbody. The buffer width was assumed to be 100 ft in all cases.

Also illustrated in Figure 5-2 are the mechanisms by which constituent emissions to surrounding media occur. In the agricultural field itself, emissions to the atmosphere occur via volatilization of gaseous phases and wind/vehicular erosion of particulate phases. Runoff and erosion processes transport surficial constituents downslope to contaminate the buffer area and the contiguous waterbody. Fate and transport processes are simulated in the buffer, similar to and concurrent with the agricultural field simulation.

5.1.1.2 LAU Assumptions. A number of assumptions inherent in the LAU model pertain primarily to how the computational engine, the GSCM, is applied to simulate application of biosolids to agricultural land. The GSCM is discussed in greater detail in Section 5.1.1.3. The LAU assumptions are summarized as follows:

- Biosolids are applied to the soil surface periodically at set intervals (e.g., biennially) and then either tilled into the soil to a depth of 20 cm in the case of crop agricultural field or mixed with the top 2 cm of soil in the case of pasture.

- Whether the biosolids are tilled into the soil or remain near the surface, the constituent concentration in the zone occupied by the biosolids is assumed to be uniformly distributed (completely mixed) after each application.

- The contaminant mass is concentrated in the solids portion of the biosolids and is repartitioned among the solid, aqueous, and gas phases in the soil column.

- Biosolids applications do not result in any buildup of the soil surface, nor does erosion significantly degrade the soil surface (i.e., the distance from the site surface [$z = 0$] to a fixed point below the surface is constant). As a result, there is no naturally occurring limit to the modeled total soil concentration. In other words, the modeled constituent concentration in the agricultural field could exceed the constituent concentration in the waste. Indeed, this is physically possible for highly immobile constituents if the waste matrix is organic (as is the case for biosolids) and decomposes, leaving behind the constituent to concentrate over multiple applications.

- The first-order loss rate due to wind erosion and other surface disturbances is applied to the surface layer of the soil only and is calculated each year as an annual average with consideration of losses from an active agricultural field due to wind erosion, vehicular activity, and tilling operations (for the crop field). The particulate emission loss rate from an inactive agricultural field or pasture includes wind erosion only.

5.1.1.3 Generic Soil Column Model. The GSCM solves the following partial differential equation in space and time

where

C_T = total (dissolved plus sorbed plus vapor-phase) chemical concentration (M/L^3)

$$\frac{\partial C_T}{\partial t} = D_E \frac{\partial^2 C_T}{\partial z^2} - V_E \frac{\partial C_T}{\partial z} - kC_T \qquad (5\text{-}1)$$

t = time (T^{-1})
D_E = effective diffusivity (L^2/T)
z = depth in the soil column (L)
V_E = effective solute advection velocity (L/T)
k = overall first-order loss rate constant (T^{-1}).

The term on the left side of Equation 5-1 represents changes in C_T over time. The first term on the right side represents vertical transport due to diffusion. The second term represents vertical transport due to bulk advective movement of water passing downward through the soil column. The last term represents the cumulative loss of chemical due to decay, hydrolysis, volatilization, or erosion losses from the surface. The vertical extent over which Equation 5-1 is solved is the depth from the soil surface down to a depth of 20 cm. Boundary conditions are $C_T = 0$ at the soil surface and a zero-gradient boundary condition at the lower soil column boundary (20 cm). A zero-gradient boundary condition implies that the concentration, whatever it may be, on either side of the boundary is identical on both sides. Initial conditions reflect the concentration profile over the soil column depth, *z*, at the time the simulation begins.

The solution technique used for solving Equation 5-1 over space and time is a hybrid of analytical and numerical methods developed to achieve a balance between simulation accuracy and execution speed. It is more fully described in Appendix F. The GSCM operates on a daily time step, with outputs aggregated to annual average values. The output of the GSCM is a time series of annual average values. A brief narrative description of how the GSCM is used to simulate fate and transport of chemical in the crop and pasture agricultural fields follows.

At the start of the simulation (time 0), the soil column is clean; that is, the chemical concentration is 0 throughout the soil column modeled depth. (Both the crop and pasture modeled soil column depths are 20 cm.) The initial waste application then occurs, introducing chemical mass into the soil column. This mass is introduced by calculating the total chemical mass associated with the waste application, "mixing" that mass into a specific depth of the soil column, and calculating the resulting uniform chemical concentration over that mixed depth. For the crop model, the depth over which waste is mixed at the time of application is 20 cm, and waste is assumed to be mechanically tilled to that depth. For the pasture model, the mixing depth is 2 cm, under the assumption that cattle activity and/or other bioturbation processes effectively mix the surface-applied biosolids to that depth.

Following incorporation of newly added waste into the soil column, the dynamic solution of Equation 5-1 then proceeds over space (the vertical soil column is disaggregated into 20 1-cm thick layers for purposes of simulating vertical gradients—concentration is uniform within a

layer, but can vary among layers) and time. As previously mentioned, the fundamental time step is daily, so that fate and transport of chemical in the surficial soil layer can respond to daily rainfall and runoff events. For example, on a dry day, chemical in the surficial soil layer (and elsewhere) is lost or transported via the mechanisms of vertical advection (long-term average infiltration/leaching), vertical diffusion, and, as appropriate for the chemical being analyzed, volatilization, hydrolysis, and biodegradation. On a day with precipitation and runoff (not all precipitation events lead to runoff), in addition to these processes, chemical is lost from the surface layer to downslope land areas (the buffer and waterbody) due to lateral advective transport of any dissolved chemical that has diffused from the soil pore water into the runoff water and due to erosion of chemical sorbed to eroded soil particles.

This dynamic solution of Equation 5-1 on a daily time step continues until the time of the next waste application. At that time, the residual chemical concentration profile (just prior to the new application time) is retrieved, and the concentrations in the soil layers receiving waste (20 cm in the crop field and in the pasture) are then increased by the newly added chemical mass, and the simulation is begun again from this new initial condition. At the end of the agricultural field operating life, when biosolids cease to be added, the simulation continues to simulate depuration or reduction of chemical. The simulation ultimately terminates when either 99 percent of the peak chemical mass has been removed via the various fate and transport processes or 200 years has elapsed (from the first application), whichever comes first. (For dioxins, 200 years comes first because of the persistence of the chemicals.)

The following major assumptions were used in the development of the GSCM:

- The contaminant partitions to three phases: sorbed (solid), dissolved (liquid), and gaseous. The total contaminant concentration in soil is calculated as follows:

$$C_T = \rho_b C_S + \theta_w C_L + \theta_a C_G \quad (5\text{-}2)$$

where

C_T = total contaminant concentration in soil
ρ_b = soil dry bulk density (M/L^3)
C_s = sorbed-phase contaminant concentration in soil (M/M of dry soil)
θ_w = soil volumetric water content (L^3 soil water/L^3 soil)
C_L = aqueous-phase contaminant concentration soil (M/L^3 of soil water)
θ_a = soil volumetric air content (L^3 soil air/L^3 soil)
C_G = gas-phase contaminant concentration in soil (M/L^3 of soil air).

- The contaminant undergoes reversible, linear equilibrium partitioning between the adsorbed and dissolved phases. The sorbed-phase contaminant concentration in soil is calculated as follows:

$$C_S = K_d C_L \quad (5\text{-}3)$$

where K_d is the linear equilibrium partitioning coefficient (L^3/M). For organic contaminants,

$$K_d = foc \times K_{oc} \quad (5\text{-}4)$$

where *foc* is the organic carbon fraction in soil and K_{oc} is the equilibrium partition coefficient, normalized to organic carbon. (It is implicit in this linear equilibrium partitioning assumption that the sorptive capacity of the soil column solids is considered to be infinite with respect to the total mass of contaminant over the duration of the simulation, i.e., the soil column sorptive capacity does not become exhausted. This condition is assumed true for this case.)

- The contaminant in the dissolved and gaseous phases is assumed to be in equilibrium and to follow Henry's law. The gas-phase contaminant concentration in soil is calculated as follows:

$$C_G = H' C_L \quad (5\text{-}5)$$

where H´ is the dimensionless Henry's law coefficient.

- Material in the soil column (including bulk waste) can be approximated as unconsolidated homogeneous porous media whose basic properties (ρ_b, *foc*, θ_w, θ_a, and η, where η is the total soil porosity) are average annual values, constant in space.

- Contaminant mass may be lost from the soil column due to one or more first-order loss processes.

- The total chemical flux is the sum of the vapor flux and the flux of the dissolved solute, diffusive losses of the dissolved phase from the surficial soil pore water into overlying runoff water during a runoff event, loss of sorbed phase due to wind and water erosion from the surficial soil, and internal sinks due to biochemical decay and hydrolysis.

- The chemical is transported in one dimension through the soil column.

- The modeled soil column remains constant in volume and fixed in space with respect to the water table.

Volatilization from the soil is calculated using accepted methods. The volatilization loss from the surface of the soil column, $M_{vol}(t)$ (g/m^2), is assumed to be due to gaseous-phase diffusion only. The equations used to estimate volatilization from the soil column are presented in Appendix F. These methods have been subjected to peer review and received no specific comments on the volatilization estimation process. EPA is not aware of any specific bias in these estimates.

The LAU model was originally conceived and designed as an improvement over the well-known "Jury" model (Jury et al., 1983, 1990). The improvements were intended to relax two restrictions of the Jury model, namely (1) the initial condition and (2) the lower boundary condition. The Jury model assumes as an initial condition that chemical concentration is constant over some depth *L*. In addition, the Jury model assumes an infinitely deep soil column (i.e., the lower boundary condition is zero concentration at infinite depth). The LAU model was intended to simulate the compounding effects of multiple applications of chemical to a LAU, rather than a single, initial application as is implicit in the Jury model's uniform concentration initial condition. (After any subsequent application, the initial concentration for that new simulation period would not be a uniform concentration.) In addition, a finite lower boundary for the modeled vertical domain was desired so that the lower boundary of the modeled soil column was not infinity, but something more meaningful (e.g., the bottom of a tilled zone in a LAU, or the vadose/saturated zone interface). A modified Jury equation could not obtain an analytical solution to accommodate this more general initial condition and a finite lower boundary condition. Thus, the "quasi-numerical" solution described in Appendix F was developed. The quasi-numerical algorithms developed to implement these modifications resolve the problem of an analytical solution.

The LAU model was never intended to be a fully rigorous treatment of these complex fate and transport phenomena, but rather a screening-level improvement over the then-available Jury model. The known limitations and simplifying assumptions, however, do not result in significant biases of the model in estimating volatile emissions. The model does in large part preserve mass balance. (There are some minor exceptions, e.g., related to erosion.) Further, the model's estimates of residual chemical mass remaining after various periods of simulation were found to agree reasonably well with observed half-lives of dioxin from several studies. Thus, if mass balance is preserved and the residual chemical has been reasonably well validated, then the possibilities for prediction biases are limited to offsetting biases among the several available loss mechanisms. The chemicals simulated are all highly sorbed so that loss via infiltration is minimal, and remaining loss mechanisms include volatilization and erosion. Erosion is simulated using empirical methods (the USLE), so that the eroded mass loss should not be subject (on average) to significant bias.

The upper boundary condition in this model was used to indicate that there was no chemical concentration above the soil surface tending to drive chemical into the soil from the air phase. The methodology used implicitly involves an upper boundary condition of zero at infinity, not at the soil surface. The diffusion step of the algorithm transports total chemical across the soil surface using the effective diffusivity. That portion of the diffused mass across this boundary that is not in gaseous form (and would not in fact diffuse across this boundary) is removed from the total volatilized mass and is then "added" back into the uppermost soil layer. Although this treatment of volatilization is admittedly simplistic, it is not based on a sharp driving gradient of zero concentration at the upper boundary, which would greatly increase volatilization. If anything, the simplistic treatment of the upper boundary condition may in fact underestimate volatile emissions (because of the implicit zero concentration at infinity assumption), although the mass balance preservation, validation of residual soil concentrations, and paucity of loss mechanisms suggest that volatilization is appropriate.

No photodegradation has been included in the modeling. As reported in the Draft Dioxin Reassessment Document (U.S. EPA, 2000),

> "Schwarz and McLachlan (1993) studied the photolysis of CDD/CDFs in an experiment designed to simulate the application of sewage sludge to an agricultural field.... No significant changes in CDD/CDF concentrations were observed during the 43-day exposure period to late summer/early fall natural sunlight. The absence of any changes indicates that neither photodegradataion nor volatilization are important mechanisms in the fate of CDD/CDF in sewage sludge following agricultural applications" (v.3, p. 2-00).

The Draft Dioxin Reassessment Document also states,

> "Welsch-Pausch and McLachlan (1995) concluded that if photodegradataion is occurring, it is a relatively insignificant factor in the accumulation of CDD/CDF in pasture grass" (v.3, p. 2-81).

These assumptions have been confirmed by a measurement study on the uptake of dioxins and furans by pasture grass. The following loss mechanisms were examined: photolysis, degradation, volatilization, cuticular shedding, and growth dilution. Photodegradataion was discounted as a significant loss mechanism because rainfall appeared to be the dominant loss mechanism (Thomas et al., 2002).

Volatilization was estimated to be very small and was considered a minor loss mechanism, but is considered extremely important to the contamination of plants grown directly on the agricultural field because of the high air-to-plant transfer factor of dioxin and dioxin-like constituents.

5.1.1.4 <u>Hydrology and Soil Erosion</u>. The hydrology model used in the agricultural field model provides estimates of daily soil moisture, runoff, potential evapotranspiration, actual evapotranspiration, and infiltration. The hydrology model is based on a daily soil moisture water balance performed on the root zone depth of the soil column. At the end of a given day, *t*, the soil moisture in the root zone of an arbitrary local watershed subarea, *i*, is updated as

$$SM_{i,t} = SM_{i,t-1} + P_t + RO_{i-1,t} - RO_{i,t} - ET_{i,t} - IN_{i,t} \qquad (5\text{-}6)$$

where

$SM_{i,t}$ = soil moisture (L) in root zone at end of day t for subarea i
$SM_{i,t-1}$ = soil moisture (L) in root zone at end of previous day for subarea i
P_t = total precipitation depth (L) on day t
$RO_{i-1,t}$ = storm runoff depth (L) on day t coming onto subarea i from i-1
$RO_{i,t}$ = storm runoff depth (L) on day t leaving subarea i
$ET_{i,t}$ = evapotranspiration (L) from root zone on day t for subarea i
$IN_{i,t}$ = infiltration (groundwater recharge) on day t (L) for subarea i.

Precipitation is undifferentiated between rainfall and frozen precipitation; that is, frozen precipitation is treated as rainfall.

Runoff is calculated as a function of soil type, soil cover, precipitation, and antecedent soil moisture using the SCS "curve number" method (USDA, 1986). Potential evapotranspiration is estimated as a function of air temperature, latitude (solar declination), and day-of-year using the Hargreaves equation (Shuttleworth, 1993). Actual evapotranspiration is estimated as a function of potential evapotranspiration, soil moisture, soil wilting point, and soil field capacity (Dunne and Leopold, 1978). Finally, infiltration is estimated as that day's residual soil moisture (net of runoff and evapotranspiration) in excess of the soil's field capacity. Maximum infiltration rates are limited to the saturated hydraulic conductivity of the soil. If the calculated infiltration exceeds the saturated hydraulic conductivity, a feedback loop is triggered that increases runoff and/or evapotranspiration (if less than potential evapotranspiration) to maintain the daily water balance.

Soil erosion is estimated based on the USLE methodology (Wischmeier and Smith, 1978), modified for application of a daily storm event. The daily application of the USLE is achieved by linearly distributing the USLE's long-term average rainfall factor (*R*) to storm-event-specific *R* values. This allocation is made based on the fraction of the long-term *R* value that is contributed by each individual storm event, as measured by the storm event's contribution to long-term average precipitation depths. A sediment delivery factor is also used in the soil erosion methodology. The sediment delivery factor accounts for the empirical observation that less eroded soil leaves a watershed per unit surface area as the size of the watershed increases; that is, soil mobilized by precipitation and runoff may be trapped in surface depressions before it can exit the watershed.

Volatilization, leaching, degradation, and erosion are considered loss mechanisms from soil. Leaching losses are, for all intents and purposes, zero for dioxin-like constituents because of the very high K_{oc} values for these constituents. K_{oc} indicates the tendency of these constituents to remain bound to soil particles and not to leach into the groundwater or volatilize into the air. However, a recent article (Kim and Lee, 2002) suggests that humic material such as biosolids facilitates the transport of dioxin-like constituents to groundwater; however, there is currently no model that adequately simulates this movement. Models that do not consider facilitated transport indicate no movement at all to groundwater. There are no measurement data to indicate that groundwater contamination by dioxins may be a potential concern.

No degradation of dioxin compounds in soil is assumed to occur. Loss of dioxin-like congeners from the soil is assumed to occur mostly through the erosion of soil particles to which dioxin-like constituents are tightly bound. These particles are assumed to erode from the biosolids-amended farm field, across the buffer area, and into the nearby stream. The erosion mechanism is responsible for the risks in the buffer area. Erosion is also responsible for contamination of the stream.

Infiltration is accounted for in the model by the "convection step" described on page F-12. After the total chemical has migrated downward through a computational layer due to infiltration (at the "effective" velocity), the total chemical mass in that layer is advected to the next lower layer. This is the third part of the three-part, series solution of the

advective/dispersive/first-order loss equation. Diffusion is simulated first, followed by first-order losses, followed by advection. The series implementation of the diffusion/decay/advection processes is an approximation of reality, which can result in some bias under certain circumstances. However, those circumstances are not relevant for the chemicals simulated in this application. Even if advective losses were omitted, that omission would not introduce much error, because the chemicals simulated in this study are both very highly sorbed and sparingly soluble, so loss of chemical via infiltration/leaching is minimal.

The quasi-numerical solution uses a set of computational elements, or soil layers, to approximate the vertical concentration gradient. Typically, these layers are 1 cm thick, so a soil column 20 cm deep would consist of 20 of these layers. Each layer is assumed to be "completely mixed" (i.e., have uniform chemical concentration) so that chemical concentration gradients can exist among these layers but not within any layer. The approximation results in a less-than-continuous concentration gradient, which mirrors what would occur in nature. The use of a numerical technique that discretizes the soil column by these layers is not a shortcoming of the model; all numerical solutions involve some sort of discretization of the prototype. If the discretization is too coarse (low spatial resolution), "hot spots" are not detected, concentration gradients are not well represented, and the accuracy of the gradient-driven dispersion estimates suffers. However, a 1 cm resolution does not fall in the category of poor spatial resolution, and the vertical concentration gradient is reasonably well approximated by this numerical technique. Indeed, if anything, vertical dispersion is underestimated because the diffusivity is based on molecular diffusion only and not on hydrodynamic dispersion.

5.1.1.5 Particulate Emissions. Wind erosion, vehicular activity, tilling operations, and other surface disturbances may result in suspension of surficial soil particles in the atmosphere. To the extent that those soil particles contain sorbed chemical, this process becomes a source of particulate chemical flux into the atmosphere. The agricultural field model includes equations to estimate particulate emissions of chemical sorbed onto particles of 30 μm diameter or smaller. These equations are based on empirical relationships developed by EPA in 1986 (updated, U.S. EPA, 1995a) and by Cowherd et al. (1985), and they are summarized in U.S. EPA (1999b). These empirical relationships estimate emission fluxes of surficial soil particles resulting from various surface-disturbing activities. The contemporaneous sorbed chemical concentration on surficial soils, estimated by the GSCM, then provides the chemical concentration also sorbed onto the airborne particles. No chemical "enrichment" is assumed to occur; that is, the sorbed concentration on the 30 μm particles is the same concentration as on the surficial soils. Land-disturbing activities for the agricultural fields (crops and pastures) are wind erosion, vehicular activity, and spreading and tilling.

5.1.1.6 Effective Soil Half-life. Although the source model used in this risk assessment to simulate chemical releases from and soil concentrations within the agricultural fields receiving biosolids has been extensively verified, it has not been validated. Verification is the process of confirming, through testing, sensitivity analysis, or benchmarking against other models, for example, that a model performs as it was intended by the modelers; that is, its functionality is verified. Validation is the more rigorous process of confirming that a model's predictions are in fact in reasonable agreement with phenomena observed in nature. Model validation requires extensive and appropriate data on observed emission rates and soil concentrations, as well as

model calibration activities, neither of which were feasible for this modeling study because data were not available for all the components of this modeling effort.

Although strict validation to actual site emission rates and soil concentrations was not feasible, an analysis was performed to estimate overall chemical half-lives at selected percentiles of the risk distribution built up by the 3,000 probabilistic simulations. A chemical half-life is simply the period of time that it takes for a chemical to depurate (be reduced) from some initial concentration to one-half of that concentration. Thus, the half-life is an overall measure of the various mechanisms by which a chemical may be reduced: physical mechanisms such as runoff/erosion or leaching or biochemical mechanisms such as decay/degradation or volatilization. Chemicals that are "quick," i.e., highly volatile or quickly degraded by biochemical processes, have correspondingly short half-lives—on the order of weeks, days, or even smaller time spans. In contrast, other chemicals have exceedingly long half-lives; for example, some radioactive isotopes have half-lives on the order of thousands of years. A chemical's half-life may also be affected by the environment in which the chemical exists. For example, some chemicals may be rapidly degraded by aerobic biochemical processes, but much more slowly degraded by anaerobic processes. Thus, the same chemical would have a much longer half-life in an anaerobic landfill than it would in an oxygen-rich environment, such as a surficial soil.

An example analysis of half-life was performed for TCDD for the LAU (using the pasture model for the proposed regulation) for selected iterations of the risk distribution. The runs selected corresponded to the runs that produced beef risk values at the 10^{th}, 25^{th}, 50^{th}, 75^{th}, 90^{th}, 95^{th}, and 99^{th} percentiles. Each of these specific model runs, out of the 3,000 probabilistic runs, is defined by its own set of input parameters. The sets of input parameters corresponding to each of these runs were retrieved from the larger database, and the source model used to represent the LAU (pasture) was executed for each set. For each of these half-life runs, the time series of annual average depth-averaged (20 cm) soil concentrations was then analyzed. This analysis first determined the year that the soil concentration reached its peak (the last year of biosolids application to the pasture), and then simply counted the number of years required for the depth-averaged soil concentration to reach half that peak value. The time series of soil concentrations for the 95^{th} percentile analysis is shown in Figure 5-3 as an example. In this example, TCDD concentration reaches its peak at year 34 and reaches one-half that peak concentration in year 82, for a half-life of 48 years. Calculated half-lives for all the selected percentiles are shown in Table 5-1.

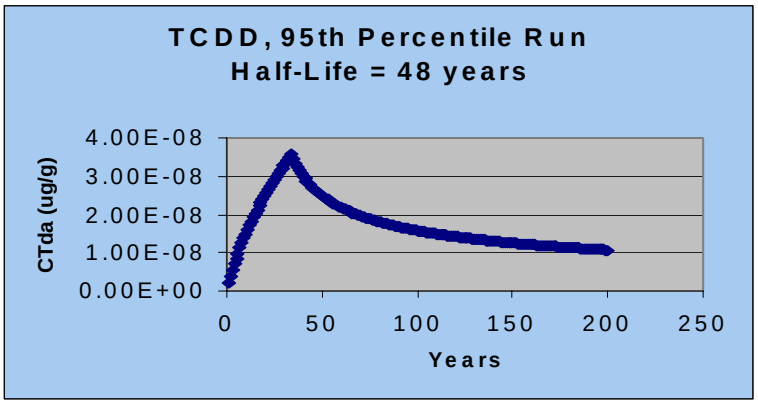

Figure 5-3. Example depth-averaged soil concentration annual time series.

Table 5-1. Calculated TCDD Half-Lives for Selected Risk Distribution Percentiles

Risk Distribution Percentile	Calculated TCDD Half-Life (years)
10th	20
20th	38
50th	39
75th	26
90th	35
95th	48
99th	37

Because each of the 3,000 sets of input parameters represents a somewhat different "environment" for TCDD, it was expected that the resulting half-lives for the selected percentiles would be variable, as indeed they are. They do not vary a great deal, however, and the conclusion of the analysis is that TCDD's half-life for this risk assessment is within the approximate range of 20 to 50 years. The Draft Dioxin Reassessment Document presents a review of the literature on the persistence of dioxin in soil (U.S. EPA, 2000; Section 2.6.1.3, Transport Mechanisms in Soil). These studies are summarized in Table 5-2. These observed half-lives seem to corroborate the range of half-lives resulting from the source model runs, thereby affording a measure of credibility to the modeled results.

Table 5-2. Soil Half-Life Data Reported in the Draft Dioxin Reassessment Document

Soil Half-Life	Study Parameters	Reference
25 to 100 years 9 to 15 years	Subsurface soil Top 0.1 cm	Paustenbach, D.J., R.J. Wenning, V. Lau, N.W. Harrington, D.K. Rennix, and A.H. Parsons, 1992. Recent developments on the hazards posed by 2,3,7,8-tetrachlorobenzo-p-dioxin in soil: implications for setting risk-based cleanup levels at residential and industrial sites. *J. Toxicol. and Environ. Health* 36:103-149.
Approximately 20 years	Biosolids-amended soil sampled from a long-term field experiment	McLachlan, M.S., A.P. Sewart, I.R. Bacon, and K.C. Jones. 1996. Persistence of PCDD/Fs in a sludge-amended soil. *Environ. Sci. Technol.* 30(8):2567-2571.
10 to 12 years	Field studies on a military test area aerially sprayed with 2,4,5-T. Data for 2,3,7,8-TCDD incorporated in the soil	Young, A.L. 1983. Long-term studies on the persistence and movement of TCDD in a natural ecosystem. In *Human and environmental risks of chlorinated dibenzodioxins and related compounds*. Tucker, R.E., A.L. Young, A.P. Gray (Eds.). Plenum Press.

Few studies are reported in the literature that address degradation of dioxins or dioxin-like constituents in soil. According to the Draft Dioxin Reassessment Document (U.S. EPA, 2000), Arthur and Frea (1989) reviewed studies on the biodegradation of dioxin and concluded that 2,3,7,8-TCDD is recalcitrant to microbial degradation. Thus, degradation was assumed to be below a level of concern and was not included in this risk analysis. The dioxin reassessment also states that the photolysis of dioxins and furans on soil has been reported to occur only in the surface film of the soil. The factors affecting the rate and extent of photolysis in soil have not been well characterized, and below the very top surface soil (i.e., the top few millimeters), photolysis is not reported to occur. Therefore, photolysis was not considered, because it was assumed to have minimal impact on the average soil concentrations over the depths of 20 cm evaluated in this analysis. The Draft Dioxin Reassessment Document (U.S. EPA, 2000) states that hydrolysis is not a loss mechanism of concern for dioxin-like constituents, so it was also not considered as a loss mechanism in this risk analysis. All loss mechanisms considered in this analysis are considered to apply in all subareas considered in the source (crop, pasture, and buffer). Given a predicted half-life of 48 years according to the mechanisms modeled, EPA concludes that the modeling approaches are appropriately and sufficiently protective.

The calculated half-life of dioxin shows that the model estimates a half-life of 48 years for TCDD, which is within the range of measured half-lives (of 9 to 50 years) for these constituents reported in the open literature. Thus, the losses calculated in the model are relatively conservative but are in general agreement with the losses measured in the environment and reported in the literature Because the soil depths are conservatively shallow and the half-lives very long, it can be concluded that the predicted soil concentrations in this assessment are protective and are not too low. Losses of dioxins are considered from pastures amended with

biosolids. Biosolids were not assumed to be mechanically incorporated into the pasture in the modeling conducted for the proposed rule; however, the same losses estimated to occur in the tilled cropland (erosion and volatilization) were assumed to occur from the untilled pasture. The half-life of TCDD displayed in Figure 5-3 shows the losses from the pasture scenario. This figure shows the increase in the concentration of TCDD due to the application of biosolids biennially for a period of 34 years. After that time, applications ceased and the soil concentration began to decline, reflecting continued losses due to volatilization and erosion. In this example, it took 48 years for the concentration in the soil to reach a concentration equal to one-half the concentration estimated at the time of peak concentration after the last addition of biosolids.

5.2 Fate and Transport Modeling

This section describes the methodology and the models that were used to predict the fate and transport of chemical constituents in the environment. The methodology is based on the methodology used in the Draft Dioxin Reassessment (U.S. EPA, 2000).

Once dioxin congeners are released, they can move through the air, soil, and food chain by natural processes. The purpose of the fate and transport modeling performed for this assessment is to estimate the concentration of dioxins in environmental media (i.e., air, soil, and food items) to which individuals may be exposed. To predict a contaminant's movement through these different media, several media-specific fate and transport models are employed. Fate and transport models typically used by EPA are either a series of computer-based algorithms or sets of equations that predict chemical movement due to natural forces. These fate and transport models integrate information on a site's geology, hydrology, and meteorology with chemical, physical, and biological processes that can take place in the environment. The result is a simulation of chemical movement in the environment and a prediction of the concentration of a constituent at a certain point called the "exposure point." Only incremental exposure is calculated by the model. Because background exposures are not dependent on the scenario being modeled, they can be estimated outside the model and added to the incremental exposure from the application of biosolids to farms. In addition, the margin of exposure (MOE) approach used to estimate exposure of infants to breast milk is based on a comparison of breast milk concentrations for mothers living on farms where biosolids are applied to crops and pastures compared to mothers who are not exposed in this manner. The following fate and transport models were used for this analysis:

- Air dispersion and deposition model
- Watershed model
- Food chain model.

These three models and the general framework for performing the fate and transport modeling are described in the following sections. Section 5.2.1 discusses the air dispersion and deposition modeling. Section 5.2.2 describes the watershed model used to determine soil and water constituent concentrations. Detailed descriptions of the models and a comprehensive list of the input values used in them can be found in Appendices G and H, respectively. The calculations of the food chain model are based on these media concentrations and are presented in Section 5.3.

5.2.1 Dispersion and Deposition Modeling

Dispersion modeling is a computer-based set of calculations used to estimate ambient ground-level constituent concentrations associated with constituent releases from biosolids management practice. The dispersion model uses information on meteorology (e.g., windspeed and wind direction, temperature) to estimate the movement of constituents through the atmosphere. Movement downwind is largely determined by windspeed and wind direction. Dispersion around the centerline of the contaminant plume is estimated by empirically derived dispersion coefficients that account for movement of constituents in the horizontal and vertical directions. In addition, constituent movement from the atmosphere to the ground is also modeled to account for deposition processes driven by gravitational settling and removal by precipitation.

The air dispersion and deposition modeling conducted for this analysis produced output data that were used to calculate environmental media concentrations and food chain concentrations (see Section 5.3). The dispersion model outputs included air concentration of vapors and particles, wet deposition of vapors and particles, and dry deposition of particles. Dry deposition of vapors was also calculated, but outside the dispersion model.

5.2.1.1 Industrial Source Complex Short-Term Dispersion Model. A number of dispersion models are available for estimating the transport of constituent through the atmosphere, several of which are available on EPA's SCRAM Bulletin Board (http://www.epa.gov/scram001/). These dispersion models were developed for a variety of applications and each has its own strengths and weaknesses. The ISCST3 model was selected for air dispersion modeling in this analysis. Because this assessment required a model with the capability to model ground-level area sources, ambient air concentrations and deposition fluxes, vapors and particulates, and annual averaging times, ISCST3 was an appropriate model to use. In addition, ISCST3 is supported by EPA's Office of Air Quality Planning and Standards and has been used extensively in regulatory applications.

ISCST3 (U.S. EPA, 1999a), a recommended dispersion model in EPA's *Guideline on Air Quality Models* (U.S. EPA, 1999c), is a steady-state, Gaussian plume dispersion model. A steady-state model is one in which the model inputs and outputs are constant with respect to time. That is, the system being modeled is assumed to be unchanging over time. The term "Gaussian plume" refers to the kind of mathematical solution used to solve the air dispersion equations. It essentially means that the constituent concentration is dispersed within the plume laterally and vertically according to a Gaussian distribution, which is another name for to a normal distribution. These assumptions and solutions hold for each hour modeled. The results for each hour are then processed to provide values for different averaging times depending on the user's needs (e.g., annual average).

ISCST3 is capable of simulating dispersion of pollutants from a variety of source types, including point, area, volume, and line sources. ISCST3 can account for both long- and short-term air concentration of particles and vapor and wet and dry deposition of particles and vapor. In addition to deposition, wet and dry plume depletion can be selected to account for removal of matter by deposition processes and to maintain mass balance. Receptor locations can be specified in polar or cartesian arrays or can be set to discrete points as needed. Flat or rolling

terrain may be modeled, but only flat terrain may be used for area sources. ISCST3 considers effects on dispersion of environmental setting by allowing the user to choose dispersion parameters representing either an urban or rural setting.

5.2.1.2 Configuration of ISCST3 for Air Dispersion and Deposition Modeling. Results of air dispersion and deposition modeling represent the initial step in the fate and transport of vapor and particle emissions in the environment. The ISCST3 model was used to estimate

- Air concentration of vapors
- Air concentration of particles
- Wet deposition of vapors and particles
- Dry deposition of particles.

Dry deposition of vapors was calculated outside of ISCST3, as explained below.

All air concentrations and deposition values developed by ISCST3 were unit values based on modeling default unit emission rates. Later in the exposure modeling process, the unit air concentrations ($\mu g/m^3$ per unit emission rate of 1 g/s-m^2) and deposition rates (g/m^2 per unit emission rate of 1 g/ s-m^2) were multiplied by chemical-specific emission rates to produce values used to calculate environmental media concentrations.

Modeling was conducted using 5 years of data obtained from each of 41 meteorological stations assumed to be representative of the climatic regions throughout the country (see Section 4.3 for a discussion of meteorological site selection). Modeling was conducted using the median farm size area in each of the 41 climatic regions as the source area.

Air Concentrations of Vapor and Particles. ISCST3 estimates air concentrations of particles and vapors based on a number of variables, including wet and dry deposition and plume depletion. The model accounts for downwind movement of the plume containing airborne vapors and particles. It also accounts for dispersion of vapors and particles around the centerline of the plume as the plume travels in a downwind direction. Removal of constituent mass from the plume occurs as a result of wet and dry deposition. Wet and dry deposition are important processes in indirect exposure modeling because they account for the movement of constituent mass from the atmosphere to soil, water, and vegetation. Deposition is discussed below. There is, however, a closely related process, known as depletion, that affects the calculation of air concentrations.

Summary of ISCST3 Modeling

- The wet and dry depletion option was activated in the dispersion modeling for particles. Wet depletion was considered for vapors.
- Area source was modeled for biosolids management.
- Modeling was conducted using unit emission rates.
- The rural option was used in the ISCST3 modeling because the agricultural management practices being assessed are typically in nonurban areas.
- Flat terrain was assumed.

Depletion is essentially the mirror of deposition. That is, while deposition

accounts for the amount of constituent that moves to the ground, depletion accounts for the amount of mass removed from the atmosphere by deposition. The ISCST3 model allows the user to model depletion and deposition separately (i.e., the user may select depletion, deposition, or both depletion and deposition). When depletion is included, the mass deposited on the ground due to wet or dry deposition is removed from the plume, thereby avoiding double counting (U.S. EPA, 1995d). In this analysis, air concentration of particles was modeled with both wet and dry depletion activated. For vapors, ISCST3 was used to model only wet deposition and depletion, and dry deposition of vapors was calculated outside the model. As a result of calculating dry deposition/depletion of vapors outside ISCST3, the mass balance for vapors was not maintained and uncertainty was introduced into the air modeling calculation, which would tend to overpredict vapor air concentrations.

Wet Deposition of Particles and Vapor. Wet deposition is the deposition of material on a surface from a plume as a result of precipitation. The amount of material removed by wet deposition from the plume is a function of the scavenging rate coefficient, which is based on particle size as shown in Table 5.3 (U.S. EPA, 1995d). To perform these calculations, wet deposition, wet depletion, and dry depletion were all selected in the input run-stream file. Precipitation data from the SAMSON CD-ROM (U.S. DOC and U.S. DOE, 1993) were required to process the meteorological inputs for this analysis.

Dry Deposition of Particles. Dry deposition refers to the deposition of material on a surface (e.g., ground, vegetation) from a plume of material as a result of processes such as gravitational settling, turbulent diffusion, and molecular diffusion. Dry deposition is calculated as the product of air concentration and dry deposition velocity. To calculate dry deposition, ISCST3 requires mass mean diameter, particle density, and mass fraction to be input into the source pathway for deposition calculations (U.S. EPA, 1995b). Dry deposition calculations also require the meteorological input file to contain surface friction velocity, hourly Monin-Obukhov length, and surface roughness length. Surface friction velocity and hourly Monin-Obukhov length were calculated in the PCRAMMET preprocessor (U.S. EPA, 1995c). More detail on the PCRAMMET preprocessor is provided in Appendix G.

Table 5-3. Particle Size and Wet Scavenging Coefficients Used in Dispersion Modeling

Particle Size Category	Mean Particle Diameter Modeled (µm)	Mass Fraction	Wet Scavenging Rate Coefficient (h/mm-s)
30 - 15 µm	22.5	0.4	6.7E-04
15 - 10 µm	12.5	0.1	6.7E-04
10 - 2.5 µm	6.3	0.3	4.N-04
< 2.5 µm	1.3	0.2	6.0E-05

When deposition and depletion of particles are being modeled, ISCST3 requires a variety of meteorological data as input. For this modeling effort, 5 years of surface and upper-air data

were obtained to determine long-term average air dispersion and deposition estimates. The surface data were obtained from the SAMSON CD-ROM (U.S. DOC and U.S. DOE, 1993) for the National Weather Service stations. These data included opaque sky, temperature, wind direction, windspeed, ceiling height, present weather, station pressure, and precipitation type and amount. The upper-air data were obtained from EPA's SCRAM bulletin board and were paired with the surface data for air dispersion modeling through the use of the meteorological preprocessor PCRAMMET. PCRAMMET pairs the surface data with the upper-air data to create a meteorological file that contains hourly windspeed, wind direction, atmospheric stability class, temperature, and mixing height. The preprocessor also requires additional inputs based on site-specific land use data. PCRAMMET inputs were derived as recommended in the PCRAMMET user's guide (U.S. EPA, 1995c) based on the site-specific land use information assessed through the use of topographic maps. These site-specific parameters are used for dry deposition calculations of particulate matter.

Dry Deposition of Vapors. Dry deposition of vapors was calculated using a step external to the ISCST3 model because chemical-specific dry deposition modeling within ISCST3 was precluded by time considerations. Using a dry deposition algorithm for particles (from the ISCST3 user's manual), dry deposition of vapor was calculated by multiplying the vapor air concentration by a default deposition velocity of 0.5 cm/s (Koester and Hites, 1992). This approach assumes that vapors behave as fine aerosols and, therefore, are amenable to modeling using the dry deposition algorithm for particles.

To calculate the weighted dry deposition velocity, land use was obtained from 1:250,000-scale quadrangles of land use and GIRAS spatial data obtained from the EPA Web site and placed in an ArcInfo format (U.S. EPA, 1994). Land use was based on data from the mid-1970s to the early 1980s. The fraction of time in each stability class was based on 5-year hourly meteorological files used in ISCST3 modeling.

Averaging Time. For the dioxins in the biosolids risk assessment, all human health risks were evaluated based on benchmarks for chronic, long-term exposure. Therefore, the air concentrations and deposition values required for the human health and ecological risk assessment were long-term averages. Long-term averages calculated by the ISCST3 model were annual averages. However, because the ISCST3 model was run using 5 years of meteorological data, it actually averages the hourly concentrations over the entire 5-year period.

Rural vs. Urban. The rural vs. urban setting in ISCST3 allows the user to account for differences between rural and urban environments. In urban environments, the built environment (e.g., buildings, roads, and parking lots) alters the dispersion character of the atmosphere, particularly at night because of building-induced turbulence and reduced nighttime cooling. Thus, there is greater nighttime mixing of constituents in urban areas compared with rural areas. For purposes of ISCST3 modeling, the urban classification applies mainly to large cities; even small cities and suburban areas are classified as rural for ISCST3 purposes. For this analysis, the rural setting was used.

Placements of Points Where Air Concentrations Were Calculated. A grid of points where air concentration and deposition values were calculated was established using a Cartesian grid. Air concentration and deposition values were produced for each point on the grid (i.e., *x, y*

coordinate) at fixed distances ranging from 0 to 20,000 m from the edge of the management site. For the agricultural application, the receptors were placed on the field and at the following distances from the edge of the field: 100, 200, 500, 1,000, 1,500, 2,000, 3,000, 5,000, 7,500, 10,000, 15,000, and 20,000 m.

Flat vs. Elevated Terrain. The ISCST3 model allows the user to account for elevated terrain by specifying an elevation for each point on the grid where air concentrations and deposition values are calculated. This feature, however, is not available for use with area sources. Because all sources modeled in this analysis were area sources, elevated terrain was not considered.

TOXICS vs. Regulatory Mode. The most recent version of ISCST3 (99155, U.S. EPA, 1999a) allows the user to select a regulatory default option or to select a TOXICS option. The regulatory default option uses the Romberg numeric integration solution to estimate air concentration from an area source. Based on the results of validation tests performed by EPA, EPA concluded that the Romberg algorithm performs very well in terms of efficiency and reasonableness (U.S. EPA, 1992). However, this algorithm takes a significant amount of time to execute for large area sources. To improve model run times, the TOXICS option was added to the area source model by EPA. The TOXICS option also uses a Romberg numeric integration solution to estimate air concentrations and deposition rates near the management site. Farther from the site, however, the TOXICS option uses a two-point Gaussian Quadrature routine instead of the Romberg solution to estimate air concentration and deposition. The two-point Gaussian Quadrature solution is computationally more efficient, which accounts for the shorter model run time. For this study, a sensitivity analysis was conducted to compare the estimated air concentrations calculated using the regulatory option with those calculated using the TOXICS mode. This analysis showed small differences between results obtained using either option (see Appendix G). Given the benefit of reduced run times, the TOXICS option was selected for this analysis.

Source Shape. Agricultural land was modeled as a ground-level area source. The ISCST3 model allows the user to model area sources as polygonal sources with 3 to 20 sides (U.S. EPA, 1999a). The ISCST3 was set up in this analysis to model an area source as a square. This option was chosen because there are no actual data on the shape of sources, and a square source is assumed most like agricultural land.

5.2.1.3 Preparing ISCST3 Input Files. Two types of input files are required to run ISCST3, a run-stream file and a meteorological file. The run-stream file is an ASCII file that contains the model option settings, source parameters, and receptor locations. The meteorological file contains hourly values of windspeed, wind direction, stability class, mixing height, ambient air temperature, and precipitation type and amount.

ISCST Run-Stream Files. The ISCST3 run-stream file is composed of six pathways that drive different model functions: the Control Pathway, Source Pathway, Receptor Pathway, Meteorology Pathway, Terrain Grid Pathway, and Output Pathway. Each of these pathways is described in Appendix G. The Terrain Grid Pathway is not presented because it is used only with point sources (i.e., for facilities with stacks), which were not modeled in this analysis.

Meteorological Files. The meteorological file was generated using the meteorological preprocessor PCRAMMET (U.S. EPA, 1995c). The preprocessor pairs hourly surface observations with upper-air measurements. For each of the 41 meteorological stations modeled, 5 years of surface and upper-air data were used. The preprocessor creates a file in binary format that contains hourly windspeed, wind direction, atmospheric stability class, temperature, and mixing height. Land use data also were required by PCRAMMET in the vicinity of each meteorological station to derive air model inputs, such as Bowen ratio, surface roughness height, minimum Monin-Obukhov length, noontime albedo, and the fraction of net radiation absorbed by the ground. Appendix G discusses the derivation of each of these model inputs.

Key Meteorological Data for the ISCST3 Model

Wind Direction determines the wind direction of the greatest impacts.

Windspeed is inversely proportional to ground-level air concentration, so the lower the windspeed, the higher the concentration.

Stability Class affects the rate of lateral and vertical diffusion. The more unstable the air, the greater the diffusion.

Mixing Height determines the height to which chemical constituents can be diffused vertically.

5.2.1.4 Source Areas Modeled. In the modeling analysis, application to agricultural land was considered. Because the ISCST3 model is sensitive to the size of the area source, the relationship between air concentrations and size of the area source was analyzed. For relatively small area sources, air concentrations increase significantly as the size of the area source increases. For large area sources, this increase in air concentrations is not as significant. The median farm size for each climatic region was modeled.

5.2.1.5 Spatial Averaging of Air Concentrations and Deposition. A GIS model was used to calculate air concentration and deposition rates for the buffer area, agricultural field, regional watershed, and waterbodies. This crucial step combines the spatial characterization of the buffer area, agricultural field, and waterbody in the site layout with air modeling outputs for each climatic region/management practice combination.

In an automated batch program, the ASCII files produced by ISCST3 were converted from a Cartesian array of values into an evenly spaced grid of concentration values distributed around the center of the site layout in the form of a GIS point coverage. To calculate the point estimate for a location, the program estimates the air concentration of vapors and particles from this GIS point coverage by selecting the grid point nearest that location. These values are used directly to determine human inhalation exposures.

To calculate the spatial averages for the buffer area, agricultural field, and waterbody polygons, the program individually overlays these areas with this point coverage and averaged the overlapping points. These mean concentration values and their associated identifiers are the output of the program and represent the average air concentrations and deposition values used in subsequent modeling steps to predict soils, water, and food chain concentrations. The distribution of average ambient air concentration estimated in the buffer using all sample concentrations used to estimate inhalation risks are presented in Table 5-4. This distribution also includes variability across the 41 climatic regions, as well as variability in agricultural practices.

Table 5-4. TCDD-TEQ Media Concentration for Ambient Air in the Residential Buffer

Percentile	TCDD-TEQ Concentration in Ambient Air (ng/m^3)	Rural Air Background
50^{th}	2.3E-7	1.7E-5
75^{th}	4.8E-7	
90^{th}	9.5E-7	
95^{th}	1.4E-6	
99^{th}	3.1E-6	

The air concentration of dioxin congeners was influenced by several factors in the risk analysis that were ranked by the statistically based sensitivity analysis according to percentage of variation accounted for by the variable. This analysis has shown that the most important factors influencing the air concentrations of dioxins are

- Agricultural application rate (how many tons of biosolids are applied to the land per unit area)
- Number of years biosolids are applied to the land.

Other factors that are also important in this analysis are linked to the geographic location of the modeled farm:

- Meteorological conditions (temperature, rainfall, windspeed, etc.)
- Soil conditions (soil foc, soil bulk density, etc.)
- Area of the farm where biosolids are assumed to be applied.

All of the factors linked to location influence the release of dioxin congeners to the air to varying degrees. The location that is linked to 26 of the 30 iterations in the highest 1 percent of the air concentrations is Phoenix, AZ. This is not unexpected in that this is an extremely hot location with large farm areas. The other locations represented in the highest 1 percent of air concentrations are Tampa, FL, and Fresno, CA, also hot locations. Other locations associated with the top 10 percent of air concentrations are mostly more southern areas (Houston, TX; Meridian, MS; Atlanta, GA; Charleston, SC; Shreveport, LA; and Las Vegas, NV) or areas with very large average farm sizes (i.e., western climate regions; Bismark, ND; Boise, ID; Boulder, CO; Casper, WY). This indicates that ambient temperature is an important climatic parameter.

5.2.2 Estimation of Soil and Sediment Concentrations

This section describes the components that make up the waterbody model and those portions of the watershed model that simulate fate and transport of chemicals that have been

aerially deposited and eroded. There are two different types of watersheds—local watersheds, which contain the agricultural land where biosolids are applied that are subject to sheet flow runoff and erosion directly from the field, and regional watersheds. The regional watershed is the drainage area upstream of the modeled waterbody. Fate and transport of eroded chemical from the agricultural field downslope across the buffer area and into the waterbody is simulated by the source model as described in Section 5.1. The watershed models discussed below consider only chemical that is airborne from either the crop or pasture and subsequently deposited onto the residential buffer area of the local watershed[1] and the regional watershed. Thus, eroded chemical contaminating the buffer area or entering the waterbody from the local watershed consists of two components: (1) chemical that was eroded directly from the agricultural field and (2) chemical that was aerially deposited and subsequently eroded. These two components are summed to determine total chemical in the buffer soils and load entering the waterbody. For the regional watershed, only the aerially deposited component is relevant. Discussions in this section are general in nature. Two appendices support the discussions with more detailed information: Appendix H contains the full set of equations used to calculate media concentrations, and Appendix D lists the physical/chemical properties used; the parameter values selected for fate, transport, and exposure modeling; and citations for the parameter values selected.

5.2.2.1 Predicting Soil Concentrations. Soil concentrations due to aerially deposited chemical were calculated for the buffer area of the local watershed and the entire regional watershed. Soil concentrations are determined by the deposition flux of chemical and loss mechanisms of that chemical from the soil. Soil losses accounted for in this analysis include only erosion. Other losses, such as biodegradation, volatilization, leaching, and dissolved loss in surface runoff, were assumed to be negligible for the chemicals considered in this analysis. No mechanical mixing is assumed in the buffer area, and it is unlikely that there is significant mixing in this area. All exposures to soil in the buffer are associated with the surficial soil, and no disturbance of the soil is assumed during these exposures (soil ingestion by adults, young children, and foraging by free-range chickens). In addition, neither the soil ingestion pathway nor the poultry or egg pathway is the driving pathway for this risk assessment.

Soil concentrations in the regional watershed were calculated using the solution to a differential equation that expresses soil concentrations over time as a function of loadings and first-order losses, as presented in Equation 5-7. This equation is based on the soil concentration equation presented in the Draft Dioxin Reassessment Document (U.S. EPA, 2000) and was modified for this application to include aerially deposited loads of congeners as inputs. One of the fundamental underlying assumptions of the approach used for the regional watershed is that the soil compartment can be modeled as completely mixed. No losses other than erosion losses were assumed in this application, i.e., $K_s = 0$.

[1] Aerial deposition from a crop or pasture back onto itself is not considered, nor is aerial deposition from the crop onto the pasture, or vice versa; only deposition onto the buffer is considered.

C_{soil_t}

$$C_{soil_t} = C_{soil_i} + \frac{Dep + Load}{SoilR + K_s \times Mass} \times 1 - e^{\left(\frac{soilR}{Mass} + K_s\right) \times T} \quad (5\text{-}7)$$

Parameter	Definition	Value
C_{soil_t}	Total soil concentration	Calculated
C_{soil_i}	Initial soil concentration (mg/kg)	Calculated
Dep	Deposition term for soil (mg/yr)	Calculated in Table H-2.8
Load	Mass of contaminant loaded to soil (mg/yr)	Calculated in Table H-2.17
Soil R	Mass of soil removed from site (kg/yr)	Calculated in Table H-2.22
K_s	Soil loss constant (1/yr)	Calculation
Mass	Mass of soil (kg)	Calculated in Table H-2.20
T	Time for which soil concentration is being calculated (yr)	

Source: Based on U.S. EPA (2000) with values for deposition load added into the equation.
Note: Depending on the value of T, this equation is used to calculate Csoil $_{t1}$, Csoil $_{t2}$, Csoil $_{td}$. The value for T is determined in either Csoil $_{1F}$ or Csoil $_{2F}$.

The USLE was used to estimate soil erosion losses *(X_e)* as shown in Equation 5-8. The USLE is an empirically derived equation originally developed by the SCS of the USDA to estimate soil erosion losses from agricultural fields during soil conservation planning. The USLE is applied in the context of the Gross Erosion Sediment-Delivery Ratio method outlined in USDA (1978) and described in greater detail in the SCS *National Engineering Handbook* (USDA, 1971). Gross erosion is defined as the summation of erosion from all sources within a watershed, as estimated for sheet and rill erosion by USLE. The sediment delivery ratio adjusts gross erosion rates to account for terrain and cover features, which effectively reduce sediment erosion.

Constituent loadings to soil in the buffer area and the regional watershed area due to aerial deposition of vapors and particles were calculated using Equation 5-9.

Soil constituent concentration changes with each year of application of biosolids to the agricultural land. During the application period, the dioxin concentrations in soils resulting from aerial deposition steadily increase for such a persistent chemical. This temporal change, combined with the assumption that a receptor can begin his or her exposure duration at any time during the facility operation period, is accounted for in the soil concentration model by dynamically estimating the soil concentration at the beginning of the exposure duration and the soil concentration at the end of the exposure duration and determining the average concentration over the exposure period.

X_e

$$X_e = R \times K \times LS \times C \times P \times \frac{907.18}{4047} \quad (5\text{-}8)$$

Parameter	Definition	Value
X_e	Loss due to erosion (kg/m^2/yr)	Calculated
R	USLE rainfall/erosivity factor (1/yr)	See Appendix E
K	USLE soil erodibility factor (short tons/acre)	See Appendix E
LS	USLE length-slope factor (unitless)	Calculated in Table H-2.20
C	USLE cover management factor (unitless)	See Appendix C
P	USLE supporting practice factor (unitless)	See Appendix C
907.18	Conversion factor (kg/short tons)	
4047	Conversion factor (m^2/acres)	

Source: U.S. EPA (1998).

Dep

$$D_{ydv} = 0.31536 \times C_{yv} \times V_{dv}$$
$$Dep = 1000 \times Q \times Area \times \left[F_v \times \left(D_{ydv} + D_{ywv}\right) + \left(1 - F_v\right) \times \left(D_{ydp} + D_{ywp}\right)\right] \quad (5\text{-}9)$$

Parameter	Definition	Value
Dep	Deposition term for soil (mg/yr)	Calculated
0.31536	Unit conversion factor (m-g-s/cm-µg-yr)	
C_{yv}	Normalized vapor-phase air concentration (µg-s-m^2/gm^3)	See Appendix G
V_{dv}	Dry deposition velocity (cm/s)	See Appendix D
1000	Unit conversion (mg/g)	
Q	Emission rate from source (g/s-m^2)	Calculated by source model
Area	Area of deposition (m^2)	See Appendix E
F_v	Fraction of air concentration in vapor phase (unitless)	See Appendix D
D_{ydv}	Normalized annual average dry deposition from vapor phase (s-m^2/m^2-yr)	Calculated
D_{ywv}	Normalized annual average wet deposition from vapor phase (s-m^2/m^2-yr)	See Appendix G
D_{ydp}	Normalized annual average dry deposition from particle phase (s-m^2/m^2-yr)	See Appendix G
D_{ywp}	Normalized annual average wet deposition from particle phase (s-m^2/m^2-yr)	See Appendix G

Source: U.S. EPA (1998).

Table 5-5 presents the soil concentrations estimated in the buffer area, tilled cropland, pasture, and stream sediment using all the samples of dioxins, furans, and PCBs as variable congener concentrations in the model.

Table 5-5. TCDD-TEQ Media Concentration for Soil in Buffer, Cropland, Pasture, and Sediment

	TCDD-TEQ Concentration (ng/kg)				
Percentile	**Buffer**	**Cropland**	**Pasture**	**Sediment**	**Applied Biosolids**
50th	0.6	0.3	1.5	0.04	24
75th	1.0	0.6	2.6	0.08	35
90th	1.6	0.9	4.2	0.15	55
95th	2.3	1.4	5.7	0.25	74
99th	8.4	3.4	21.4	0.7	453

The individual congeners in each biosolids sample are modeled individually in the source partition model. However, the congeners remained linked throughout the modeling by their sample number. Thus, all media concentrations of the dioxin congeners can be summed using the TEF system to produce a single TEQ media concentration resulting from the application of biosolids represented by a specific sample. Therefore, the results of the probabilistic source partition model may be expressed as a distribution of TEQ soil concentration in the crop, pasture, and buffer soils. Table 5-5 presents TEQ soil concentrations that show specific percentiles from this distribution. The background concentration for rural soil is 2.5 ng/kg TCDD-TEQ, and the national average background concentration for sediment is 5.8 ng/kg TCDD-TEQ.

The dioxin congener concentrations in the soils of the cropland, pasture, and residential area are influenced by the following factors in the risk analysis. These factors were identified by the statistically based sensitivity analysis described in detail in Section 8.1.2.6 and are ranked according to the percentage of variation they account for in the estimation of the soil concentrations:

- The year during biosolids application that the farm family moves to the farm
- Agricultural application rate (tons of biosolids applied to the land per unit area)
- Number of years biosolids are applied to the agricultural area.

Other less important factors in this analysis (as ranked by the sensitivity analysis) are linked to the geographic location of the modeled farm:

- Soil conditions (soil foc, soil bulk density, etc.)
- Meteorological conditions (temperature, rainfall, windspeed, etc.)

- Area of the farm where biosolids are assumed to be applied.

The greater the loading of biosolids to the soil during the period of time the farm family is exposed, the greater the soil media concentration to which the family is exposed. The farm family is assumed to move to the farm where biosolids are applied during the period of biosolids application. The later the farm family moves to the farm, the greater their estimated exposure because dioxins are persistent and accumulate during the period of application and then remain at high levels for many years after applications cease.

All of the factors linked to location influence the concentration of dioxin congeners in the soil. The locations linked to the highest 1 percent of the soil concentrations are more varied than the locations associated with the highest 1 percent of air concentrations. The highest 1 percent of soil concentrations are linked to cooler locations with smaller average farm sizes. There is no single location that is linked to more than 5 of the top 30 soil concentrations. The locations and the number of iterations in the top 30 for the location are Little Rock, AR (5); Burlington, VT (4); Salem, OR (4); Seattle, WA (4); Muskegon, MI (3); Boise, ID (3); Bismark, ND (2); Winnemucca, WI (2); Minneapolis, MN (1); Salt Lake City, UT (1); and Chicago, IL (1).

5.2.2.2 Predicting Surface Water Concentrations. The waterbody in this analysis is a stream located downslope of the waste management unit. For modeling purposes, the stream is shaped as a rectangle 5.5 m wide and as long as the width of the agricultural fields. It was assumed that the stream is 5.5 m wide because this width is the median of a third-order fishable stream (van der Leeden et al., 1990). A third-order stream refers to a type of stream segment classification. In this classification scheme, a first-order stream segment is one with no tributaries. That is, a first-order stream segment receives all of its flow from runoff from the surrounding watershed soils. A second-order stream segment is produced when two first-order stream segments come together. A third-order stream segment occurs when two second-order segments come together, but not when a second-order and a first-order stream segment combine. The third-order steam segment, therefore, has the combined flow of at least two second-order stream segments. The third-order stream was selected because it reasonably represents the smallest waterbody that would routinely support recreational fishing of consumable fish.

Constituents can enter the waterbody by one of four pathways:

- Constituents in the air above the waterbody can be deposited directly onto the waterbody's surface. This occurs for airborne particles via dry and wet deposition due to gravitational settling and scavenging by precipitation, respectively.

- Vapors can also deposit directly onto the waterbody's surface via scavenging by precipitation (i.e., wet deposition).

- Constituents on the soils in the local watershed can enter the waterbody through runoff and erosion.

- Constituents on the soils in the upstream regional watershed can also enter the waterbody through runoff and erosion.

Thus, the total chemical load to the waterbody is the sum of

- Direct atmospheric inputs
- Eroded load from the local watershed (which itself is the sum of chemical eroded directly from the agricultural fields plus aerially deposited and eroded load from the buffer)
- Eroded load from the regional watershed.

Once in the waterbody, constituents are assumed to be uniformly mixed in a single stream segment. There is water flow in and out of the stream segment, which is predicted by the regional watershed model as described next. Water flowing into the upstream boundary of the waterbody is assumed to have a constituent concentration determined by the application of the soil concentration algorithms described in Section 5.2.2.1 applied to the soils in the regional watershed. The waterbody is modeled based on the waterbody model described in the Draft Dioxin Reassessment Document (U.S. EPA, 2000). The equations used are presented in Appendix H; they partition the chemical mass into chemical sorbed to suspended solids in the water column and chemical sorbed to sediment solids. The soluble fractions are assumed to be zero.

Regional Watershed Model and Waterbody Streamflow. Because the chemicals of concern in this analysis have a strong tendency to be both persistent and accumulative in soils and sediments, it was considered essential to include in the analysis inputs to the waterbody that result from aerial deposition over the upstream watershed and subsequent erosion. As discussed, that upstream watershed is termed here the regional watershed to distinguish it from the local watershed, i.e., the hillside area containing the agricultural fields or landfill. Chemicals deposited onto the regional watershed will be transported in their particulate form on eroded soils into the waterbody network that drains the regional watershed and hence downstream into the modeled waterbody where fishing is assumed to occur. (Not all soils that are eroded from the regional watershed complete the journey downstream to the modeled waterbody. A sediment delivery ratio is included in the calculations that estimates the fraction of mobilized soil that actually arrives at the modeled waterbody as a function of regional watershed area.) A schematic diagram illustrating the regional watershed and its relationship to the agricultural fields and the local watershed is shown in Figure 3-1.

The regional watershed was modeled to provide estimates of two inputs to the modeled waterbody: streamflow and chemical loads associated with eroded soil. Suspended solids concentrations in the waterbody were not modeled, but were assumed to be a constant of 10 mg/L, in accordance with the Draft Dioxin Reassessment Document (U.S. EPA, 2000). Chemical loads associated with eroded soils were estimated using the same equations used for aerially deposited chemical in the local watershed, as discussed in Section 5.2.2.1. Methods used for estimating streamflow are discussed below.

Streamflow in the modeled waterbody consists of surface runoff from the upstream regional watershed, a baseflow component, and surface runoff from the local watershed (for agricultural fields only). Surface runoff from the upstream regional watershed was estimated

using the hydrology algorithm from the source partition model. Because the hydrology algorithm is not stand-alone, executing it required running the source partition model in a mode termed the "LAU as Regional Watershed" (see Appendix F). In this mode, the model is run to estimate the surface water runoff.

Baseflow represents the component of streamflow that is not direct surface runoff. Baseflow was estimated as a function of regional watershed area and U.S. Geological Survey (USGS) Hydrological Unit Code (HUC) number using regional regression models. These regression models predict HUC-specific 30Q2 low flows as a function of watershed area. The 30Q2 flow is a statistical estimate of the 30-day average low flow expected to occur, on average, every other year (2-year return period). The 30Q2 low flow was assumed (for this analysis) to be a reasonable representation of stream baseflow.

The third component of streamflow is direct surface runoff from the local watershed, i.e., the tributary hillside containing the agricultural fields. This runoff is a modeled output of the model used for the agricultural fields; however, the monofill is assumed to have no runoff. Thus, surface runoff for the agricultural field local watershed was available and was used as a contributor to total streamflow. For the landfill (monofill) scenario, streamflow is composed only of surface runoff from the upstream regional watershed and baseflow.

5.3 Calculation of Food Chain Concentrations

Constituents can pass from contaminated air, soil, and surface water to reach individuals through the food chain. For example, constituents that are entrained in air may be deposited on plants growing in the agricultural field or home garden. Constituents from the air and soil may accumulate in fruits and vegetables that are consumed by people. In addition, beef and dairy cattle may feed on forage and silage that are grown in biosolids-amended soil. The beef and dairy products may be subsequently consumed by people. Free-range chickens may also consume contaminated soil. Similarly, constituents that erode into surface water may accumulate in fish, which are subsequently consumed by a recreational fisher.

This section presents the methodology used to calculate contaminant concentrations for each of the food chain pathways considered. An approach was developed for a terrestrial food chain to calculate concentrations of produce, poultry, eggs, beef, and milk that are consumed by the adult and child farmer evaluated in this assessment. In addition, an approach was developed for an aquatic food chain to calculate concentrations in fish that may be consumed by a recreational fisher.

5.3.1 Terrestrial Food Chain

The terrestrial food chain is designed to predict the accumulation of a contaminant in the edible parts of aboveground vegetation from direct deposition of contaminants in air. Concentrations are predicted for three main categories of food crops presumed to be eaten by humans: exposed fruits, exposed vegetables, and root vegetables. The term "exposed" refers to the fact that the edible portion of the produce is exposed to the atmosphere. Examples of the three categories include tomatoes (exposed vegetable), apples (exposed fruit), and potatoes (root vegetables). Figure 5-4 shows the data flow into and out of the food chain model.

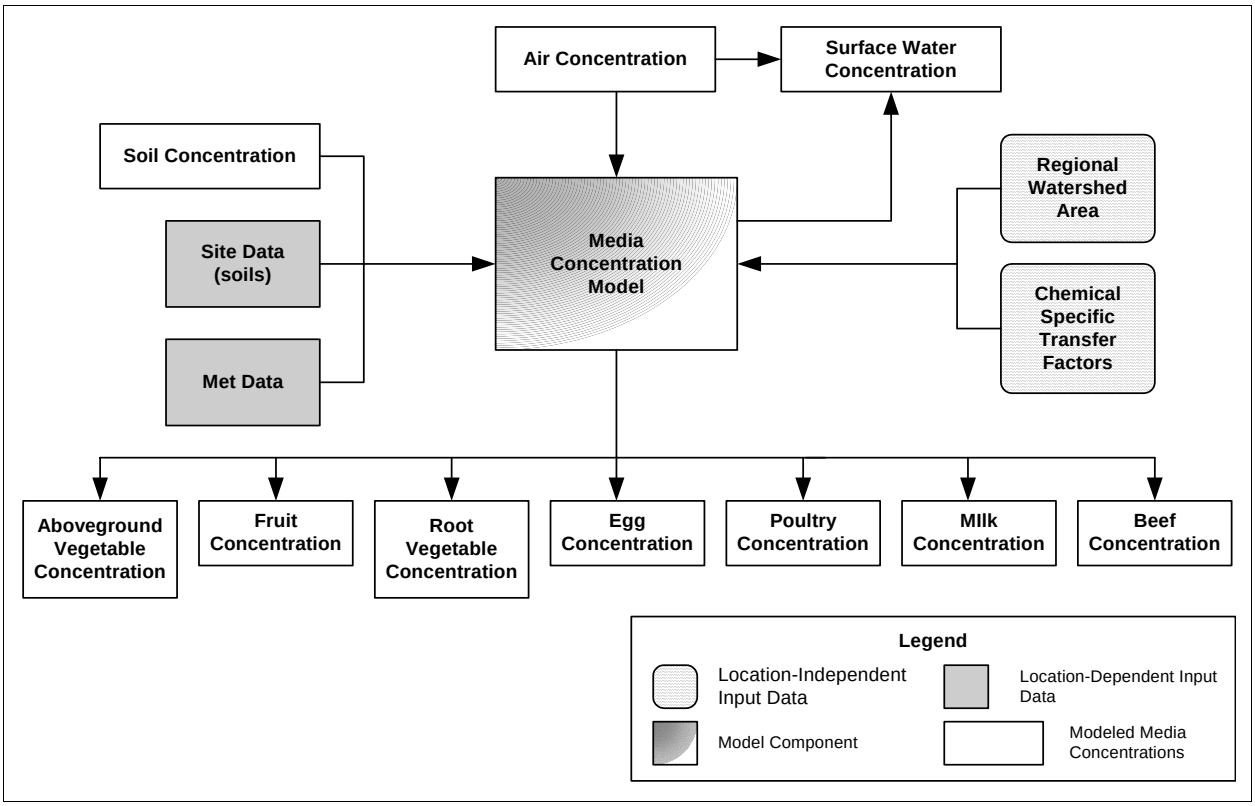

Figure 5-4. Biosolids application to agricultural fields media concentration module.

In addition, the terrestrial food chain estimates the contaminant concentration in farm crops for cattle. Vegetation consumed by cattle includes grain, forage, and silage. Forage is considered exposed vegetation. Silage is calculated as exposed vegetation; however, an empirical correction factor for silage takes into account that silage is partly protected and partly exposed.

Table 5-6 summarizes the mechanisms by which vegetation can be exposed to contaminants. The two mechanisms are deposition of particle-bound contaminants to exposed plant tissues and vapor-phase deposition of contaminants to exposed plant tissues. Exposed vegetation is subject to contamination via particulate deposition and vapor-phase deposition, while protected vegetation is not contaminated because the edible portion of the vegetation is not in direct contact with air.

5.3.1.1 <u>Aboveground Vegetation</u>. Aboveground vegetation is subject to contamination via deposition of particle-bound contaminants and vapor transfer of contaminants. Equation 5-10 is used to calculate the concentration of contaminant in aboveground vegetation.

Table 5-6. Terrestrial Food Chain Vegetation

Type of Vegetation	Particulate Deposition	Vapor-Phase Deposition
Human ingestion		
Exposed vegetables	✓	✓
Exposed fruit	✓	✓
Beef and dairy cow ingestion		
Forage	✓	✓
Silage	✓	✓

Deposition of Particle-Bound Contaminants. Airborne particle-bound contaminants are deposited by wet and dry deposition; thus they affect only exposed vegetation. As described earlier, the air dispersion model ISCST3 was used to calculate the wet and dry deposition rates for the particle-bound contaminants. Not all airborne particles will settle on a plant's edible surface. Some will fall to the ground; others will fall on other surfaces that will undergo weathering processes, such as wind removal, water removal, and growth dilution; and most will end up in the soil or eroded soil. Thus, only a fraction of the total deposition rate per area is used to estimate the amount of airborne particles that contacts the edible portion of the plant.

The calculation of vegetative concentration due to deposition also takes into account the length of time plants are exposed to contaminants. One determination of the length of exposure is the growing season. For instance, the time from when a tomato begins to grow until it is harvested equals its length of exposure to deposition. The productivity level of the plant or biomass is also a factor. The biomass is determined by the amount of standing crop for the average farm. The biomass is needed to take into account the dilution of constituent by biomass growth. Equation 5-11 is used to calculate the concentration of congeners due to direct deposition.

Vapor-Phase Transfer of Contaminants. The concentration of contaminants due to vapor-phase transfer depends on the constituent being considered. Evidence shows that wet deposition is negligible and contact of vapor phase with the plant surface is the primary mechanism of plant uptake; therefore, a different equation is used based on the vapor-phase air concentration of the constituent. Equation 5-12 is used to calculate the concentration of congeners in aboveground vegetation due to air-to-plant transfer.

Vapor-phase transfer for high log K_{ow} constituents, such as dioxins, furans, and coplanar PCBs, uses a congener-specific air-to-plant biotransfer factor to estimate the concentration of contaminants in vegetation. The air-to-plant biotransfer factor is defined as the ratio of contaminant concentration in exposed plant parts to the vapor-phase concentration of contaminant in air. The biotransfer factors have been measured for these constituents (U.S. EPA, 2000). In addition, an empirical correction factor (VG_{ag}) is recommended by EPA (U.S.

P_{veg}

$$P_{veg_{ww}} = \left(P_{d_{veg}} + P_{v_{veg}} + P_{r_{veg}} \right) \times \frac{\left(100 - MAF\right)}{100}$$

$$P_{veg_{DW}} = \left(P_{d_{veg}} + P_{v_{veg}} + P_{r_{veg}} \right) \quad (5\text{-}10)$$

Parameter	Definition	Value
P_{veg}	Vegetation concentration (mg/kg)	Calculated
P_{veg_ww}	Vegetation concentration [wet weight (mg/kg-WW)]	Calculated
P_{veg_DW}	Vegetation concentration [dry weight (mg/kg-DW)]	Calculated
P_{d_veg}	Vegetative concentration due to direct deposition (mg/kg - DW)	Calculated in Table H-3.12
P_{v_veg}	Vegetative concentration due to air-to-plant transfer (mg/kg - DW)	Calculated in Table H-3.14
P_{r_veg}	Aboveground vegetation concentration due to root uptake, zero for this analysis (mg/kg - DW)	0
MAF	Plant tissue-specific moisture adjustment factor to convert DW concentration into WW (percent)	

Source: U.S. EPA (1998).
Note: For exposed vegetation, MAF is 92; for exposed fruit, MAF is 85. Dry weight (DW) is used for silage and feed. Wet weight (WW) is used for exposed vegetation and exposed fruit.

P_d

$$P_d = \frac{\left(D_p \times R_p\right)}{\left(Y_p \times K_p Par\right)} \quad (5\text{-}11)$$

Parameter	Definition	Value
P_d	Vegetation concentration due to air deposition (mg/kg DW)	Calculated
D_p	Deposition term for plants (mg/m^2-yr)	Calculated
R_p	Interception fraction - aboveground vegetables (fraction)	See Appendix I Exposed fruits and vegetables 0.48 Forage 0.35 Feed 0.62
Yp	Crop yield (kg DW/m^2)	See Appendix I Exposed fruits and vegetables 1.17 Forage 0.15 Feed 0.63
K_pPar	Plant surface loss coefficient, particulate (1/yr)	18.07

Source: U.S. EPA (2000).

P_v

$$P_v = \frac{\left(C_{vapor} \times B_v \times VG_{ag} \times 1000\right)}{1200} \quad (5\text{-}12)$$

Parameter	Definition	Value
P_v	Plant concentration due to vapor (mg/kg DW)	Calculated
C_{vapor}	Concentration of vapor (mg/m^3)	Calculated
B_v	Air-to-plant biotransfer factor (µg/g DW plant/µg/g air)	Constituent-specific
VG_{ag}	Empirical correction factor for aboveground vegetables (unitless)	Exposed fruits and vegetables 0.1 Forage 1.00 Feed 0.5
1000	Conversion factor (g/kg)	1,000
1200	Rho - the density of air (g/m^3)	1,200

Source: U.S. EPA (1998).

EPA, 1997) to be applied to the calculation of concentrations in each type of vegetation. The factor is used to adjust the air-to-plant bioconcentration factors that are developed using the different types of vegetation considered in this analysis. This factor also is applied to take into account the difference between outer-surface and whole-plant concentrations. This is important for lipophilic organic chemicals that tend to remain on the outer portion of the plant surface because washing and peeling fruits and vegetables reduces the outer surface residues. Because silage is assumed to be partly protected and partly exposed, the correction factor for silage takes into account that some of the vegetation is not contaminated as a result of vapor deposition onto plant surfaces. Table 5-7 presents the percentile concentrations estimated in exposed aboveground fruits and vegetables using all biosolids samples of dioxins, furans, and PCBs as variable congener concentrations in the model.

Table 5-7. TCDD-TEQ Media Concentration for Exposed Aboveground Fruits and Vegetables

	TCDD-TEQ Concentration (ng/kg)	
Percentile	Fruits	Vegetables
50th	0.00010	0.00005
75th	0.00024	0.00013
90th	0.00046	0.00024
95th	0.00069	0.00037
99th	0.0018	0.00096

The exposed aboveground vegetation media concentrations of dioxins are driven by the air concentrations of vapors; therefore, the factors that increase the vapor concentrations increase the aboveground vegetation concentrations also. (No background concentrations for exposed vegetables and fruits are presented in the Draft Dioxin Reassessment Document (U.S. EPA, 2000).)

5.3.1.2 <u>Belowground Vegetation</u>. In belowground plants, roots can take in contaminants from the soil that may accumulate in the edible portion of the plant. For organic constituents, the calculation is a function of the root concentration factor, which is used to estimate the amount of constituent moving from the soil into the root vegetable. Equation 5-13 gives the equation for calculating the concentration of congeners in root vegetables.

P_{r_bg}

$$P_{r_{bg}} = \frac{\left(C_{soil} \times RCF \times VG_{bg}\right)}{\left(K_d\right)} \qquad (5\text{-}13)$$

Parameter	Definition	Value
P_{r_bg}	Concentration in root vegetables (mg/kg)	Calculated
C_{soil}	Concentration of contaminant in soil (mg/kg)	Calculated
RCF	Root concentration factor (µg/g - WW plant)/(µg/mL soil water)	Congener-specific
VG_{bg}	Empirical correction factor for belowground vegetables (unitless)	0.25
K_d	Soil water partition coefficient	Calculated

Source: U.S. EPA (1998).

In addition, an empirical correction factor *(VG_{bg})* is applied to the concentrations in belowground vegetables. The correction factor is applied to adjust the root concentration factor so that it is appropriate for bulky belowground root crops. This factor adjusts for the concentration gradient from the outside of the root vegetable to the center. Another factor also accounts for constituent losses due to cleaning and cooking and the tendency of lipophilic contaminants to remain in the outer portions of the root (U.S. EPA, 1997). The assumptions concerning the concentration of dioxins/PCBs in fruits and vegetables do not include a gradient through the item for decreasing concentration of the constituents toward the center of the food item. The VG_{ag} and VG_{bg} terms are used in the analysis to distribute the concentration of constituent in an above- or belowground vegetable equally throughout the food item. Thus, all loss terms are applied to the entire quantity of the food item and not selectively to the outer portion of the food item. Table 5-8 presents the percentile concentrations estimated in belowground fruits and vegetables using all biosolids samples of dioxins, furans, and PCBs as variable congener concentrations in the model.

Table 5-8. TCDD-TEQ Media Concentration for Belowground Vegetables

Percentile	TCDD-TEQ Concentration in Belowground Vegetables (ng/kg)
50th	0.0071
75th	0.014
90th	0.028
95th	0.040
99th	0.090

(No background concentration for root vegetables is presented in the Draft Dioxin Reassessment Document (U.S. EPA, 2000).)

The dioxin congener concentrations in root crops are influenced by the following factors in the risk analysis. These factors were identified by the statistically based sensitivity analysis (see Appendix K) and are presented according to the percentage of variation they account for in the estimation of the root concentrations:

- Soil foc
- The year during biosolids application that the farm family moves to the farm
- Agricultural application rate (tons of biosolids applied to the land per unit area)
- Number of years biosolids are applied to the agricultural area.

Another factor important in this analysis is linked to the geographic location of the modeled farm:

- Soil bulk density.

The greater the loading of biosolids to the soil during the period of time the farm family is exposed, the greater the soil media concentration. The farm family is assumed to move to the farm where biosolids are applied during the period of biosolids application. The later the farm family moves to the farm, the greater their estimated exposure because dioxins are persistent and accumulate during the period of application and then remain at high levels for many years after applications cease.

All of the factors linked to location influence the behavior of dioxin congeners in soil to varying degrees. The locations that are linked to the highest 30 estimations of the root concentrations are Las Vegas, NV (21), and Phoenix, AZ (9). The soils in these locations are very arid and have low organic content. These are the properties identified by the sensitivity analysis.

5.3.1.3 Animal Tissue Concentration. The animal products considered in this risk analysis are beef and milk from beef and dairy cattle, respectively, and poultry and eggs. The contaminant concentrations in beef tissue and milk were estimated based on the amount of contaminant the cattle were assumed to have consumed through ingestion. Specifically, the diet for cattle was assumed to comprise a specific fraction of soil, forage, and silage. The animals were assumed to ingest soil, with which they come in contact during grazing or other activities on untilled soils. Different diet fractions were used for beef and dairy cattle, depending on the amount of feed they consume and the activity patterns of the animals. For example, beef cattle are assumed to spend more time grazing and, therefore, have a higher incidental ingestion rate of soil and forage. The animal concentrations also depend on biotransfer factors, which are the ratio of the contaminant concentration in animal tissue to the daily intake of contaminant by the animal. Congener-specific biotransfer factors derived for milk were suggested for use for both milk and beef in the Draft Dioxin Reassessment Document (U.S. EPA, 2000). Chemical concentrations in feed and soil are multiplied by their respective diet fraction and by constituent-specific biotransfer factors and then summed to obtain the concentration of individual constituents in tissue. In this risk assessment, the beef concentration represents the concentration in edible muscle based on the percent of lipid in the tissue. For dairy exposure, milk ingestion was considered because it is a major source of exposure to dairy products and the one for which the best consumption data are available. Milk is also the dairy product most likely to be home produced. Equation 5-14 is used to calculate the concentration of congeners in beef. Equation 5-15 is used to calculate the concentration in milk.

Table 5-9 presents the percentile concentrations estimated in beef using all biosolids samples of dioxins, furans, and PCBs as the variable congener concentrations in the model. Table 5-10 presents the percentile concentrations estimated in milk using all biosolids samples of dioxins, furans, and PCBs as the variable congener concentrations in the model.

The bioavailability of dioxins in biosolids was considered to be the same as the availability of the same constituents in soil. Bioavailability of dioxins from soil was considered in the development of health benchmarks and soil ingestion exposure equations; thus, no additional consideration was made for this factor.

In this risk assessment, the dairy cattle diet is based on the assumptions presented in the Draft Dioxin Reassessment Document (U.S. EPA, 2000). In the Draft Dioxin Reassessment Document, dairy cattle are assumed confined to the barn for most of their lifetime and spend little time foraging freely. However, silage material produced on the amended land is assumed brought to the dairy herd in the barn. The silage material harvested for the dairy cattle is assumed to include soil amended with biosolids associated with the plant material. For this reason, dairy cattle are assumed to consume soil as 2 percent of their diet (same as beef cattle) even though they spend much less time foraging freely in the pasture.

A_{beef}

$$A_{beef} = C_{fat} \times 0.2 \quad (5\text{-}14)$$

$$C_{fat} = \left(BCF_{cattle} \times FF\right) \times \left(DF_{beef_{soil}} \times B_s \times C_{soil} + DF_{beef_{forage}} \times P_{forage} + DF_{beef_{feed}} \times P_{feed}\right)$$

Parameter	Definition	Value
A_{beef}	Concentration in beef (mg/kg)	Calculated
C_{fat}	Concentration of dioxin (2,3,7,8-TCDD) in beef fat (mg/kg)	Calculated
0.2	Fraction of fat in beef (unitless)	
BCF_{cattle}	Bioconcentration ratio of contaminant as determined from cattle vegetative intake (pasture grass or feed)	See Appendix D Congener-specific
FF	Feedlot factor for beef fat calculation ($\leq$1 for beef fat and = 1 for milk fat) (unitless)	See Appendix I 1.0
$DF_{beef\ soil}$	Fraction of cattle diet that is soil (unitless)	0.04
B_s	Bioavailability of contaminant on the soil vehicle relative to the vegetative vehicle (unitless)	0.65
C_{soil}	Average contaminant soil concentration (mg/kg)	Calculated in Tables H-2.3, H-2.4
DF_{beef_forage}	Fraction of cattle diet that is pasture grass (unitless)	0.48
P_{forage}	Average concentration of contaminant on pasture grass (mg/kg)	Calculated
DF_{beef_feed}	Fraction of cattle diet that is feed (unitless)	0.48
P_{feed}	Average concentration of contaminant in feed (mg/kg)	Calculated

Source: U.S. EPA (2000).

A_{milk}

$$A_{milk} = C_{fat} \times 0.04 \qquad (5\text{-}15)$$

$$C_{fat} = \left(BCF_{cattle} \times FF\right) \times \left(DF_{dairy_{soil}} \times B_s \times C_{soil} + DF_{dairy_{forage}} \times P_{forage} + DF_{dairy_{feed}} \times P_{feed}\right)$$

Parameter	Definition	Value
A_{milk}	Concentration in milk (mg/kg)	Calculated
C_{fat}	Concentration of dioxin (2,3,7,8-TCDD) in milk fat (mg/kg)	Calculated
0.04	Fraction of fat in milk (unitless)	
BCF_{cattle}	Bioconcentration ratio of contaminant as determined from cattle vegetative intake (pasture grass or feed) (unitless)	See Appendix D Congener-specific
FF	Feedlot factor for beef fat calculation ($\leq$1 for beef fat and = 1 for milk fat) (unitless)	1.0
DF_{dairy_soil}	Fraction of cattle diet that is soil (unitless)	0.02
B_s	Bioavailability of contaminant on the soil vehicle relative to the vegetative vehicle (unitless)	See Appendix I 0.65
C_{soil}	Average contaminant soil concentration (mg/kg)	Calculated in Tables H-2.3, H-2.4
DF_{dairy_forage}	Fraction of cattle diet that is pasture grass (unitless)	0.08
P_{forage}	Average concentration of contaminant on pasture grass (mg/kg)	Calculated
DF_{dairy_feed}	Fraction of cattle diet that is feed (unitless)	0.90
P_{feed}	Average concentration of contaminant in feed (mg/kg)	Calculated

Source: U.S. EPA (2000).

The contaminant concentrations in poultry and eggs were estimated based on the amount of contaminant the chickens were assumed to have consumed through ingestion. Specifically, the diet for chickens was assumed to comprise a specific fraction of soil and feed. The animals were assumed to ingest soil with which they came in contact during free-range activities in the contaminated chicken yard. The chicken diet was assumed to contain 20 percent soil. The chicken feed was assumed to be uncontaminated. Bioaccumulation factors specific for chickens and eggs and based on ingestion of contaminated soils are from the Draft Dioxin Reassessment Document (U.S. EPA, 2000). Equations 5-16 and 5-17 are used to calculate the concentration of congeners in poultry and eggs, respectively.

Table 5-9. TCDD-TEQ Media Concentration by Percentile for Beef

Percentile	TCDD-TEQ Concentration in Beef (ng/kg)
50th	0.088
75th	0.16
90th	0.28
95th	0.40
99th	0.86
Background	0.29

Table 5-10. TCDD-TEQ Media Concentration by Percentile for Milk

Percentile	TCDD-TEQ Concentration in Milk (ng/kg)
50th	0.0081
75th	0.015
90th	0.027
95th	0.038
99th	0.094
Background	0.047

$A_{poultry}$

$$A_{poultry} = C_{fat} \times 0.1$$

(5-16)

$$C_{fat} = BCF_{poultry} \times \left(DF_{poultry_{soil}} \times B_s \times C_{soil} + DF_{poultry_{forage}} \times P_{forage} + DF_{poultry_{feed}} \times P_{feed} \right)$$

Parameter	Definition	Value
$A_{poultry}$	Concentration in poultry (mg/kg)	Calculated
C_{fat}	Concentration of dioxin (2,3,7,8-TCDD) in chicken fat (mg/kg)	Calculated
0.1	Fraction of fat in poultry (unitless)	
$BCF_{poultry}$	Bioconcentration ratio of contaminant developed for chicken vegetative intake (unitless)	See Appendix D Congener-specific
$DF_{poultry\_soil}$	Fraction of chicken diet that is soil (unitless)	See Appendix I 0.05
B_s	Bioavailability of contaminant on the soil vehicle relative to the vegetative vehicle (unitless)	See Appendix I 0.65
C_{soil}	Average contaminant soil concentration (mg/kg)	Calculated in Tables H-2.3, H-2.4
$DF_{poultry\_forage}$	Fraction of chicken diet that is incidental vegetation while free ranging (unitless)	See Appendix I 0.05
P_{forage}	Average concentration of contaminant on free-range vegetation (mg/kg)	Calculated
$DF_{poultry\_feed}$	Fraction of chicken diet that is feed (unitless)	See Appendix I 0.85
P_{feed}	Average concentration of contaminant in feed (mg/kg)	0

Source: U.S. EPA (2000).

A_{eggs}

$$A_{eggs} = C_{fat} \times 0.1 \quad (5\text{-}17)$$

$$C_{fat} = BCF_{egg} \times \left(DF_{poultry_{soil}} \times B_s \times C_{soil} + DF_{poultry_{forage}} \times P_{forage} + DF_{poultry_{feed}} \times P_{feed} \right)$$

Parameter	Definition	Value
A_{eggs}	Concentration in eggs (mg/kg)	Calculated
C_{fat}	Concentration of dioxin (2,3,7,8-TCDD) in egg fat (mg/kg)	Calculated
0.1	Fraction of fat in eggs (unitless)	
BCF_{egg}	Bioconcentration ratio of contaminant developed for chicken vegetative intake (unitless)	See Appendix D Congener-specific
$DF_{poultry\_soil}$	Fraction of chicken diet that is soil (unitless)	See Appendix I 0.10
B_s	Bioavailability of contaminant on the soil vehicle relative to the vegetative vehicle (unitless)	See Appendix I 0.65
C_{soil}	Average contaminant soil concentration (mg/kg)	Calculated in Tables H-2.3, H-2.4
$DF_{poultry\_forage}$	Fraction of chicken diet that is incidental vegetation while free ranging (unitless)	See Appendix I 0.05
P_{forage}	Average concentration of contaminant on free-range vegetation (mg/kg)	Calculated
$DF_{poultry\_feed}$	Fraction of chicken diet that is feed (unitless)	See Appendix I 0.85
P_{feed}	Average concentration of contaminant in feed (mg/kg)	0

Source: U.S. EPA (2000).

Table 5-11 presents the percentile concentrations estimated in poultry using all biosolids samples of dioxins, furans, and PCBs as variable congener concentrations in the model. Table 5-12 presents the percentile concentrations estimated in eggs using all biosolids samples of dioxins, furans, and PCBs as variable congener concentrations in the model.

All of the factors linked to location for the poultry and egg ingestion pathway influence the soil concentration of dioxin congeners in the residential buffer. The ingestion of soil in the buffer area is the exposure pathway for the free-range chickens raised and eaten by the farm family. The geographic locations linked to the highest 30 estimations of dioxin concentrations in poultry meat and eggs are linked to colder locations with soils with higher soil foc, which binds dioxins to the soil particles. These locations are not confined to a single area of the country, but

Table 5-11. TCDD-TEQ Media Concentration for Poultry Thigh Meat

Percentile	TCDD-TEQ Concentration in Poultry Thigh Meat (ng/kg)
50th	0.021
75th	0.036
90th	0.060
95th	0.088
99th	0.18
Background	0.16

Table 5-12. TCDD-TEQ Media Concentration for Eggs

Percentile	TCDD-TEQ Concentration in Eggs (ng/kg)
50th	0.026
75th	0.046
90th	0.075
95th	0.11
99th	0.32
Background	0.13

are more dispersed as indicated by the following locations associated with the top 1 percent of the poultry and egg concentration estimates (listed in order of decreasing frequency of occurrence):

- Burlington, VT (6)
- Salem, OR (6)
- Chicago, IL (5)
- Little Rock, AR (2)
- Portland, ME (2)
- Williamsport, PA (2)
- Muskegon, MI (2)
- Minneapolis, MN (2)
- Atlanta, GA (1)
- Cleveland, OH (1)
- Seattle, WA (1).

5.3.2 Aquatic Food Chain

An aquatic food chain model was used to estimate the concentration of constituent that may accumulate in fish. It is assumed for this analysis that fish is a food source for a recreational fisher. T3 and T4 fish were considered in this analysis. T3 fish are those that consume invertebrates and plankton. T4 fish are those that consume other fish. Most of the fish that humans eat are T4 fish (e.g., salmon, trout, walleye, bass) and medium to large T3 fish (e.g., carp, smelt, perch, catfish, sucker, bullhead, sauger).

The concentration of constituent that accumulates in fish is calculated using the concentration calculated for the sediment in the waterbody adjacent to the buffer. Fish tissue concentrations are dependent on a BSAF. These factors are used to estimate the amount of constituent being transferred from the sediment into the fish tissue. Specifically, they reflect the ratio between the tissue concentration in fish and the appropriate sediment concentration. BSAFs only take into account partitioning from the sediment to the fish and do not consider accumulation through the food chain. The fish concentrations calculated for human receptors are generally lower than whole fish concentrations. Human receptors usually consume only the filet portion of the fish, which has a lower lipid content. Because constituents tend to accumulate in the fatty tissue, the concentration in the filet portion of the fish is lower than the concentration in the whole fish. Equation 5-18 is used to calculate the concentration of congeners in fish. Because the variation in fish concentration is dependent only on the variation in the sediment concentration, the discussion on the variation in the sediment concentration also applies to fish concentration.

C_{fish}

$$C_{fish} = C_{fish_{lipid}} \times LF$$

$$C_{fish_{lipid}} = BASF \times C_{sed} \qquad (5\text{-}18)$$

Parameter	Definition	Value
C_{fish}	Concentration in fish (mg/kg)	Calculated
C_{fish_lipid}	Concentration of contaminant in fish lipid (mg/kg)	Calculated
LF	Lipid fraction (unitless)	T3, 0.0182 T4, 0.031
BASF	Biota sediment accumulation factor (unitless)	See Appendix D Congener-specific
C_{sed}	Concentration in sediment settling to bottom (mg/kg)	Calculated in Table H-2.2

Source: U.S. EPA (1998).

5.4 Infant Breast Milk Exposure

The concentrations of dioxins in breast milk are modeled using a steady-state first-order kinetics model obtained from U.S. EPA (1998). This approach allows infant exposures to both lipophilic and nonlipophilic constituents to be modeled based on projected constituent concentrations in maternal breast milk. Lipophilic compounds, such as dioxins, are assumed to accumulate in the lipid fraction of breast milk, and the concentrations in breast milk are equal to concentrations in maternal body fat. Nonlipophilic constituents are assumed to accumulate in the aqueous phase of breast milk and to be proportional to the concentrations in maternal blood plasma. Dioxins are assumed to accumulate exclusively in the lipid phase of breast milk. The equation for estimating the dioxin concentration in milk fat is presented in Equation 5-19.

$C_{milkfat}$

$$C_{milkfat} = \frac{ADD_{mat} \times f_{am} \times f_f}{(ln2)/t_{1/2}^{b} \times f_{fm}} \quad (5\text{-}19)$$

Parameter	Definition	Value
$C_{milkfat}$	Concentration in maternal milk fat (mg/kg)	Calculated
ADD_{mat}	Average daily dose consumed by the mother (mg/kg-day)	Calculated
f_{am}	Fraction of ingested contaminant absorbed by the mother (unitless)	1.0
f_f	Fraction of contaminant stored in maternal fat (unitless)	0.9
$t_{1/2}^{b}$	Biological half-life of contaminant in lactating women (days) (used to calculate biological elimination constant for the contaminant in nonlactating women)	2,555 days (7 y)
f_{fm}	Fraction of mother's weight that is fat (unitless)	0.3

Source: U.S. EPA (1998).

The concentration of dioxins in maternal milk fat is dependent on the maternal exposure and the biological half-life for the contaminant. A range of 5 to 7 years was identified for biological half-life (U.S. EPA, 1998); for this analysis, an upper bound of the range (7 years) was used. This assumption will result in a longer time to steady state and in a higher dioxin concentration in maternal fat and, thus, breast milk. This is a protective assumption.

In this risk assessment, the maternal body burdens are assumed to have reached steady state. Reductions in maternal body burden resulting from losses from breastfeeding are not considered. These assumptions may introduce error if the constituent being modeled has a relatively long half-life and the maternal exposure duration used for the mother prior to the start of lactation is relatively short. In this analysis, maternal body burdens approach steady-state

concentrations; thus, the amount of error introduced by not considering losses due to breastfeeding are expected to be small. These losses have been shown to be greatest during the initial stages of maternal exposure, when body burden levels are low and the breast milk loss mechanism is more significant.

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6.0 Human Exposure Assessment

This section describes the human exposure assessment that was conducted for this risk assessment. An exposure assessment is the determination or estimation of the magnitude, frequency, duration, and route of exposure to contaminants that an individual may experience. The term "exposure," as defined by EPA's *Guidelines for Exposure Assessment* (U.S. EPA, 1992), is the condition that occurs when a contaminant comes into contact with the outer boundary of the body. The exposure of an individual to a contaminant is what completes an exposure pathway (i.e., the course a constituent takes from the agricultural land amended with biosolids to an exposed individual). Once the body is exposed, the constituent can cross the outer boundary and enter the body. The amount of contaminant that crosses and is available for adsorption at internal exchange boundaries is referred to as the "dose" (U.S. EPA, 1992). Each exposure pathway, as illustrated in Figure 6-1, includes an exposure point and exposure route.

The biosolids agricultural application risk assessment evaluated the risk to farmers and their families and adult fishers.

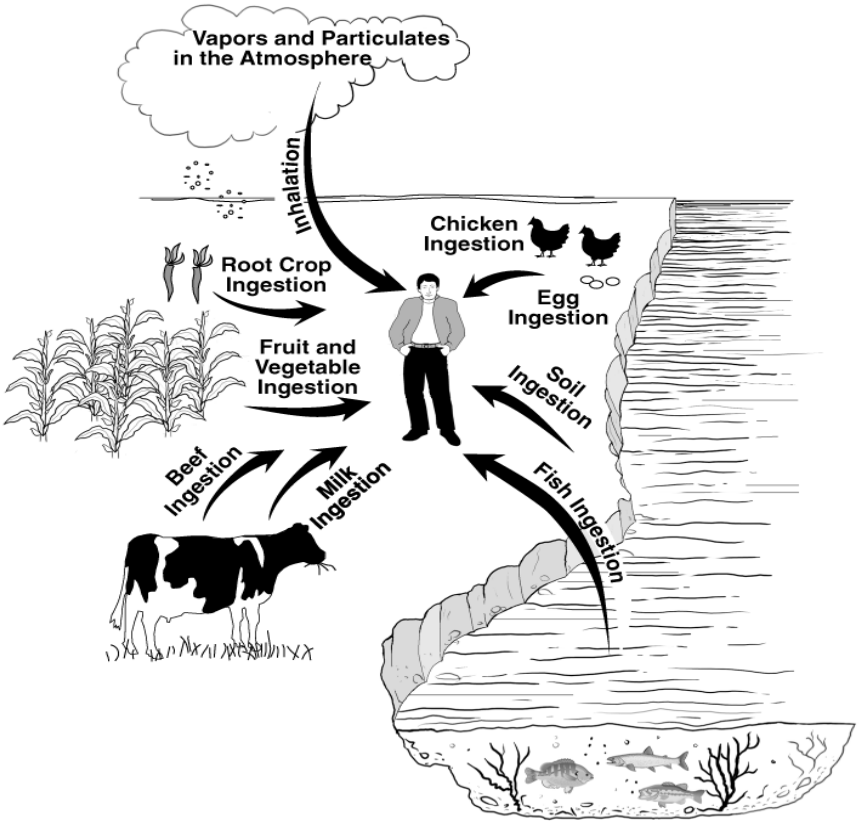

Figure 6-1. Human exposure pathways.

Although all fishers and farmers are exposed to dioxins in biosolids, not all individuals experience the same exposure. Different individuals will have a different magnitude, frequency, duration, and route of exposure. Steps were taken in this analysis to capture the variability in individual exposures by taking into account differences in physiological characteristics and daily activity patterns. One step was to vary the values (i.e., exposure factors) used to calculate exposure/intake for fishers, farmers, and their infants and children. Section 6.1 presents an overview of the selected exposure pathways and exposure scenarios considered for this assessment. Section 6.2 presents particular exposure factors (i.e., values needed to calculate human exposure) used in the analysis. Section 6.3 describes the methods used to estimate dose, including average daily dose (ADD) and LADD.

6.1 Receptors and Exposure Pathways

Four types of human receptors were assumed to be representative of the individuals who might be exposed to dioxin-like compounds in biosolids: an infant of a farmer, a child of a farmer, an adult farmer, and an adult recreational fisher. These receptors reflect the range of possible individual exposures for direct and indirect exposure pathways. The routes of exposure differ for the farmer and fisher. For example, for this assessment, it is assumed that a farmer consumes produce grown on the farm, as well as animal products (i.e., beef, dairy, poultry, and eggs).

Table 6-1 lists each receptor along with the specific exposure pathways that apply to that receptor. The adult and child farmer are exposed via the inhalation of air and the ingestion of soil, homegrown above- and belowground produce, beef, dairy, poultry, and egg products. The fisher is assumed to be a recreational angler who catches and consumes fish from the nearby waterbody. Infants of farmers are exposed via the ingestion of breast milk only. For very lipophilic constituents that have low volatility, such as dioxins and PCBs, infant exposures from breast milk were assumed to be much greater than exposures through other potential infant pathways, i.e., inhalation or incidental soil ingestion. Therefore, only the breast milk pathway was evaluated in this risk analysis for infants. Infants were considered separately from other childhood exposures.

Table 6-1. Receptors and Exposure Pathways

Receptor	Inhalation of Ambient Air	Ingestion of Soil	Ingestion of Above- and Belowground Produce	Ingestion of Beef and Dairy Products	Ingestion of Poultry and Egg Products	Ingestion of Fish	Ingestion of Breast Milk
Adult farmer	✓	✓	✓	✓	✓		
Child farmer	✓	✓	✓	✓	✓		
Infant farmer							✓
Adult fisher						✓	

6.1.1 Childhood Exposure

Children are an important subpopulation to consider in a risk assessment. They are likely to be more susceptible to exposures, compared with adults, because they may eat more food and drink more fluids per unit of body weight. This higher intake-rate-to-body-weight ratio can result in a higher ADD than adults experience.

As children mature, however, their physical characteristics and behavior patterns change. To capture these changes in the analysis, the life of a child was divided into several age ranges: ages 1 to 5, 6 to 11, 12 to 19, and 20 to 70 (adult). Each age range has distributions of the values, called "exposure parameters," that are required to calculate exposure to an individual. The exposure parameter distributions for each age range reflect the physical characteristics and behavior patterns of that age range. Data from the *Exposure Factors Handbook* (EFH) were used to derive distributions appropriate for each age range (U.S. EPA, 1997a,b,c). The distributions for the 20- to 70-year-old cohort were used for adult receptors.

Development of the child exposure parameters consisted of three steps:

1. Define the start age of the child.
2. Select the exposure duration of the child.
3. Calculate time-weighted exposure parameters.

To capture the higher intake-rate-to-body-weight ratio of children, a start age between the ages of 1 and 6 was selected for all children. For the probabilistic analysis, a start age between these ages was selected randomly for each iteration.

To select the exposure duration for each of the 3,000 iterations in the analysis, a distribution was chosen to define the exposure duration based on the start age. For example, if the start age was 2, the distribution for cohort 1 (children between ages 1 and 5) was used to define exposure duration. However, if the start age was 6, the distribution developed for cohort 2 (children between ages 6 and 11) was used to define exposure duration.

After the start age and the exposure duration were defined for a given iteration, all the other exposure parameters needed to calculate exposure to a child were developed using the distributions associated with each of the age groups through which the child would age. In this process, an exposure parameter selected from each age group was time-weighted and combined with values from the other age groups to create a single time-weighted exposure parameter. For example, the beef ingestion rates selected from each age group were time-weighted according to the number of years the child remained in the age group and were combined to generate a single time-adjusted beef ingestion rate for the child. The same was done for all the parameters (e.g., body weight, inhalation rate, fruit ingestion rate) required to assess exposure. Equation 6-1 was used to combine each child's exposure parameters into one time-weighted exposure parameter:

$$EP_{TW} = \frac{(EP_1 \times ED_1) + (EP_2 \times ED_2) + (EP_3 \times ED_3) + (EP_4 \times ED_4)}{ED} \qquad (6\text{-}1)$$

where

EP_{TW}	=	time-weighted exposure parameter (e.g., ingestion rate of milk, body weight)
EP_1	=	exposure parameter for ages 1 to 5
ED_1	=	time spent in age group 1
EP_2	=	exposure parameter for ages 6 to 11
ED_2	=	time spent in age group 2
EP_3	=	exposure parameter for ages 12 to 19
ED_3	=	time spent in age group 3
EP_4	=	exposure parameter for ages 20 to 70
ED_4	=	time spent in age group 4
ED	=	total exposure duration of the receptor (sum of $ED_1 + ED_2 + ED_3 + ED_4$).

The general population exposure factors used for children are lower than the exposure factors used for the farm population. Farm residents tend to eat more homegrown produce and animal products than the general population because of the greater availability of homegrown products. Farm residents also have less residential mobility than other segments of the population. Although fewer data are available specifically for the farm child population, these differences from the general population are assumed to be true of the farm children as well. The use of general population data for farm children is reasonable in the absence of data on the farm child, but these data probably underestimate exposure to these individuals rather than overestimating them.

In some cases, the time-weighted exposure parameter methodology resulted in a higher ADD for children than for adults. However, even in those cases where the ADD was higher for children than for adults, the LADD (used for assessing long-term cumulative endpoints, such as cancer) was lower for children than for adults. The reason for this is that total exposure duration is usually shorter for children than for adults, while the same 70-year average lifetime is assumed for averaging the LADD for both children and adults.

6.1.2 Infant Exposure

Infants are an important subpopulation to consider in this risk assessment because they may be exposed to dioxin-like compounds via the ingestion of breast milk. The characterization of risks to infants of farmers and home gardeners was considered separately from the characterization of risks to older children (i.e., aged 1 year or older).

6.1.3 Exposure Pathways

Human receptors may come into contact with dioxins, furans, and PCBs present in environmental media by a variety of pathways. In general, exposure pathways are either direct, such as inhalation of ambient air, or indirect, such as the farm food chain pathways. The exposure pathways considered in this assessment were inhalation of ambient air and ingestion of soil, aboveground produce, belowground produce (i.e., root crops), beef, dairy products, poultry, eggs, fish, and breast milk (infants only).

6.1.3.1 Inhalation of Ambient Air. Both vapors and particles can be inhaled in ambient air by a receptor. Both adults and children (except infants) were affected via direct inhalation.

6.1.3.2 Ingestion of Soil. Both adults and children (except infants) were exposed to soil based on incidental ingestion, mostly due to hand-to-mouth behavior. Soil ingested was modeled as the top 1 cm of soil, untilled for children and adults. Soil ingestion data needed to develop a distribution of soil intake rates for specific receptor groups were not available. Data on soil ingestion by adults or children are scarce and insufficient to support a distribution of soil intake rates for any adult or child receptors, much less account for the differences in incidental soil ingestion by a specific receptor group. If data were available to support the weighting of soil intake data for these groups, the data could be included in the modeling. Until more data are available, the fixed values of 50 mg/d for adult soil ingestion and 100 mg/d for soil ingestion for children under the age of 6 are recommended by the EFH (U.S. EPA, 1997a,b,c). No data were available for weighting the exposure of the farmer for contact with soil in the pasture, cropland, or buffer. It seems appropriate for child soil ingestion to occur in the area nearest the residence (the buffer area). The farmer's exposure in this analysis was also assumed to come from the buffer area. The risks from the soil ingestion pathway remain very low, and soil ingestion was not a driving pathway in this analysis.

6.1.3.3 Ingestion of Above- and Belowground Produce. Ingestion of the following categories of produce was considered in this risk assessment: exposed fruit, exposed vegetables, and root vegetables. For aboveground produce, the term "exposed" refers to the fact that the edible portion of the plant is exposed to the atmosphere. It was assumed that farmers grow a portion of their fruits and vegetables on land amended with biosolids and that these fruits and vegetables become contaminated via soil and air. Belowground produce refers to root crops grown by the farmer. The soil that root crops were grown in was assumed to be tilled, so dioxins, furans, and PCBs were mixed throughout the root zone.

6.1.3.4 Ingestion of Beef and Dairy Products. Beef and dairy cattle were assumed to be exposed to dioxins, furans, and PCBs via differing intake rates of contaminated soil, forage, and feed. Adult and child farmer receptors were assumed to consume beef and drink milk from cattle that grazed in the pasture amended with biosolids.

6.1.3.5 Ingestion of Poultry and Egg Products. Chickens were assumed to be exposed to dioxins, furans, and PCBs via intake rates of contaminated soil while free-range feeding. Adult and child farmer receptors were assumed to consume poultry and eggs from the chicken.

6.1.3.6 Ingestion of Fish. Fish are exposed to dioxins, furans, and PCBs via uptake of contaminants from surface waters. Adult fishers were assumed to consume fish caught in local waterbodies. The scenario was meant to be protective of individuals who catch and eat fish from a small stream adjacent to an agricultural field amended with biosolids. The median fish ingestion rate was estimated to be 2 gWW/d or approximately 1.5 lb/yr. This is not an excessive amount of fish to come from a third-order stream.

6.1.3.7 Ingestion of Breast Milk. Adult women farmers were assumed to be exposed to dioxins, furans, and PCBs via the consumption of contaminated food items and soil and inhalation of contaminated ambient air until they reach a steady-state concentration. Infants of

farmer receptors were assumed to consume breast milk from exposed adult receptors for the first year of life.

6.2 Exposure Factors

Table 6-2 lists the exposure factors used in this risk assessment, along with their data sources and whether they were represented by a distribution or a fixed value in the Monte Carlo analysis. Exposure factors are used to calculate the dose of a chemical based on contact with contaminated media or food, the duration of that contact, and the body weight of the exposed individuals. The primary data source of human exposure model inputs used in this risk assessment was EPA's EFH (U.S. EPA, 1997a,b,c). The EFH summarizes data on human behaviors and characteristics related to human exposure from relevant key studies and provides recommendations and associated confidence estimates on the values of exposure factors. EPA carefully reviewed and evaluated the quality of the data before including values in the EFH. EPA's evaluation criteria included peer review, reproducibility, pertinence to the United States, currency, adequacy of the data collection period, validity of the approach, representativeness of the population, characterization of the variability, lack of bias in study design, and measurement error (U.S. EPA, 1997a,b,c).

Table 6-2. Human Exposure Factor Input Parameters and Data Sources

Parameter	Variable Type	Data Source
Body weight (adult, child, infant)	Distribution	U.S. EPA (1997a)
Inhalation rate (adult, child)	Distribution	U.S. EPA (1997a)
Ingestion rate: soil (adult, child)	Fixed (constant)	U.S. EPA (1997a)
Consumption rate for farmer: exposed vegetables (adult, child)	Distribution	U.S. EPA (1997b)
Consumption rate for farmer: root vegetables (adult, child)	Distribution	U.S. EPA (1997b)
Consumption rate for farmer: exposed fruit (adult, child)	Distribution	U.S. EPA (1997b)
Consumption rate for recreational fisher: fish (adult)	Distribution	U.S. EPA (1997b)
Consumption rate for farmer: beef (adult, child)	Distribution	U.S. EPA (1997b)
Consumption rate for farmer: milk (adult, child)	Distribution	U.S. EPA (1997b)
Consumption rate for farmer: poultry (adult, child)	Distribution	U.S. EPA (1997b)
Consumption rate for farmer: eggs (adult, child)	Distribution	U.S. EPA (1997b)
Consumption rate for farmer: breast milk (infant)	Distribution	U.S. EPA (1997b)
Exposure duration (adult, child)	Distribution	U.S. EPA (1997c)
Exposure frequency (adult, child)	Fixed (constant)	U.S. EPA policy
Fraction contaminated: soil	Fixed (constant)	U.S. EPA policy

(continued)

Table 6-2. (continued)

Parameter	Variable Type	Data Source
Fraction contaminated for recreational fisher: fish	Fixed (constant)	U.S. EPA (1997b)
Fraction homegrown for farmer: exposed vegetables	Fixed (constant)	U.S. EPA (1997b)
Fraction homegrown for farmer: root vegetables	Fixed (constant)	U.S. EPA (1997b)
Fraction homegrown for farmer: exposed fruit	Fixed (constant)	U.S. EPA (1997b)
Fraction contaminated (home-raised) for farmer: beef	Fixed (constant)	U.S. EPA (1997b)
Fraction contaminated (home-raised) for farmer: dairy	Fixed (constant)	U.S. EPA (1997b)
Fraction contaminated (home-raised) for farmer: poultry	Fixed (constant)	U.S. EPA (1997b)
Fraction contaminated (home-raised) for farmer: eggs	Fixed (constant)	U.S. EPA (1997b)
Fraction of T3 fish consumed	Fixed (constant)	U.S. EPA (1997b)
Fraction of T4 fish consumed	Fixed (constant)	U.S. EPA (1997b)
Food preparation and cooking losses: exposed vegetables	Fixed (constant)	U.S. EPA (1997b)
Food preparation and cooking losses: root vegetables	Fixed (constant)	U.S. EPA (1997b)
Food preparation and cooking losses: exposed fruit	Fixed (constant)	U.S. EPA (1997b)
Food preparation and cooking losses: beef	Fixed (constant)	U.S. EPA (1997b)
Food preparation and cooking losses: poultry	Fixed (constant)	U.S. EPA (1997b)
Human lifetime (used in carcinogenic risk calculation)	Fixed (constant)	U.S. EPA policy

For probabilistic risk analyses, probability distribution functions were developed from the values in the EFH (U.S. EPA, 1997a,b,c). Appendix K presents the exposure factors used in the probabilistic analysis. Appendix K also describes the rationale and data used to select the parametric models (i.e., gamma, lognormal, and Weibull) for those exposure factors that were varied and the maximum and minimum exposure parameter values used in the analysis.

6.2.1 Intake Factors

This section presents the basis for the intake rates used for soil and food items in the probabilistic analysis. Adult and child receptor intake rates for soil and food items were derived from data in the EFH (U.S. EPA, 1997a,b). There is no assumed correlation among the consumption rates for any dietary item. There is no defensible way to establish correlations among consumption rates, although correlations may seem intuitively appropriate.

6.2.1.1 Soil Ingestion. Ingestion of contaminated soil is a pathway common to all receptors. Because most available data are from studies measuring soil ingestion in children under the ages of 5 or 6, the adult soil ingestion rate was used for children older than age 5. Thus, soil ingestion rates used in the probabilistic analysis were not varied for any age group. The constant rates used for soil ingestion in this analysis are presented in Table 6-3.

Table 6-3. Soil Ingestion Rates Used in This Risk Analysis

Receptor	Soil Intake Rate (mg/d)
Child	100
Adult	50

6.2.1.2 Fruit and Vegetable Ingestion. Ingestion of contaminated homegrown fruits and vegetables is a potential pathway of exposure for adult farmers and home gardeners and their children. Consumption rate data of homegrown exposed fruit, exposed vegetables, and root vegetables by these receptors were obtained from the EFH. Examples of exposed fruits are apples, peaches, pears, and berries. Aboveground exposed vegetables include tomatoes, green leafy vegetables (e.g., lettuce, cabbage, kale), cucumber, summer squash, peppers, broccoli, okra, and snap beans. Common root vegetables include carrots, onions, potatoes, and beets (U.S. EPA, 1997b).

Because farmers grow much but generally not all of their food, the fraction of the farmers' diets that may be contaminated was considered. The EFH provides recommendations on the percentage of the total diet of farmers that is homegrown. In examining the amount of homegrown produce consumed by the farm family, the percentage of each family member's diet that is assumed grown on the contaminated cropland was considered rather than the percentage of produce grown on the cropland that is eaten by the farm family (50 percent of what is grown might far exceed the family's diet, depending on the size of the farm). Thus, it was assumed that a percentage of the farm family's dietary intake of various food items was home-produced on the family's farmland and amended with biosolids. The remainder of the farm family's diet was assumed to come from uncontaminated commercial sources. In addition, produce consumption rate data were adjusted to account for food preparation and cooking losses.

Table 6-4 presents exposed fruit consumption data used in the Monte Carlo analysis. Data for consumption of homegrown exposed fruit were obtained from Table 13-61 of the EFH (U.S. EPA, 1997b). Data (in g WW/kg-d) were presented by age groups and for farmers and home gardeners (adults). For the 1- to 5-year-old age group, data were only available for those aged 3 to 5 years; therefore, these data were used for the entire 1- to 5-year-old age group. Percentile data were used to fit parametric models (gamma, lognormal, and Weibull) using maximum likelihood estimation. Measures of goodness of fit were used to select the most appropriate model. The fraction of exposed fruit intake that is home-produced is 0.328 for households that farm and 0.116 for households that garden (Table 13-71, U.S. EPA, 1997b). Figure 6-2 presents these distributions graphically. The distributions were truncated at the maximum value shown in the table and graph.

Table 6-4. Exposed Fruit Consumption Data and Distributions

Age Cohort	N	EFH Data (g WW/kg-d)											Distributions			
		Data Mean	Data SDev	P01	P05	P10	P25	P50	P75	P90	P95	P99	Distribution	Pop-Estd Mean	Pop-Estd SDev	Max
1-5	49	2.6	3.947			0.373	1	1.82	2.64	5.41	6.07		Gamma	2.25	1.89	16
6-11	68	2.52	3.496		0.171	0.373	0.619	1.11	2.91	6.98	11.7		Lognormal	2.78	5.12	36
12-19	50	1.33	1.457		0.123	0.258	0.404	0.609	2.27	3.41	4.78		Lognormal	1.54	2.44	18
Adult Farmer	112	2.32	2.646	0.072	0.276	0.371	0.681	1.3	3.14	5	6.12	15.7	Lognormal	2.36	3.33	31

N = Number of samples; P01-P99 = Percentiles; Pop-Estd = Population-estimated; SDev = Standard deviation; Minimum is assumed = 0

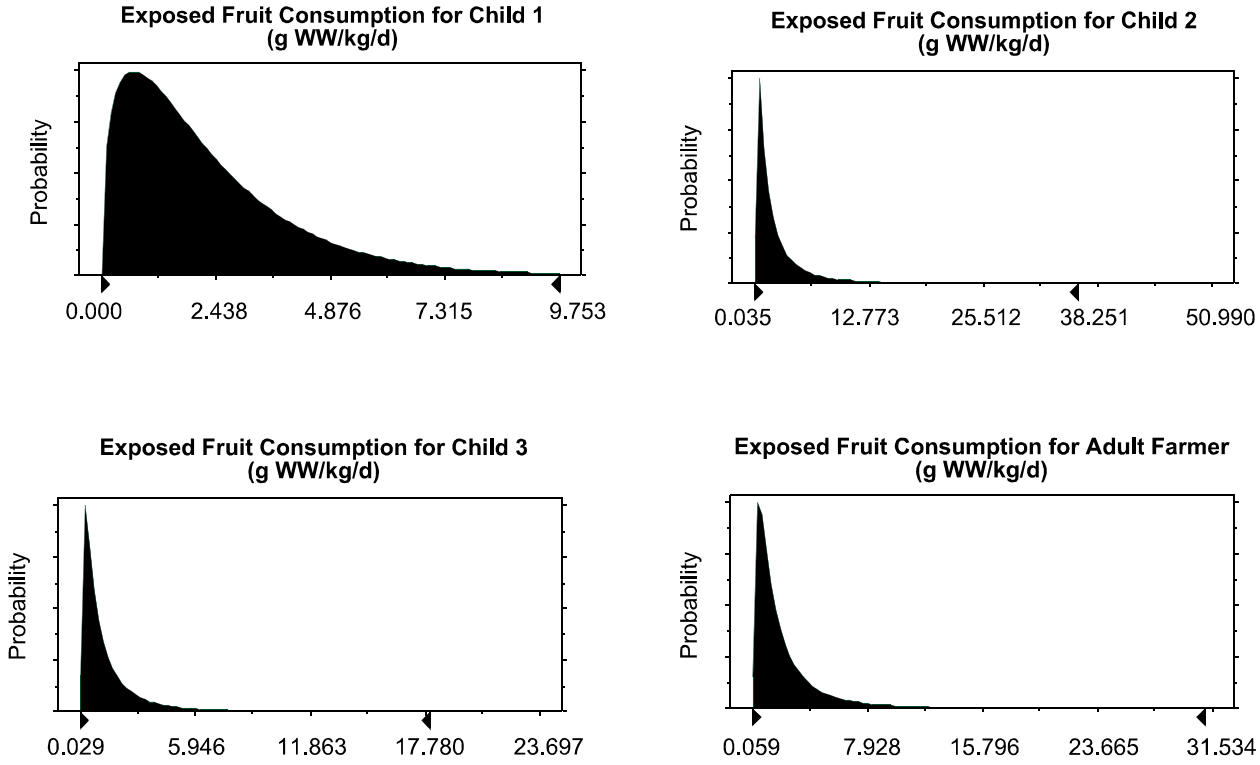

Figure 6-2. Distribution of exposed fruit consumption rates by age group.

Exposed Vegetable Consumption. Table 6-5 presents exposed vegetable consumption data and distributions. Data for consumption of homegrown exposed vegetables were obtained from Table 13-63 of the EFH (U.S. EPA, 1997b). Data (in g WW/kg/d) were presented for those aged 1 to 2, 3 to 5, 6 to 11, 12 to 19, 20 to 39, and 40 to 69 years, as well as farmers and home gardeners. Weighted averages of percentiles, means, and standard deviations were calculated for the 1- to 5-year-old age group (combining groups of those aged 1 to 2 years and 3 to 5 years).

Percentile data were used to fit parametric models (gamma, lognormal, and Weibull) using maximum likelihood estimation. Measures of goodness of fit were used to select the most appropriate model. The fraction of exposed vegetable intake that is home-produced is 0.42 for households that farm and 0.233 for households that garden (Table 13-71, U.S. EPA, 1997b). Figure 6-3 presents these distributions graphically. The distributions were truncated at the maximum value shown in the table and graph.

Table 6-5. Exposed Vegetable Consumption Data and Distributions

		EFH Data (g WW/kg-d)										Distributions				
Age Cohort	N	Data Mean	Data SDev	P01	P05	P10	P25	P50	P77	P90	P95	P99	Distribution	Pop-Estd Mean	Pop-Estd SDev	MAX
1-5	105	2.453	2.675		0.102	0.37	0.833	1.459	3.226	6.431	8.587		Gamma	2.55	2.58	21
6-11	134	1.39	2.037		0.044	0.094	0.312	0.643	1.6	3.22	5.47	13.3	Lognormal	1.64	3.95	27
12-19	143	1.07	1.128		0.029	0.142	0.304	0.656	1.46	2.35	3.78	5.67	Gamma	1.08	1.13	11
Adult farmer	207	2.17	2.316		0.184	0.372	0.647	1.38	2.81	6.01	6.83	10.3	Lognormal	2.38	3.5	26

N = Number of samples; P01-P99 = Percentiles; Pop-Estd = Population-estimated; SDev = Standard deviation; Minimum is assumed = 0

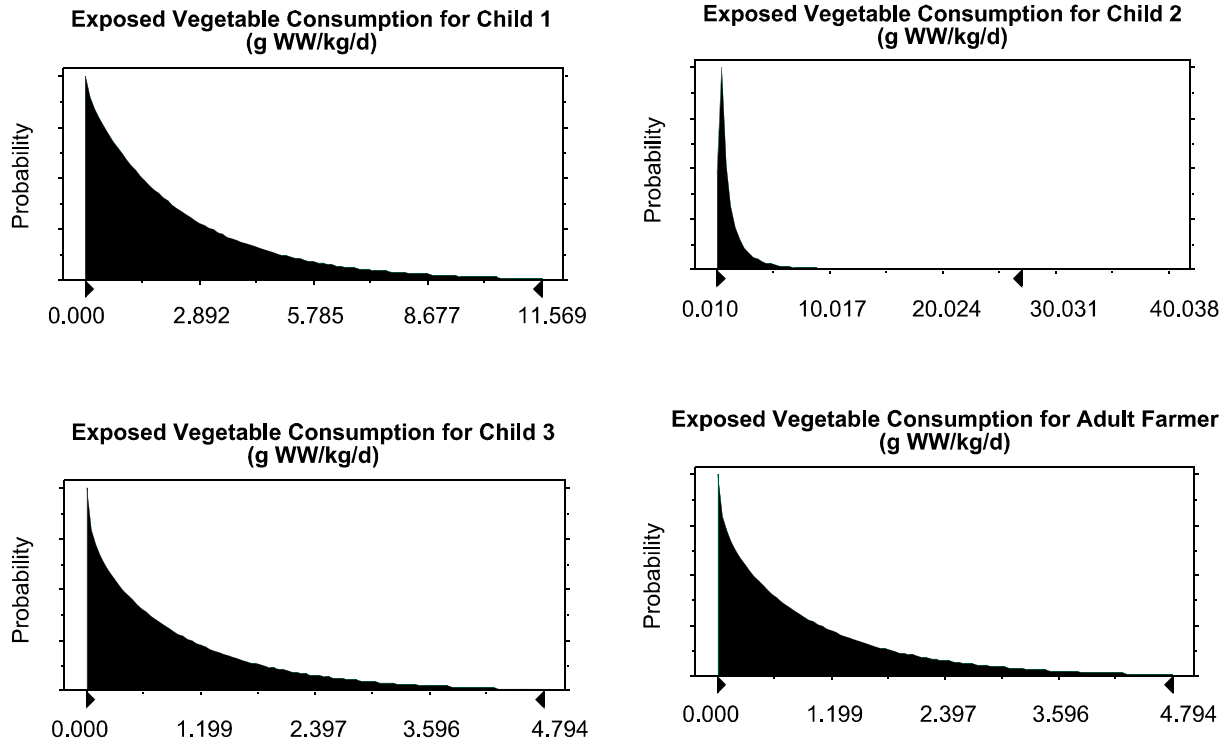

Figure 6-3. Distribution of exposed vegetable consumption rates by age group.

Root Vegetable Consumption. Table 6-6 presents root vegetable consumption rates and distributions. Homegrown root vegetable consumption data were obtained from Table 13-65 of the EFH (U.S. EPA, 1997b). Data (in g WW/kg/d) were presented for those aged 1 to 2, 3 to 5, 6 to 11, 12 to 19, 20 to 39, 40 to 69 years, and adult farmers and home gardeners. Weighted averages of percentiles, means, and standard deviations were calculated for the 1- to 5-year-old age group (combining groups of those aged 1 to 2 and 3 to 5 years). Percentile data were used to fit parametric models (gamma, lognormal, and Weibull) using maximum likelihood estimation. Measures of goodness of fit were used to select the most appropriate model. The fraction of root vegetable intake that is home-produced is 0.173 for households that farm and 0.106 for households that garden (Table 13-71, U.S. EPA, 1997b). Figure 6-4 presents these distributions graphically. The distributions were truncated at the maximum value shown in the table and graph.

Table 6-6. Root Vegetable Consumption Data and Distributions

		EFH Data (g WW/kg-d)										Distributions				
Age Cohort	N	Data Mean	Data SDev	P01	P05	P10	P25	P50	P75	P90	P95	P99	Distribution	Pop-Estd Mean	Pop-Estd SDev	MAX
1-5	45	1.886	2.371		0.081	0.167	0.291	0.686	2.653	5.722	7.502		Lognormal	2.31	6.05	41
6-11	67	1.32	1.752		0.014	0.036	0.232	0.523	1.63	3.83	5.59		Weibull	1.38	2.07	15
12-19	76	0.937	1.037		0.008	0.068	0.269	0.565	1.37	2.26	3.32		Weibull	0.99	1.19	9
Adult farmer	136	1.39	1.469	0.111	0.158	0.184	0.365	0.883	1.85	3.11	4.58	7.47	Lognormal	1.45	2.06	15

N = Number of samples; P01-P99 = Percentiles; Pop-Estd = Population-estimated; SDev = Standard deviation; Minimum is assumed = 0

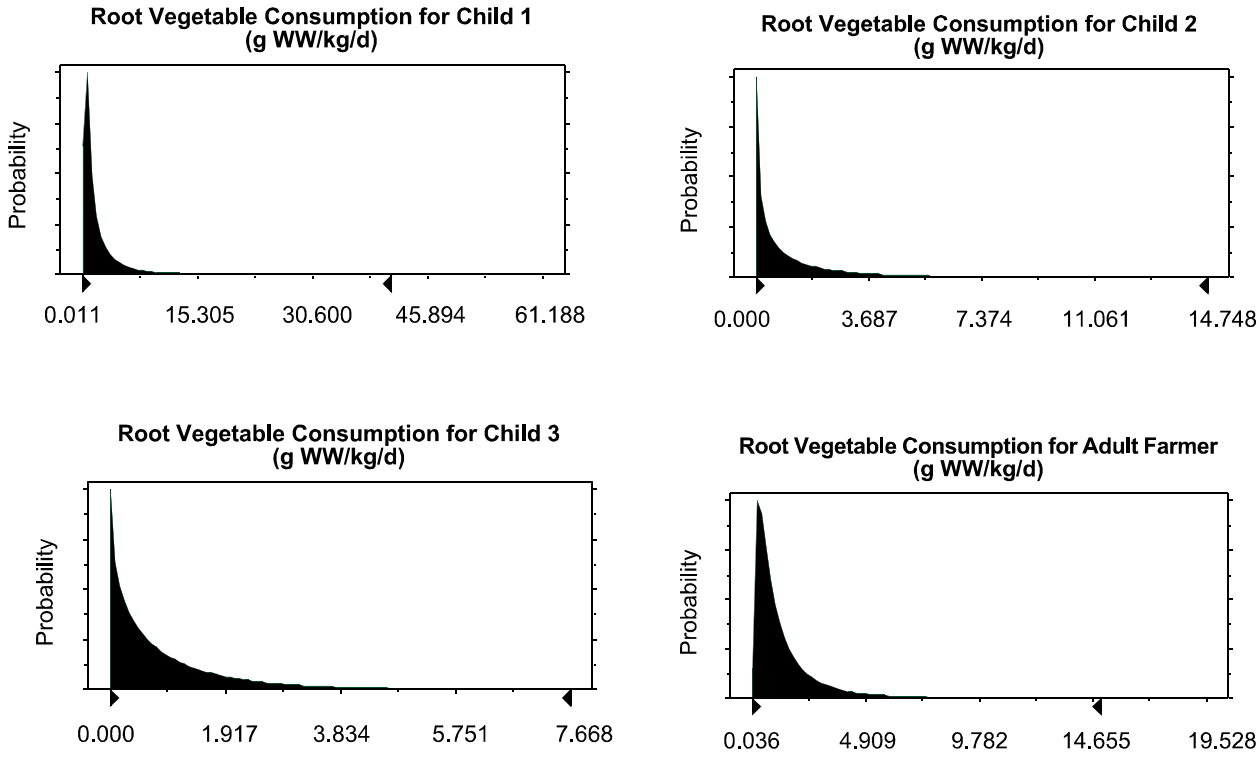

Figure 6-4. Distribution of root vegetable consumption rates by age group.

6.2.1.3 <u>Beef and Dairy Ingestion</u>. The farmer (adult and child) is assumed to ingest beef and dairy products from cattle raised on pastures amended with biosolids. As with fruits and vegetables, it was necessary to consider the fraction of the total beef and dairy in the farmer's diet that consists of products raised on the amended pasture. In addition, beef consumption rate data were adjusted to account for food preparation and cooking losses.

<u>Beef Consumption</u>. Table 6-7 presents beef consumption data and distributions. Home-produced beef consumption data were obtained from Table 13-36 of the EFH (U.S. EPA, 1997b). Data (in g WW/kg-d) were presented for farmers and those aged 6 to 11, 12 to 19, 20 to 39, and 40 to 69. Percentile data were used to fit parametric models (gamma, lognormal, and Weibull) using maximum likelihood estimation. Measures of goodness of fit were used to select the most appropriate model.

Data were not available for those aged 1 to 2 and 3 to 5. For beef consumption for 1- to 5-year-olds, the lognormal model was used because, among the other age groups, it was the best-fitted model in all but one case. The population-estimated mean and standard deviation for 6- to 11-year-olds were used for 1- to 5-year-olds for the analysis (normalized for body weight) and are supported by data in Table 11-3 of the EFH (per capita intake for beef, including store-bought products), which indicate that those aged 1 to 2, 3 to 5, and 6 to 11 have the highest consumption rate of beef on a g WW/kg/d basis. Figure 6-5 presents these data graphically. The distribution of beef consumption rates was truncated at the maximum value indicated in the table

and graph. The fraction of beef intake that is home-produced is 0.485 for households that farm (Table 13-71, U.S. EPA, 1997b).

Table 6-7. Beef Consumption Data and Distributions

Age Cohort	N	EFH Data (g WW/kg-d)										Distributions				
		Data Mean	Data SDev	P01	P05	P10	P25	P50	P75	P90	P95	P99	Distribution	Pop-Estd Mean	Pop-Estd SDev	MAX
1-5		ND	ND										Lognormal	3.88	4.71	36
6-11	38	3.77	3.662		0.663	0.753	1.32	2.11	4.43	11.4	12.5		Lognormal	3.88	4.71	36
12-19	41	1.72	1.044		0.478	0.513	0.896	1.51	2.44	3.53	3.57		Gamma	1.77	1.12	10
Adult farmer	182	2.63	2.644	0.27	0.394	0.585	0.896	1.64	3.25	5.39	7.51	11.3	Lognormal	2.5	2.69	23

N = Number of samples; P01-P99 = Percentiles; Pop-Estd = Population-estimated; SDev = Standard deviation; Minimum is assumed = 0

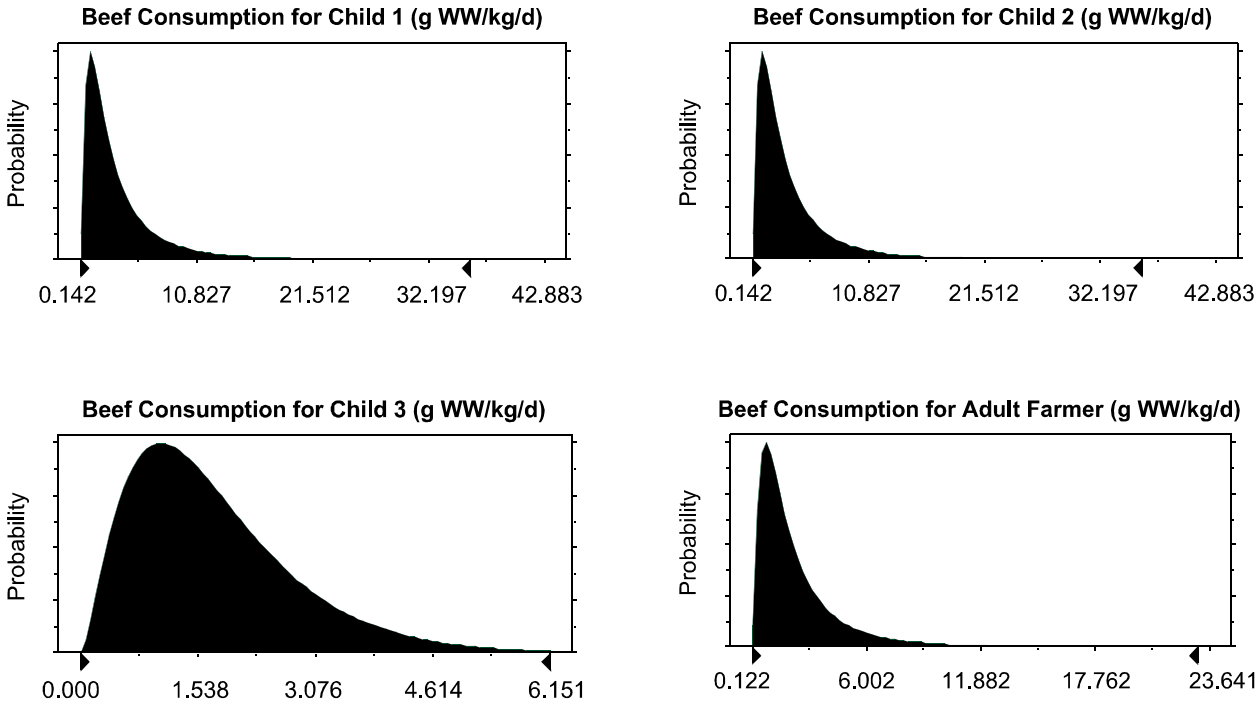

Figure 6-5. Distribution of beef consumption rates by age group.

Beef consumption rate data were adjusted to account for food preparation and cooking losses. A mean net cooking loss of 27 percent accounts for dripping and volatile losses during cooking (averaged over various cuts and preparation methods). A mean net postcooking loss of 24 percent accounts for losses from cutting, shrinkage, excess fat, bones, scraps, and juices. These data were obtained from Table 13-5 of the EFH (U.S. EPA, 1997b). The food preparation losses do not apply preferentially to the fat content of the dietary items. In the case of beef and poultry, the lipid fraction assumed for each item corresponds to the lipid fraction in the animal product as consumed. The preparation losses estimated using the factors in the EFH (U.S. EPA, 1997a,b,c) include dripping, volatile losses, and other losses, including removing bones, excess fat, scraps, and juices for a variety of cuts of meat and cooking methods. An average of these losses was used to yield a mean net-cooking and postcooking loss term, which was used in the analysis. A recent article reported that the mean concentration of dioxin-like congeners in hamburger (measured as pg TEQ/kg) remained constant after broiling; however, the measured congener concentrations (pg/kg) increased 14 percent on average during cooking as compared to the concentrations in the uncooked meat (Schecter et al., 1998). These data indicate that the assumptions used by EPA in this analysis are reasonable and protective, but not overly conservative.

Dairy Products (Milk) Consumption. Table 6-8 presents summary statistics on consumption of dairy products. Home-produced dairy product consumption rate data were obtained from Table 13-28 of the EFH (U.S. EPA, 1997b) for farmers, all ages combined, and individual age groups. No age-specific data for children were available for home-produced dairy products consumption. Per capita intake data for dairy products (including store-bought products), however, were available from the EFH and from CSFII (USDA, 1997) for those aged 1 to 2, 3 to 5, 6 to 11, and 12 to 19; the data in the EFH were based on the 1989–1991 CSFII, so the more recent 1994–1996 CSFII raw data were used. Therefore, data for the general population were used to calculate adjustment factors to develop distributions for the nonadult age groups for consumption of home-produced dairy products. Figure 6-6 presents these distributions graphically. The distributions were truncated at the maximum value as shown in the table and graph.

Table 6-8. Dairy Products (Milk) Consumption Data and Distributions

Source	Age Cohort	Data (g WW/kg-d)									Distributions			
		Data Mean	Data SDev	P05	P10	P25	P50	P75	P90	P95	Distribution	Pop-Estd Shape	Pop-Estd Scale	Max
CSFII (gen)	All	6.81	10.8	0.199	0.392	1.14	3.25	7.59	16.9	26.1				
CSFII (gen)	1-5	27.4	22.3	1.12	4.39	12.2	22.3	37.1	55.9	70.1				
CSFII (gen)	6-11	14	10	0.826	2.16	6.48	12.3	19.2	27.3	33.5				
CSFII (gen)	12-19	6.2	5.87	0.264	0.484	1.88	4.55	8.88	13.5	17.8				
CSFII (gen)	20-69	3.23	3.3	0.162	0.303	0.854	2.22	4.48	7.45	9.88				
HP	1-5										Gamma	0.961	61.80	482
HP	6-11										Gamma	0.961	31.40	245

Table 6-8. (continued)

Source	Age Cohort	Data (g WW/kg-d)									Distributions			
		Data Mean	Data SDev	P05	P10	P25	P50	P75	P90	P95	Distribution	Pop-Estd Shape	Pop-Estd Scale	Max
HP	12-19										Gamma	0.961	13.90	109
EFH (HP)	20_39	7.41	6.12	0.396	0.446	1.89	6.46	12.1	15.4	19.5	Gamma	0.961	8.01	
EFH (HP)	All	14	15.28	0.446	0.508	3.18	10.2	19.5	34.2	44	Gamma	0.78	18.26	
EFH (HP)	Adult farmer	17.1	15.8	0.736	3.18	9.06	12.1	20.4	34.9	44	Gamma	1.38	11.85	116

CSFII = CSFII (USDA, 1997); gen = general population data; EFH = U.S. EPA (1997b); HP = home-produced data; P05-P95 = Percentiles; Sdev = standard deviation; Pop-Estd = population-estimated; Minimum is assumed = 0

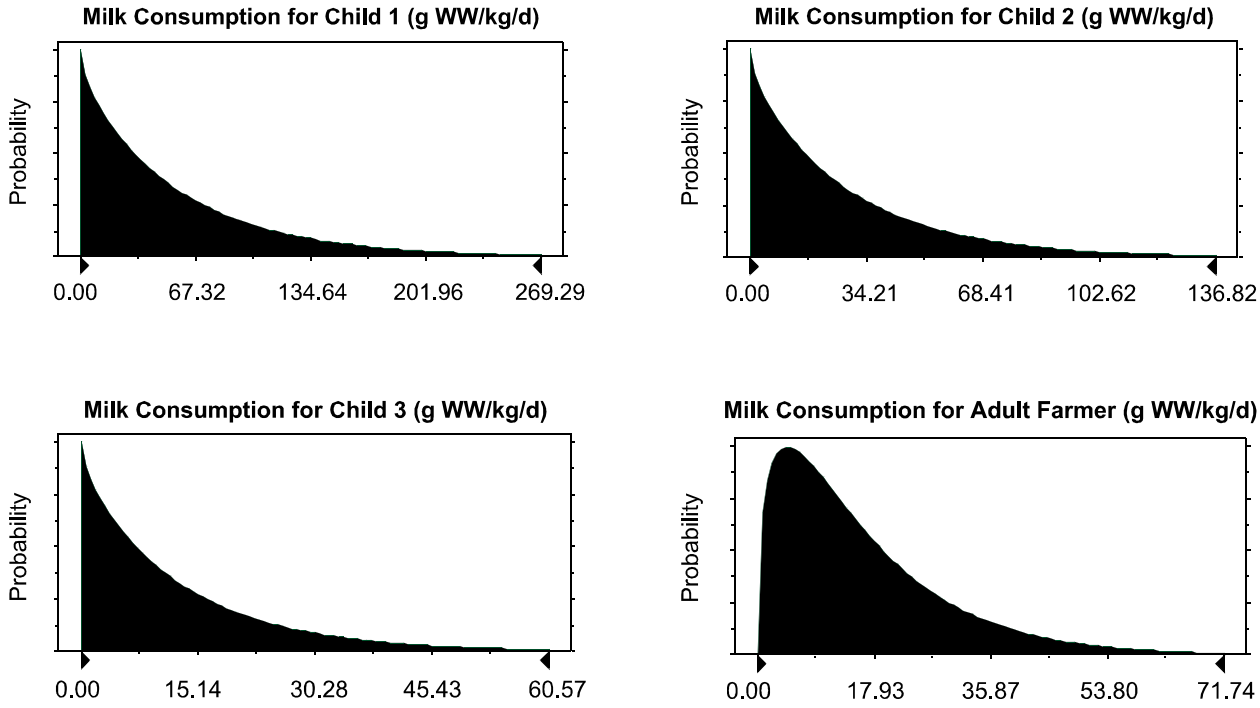

Figure 6-6. Distribution of milk consumption rates by age group.

Percentile data (USDA, 1997) were used to fit parametric models (gamma, lognormal, and Weibull) using maximum likelihood estimation. Measures of goodness of fit were used to select gamma as the most appropriate model in all cases. Tables J-19 and J-20 (Appendix J) provide the data used to develop the distributions and adjustment factors. It was assumed that the relative standard deviations (RSDs) for consumption rates were the same for all age groups; the similarity of coefficients of variation (CVs) suggests that this is a reasonable approximation for the general population. The other assumption used to develop distributions for the child age groups for the consumption of home-produced dairy products was that the mean intake rates have the same fixed ratio for all the age groups of a given food type. That is, the ratio of the

mean amount consumed of home-produced dairy products divided by the mean amount of dairy products consumed in the general population is the same for any two age groups. These two assumptions, of constant RSD and constant mean ratio, were used to infer the parameters of the gamma distributions for the home-produced foods from those of the general population (i.e., mean, standard deviation, shape, and scale).

The fraction of dairy product intake that is home-produced is 0.254 for households that farm (Table 13-71, U.S. EPA, 1997b).

6.2.1.4 Poultry and Egg Ingestion. The farmer (adult and child) is assumed to ingest poultry and egg products from chickens raised on the farm using biosolids as a soil amendment. As with fruits and vegetables, it was necessary to consider the fraction of the total poultry and eggs in the farmer's diet that consists of products raised on the farm. In addition, poultry consumption rate data were adjusted to account for food preparation and cooking losses.

Poultry Consumption. Table 6-9 presents summary statistics on consumption of poultry. Home-produced poultry consumption rate data were obtained from Table 13-55 of the EFH (U.S. EPA, 1997b) for farmers, all ages combined, and individual age groups 20 to 39 and 40 to 69; statistics for the 20- to 69-year-old age group were calculated as simple averages of the statistics for the 20- to 39- and 40- to 69-year-old age groups. No age-specific data for children were available for home-produced poultry consumption. Per capita intake data for poultry (including store-bought products), however, were available for those aged 1 to 2, 3 to 5, 6 to 11, and 12 to 19 years old from the EFH and from CSFII (USDA, 1997); the data in the EFH were based on the 1989–1991 CSFII, so the more recent 1994–1996 CSFII raw data were used. Therefore, data for the general population were used to calculate adjustment factors to develop distributions for the nonadult age groups for consumption of home-produced poultry. Figure 6-7 presents these distributions graphically. The distributions for poultry consumption were trancated at the maximum value indicated in the table and graph.

Table 6-9. Poultry Consumption Data and Distributions

Source	Age Cohort	Data (g WW/kg-d)									Distributions			
		Data Mean	Data SDev	P05	P10	P25	P50	P75	P90	P95	Distribution	Pop-Estd Shape	Pop-Estd Scale	MAX
CSFII (gen)	All	0.688	0.942	0.018	0.034	0.111	0.334	0.917	1.76	2.47				
CSFII (gen)	1-5	1.43	1.73	0.025	0.056	0.192	0.736	2.2	3.63	4.66				
CSFII (gen)	6-11	0.884	1.15	0.019	0.036	0.116	0.365	1.29	2.42	3.22				
CSFII (gen)	12-19	0.645	0.795	0.019	0.034	0.103	0.346	0.896	1.71	2.23				
CSFII (gen)	20-69	0.57	0.712	0.017	0.032	0.105	0.303	0.804	1.4	1.92				
HP	1-5										Gamma	1.69	1.92	21
HP	6-11										Gamma	1.69	1.21	14
HP	12-19										Gamma	1.69	0.87	10

Table 6-9. (continued)

Source	Age Cohort	Data (g WW/kg-d)									Distributions			
		Data Mean	Data SDev	P05	P10	P25	P50	P75	P90	P95	Distribution	Pop-Estd Shape	Pop-Estd Scale	MAX
EFH (HP)	20-69	1.34	1.088	0.299	0.352	0.524	0.962	2.03	2.545	3.765	Gamma	1.69	0.80	
EFH (HP)	All	1.57	1.178	0.303	0.418	0.637	1.23	2.19	3.17	3.83	Gamma	1.83	0.85	
EFH (HP)	Adult farmer	1.54	1.375	0.228	0.303	0.595	1.06	2.18	3.47	4.83	Gamma	1.38	1.16	11

CSFII = (USDA, 1997); gen = general population data; EFH = U.S. EPA (1997b); HP = home-produced data; P05-P95 = Percentiles; Sdev = standard deviation; Pop-Estd = population-estimated; Minimum is assumed = 0

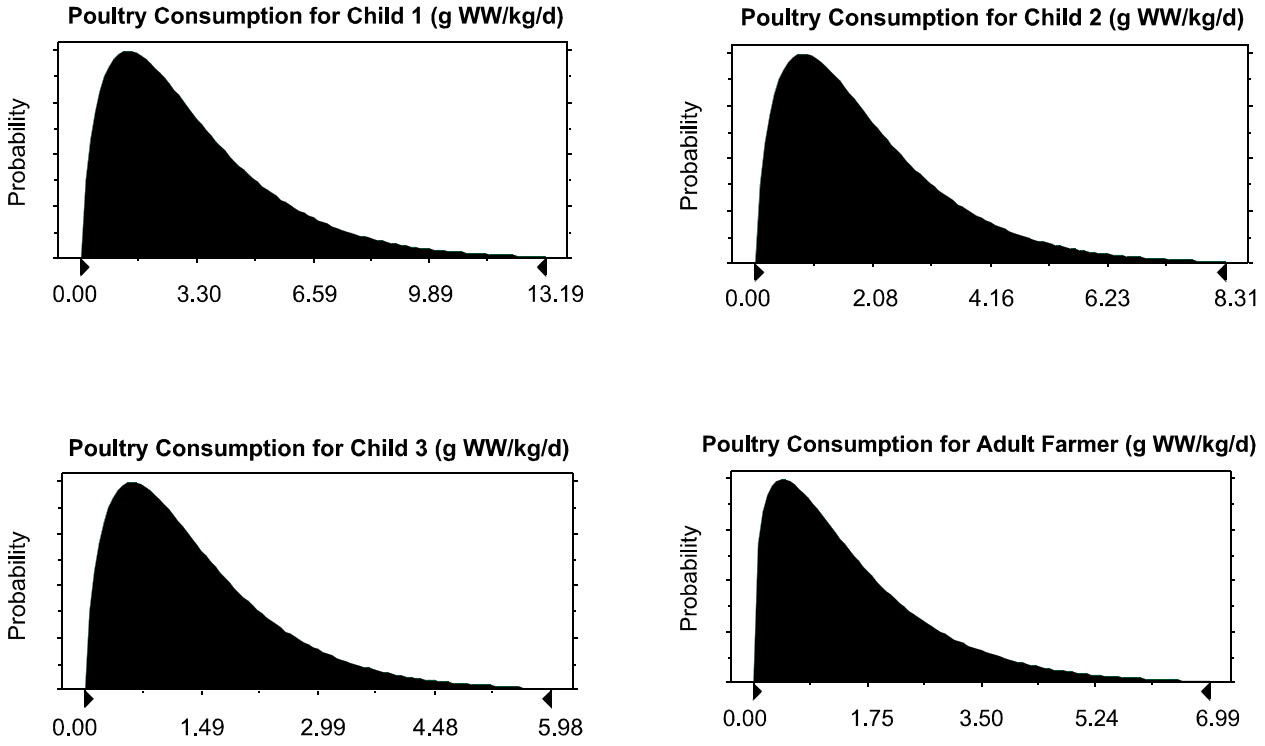

Figure 6-7. Distribution of poultry consumption rates by age group.

Percentile data (USDA, 1997) were used to fit parametric models (gamma, lognormal, and Weibull) using maximum likelihood estimation. Measures of goodness of fit were used to select gamma as the most appropriate model in all cases. Tables J-19 and J-20 (see Appendix J) provide the data used to develop the distributions and adjustment factors. Constant RSD and constant mean ratio were assumed, and these data were used to infer the parameters of the gamma distributions for the home-produced foods from those of the general population (i.e., mean, standard deviation, shape, and scale). The fraction of poultry intake that is home-produced is 0.156 for households that farm (Table 13-71, U.S. EPA, 1997b).

Egg Consumption. Table 6-10 presents summary statistics on consumption of eggs. Home-produced egg consumption rate data were obtained from Table 13-43 of the EFH (U.S. EPA, 1997b) for farmers, all ages combined, and individual age groups 20 to 39 and 40 to 69; statistics for the 20- to 69-year-old age group were calculated as simple averages of the statistics for the 20- to 39- and 40- to 69-year-old age groups. No age-specific data for children were available for home-produced egg consumption. Per capita intake data for eggs (including store-bought products), however, were available from the EFH and from CSFII (USDA, 1997) for those aged 1 to 2, 3 to 5, 6 to 11, and 12 to 19; the data in the EFH were based on the 1989–1991 CSFII, so the more recent 1994–1996 CSFII raw data were used. Therefore, data for the general population were used to calculate adjustment factors to develop distributions for the nonadult age groups for consumption of home-produced eggs. Figure 6-8 presents these distributions graphically. The distribution of egg consumption rates was truncated at the maximum value shown in the table and graph.

Table 6-10. Egg Consumption Data and Distributions

		Data (g WW/kg-d)									Distributions			
Source	Age Cohort	Data Mean	Data SDev	P05	P10	P25	P50	P75	P90	P95	Distribution	Pop-Estd Shape	Pop-Estd Scale	MAX
CSFII (gen)	All	1.01	1.04	0.133	0.253	0.422	0.724	1.22	1.99	2.82				
CSFII (gen)	1-5	2.41	1.94	0.101	0.328	1.16	1.88	3.23	5.03	6.15				
CSFII (gen)	6-11	1.44	1.25	0.125	0.302	0.641	1.08	1.87	2.95	3.45				
CSFII (gen)	12-19	0.962	0.708	0.092	0.328	0.469	0.821	1.22	1.71	2.24				
CSFII (gen)	20-69	0.792	0.663	0.145	0.248	0.389	0.633	1.01	1.52	1.88				
HP	1-5										Gamma	1.88	0.839	10
HP	6-11										Gamma	1.88	0.493	6
HP	12-19										Gamma	1.88	0.334	4
EFH (HP)	20-69	0.611	0.442	0.106	0.183	0.308	0.465	0.829	1.31	1.645	Gamma	1.88	0.336	
EFH (HP)	All	0.731	1.114	0.15	0.175	0.268	0.466	0.902	1.36	1.69	Gamma	1.81	0.357	
EFH (HP)	Adult farmer	0.898	1.128	0.165	0.177	0.272	0.666	1.19	1.65	1.85	Gamma	1.64	0.488	13

CSFII = CSFII (USDA, 1997); gen = general population data; EFH = U.S. EPA (1997b); HP = home-produced data; Sdev = standard deviation; Pop-Estd = population-estimated; Minimum is assumed = 0

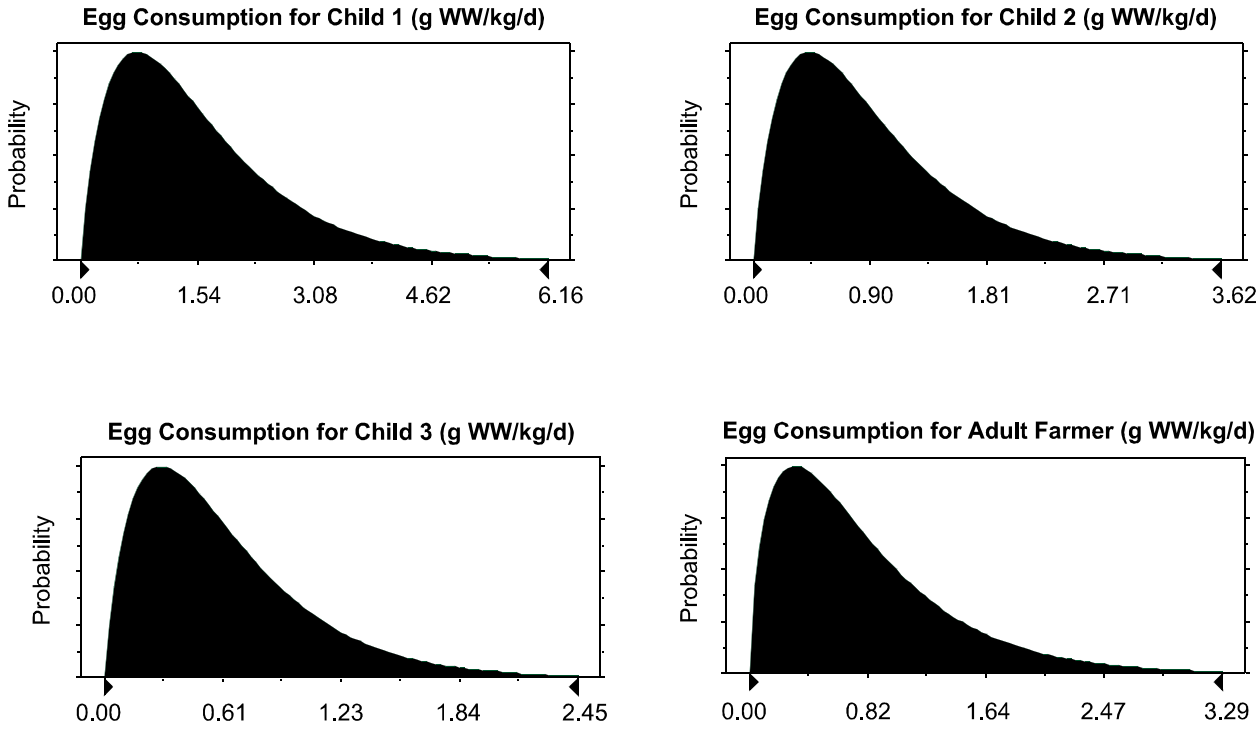

Figure 6-8. Distribution of egg consumption rates by age group.

Percentile data (USDA, 1997) were used to fit parametric models (gamma, lognormal, and Weibull) using maximum likelihood estimation. Measures of goodness of fit were used to select gamma as the most appropriate model in all cases. Tables J-19 and J-20 (see Appendix J) provide the data used to develop the distributions and adjustment factors. It was assumed that the RSDs for consumption rates were the same for all age groups; the similarity of CVs suggests that this is a reasonable approximation for the general population. The other assumption used to develop distributions for the child age groups for the consumption of home-produced eggs was that the mean intake rates have the same fixed ratio for all the age groups of a given food type. That is, the ratio of the mean amount consumed of home-produced eggs divided by the mean amount of eggs consumed in the general population is the same for any two age groups. These two assumptions, of constant RSD and constant mean ratio, were used to infer the parameters of the gamma distributions for the home-produced foods from those of the general population (i.e., mean, standard deviation, shape, and scale).

The fraction of egg intake that is home-produced is 0.146 for households that farm (Table 13-71, U.S. EPA, 1997b).

6.2.1.5 <u>Fish Ingestion</u>. Fish ingestion rates were based on an adult recreational angler who catches and eats some fish from a stream affected by contaminants released from biosolids. All fish are assumed to be home-caught and contaminated for households that fish. This is a protective assumption. The median fish ingestion rate is estimated to be 2 gWW/d, or approximately 1.5 lb/yr. This is not an excessive amount of fish to come from a third-order stream.

Fish Consumption. Table 6-11 presents fish consumption data and distribution. Fish consumption data were obtained from Table 10-64 of the EFH (U.S. EPA, 1997b). Data (in g/d) were available for adult freshwater anglers in Maine. The Maine fish consumption study was one of four recommended freshwater angler studies in the EFH (U.S. EPA, 1997b). The other recommended fish consumption studies (i.e., Michigan and New York) had large percentages of anglers who fished from the Great Lakes, which is not consistent with the modeling scenarios used in this risk analysis. The anglers in the Maine study fished from streams, rivers, and ponds; these data are more consistent with modeling scenarios for this risk analysis. Although the Maine data have a lower mean than the Michigan data, the Maine data compared better with a national USDA study. Also, the Maine study had percentile data available, which were necessary to develop a distribution. Figure 6-9 presents fish consumption rate distribution for adults. The distribution of fish consumption rates was truncated at the maximum value shown in the table and graph.

Table 6-11. Fish Consumption Data and Distributions

Age Cohort	N	EFH Data (g/d)							Distributions			
		Data Mean	Data SDev	P50	P66	P75	P90	P95	Distribution	Pop-Estd Mean	Pop-Estd SDev	MAX
Adult	1,053	6.4		2	4	5.8	13	26	Lognormal	6.48	19.9	1500

N = Number of samples; P50-P95 = Percentiles; Pop-Estd = Population-estimated; SDev = Standard deviation.

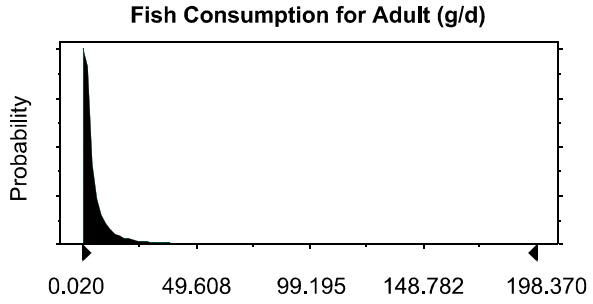

Figure 6-9. Distribution of adult fish consumption rates.

Percentile data were used to fit parametric models (gamma, lognormal, and Weibull) and measures of goodness of fit were used to select lognormal as the most appropriate model. The fraction of fish intake that is locally caught is 0.325 for adult fishers (Table 13-71, U.S. EPA, 1997b). The fractions of consumed T3 and T4 fish were 0.36 and 0.64, respectively (Table 10-66, U.S. EPA, 1997b).

6.2.1.6 Breast Milk Ingestion. Ingestion of contaminated breast milk is a potential pathway of exposure for infants of farmers. Consumption rate data were obtained from the EFH.

Breast Milk Consumption. Table 6-12 presents breast milk consumption data for infants. The data mean and upper percentile for breast milk consumption in 1- to 12-month-olds were 688 and 980 mL/d, respectively (Table 14-16, U.S. EPA, 1997b). The triangular model was used for breast milk consumption (12-month-olds) because no percentile or related data were available; other distributions (e.g., lognormal) resulted in overestimation of the upper percentile. Figure 6-10 presents this distribution graphically. The EFH population mean for breast milk consumption was 688 mL/d and was assumed to equal the mode. The distribution of breast milk consumption rates was truncated at the maximum value shown in the table and graph.

Table 6-12. Breast Milk Consumption Data and Distribution

Age Cohort	Data Mean (mL/d)	Data SDev	Upper Percentile	Distribution	Pop-Estd Mode (mL/d)	Pop-Estd SDev (mL/d)	Max
<1	688	ND	980	Triangular	688	688	1380

Pop-Estd = population-estimated; SDev = Standard deviation; ND = No data.

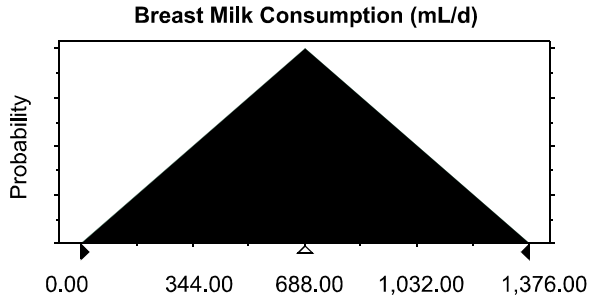

Figure 6-10. Distribution of breast milk consumption rates.

6.2.1.7 Inhalation Rates. The EFH reports inhalation values by age, gender, activity pattern, and outdoor workers; however, it does not provide high-end values in most cases. The inhalation rate is the same for all adults, whether farmer or fisher, whereas child receptors use a single child inhalation rate.

Inhalation Rate. Table 6-13 presents inhalation rate data and distribution. No percentile data were available for the inhalation rate, and the default lognormal model was assumed. In an analysis of inhalation data, Myers et al. (U.S. EPA, 2000) found that, for those younger than 3 years, CV was close to 70 percent; for other age groups, it was close to 30 percent. The lognormal distribution was fitted by using CV = 50 percent [(30+70)/2] for the

1- to 5-year-old age group and CV = 30 percent for the 6- to 11-year-olds, 12- to 19-year-olds, and adult age groups. Figure 6-11 presents this distribution graphically. The distribution of inhalation rates was truncated at the minimum and maximum values shown in the table and graph.

Table 6-13. Inhalation Rate Data and Distribution

Age Cohort	Distribution	Population-Estimated Mean (m^3/d)	Population-Estimated SDev (m^3/d)	Min	Max
1-5	Lognormal	7.55	3.78	1	40
6-11	Lognormal	11.75	3.53	1	45
12-19	Lognormal	14.0	4.2	1	55
Adult	Lognormal	13.3	3.99	1	50

SDev = Standard deviation.

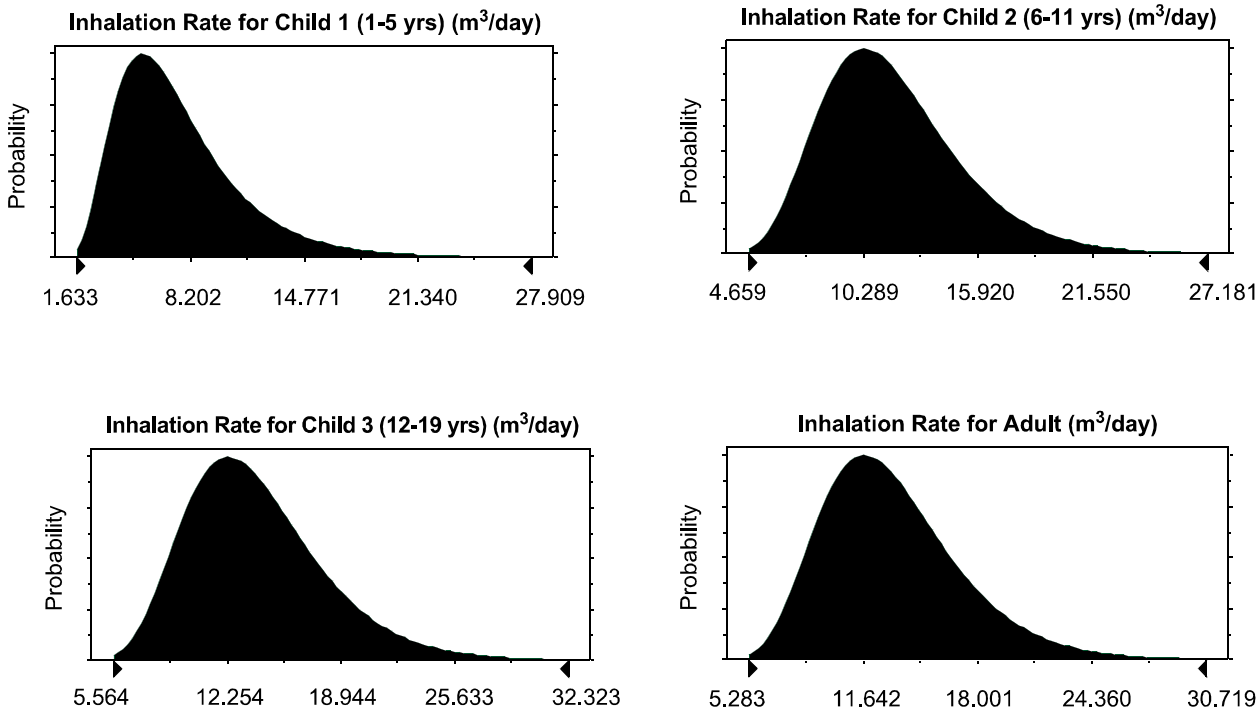

Figure 6-11. Distribution of inhalation rates by age group.

6.2.2 Other Exposure Factors

6.2.2.1 Body Weights. Distributions of body weight were developed for adult (farmer and fisher), child (farmer), and infant (farmer) receptors based on data from the EFH.

Table 6-14 presents body weight data and distributions. Body weight data were obtained from Tables 7-2 through 7-7 of the EFH (U.S. EPA, 1997a). Data (in kg) were presented by age and gender. Weighted averages of percentiles, means, and standard deviations were calculated for infants (<1 year old), 1- to 5-year-olds, 6- to 11-year-olds, 12- to 19-year-olds, and adult age groups; male and female data were weighted and combined for each age group. These percentile data were used as the basis for fitting distributions. These data were analyzed to fit parametric models (gamma, lognormal, and Weibull) using maximum likelihood estimation. Measures of goodness of fit were used to select the most appropriate model. Figure 6-12 presents these distributions graphically. The body weight distributions are truncated at the maximum values shown in the table and graph.

Table 6-14. Body Weight Data and Distributions

		EFH Data (kg)											Distributions				
Age Cohort	N	Data Mean	Data SDev	P05	P10	P15	P25	P50	P75	P85	P90	P95	Distribution	Pop-Estd Mean	Pop-Estd SDev	Min	Max
<1	356	9.102	1.287	7.053	7.451	7.852	8.252	9.151	9.752	10.4	10.65	11.15	Gamma	9.09	1.23	2	26
1-5	3,762	15.52	3.719	12.5	13.1	13.45	14.03	15.26	16.67	17.58	18.32	19.45	Lognormal	15.5	2.05	4	50
6-11	1,725	30.84	9.561	22.79	24.05	25.07	26.44	29.58	33.44	36.82	39.66	43.5	Lognormal	30.7	5.96	6	200
12-19	2,615	58.45	13.64	43.84	46.52	48.31	50.94	56.77	63.57	68.09	71.98	79.52	Lognormal	58.2	10.2	13	300
20+	12,504	71.41	15.45	52.86	55.98	58.21	61.69	69.26	78.49	84.92	89.75	97.64	Lognormal	71.2	13.3	15	300

N = Number of samples; P05-P95 = Percentiles; Pop-Estd = Population-estimated; SDev = Standard deviation.

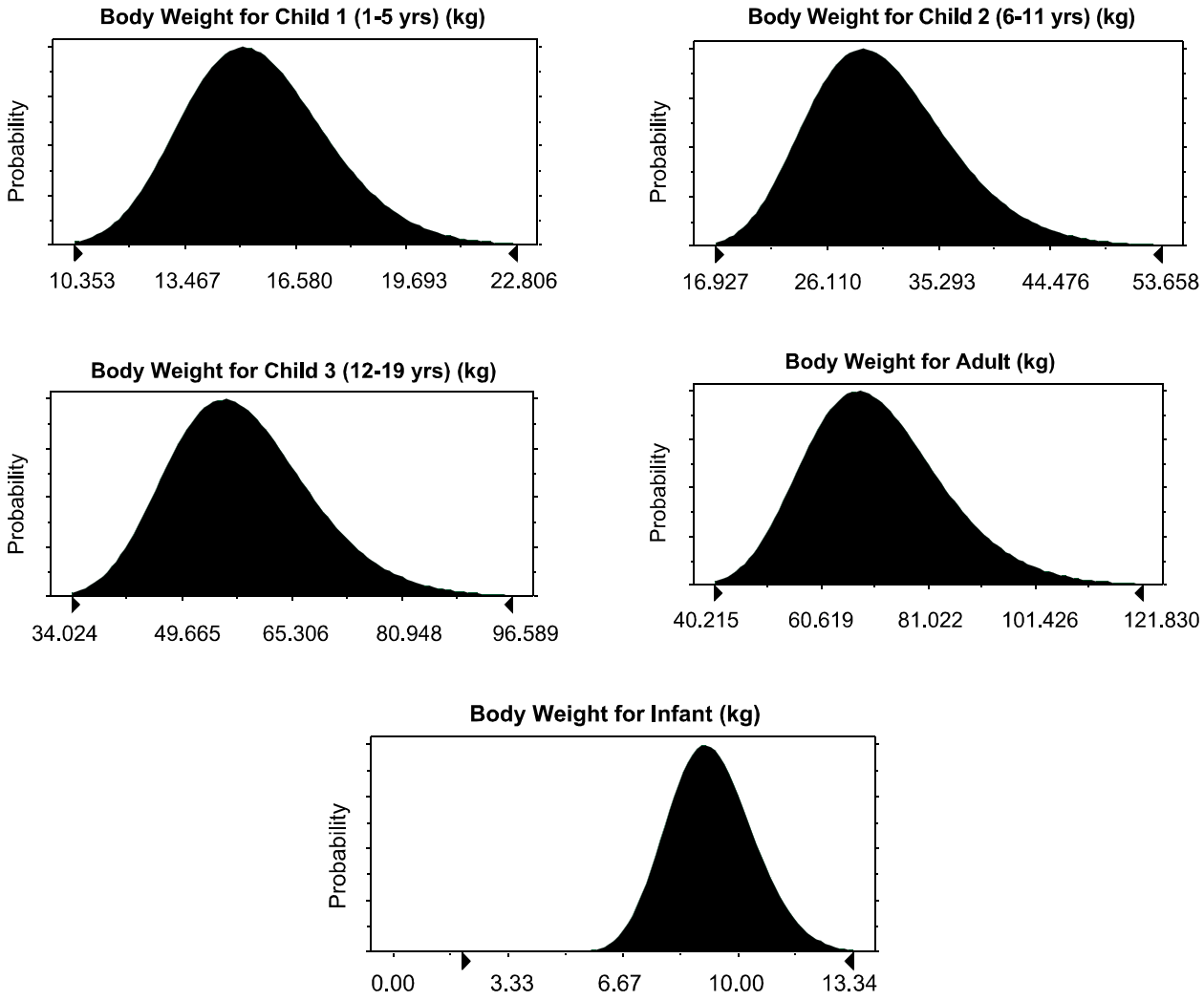

Figure 6-12. Distribution of body weights by age group.

6.2.2.2 <u>Exposure Duration</u>. Exposure duration refers to the amount of time that a receptor is exposed to a contaminant source. For this risk analysis, exposure duration was assumed to correspond to the receptor's residence time in the same house. Exposure durations were determined using data on residential occupancy from the EFH (U.S. EPA, 1997c). Separate distributions were developed for both adult and child adult farmers. Children of farmers were assumed to have the same exposure duration as rural resident children because no age-specific data were available for residential occupancy for farmers.

Exposure duration for all adult and child receptors was capped at a total lifetime of 100 years.

Table 6-15 presents exposure duration data and distributions. Exposure duration was assumed to be equivalent to the average residence time for each receptor. Exposure durations for adult residents and children (resident and farmer) were determined using data on residential

occupancy from the EFH, Table 15-168 (U.S. EPA, 1997c). The data represent the total time a person is expected to live at a single location, based on age. The table presented male and female data combined. For adult residents, age groups from 21-year-olds to 90-year-olds were pooled. For children, the 3-year-old age group was used for the 1- to 5-year-olds. Figure 6-13 represents these distributions graphically.

Table 6-15. Exposure Duration Data and Distributions

EFH Data		Distributions				
Age Cohort	**Data Mean (yr)**	**Distribution**	**Pop-Estd Shape (yr)[a]**	**Pop-Estd Scale (yr)**	**Min**	**Max**
Child (1- to 5-year-olds)	6.5	Weibull	1.32	7.059	1	100
Adult farmer	18.75	Gamma	0.607	29.76	1	100

Pop-Estd = Population-estimated.
[a] Distributions used in risk assessment.

Figure 6-13. Distribution of exposure duration for child and adult.

In an analysis of residential occupancy data, Myers et al. (U.S. EPA, 2000) found that the data for most ages were best fit by a Weibull distribution. The Weibull distribution as implemented in Crystal Ball® is characterized by three parameters: location, shape, and scale. Location is the minimum value and, in this case, was presumed to be 0. Shape and scale were determined by fitting a Weibull distribution to the pooled data, as follows: to pool residential occupancy data for the age cohorts, an arithmetic mean of data means was calculated for each age group. Then, assuming a Weibull distribution, the variance within each age group (e.g., 6-year-olds) was calculated in the age cohort. These variances in turn were pooled over the age cohort using equal weights. This is not the usual type of pooled variance, which would exclude the variation in the group means. However, this way the overall variance reflected the variance of means within the age groups (e.g., within the 6-year-old age group). The standard deviation was estimated as the square root of the variance. The CV was calculated as the ratio of the standard deviation divided by the Weibull mean. For each cohort, the population-estimated parameter uncertainty information (e.g., shape and scale) was calculated based on a Weibull distribution, the calculated data mean for the age cohort, and the CV.

Exposure duration for adult farmers was determined using data on residential occupancy from the EFH, Tables 15-163 and 15-164 (U.S. EPA, 1997c). The data represent the total time a person is expected to live at a single location, based on household type. Age-specific data were not provided. For residence duration of farmers (U.S. EPA 1997c, Tables 15-163 and 15-164), the gamma model was used because it was the best-fitted model in five age groups and was the second-best-fitted model in two cases (based on data in U.S. EPA 1997c, Tables 15-167 and 15-168). A population mean of 18.07 years and a population standard deviation of 23.19 years were calculated for adult farmers.

6.2.2.3 Exposure Frequency. Exposure frequency is the frequency at which the receptor is exposed to the contaminated source during the exposure duration. Exposure frequency is not expected to vary much, so distributions were not developed. All receptors were assumed to be exposed to the contaminant source 350 d/yr. This value is based on an assumption that individuals are away from their homes (e.g., on vacation) approximately 2 weeks out of the year. The exposure frequency of 350 d/yr is standard for EPA risk assessments. However, in the case of the farm family, this assumption is not conservative. Although farm families may work and go to school away from the farm during the day, they must remain on the farm to care for the livestock and crops most of the time. It is difficult for individuals on family farms to leave their responsibilities for long periods of time; therefore, the standard exposure frequency of 350 d/yr is not excessive.

6.2.2.4 Lifetime and Averaging Time. Averaging time is the period of time over which a receptor's dose is averaged. When evaluating carcinogens, total dose is averaged over the lifetime of the individual, assumed to be 70 years for exposure durations of equal to or less than 50 years. For exposures greater than a lifetime of 70 years, the lifetime averaging time was assumed to be the lifetime of the individual evaluated in the risk assessment. For example, if an adult is assumed to have an exposure duration of 70 years (adult exposure period starts at age 20), that person is assumed to have a total lifetime (averaging time) of 90 years.

6.3 Dose Estimates

The purpose of the exposure assessment was to estimate the dose to each receptor by combining intake values with media concentrations. Estimates of exposure were based on the potential dose (e.g., the dose ingested or inhaled) rather than the applied dose (e.g., the dose delivered to the gastrointestinal tract) or the internal dose (e.g., the dose delivered to the target organ). This is generally consistent with the exposure metric used in most epidemiologic and toxicologic studies that serve as the basis for establishing the toxicological benchmarks used for risk assessment (see Section 9.2).

Doses from individual pathways (e.g., soil, exposed vegetables) were calculated by multiplying the contaminant concentration with the respective intake rate on a per kgBW basis. Doses received from the various ingestion pathways (e.g., soil, food) were then summed over the period of time in which exposure occurred, resulting in an ADD received from ingestion exposure. The ADD was used for the calculation of maternal body burden. For cancer effects, where the biological response is described in terms of lifetime probabilities, even though exposure may not occur over the entire lifetime, dose is presented as an LADD. The LADD was used to assess cancer risks from each exposure route (i.e., inhalation and ingestion).

6.3.1 Average Daily Dose

For the purposes of this risk analysis, ADD was defined as

$$\mathbf{ADD = C \times IR} \qquad (6\text{-}2)$$

where

ADD = average daily dose (mass constituent/body weight mass/time)

C = concentration (mass/volume or mass/mass)

IR = intake rate (mass/body weight mass/time or volume/body weight mass/time).

Contaminant concentration represents the concentration of a chemical in a medium that contacts the body. Intake rate for the respective ingestion pathway was applied. For several food parameters, intake rates were provided in mg/kgBW/d. However, intake rates for fish and soil were adjusted by body weight in order to be on a mg/kgBW/d basis.

Pathway-specific ADDs, designated as $ADD_i s$, were calculated for individual ingestion pathways (e.g., soil, exposed vegetables). The summation of the $ADD_i s$ results in an ADD for the ingestion pathway (ADD_{ingest}), which was used to calculate maternal body burdens and assess risk to infants of farmers and home gardeners resulting from the ingestion of breast milk.

6.3.2 Lifetime Average Daily Dose

The LADD, used for assessing risks for carcinogenic effects, was defined as

$$\mathbf{LADD = \frac{C \times IR \times ED \times EF}{AT \times 365}} \qquad (6\text{-}3)$$

where

LADD = lifetime average daily dose (mass constituent/body weight mass/time)

C = average concentration (mass/mass or mass/volume)

IR = intake rate (mass/body weight mass/time or volume/body weight mass/time)

ED = exposure duration (yr)

EF = exposure frequency (d/yr)

AT = averaging time (yr)

365 = unit conversion factor (d/yr).

The contaminant concentration represents the concentration of a chemical in a medium that contacts the body. Intake rate depends on the route of exposure; for example, it might be an inhalation rate or an ingestion rate. Exposure frequency is the number of days per year the receptor is exposed to the contaminated source during the exposure duration.

For cancer effects, biological responses are described in terms of lifetime probabilities, even though exposure may not be lifelong. Here, the exposure duration (the length of time of contact with a contaminant) was used to average the ADD over a lifetime (70 years or more). The media concentrations used in the analysis for assessing the LADD (e.g., soil concentration) were generally averaged explicitly over the duration of exposure. This provides a more exact estimate of the LADD. An $LADD_{ingest}$ was calculated for ingestion exposures and an $LADD_{inh}$ was calculated for inhalation exposures.

6.4 References

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7.0 Human Health Risk Results

The final step of the risk assessment process was to characterize the risk posed to receptors (e.g., farmers and fishers). In this step, the preceding components of the risk assessment— estimates of toxicity (the health benchmarks) and exposure assessments—were summarized and integrated into quantitative expressions of risk. For this risk assessment, estimates of dose and toxicity were used to calculate individual excess lifetime carcinogenic risk estimates for all dioxin, furan, and PCB congeners in biosolids as a total TEQ. Section 7.1 describes the risk calculations completed for this analysis. Section 7.2 describes multipathway risks.

7.1 Human Health Risk Characterization

The goal of this risk assessment was to estimate a national distribution of the incremental increase in individual lifetime risk of developing cancer due to exposure to dioxins, furans, and PCBs potentially present in the biosolids for farm families who apply biosolids as fertilizer or soil conditioner. The probabilistic analysis was designed so that biosolids are equally applied to farms nationwide (i.e., no region is more likely to have this practice than another). The farmer is assumed to apply biosolids at agronomic rates once every other year for a maximum of 40 years (maximum 20 additions). The concentrations of dioxins, furans, and PCBs used in this analysis reflect the distribution of concentrations measured in biosolids sampled during the 2001 NSSS. The biosolids are assumed tilled into cropland but not tilled into pastureland. The farmer is assumed to consume a significant portion of his diet from homegrown items produced on the biosolids-amended land. This scenario does not represent the general population but intentionally reflects the risks to highly exposed individuals within the subpopulation of farmers who apply biosolids.

7.1.1 Lifetime Excess Cancer Risk

Cancer risk was characterized using lifetime excess cancer risk estimates to represent the excess probability of an individual developing cancer over a lifetime as a result of exposure to dioxins, furans, or PCBs in biosolids. Lifetime excess cancer risk estimates use the LADD as the measure of exposure and are the product of the LADD, expressed as a toxicity equivalent of 2,3,7,8-TCDD for a specific receptor (i.e., adult farmer), and the CSF for 2,3,7,8-TCDD, as shown in Equation 7-1. Lifetime excess cancer risk estimates are calculated independently for each route of exposure and for the receptor, assuming multipathway exposures:

$$\text{Lifetime excess cancer risk} = \text{LADD} \times \text{CSF} \quad (7\text{-}1)$$

where

LADD = lifetime average daily dose (mg/kg BW/d)
CSF = cancer slope factor $(mg/kg\ BW/d)^{-1}$.

7.1.2 Total Lifetime Excess Cancer Risk

Congener-specific individual incremental increases in lifetime excess cancer risks were generated for each receptor for each inhalation and ingestion exposure pathway. These pathway-specific lifetime excess cancer risks for each congener were then summed to generate a total risk due to exposure to all dioxin, furans, and PCBs in biosolids; this total risk for all congeners combined is presented in this section. This total risk is estimated for multipathway exposures, as well as for individual exposure pathways for each of the 3,000 iterations in the probabilistic analysis.

7.1.3 Risk Results

The results of the risk analysis yielded distributions of risk for each receptor for each potential exposure pathway individually and a distribution of risk for each receptor considering multipathway exposures. When each pathway is considered individually, the percentiles of the risk distribution describe the risk from only that single pathway. For example, the risk distribution for the aboveground vegetable ingestion pathway considers only the factors that are included in that pathway, including all factors that increase the concentration of dioxin-like congeners in aboveground vegetation and ingestion rates for this dietary item. The inputs to the risk analysis iteration that yield the 90^{th} percentile risk from the ingestion of aboveground vegetation pathway are highly unlikely to occur in the same iteration as the set of inputs (individual) that yield the 90^{th} percentile risk for the beef ingestion pathway. In addition, the multipathway analysis considered the risk from all pathways simultaneously; thus, the individual with the 90^{th} percentile multipathway risk may not be, and frequently is not, the same individual with the 90^{th} percentile risk for a single pathway.

Risk represents the combination of the exposure point media concentration and the receptor-dependent exposure factors. The distributions of media concentrations used in the risk calculations and the representative percentiles from the distributions are presented in Section 5.0. The distributions of the exposure factors used in this risk assessment are presented in Section 6.0.

A statistical sensitivity analysis was performed using the inputs and outputs to the probabilistic analysis risk to identify and rank the most influential factors in calculating the risk for each pathway. For all pathways, exposure duration and consumption rate are the two most important factors in the risk calculation. Of the factors that affect the loading of dioxins in biosolids to the soil, the most important factors appear to be the number of applications of biosolids made to the soil prior to the start of the exposure and the rate at which the biosolids are applied. The later in the period of application the family lives on the farm, the higher the average soil concentration during the exposure period because the total soil loadings to which the farmers are exposed are higher. The number of additions of biosolids and the rates at which those additions are made determine the total loading of dioxins in biosolids to the soil. The sensitivity analysis used to identify these parameters is described in detail in Section 8.1.2.6. The following sections present the percentiles for the incremental increase in individual lifetime

risk to the adult and child farmers for each pathway in the probabilistic analysis. All dioxin-like congener concentrations were modeled individually in the exposure analysis.

7.1.3.1 Soil Ingestion. Soil is assumed ingested incidentally by adult farmers and their children. Adult farmers and children are assumed to be exposed to soil concentrations at the residence location (buffer area). The buffer soil is assumed to receive erosion, runoff, and air deposition from both the cropland (tilled) and pasture (untilled) areas. Thus, the soil concentration in the buffer is slightly lower than the soil concentration in the crop area or pasture area. All soil assumed ingested by the adult farmer and child is assumed to be from the family's own farm where biosolids are applied (contaminated fraction = 1). The data on soil ingestion rates for both adults and children are limited; therefore, the soil ingestion rate is assumed constant in this analysis. From age 1 to 7, the child is assumed to ingest 100 mg/d (this does not include pica behavior), and all individuals over age 7 (older children and all adults) are assumed to ingest 50 mg/d. Because ingestion rates are assumed constant for soil, risks are driven by the exposure duration and soil concentration. The LADD for soil ingestion is presented below:

$$LADD = I_{soil} \times C_{soil} \times ED \times 365 \times 10^{-6} \quad (7\text{-}2)$$

where

LADD	=	lifetime average daily dose ($mg_{constituent}/kg_{BW}/d$)
I_{soil}	=	intake of soil (mg_{soil}/day)
C_{soil}	=	concentration of in soil (mg/kg_{soil})
ED	=	exposure duration (yr)
365	=	conversion factor (d/yr)
1×10^{-6}	=	conversion factor (kg/mg)
BW	=	body weight (kg).

The most important factor in the soil ingestion risk is the length of time that the individual is exposed. The soil concentration to which the individual is exposed is driven by the total loading of the soil with dioxins at the time the individual is exposed. The factors that affect this exposure concentration are the number of applications that have occurred before or during the time of exposure and the rate at which the biosolids are applied to the land. Of these factors, the most important factor, as shown by the sensitivity analysis, is the start year of exposure, which is an indication of how many applications have occurred before the individual moves to the farm (i.e., the later in the process the farmer starts his exposure, the higher the average concentration to which he is exposed, because even if additions of biosolids cease, concentrations fall slowly due to the extended half-life of dioxin in soil). Table 7-1 presents the risks for the soil ingestion pathway for adult farmers and their offspring who begin their exposure in childhood.

Dermal soil exposures were not considered in this risk assessment because they were assumed to add minimal exposure in comparison to other routes included in the analysis. They also are usually subject to greater uncertainty than other routes of exposure. However, according

Table 7-1. Percentile Risk for Soil Ingestion Pathway

Percentile	Lifetime Individual Risk	
	Adult	**Child**
50th	8E-9	2E-8
75th	2E-8	4E-8
90th	5E-8	7E-8
95th	8E-8	1E-7
99th	2E-7	2E-7

to the Draft Dioxin Reassessment Document (U.S. EPA, 2000), dermal exposure can be estimated as follows:

$$R_{sd} = q_1^* \times LADD_{sd} \times AF \times AC$$

where

R_{sd} = lifetime excess cancer risk from soil dermal exposure (unitless)
q_1^* = cancer potency factor $(mg/kg\text{-}d)^{-1}$
$LADD_{sd}$ = administered dose from soil dermal exposure (mg/kg-d)
AF = absorption fraction (unitless) = 0.03
AC = absorption correction fraction (unitless) = 1.8 (100% / 55%).

According to the Draft Dioxin Reassessment Document, the soil dermal contact pathway requires an adjustment from total dose to absorbed dose to accurately calculate lifetime excess cancer risk. This is also the case for the soil ingestion pathway. For the soil dermal pathway, the absorption of dioxin through soil contact has been estimated to range from 0.5 to 3.0 percent, with assessments typically assuming 3.0 percent as a protective estimate. A fraction of 0.03 (equivalent to 3.0 percent) was assumed here for the absorption fraction, *AF* (U.S. EPA, 2000).

If the dermal soil pathway were assessed, it would make only a minimal contribution to the overall dose to the farmer in comparison to the ingestion and inhalation pathways. As a general principal, risk should not be reported to more than one significant figure, and the dermal risk would not contribute enough to the total risk to change the reported total risk value. Specifically, food consumption risks in these farming scenarios were close to 1×10^{-5}, and dermal risk was calculated to be less than the soil ingestion pathway, which was less than 1×10^{-7}, depending on assumptions made. The addition of the soil dermal pathway would, therefore, not add to the total risk for the child or adult.

7.1.3.2 <u>Exposed Produce</u>. Exposed produce is assumed to be grown on tilled cropland that is amended with biosolids. The fruits and vegetables receive exposure to dioxin-like congeners only through the air pathway (there is no root uptake of dioxin-like congeners to aboveground vegetation). The concentrations in the produce result primarily from vapor uptake through the leaves and fruit as represented by the air-to-plant transfer factors. The home-produced exposed vegetables are assumed to represent a fraction (fruit = 0.328; vegetables = 0.42) of the total amount of exposed produce the farmer and his offspring consume throughout

the year. The exposure factors (exposure duration and intake rate) are the major driving components in the risk equation for this pathway as well. In addition, because this pathway is driven by the air-to-plant transfer of dioxins, the factors that increase the tendency of constituents to volatilize are also important. These factors include the soil texture, as represented by the soil moisture retention factor *b*, and climate factors, such as ambient temperature as noted in Section 5. Table 7-2 presents the risks for the exposed produce ingestion pathway.

Table 7-2. Percentile Risk for Exposed Produce Ingestion Pathway

	Lifetime Individual Risk	
Percentile	**Adult**	**Child**
50th	1E-9	8E-10
75th	5E-9	2E-9
90th	2E-8	6E-9
95th	3E-8	1E-8
99th	1E-7	3E-8

7.1.3.3 Belowground Vegetables. Belowground vegetables are assumed produced on tilled cropland that is amended with biosolids. The farm family is assumed to consume these home-produced root vegetables as a fraction (0.173) of its total intake of root vegetables. Root vegetables absorb dioxin-like congeners directly from the soil. The exposure factors (exposure duration and intake rate) are most important to the risk calculation; however, for root vegetables, soil parameters are more important than for other pathways. The soil parameter that is identified in the sensitivity analysis is the soil foc, which is a measure of the soil organic carbon content. Because the concentration in the soil is the media concentration that drives this pathway, the factors that reduce losses of dioxins to the environment through volatilization or erosion increase the concentration in the soil. Table 7-3 presents the risks for the belowground vegetable ingestion pathway.

Table 7-3. Percentile Risk for Belowground Vegetable Ingestion Pathway

	Lifetime Individual Risk	
Percentile	**Adult**	**Child**
50th	2E-8	1E-8
75th	6E-8	3E-8
90th	2E-7	9E-8
95th	4E-7	2E-7
99th	1E-6	4E-7

7.1.3.4 Poultry. Free-range chickens are assumed to be raised by the farm family near the residence. The chickens are assumed to be confined to the buffer area and, thus, are assumed to consume soil only from that area. The chicken feed is assumed to be purchased from an

uncontaminated source. The concentration of dioxin-like congeners in poultry is calculated based on the lipid concentration of chicken thigh meat. The farm family is assumed to consume homegrown chickens as a fraction (0.156) of its total poultry consumption. The exposure factors (exposure duration and intake rate) are again the most important factors in the risk calculation. The media concentration that drives this pathway is the soil concentration in the buffer area. This soil receives dioxins predominantly from erosion from the cropland and pasture amended with biosolids with some contribution from air deposition from these areas. Thus, the factors that lead to higher concentrations in the soil also lead to higher concentrations in the poultry. These factors include higher application rates and a greater number of applications at the time of exposure. Table 7-4 presents the risks for the poultry ingestion pathway.

Table 7-4. Percentile Risk for Poultry Ingestion Pathway

	Lifetime Individual Risk	
Percentile	**Adult**	**Child**
50th	3E-8	3E-8
75th	1E-7	8E-8
90th	3E-7	2E-7
95th	5E-7	2E-7
99th	1E-6	6E-7

7.1.3.5 Eggs. The free-range chicken scenario used in the poultry scenario was also assumed for the egg ingestion scenario. The farm family is assumed to consume home-produced eggs as a fraction (0.146) of its total egg consumption. The factors important to the poultry ingestion pathway are identical to the egg ingestion pathway. Table 7-5 presents the risks for the egg ingestion pathway.

Table 7-5. Percentile Risk for Egg Ingestion Pathway

	Lifetime Individual Risk	
Percentile	**Adult**	**Child**
50th	4E-8	4E-8
75th	1E-7	9E-8
90th	3E-7	2E-7
95th	6E-7	2E-7
99th	2E-6	7E-7

7.1.3.6 Beef. Beef cattle are assumed to be raised on the pasture that is amended with biosolids. The cattle are assumed to graze in the amended pasture, obtaining 48 percent of their diet from forage, 48 percent from silage, and 4 percent from incidental ingestion of surficial soil while grazing in the pasture. The cattle consumed by the farm family are assumed *not* finished

in a feed lot. Exposure factors (exposure duration and intake rate) and soil loading factors (application rate and number of applications) also drive this pathway. The majority of the concentration in the beef is due to the concentration of dioxins in the pasture grass where the cattle forage. The concentration in the forage is due to air-to-plant transfer of vapors. Thus, higher loadings of biosolids to the soil, especially in areas where it is hot and dry to promote volatilization of constituents from the soil, increase the risk from the beef ingestion pathway. The farm family that raises beef cattle is assumed to obtain 49 percent of the beef it consumes from home-raised cattle. Table 7-6 presents the risks for the beef ingestion pathway.

Table 7-6. Percentile Risk for Beef Ingestion Pathway

	Lifetime Individual Risk	
Percentile	**Adult**	**Child**
50th	6E-7	6E-7
75th	2E-6	1E-6
90th	6E-6	5E-6
95th	1E-5	5E-6
99th	3E-5	1E-5

7.1.3.7 Milk. Dairy cattle are also assumed to be raised on a pasture that is amended biennially with biosolids. The cattle are assumed to graze in the amended pasture; however, dairy cattle are assumed to obtain only 8 percent of their diet from forage, 90 percent from silage, and 2 percent from incidental ingestion of surficial soil in the pasture. The same factors that drive the risk from the beef pathway also drive the risks from the dairy pathway, although the dairy cattle are assumed to eat less forage. The silage that dairy cattle are assumed to consume is grown on cropland that is amended with biosolids. Thus, the silage is assumed to receive dioxins through air-to-plant transfer to the nongrain portion of the silage (0.5). The concentration of dioxins in silage is less than that in forage; however, it is still a significant source of dioxin in milk. The farm family that raises dairy cattle is assumed to obtain 25 percent of its total milk consumption from home-raised cattle. Table 7-7 presents the risks for the milk ingestion pathway.

Table 7-7. Percentile Risk for Milk Ingestion Pathway

	Lifetime Individual Risk	
Percentile	**Adult**	**Child**
50th	3E-7	5E-7
75th	1E-6	1E-6
90th	3E-6	3E-6
95th	6E-6	5E-6
99th	2E-5	1E-5

7.1.3.8 Fish. Edible fish are assumed to be caught from a stream adjacent to the farm where biosolids are applied. The stream, therefore, receives runoff, erosion, and air deposition from the amended cropland and pasture. The eroded soil from the farm is transported across the buffer directly to the stream. The stream also receives direct air deposition of particles and vapors from the cropland and pasture. In addition, particles and vapors from the cropland and pasture are transported and deposited on the much larger area of the regional watershed from which they are also eroded to the modeled stream. The fish that live in the stream are assumed to include T3 and T4 fish (i.e., edible species). These fish are assumed to be caught and consumed by a recreational fisher. This fisher may also be the farmer who applies the biosolids or an individual from a nearby town who has no other pathways of exposure. The recreational fisher is assumed to catch all the home-caught fish he consumes from this single stream adjacent to the biosolids-amended field. The stream modeled in this assessment is of sufficient size to produce this amount of fish. There are no fish consumption rate data in the EFH (U.S. EPA, 1997a,b,c) for children that are comparable to the adult data used in this analysis. When appropriate child consumption rates are identified for fish, this pathway can be added. In this analysis, no childhood consumption of fish was considered. The adult risk is indicative of the relative risk from this pathway expected for children.

The BSAF used for dioxins and furans accounts for food chain transfer to fish. The BSAF is based on the measured concentrations in the sediment and the measured concentrations in fish. The fish on which the selected BSAFs are based are T4 (trout or white fish) species. Thus, by basing the BSAF values used in the analysis on a T4 fish, the food chain transfer to fish is included by definition in the BSAF value itself. Table 7-8 presents the risks for the fish ingestion pathway.

Table 7-8. Percentile Risk for Fish Ingestion Pathway

	Lifetime Individual Risk
Percentile	**Adult**
50th	8E-10
75th	4E-9
90th	2E-8
95th	4E-8
99th	2E-7

7.1.3.9 Ambient Air. The ambient air concentration that the farm family is assumed to breathe is the average air concentration estimated over the residential buffer. The vapor and particulate air concentrations are estimated independently in the air modeling, but are summed in the inhalation risk estimates. The risks for this pathway are driven predominantly by exposure factors (exposure duration and inhalation rate), also. Other factors that influence this pathway are the loading to the soil and the soil and climate properties that lead to greater air emissions from the amended soil. Table 7-9 presents the risks for the air inhalation pathway.

Table 7-9. Percentile Risk for Air Inhalation Pathway

Percentile	Lifetime Individual Risk	
	Adult	Child
50th	7E-10	9E-10
75th	2E-9	2E-9
90th	7E-9	5E-9
95th	1E-8	8E-9
99th	3E-8	2E-8

7.1.3.10 Breast Milk. The lactating woman is an adult member of the farm family and, therefore, is assumed to consume all types of home-produced food with the consumption rates and fractions homegrown presented in the preceding sections for each of the following dietary items: exposed produce, root vegetables, poultry, eggs, beef, and milk. The mother is assumed to have reached a steady-state concentration of dioxins in lipids before lactation begins. The maternal concentrations of dioxins are then modeled to partition each congener to the lipid fraction of breast milk, which is subsequently assumed ingested by an infant. The infant is assumed to consume no homegrown dietary items directly and, thus, obtains exposures only through the ingestion of breast milk during the first year of life. Table 7-10 presents the intake of dioxin-like constituents by the infant by the breast milk ingestion pathway.

Table 7-10. Percentile Dioxin Ingestion Through the Breast Milk Ingestion Pathway

Percentile	Infant Ingestion (mg/kg/d)
	Infant
50th	2E-9
75th	4E-9
90th	8E-9
95th	1E-8
99th	3E-8

Adding breast milk to the child scenario is an admirable goal for future dioxin risk analysis. Currently, the breast milk exposure is a separate calculation and is expressed as a margin of exposure and is an incremental dose received by the infant in comparison with the background environmental dose that would be expected if biosolids were not applied to the farm land. This modeling is not performed in the same modeling structure as the childhood exposure. The exposure of the infant is predicated on assumptions that the mother is at a steady-state dioxin concentration prior to lactation, and infant dose is based on maternal intake. The infant is assumed to be exposed only through the ingestion of breast milk. Also, inhalation dose is trivial in comparison with breast milk dose. The infant metabolism and endpoints are most likely different from the older child's and the adult's. Until the mechanism of action for dioxin-like

constituents is better understood in the infant and child, it may not be appropriate to add these doses together.

Quantifying in utero exposure to the fetus and adding this exposure to the infant and child is also not supported by current science and is only addressed qualitatively in the Draft Dioxin Reassessment Document (U.S. EPA, 2000). The developing fetus probably does not have the same intake mechanisms or metabolism as an infant, child, or adult; therefore, an entirely new set of exposure, transfer, and health benchmark data would be required to address fetal exposures.

7.2 Multipathway Risks

The structure of the probabilistic analysis is based on the modeling of 3,000 individual exposure scenarios for adults and children. This means that for each individual (iteration) in the analysis, a set of intake rates is chosen from the distribution for each pathway for an adult receptor and a child receptor. The intake rates for dietary items are not correlated in any way. Insufficient data are available to enable correlation. This process allows the evaluation of risk from each pathway independently, and it also allows the evaluation of multipathway risks. The distribution of multipathway risks is the distribution of the sum of the risks across pathways for each of the 3,000 individual adults and children in the analysis. Thus, for example, the 90th percentile multipathway risk to an adult receptor may not correspond to the 90th percentile risk for any single pathway, but it is selected from the distribution of 3,000 risks summed across all pathways. Multipathway risks were also evaluated for the adult farmer and his child. The multipathway results presented in Table 7-11 are from the distribution of the total risk. Table 7-11 presents the multipathway risks to the adult and child members of the farm family and includes the LADD that produced these risks.

Table 7-11. Multipathway Risks and Associated LADD for Adult and Child Farm Family Members— Baseline All Samples from 2001 NSSS

Percentile	Adult		Child	
	Risk	Daily Exposure, pg TEQ/kg-d	Risk	Daily Exposure, pg TEQ/kg-d
50th	1.3×10^{-6}	0.0086	1.5×10^{-6}	0.0094
75th	4.0×10^{-6}	0.026	3.2×10^{-6}	0.021
90th	9.9×10^{-6}	0.064	6.6×10^{-6}	0.042
95th	1.6×10^{-5}	0.11	9.6×10^{-6}	0.062
99th	4.4×10^{-5}	0.28	2.3×10^{-5}	0.15

7.3 References

U.S. EPA (Environmental Protection Agency). 1997a. *Exposure Factors Handbook, Volume I, General Factors.* EPA/600/P-95/002Fa. Office of Research and Development, Washington, DC. August.

U.S. EPA (Environmental Protection Agency). 1997b. *Exposure Factors Handbook, Volume II, Food Ingestion Factors.* EPA/600/P-95/002Fa. Office of Research and Development, Washington, DC. August.

U.S. EPA (Environmental Protection Agency). 1997c. *Exposure Factors Handbook, Volume III, Activity Factors.* EPA/600/P-95/002Fa. Office of Research and Development, Washington, DC. August.

U.S. EPA (Environmental Protection Agency). 2000. *Exposure and Human Health Reassessment of 2,3,7,8-Tetrachlorodibenzo-p-Dioxin (TCDD) and Related Compounds*. EPA/600/P-00/001Bg. Washington, DC: National Center for Environmental Assessment, Office of Research and Development. September.

8.0 Analysis of Variability and Uncertainty

This section discusses the methods that were used in the risk assessment for dioxins, furans, and PCBs in biosolids to account for variability and uncertainty. Variability and uncertainty are fundamentally different. Variability represents true heterogeneity in characteristics, such as body weight differences within a population or differences in contaminant levels in the environment. It accounts for the distribution of risk within the exposed population. Uncertainty, on the other hand, represents lack of knowledge about factors, such as adverse effects from contaminant exposure, that may be reduced with additional research to improve data or models.

Variability arises from true heterogeneity in characteristics, such as body weight differences within a population or differences in contaminant levels in the environment.

Uncertainty represents lack of knowledge about factors, such as the nature of adverse effects from exposure to constituents, that may be reduced with additional research.

This discussion describes the treatment of variability and uncertainty in reference to some parameters used to describe human exposures and risk. Treatment of variability using a Monte Carlo simulation forms the basis for the human health risk distributions, which in turn are the basis for calculating a protective concentration for dioxins, furans, and PCBs in biosolids. Previous sections of this document describe how distributions were generated and point values estimated for input parameters. They also describe how these values were used in the models and in calculations to produce a national-level TEQ concentration in biosolids that is protective of human health. Uncertainty necessitated the use of assumptions and default values in this study. This discussion focuses on how this treatment of variability and uncertainty affects the results.

8.1 Variability

Variability is often used interchangeably with the term uncertainty, but the two are not synonymous. Variability is tied to variations in physical, chemical, and biological processes and cannot be reduced with additional research or information. Although variability may be known with great certainty (e.g., age distribution of a population may be known and represented by the mean age and its standard deviation), it cannot be eliminated and needs to be treated explicitly in the analysis. Spatial and temporal variability in parameter values used to model exposure and risk account for the distribution of risk in the exposed population.

For example, the meteorological parameters used in dispersion modeling, such as windspeed and wind direction, are measured hourly by the National Weather Service at many

locations throughout the United States, and statistics about these parameters are well documented. Although the distributions of these parameters may be well known, their actual values vary spatially and temporally and cannot be predicted exactly. Thus, the concentration calculated by a dispersion model for a particular receptor for a particular time period will provide information on average conditions that may over- or underpredict actual concentrations. Much of the temporal variation is accounted for by using models such as ISCST3 that calculate concentrations hourly and sum these hourly values to provide annual concentration estimates. Additionally, using meteorological data from multiple monitoring stations located throughout the United States can account for some but not all spatial variability.

In planning this analysis, it was important to specifically address as much of the variability as possible, either directly in the Monte Carlo analysis or through disaggregation of the data into discrete elements of the analysis. For example, use of a refined receptor grid accounts for spatial variability in concentrations on and around the agricultural field where biosolids are applied. Variability in agricultural practices is accounted for by using distributions that represent the range of possible agricultural practices.

Spatial variability in environmental setting was accounted for by using 41 different climatic regions throughout the contiguous 48 states. Because biosolids are generated nationwide, the application of biosolids to agricultural fields may occur nationwide; thus, this analysis characterized environmental conditions that influence the fate and transport of constituents in the environment using regional data based on climatic conditions.

The risk assessment components discussed include

- Source characterization and emissions modeling
- Fate and transport modeling
- Exposure modeling.

8.1.1 Source Characterization and Emissions Model Variables

The specific agricultural fields where biosolids were applied were not known; however, EPA assumed that biosolids could be applied to any agricultural land. For this analysis, agricultural field areas were varied according to climatic regions. The median farm size for each climatic region was used to represent the regional variability of farm size. However, uncertainty about farm size within a climatic region remained. Distributions were used to capture nationwide variability in agricultural practices. The variation in median farm size based on regions and the nationwide distribution of agricultural practice parameters was used in the probabilistic analysis to characterize the national variation in farm areas and operating characteristics.

Source partition modeling was performed for 41 different climatic regions, which allowed variation in location-dependent parameters (e.g., soil, temperature, precipitation) to be considered explicitly in the modeling. Variation in these parameters influenced variation in predicted air emissions rates. These meteorological data sets were combined with the surface area of the agricultural field to provide unit air concentrations (UACs), which were used with emissions data to estimate air concentrations for cropland and pastures.

In the Monte Carlo analysis, the agricultural field characteristics, environmental conditions from 41 climatic regions, and parameter values for biosolids characteristics were combined to produce the 3,000 iterations of the source partition model calculations. The source model calculations generated the distribution of environmental releases used in the fate and transport modeling.

8.1.2 Fate and Transport Modeling Variables

The parameter values required to model contaminant fate and transport were obtained from regional databases. The treatment of regional variation in location-dependent parameters used in fate and transport modeling is discussed in the following sections.

8.1.2.1 Air Dispersion Modeling Variables. To capture geographic variation, dispersion modeling was conducted using meteorological data sets from 41 different meteorological stations throughout the contiguous 48 states. This provided regional representation of the variability in meteorological data. Obviously, 41 meteorological stations do not represent every site-specific condition that could exist in the 48 states. However, in selecting the climatic regions, consideration was given to representing different Bailey's ecological regions and to not excluding from the analysis those areas with unique dispersion characteristics (e.g., coastal areas). Thus, it is believed that these 41 climatic regions are a reasonable representation of the variability in meteorological conditions for the United States.

8.1.2.2 Soil and Water Modeling Variables. Soil characteristics were based on the location of the 41 climatic regions used in the modeling. Soil characteristics for all nonurban soil within the climatic region were used to determine the soil characteristics for watershed modeling. This approach captured the national distribution of soil types and accounted for regional variation in soil characteristics.

Waterbody characteristics were not varied in the fate and transport modeling. However, in addition to variation in soil type and precipitation, watershed modeling also took into account regional variation in agricultural field size and regional watershed size, which can affect constituent loading to the waterbody via runoff and erosion. Otherwise, regional variations in waterbody were not accounted for in this analysis.

8.1.2.3 Terrestrial and Aquatic Food Chain Variables. To the extent that agricultural field size and variation in regional watershed areas affects runoff and erosion of constituents into the waterbodies modeled in this assessment, the variation had an effect on runoff and erosion loadings to the waterbody. Otherwise, no regional variations were considered for the aquatic food chain modeling.

8.1.2.4 Exposure Modeling Variables. Individual physical characteristics, activities, and behavior are quite different. As such, the exposure factors that influence the exposure of an individual, including inhalation rate, ingestion rate, body weight, and exposure duration, are quite variable. To include this variability explicitly in the analysis, statistical distributions for these variables were used for each receptor in the analysis: adult, child, and infant in the farm family and a recreational fisher. For adults, a single exposure factor distribution was used for males and females. For child exposures, one age group (ages 1 to 6) was used to represent the

age at the start of exposure, because this age group is considered to be most sensitive for most health effects. The infant was evaluated only for breast milk ingestion during the first year of life. Exposure parameter data from the EFH (U.S. EPA, 1997a,b,c) were used to establish statistical distributions of values for each exposure parameter for each receptor.

8.1.2.5 Summary of Variability Considerations. In summary, a protective biosolids concentration was developed that includes specific consideration of the variability in

- Agricultural field size and biosolids characteristics
- Agricultural practices
- Regional-specific environmental conditions
- Exposure factors for each receptor.

Taken together, these provide nationally applicable risk-specific TEQ concentration for dioxins, furans, and PCBs in biosolids.

8.1.2.6 Sensitivity Analysis. A statistically based sensitivity analysis was performed to rank the variable parameters in the analysis according to their contribution to the variability of the resulting risk for each pathway. This methodology is referred to as a response surface regression approach because it uses models characteristic of those used in a response surface experiment. Response surface methodology involves a statistical approach to designing experiments and an associated model estimation methodology. The terminology "response surface" derives from the fact that a regression model involving a number of continuous independent variables can be viewed as providing an estimated surface of the results in space. Often, a goal of response surface experimentation is to ascertain the combination(s) of input variable values that will yield a minimum or a maximum response. The complexity of the model (e.g., whether it contains only first- and second-order terms or terms of higher degree) determines the general shape of the contours and the degree to which the "true" surface can be approximated.

In this analysis, a regression analysis was applied to a linear equation to estimate the relative change in the output of a probabilistic simulation relative to the changes in the input variable values. This methodology is one of the recommended methods for conducting a sensitivity analysis based on the results of a Monte Carlo analysis described in Appendix B of *RAGS 3A - Process For Conducting Probabilistic Risk Assessment - Draft* (1999) (U.S. EPA, 1999).

Sensitivity analyses historically were conducted by evaluating how much change in risk occurred as a result of varying an individual input variable from a median or mean value to a 90^{th} percentile or high-end value. When the risk depends on the aggregate impact of a number of input variables, however, such an approach may not necessarily identify the most important one. This may occur for several reasons:

- The ranges chosen for the various input variables may not be defined consistently.

- Various input variables may interact with one another (i.e., the effect of input X_1 on an outcome Y depends on the level of other inputs X_2, X_3, etc., so that the

observed effect of X_1 depends on what values were chosen for the other variables as well).

- Nonlinear effects may obscure the effect of the input variable (e.g., if only low and high values of an input variable are examined but the relationship between the risk and the input variable is of a quadratic nature, then the importance of the input variable may be overlooked).

To address such issues, statistical regression methods were used to perform the sensitivity analyses. Although regression methods have distinct advantages over previous approaches, certain limitations remain. Regression methods are not capable of determining the sensitivity of model results to input variables that are not varied in the analysis (e.g., assumptions) or are not otherwise included within the scope of the analysis (e.g., model-derived variables). If, for some reason, the most important variables are not varied or their variability is improperly characterized, the sensitivity analysis may not identify them as being important.

The sensitivity analysis was conducted on a data set generated during modeling of each pathway. For example, a set of input variables (X_1, X_2, ..., X_p) was used in the modeling simulation.

The result of interest is the individual risk calculated for each pathway as a result of exposure to all dioxin-like congeners as expressed as a TEQ. In this case, the *Xs* are parameters associated with agricultural practices, site, environmental conditions, and exposure parameters.

The regression approach uses the various combinations of *X* values that were used during the simulation and the resulting risk values as input data to a regression model. Functions of the results variables (denoted as *Ys*) were treated as dependent variables; for example, *Y* denoted the logarithm of the risk. Functions of the *Xs* were treated as independent variables. The goals of the approach were

1. To determine a fairly simple polynomial approximation to the simulation results that expressed the *Ys* as functions of the *Xs*

2. To optimize this "response surface" and assess the importance of the various *Xs* by performing statistical tests on the model parameters

3. To rank the *Xs* based on their relative contribution (in terms of risk) to the final response surface regression model.

These goals were realized using a second-order regression model. Such a model takes the following form:

$$\hat{Y} = \hat{\beta}_0 + \sum_{k=1}^{p} \hat{\beta}_k x_k + \sum_{k=1}^{p} \hat{\beta}_{kk} x_k^2 + \sum_{k=1}^{p-1} \sum_{j=k+1}^{p} \hat{\beta}_{kj} x_k x_j \qquad (8\text{-}1)$$

where the β*s* are the least squares regression estimates of the model parameters.

The statistical significance of the parameters associated with the first-order, squared, and cross-product terms were tested and all nonsignificant terms were removed from the model. The parameters in this reduced model were then reestimated and the process of testing was repeated. This was done to capture the most important independent variables (*Xs*) that influence the dependent variables (*Ys*).

Once the final regression model was developed, the input parameters (*Xs*) were ranked based on percentage of risk accounted for by that parameter. The percent risk was calculated using the following equation:

$$Percent\ Risk = \frac{[FMSS - RMSS]}{[FMSS + ERSS]} \tag{8-2}$$

where

FMSS = model sum of squares for the final model

RMSS = model sum of squares for a model in which all terms involving x_u are removed (i.e., a reduced model)

ERSS = model error sum of squares.

The two parameters responsible for the largest percentage of the risk are the two parameters set to high-end values in the deterministic analysis.

The major steps in the sensitivity analysis are identified below, along with details on the reasons for these steps.

- **Perform any necessary manipulations to the data set.** To perform the sensitivity analysis, the data set must contain only one record for each Monte Carlo iteration, and all variables in the data set must be numeric.

- **Remove any variables that are constants.** Any variable that was constant across all Monte Carlo iterations does not have any effect on the resulting risk and was removed from the data set prior to the start of the regression analysis.

- **Perform transformations (log, square root, etc.) to the continuous input variables, if necessary, so that all input variables will have approximately symmetric distributions.** Transforming the input variables so that each one has an approximately symmetric distribution is necessary to make the standardization of the variables meaningful (i.e., so the mean is near the midpoint of the extremes, and the mean and standard deviation are not highly related).

- **Check the correlations of the transformed input variables. Remove any input variables that are highly correlated with other input variables in the data set.** Regression analysis measures the linear relationship between the terms

in the model and the response variable. If two or more input variables are highly correlated with one another, then there is a strong linear relationship between those input variables. Keeping all highly correlated variables in the model will reduce the significance of each of the correlated input variables because each one is essentially explaining the same linear relationship with the response variable (i.e., the effect of one such variable may mask the effect of another).

- **Standardize the transformed variables.** Standardizing the input variables (i.e., subtracting the mean and dividing by the standard deviation) allows the regression results to be independent of the magnitude of the value of the input variables. The larger value input variables could cause the regression results to seriously underestimate the effects of the smaller value input variables on the changes in environmental concentration and risk. The combination of transforming and standardizing the input variables creates more optimal conditions for regression analysis.

- **Use response surface regression methods to test for the main effects, squared terms, and cross products that have the greatest effect on the log(environmental concentration). Develop a model for log(environmental concentration) based on the results of the regression analysis.** After the response surface regression results are obtained, the significance of each term on environmental concentration is evaluated. First, any second-order terms that are determined not to have a significant effect on the environmental concentration are dropped from the model. Any first-order term that is part of a significant second-order term will remain in the model, regardless of the level of significance of that first-order term. For example, if the second- order term $X_1 \times X_2$ has a significant effect on the environmental concentration and remains in the model, then both of the first-order terms, X_1 and X_2, will also remain in the model. Any first-order terms that are determined not to be significant and not to have any significant second-order terms are dropped from the model. The regression analysis is then conducted on the reduced model. This process is repeated until all of the second-order terms in the model have significant effects on the environmental concentration and no more terms can be removed. The iterative process of dropping insignificant terms and reevaluating the model allows only the input variables with the most effect on the environmental concentration to remain in the model.

- **Use the model for log(environmental concentration) as part of the model for the log(risk).** The equation that must be evaluated is

$$risk = \frac{environmental\ concentration \times risk\ factor \times exposure\ duration \times intake}{body\ weight} \qquad (8\text{-}3)$$

Taking the log of both sides of the above equation results in

$$\log(risk) = \log(environmental\ concentration) + \log(risk\ factor) + \log(exposure\ duration) + \log(intake) - \log(body\ weight) \quad (8\text{-}4)$$

The log(environmental concentration) in the above equation is replaced with the final model of input variables from the regression analysis in the previous analysis step. Regression analysis is performed on the new model for log(risk).

- **Test for the effect of each variable on log(risk) and use the *p*-values to rank the variables by the amount of effect each variable has on log(risk).** Because the final model will most likely contain first- and second-order terms involving the same input variables, *F*-tests need to be performed to evaluate the effect of each input variable in the final model on the log(risk). The *F*-tests of each variable will be of the form

$$F = \frac{[FMSS - RMSS] \ / \ [FMDF - RMDF]}{FRSS \ / \ FRDF} \quad (8\text{-}5)$$

where

FMSS	=	model sum of squares for full model containing all significant terms
RMSS and RMDF	=	model sum of squares and degrees of freedom, respectively, for reduced model
FMDF	=	model degrees of freedom for full model
FRSS and FRDF	=	residual sum of squares and degrees of freedom, respectively, for full model.

The full model refers to the model containing all significant terms in the final log(risk) model. The reduced model refers to the full model minus all terms containing the input variable *X* whose significance is being tested. The *F*-tests evaluate the effect of variable *X* on the risk by evaluating the differences when variable *X* is in the regression model (full model) and when all model terms containing variable *X* are removed (reduced model). If a substantial increase in the residuals results from ignoring terms involving the variable *X*, then *F* will be "large," implying that these factors can be considered important, in the sense that they require different regression coefficients for the *X*s. The ordering of the *p*-values from such tests can then be used to rank the importance of the various factors on the risk. The most important four parameters for each pathway identified by the sensitivity analysis are presented in Table 8-1. Detailed results of the sensitivity analysis are presented in Appendix K.

Table 8-1. Results of Sensitivity Analysis by Pathway

Pathway	Sensitivity Variables	Percent of Risk Accounted for by Variable
Air	Exposure duration	66
	Inhalation rate	4
	Soil moisture retention exponent *b*	2
	Application rate	2
Soil	Exposure duration	78
	Average year that the farm family moves in	3
	Application rate	2
	Body weight	1.5
Aboveground vegetables and fruit	Exposure duration	Fruit 56, Veg. 59
	Consumption rate	Fruit 11, Veg. 6
	Average year that the farm family moves in	Fruit 2, Veg. 3
	Soil moisture retention exponent *b*	Fruit 2, Veg. 2
Root vegetable	Exposure duration	49
	Consumption rate	30
	Soil foc	10
	Average year that the farm family moves in	4
Poultry	Exposure duration	55
	Consumption rate	33
	Average year that the farm family moves in	2
	Application rate	1
Egg	Exposure duration	60
	Consumption rate	28
	Average year that the farm family moves in	2
	Application rate	1
Beef	Exposure duration	60
	Consumption rate	26
	Application rate	1
	Average year that the farm family moves in	1
Milk	Exposure duration	54
	Consumption rate	32
	Average year that the farm family moves in	1
	Application rate	1
Fish	Consumption rate	47
	Exposure duration	34
	Average year that the farm family moves in	1
	Application rate	1

8.2 Uncertainty

Uncertainty is a description of the imperfection in knowledge of the true value of a particular parameter. In contrast to variability, uncertainty is reducible by additional information-gathering or analysis activities (e.g., better data, better models). EPA typically classifies the major areas of uncertainty in risk assessments as scenario uncertainty, model uncertainty, and parameter uncertainty. Scenario uncertainty refers to missing or incomplete information needed to fully define exposure and dose. Model uncertainty is a measure of how well the model simulates reality. Parameter uncertainty is the lack of knowledge regarding the true value of a parameter used in the analysis.

Although some aspects of uncertainty were directly addressed in this analysis, much of the uncertainty associated with this analysis could only be addressed qualitatively. Significant sources of uncertainty are presented in this section. If the analysis directly addressed uncertainty, the approach used is described. If the analysis did not directly address uncertainty, a qualitative discussion of its importance is provided.

8.2.1 Scenario Uncertainty

Sources of scenario uncertainty include the assumptions and modeling decisions that are made to represent an exposure scenario. The hypothetical farm scenario is a major source of uncertainty in this analysis. The analysis is based on a single conceptual site model that assumes that biosolids are applied to a farm that is half cropland and half pasture and that the farm family lives adjacent to those areas where biosolids are applied. There are no data about the specific farms where biosolids are applied. However, it is known that biosolids are applied to both cropland and pastures nationwide. Therefore, a hypothetical farm was developed to allow the estimation of risk from the application of biosolids to farms producing all types of agricultural products anywhere in the nation. These are reasonable assumptions; however, much uncertainty is associated with the scenario. The lack of information or resources to define and model actual exposure conditions introduced uncertainty into this analysis, but the analysis is reasonable in the light of the associated scenario uncertainty.

Scenario uncertainties that are important to understand in interpreting the results of this study are discussed in the following subsections.

8.2.1.1 Farm Characteristics. The farm is assumed to be split evenly between land for growing crops and land for pasture for cattle. This division may not accurately reflect the division in land use in any particular area; however, this scenario allows the crop and pasture scenario to be evaluated in each geographical region with the full range of applicable environmental fate and transport variables. Although these assumptions include scenario uncertainty, they are protective and reasonable and can be included in the qualitative understanding of the scenario uncertainty.

8.2.1.2 Receptor Populations Evaluated. The land use for the application of biosolids to agricultural fields is assumed to be agricultural. As such, human receptors evaluated include an adult farmer, the child and infant of the farmer, and a resident who is a recreational fisher at a nearby waterbody. Risk estimates presented in this document address hypothetical chronic

exposures for these receptors and are designed to provide a realistic range of potential scenarios. It is possible for any type of receptor to be present on a farm where biosolids are applied. In order to ensure that all potential receptors and pathways are evaluated, it was assumed that an adult farmer, a child, and a lactating mother with an infant lived on every farm. This assumption is obviously not true in all cases; however, it allows the evaluation of all receptors and pathways in all locations. Although these assumptions include scenario uncertainty, they are reasonable assumptions that can be included in the qualitative evaluation of scenario uncertainty.

8.2.1.3 Characteristics and Location of Waterbodies. One aspect of the site layout of particular relevance to aquatic food chain modeling is the location and characteristics of the waterbodies. The size of the waterbody affects constituent concentration predicted for that waterbody. The waterbody characteristics selected were for a third-order stream, intended to represent a small but fishable waterbody. This small size would tend to ensure that calculated waste concentrations would be protective of routes of exposure from surface water. The location of the waterbody was assumed to be at the edge of the agricultural field. Because there are no site-specific locations for the farms and nearby waterbodies, there is uncertainty associated with the placement and dimensions of the nearest waterbody and associated regional watershed. The assumptions made for this risk assessment allow the evaluation of the fish ingestion pathway based on reasonable and protective assumptions. The uncertainty associated with this portion of the scenario must also be considered in the qualitative evaluation of uncertainty. The assumptions about the location and size of the stream may bias the risk results for the fish ingestion pathway, resulting in higher risk estimates.

8.2.2 Model Uncertainty

Model uncertainty is associated with all models used in all phases of a risk assessment because models and their mathematical expressions are simplifications of reality that are used to approximate real-world conditions and processes and their relationships. Computer models are simplifications of reality, requiring exclusion of some variables that influence predictions but cannot be included in models either because of their complexity or because data are lacking on a particular parameter. Models do not include all parameters or equations necessary to express reality because of the inherent complexity of the natural environment and the lack of sufficient data to describe the natural environment. Because this is a probabilistic assessment that predicts what may occur with the management of biosolids under assumed scenarios, it is not possible to compare the results of these models (sometimes referred to as model validation) to any specific situation that may exist. The risk assessor needs to consider the importance of excluded variables on a case-by-case basis, because a given variable may be important in some instances and not in others. A similar problem can occur when a model that is applicable under average conditions is used for conditions that differ from the average. In addition, in some instances, choosing the correct model form is difficult when conflicting theories seem to explain a phenomenon equally well. In other instances, EPA does not have established model forms from which to choose to address certain phenomena, such as facilitated transport.

Models used in this risk assessment were selected based on science, policy, and professional judgment. These models were selected because they provide the information needed for this analysis and because they are generally considered to be state of the science. Even though the models used in the risk analyses are used widely and have been accepted for

numerous applications, they each retain significant sources of uncertainty. Evaluated as a whole, the sources of model uncertainty in this analysis could result in either an overestimation or underestimation of risk.

Another issue in model uncertainty is the number of iterations necessary to achieve convergence of the analysis, especially at the higher ends of the distribution. In order to determine the convergence of this analysis, the results from various portions of the iterations were selected from the total number of iterations. The percentile values for the 90th, 95th, and 99th percentiles of the smaller number of iterations were compared to the 90th, 95th, and 99th percentiles for 10,000 iterations. Convergence at the 95th percentile was achieved with 2,500 to 3,000 iterations. Thus, for this analysis, 3,000 iterations was assumed to be sufficient to estimate a reliable distribution of risks, including risks at and above the 95th percentile. Figure 8-1 presents the convergence analysis of risk values.

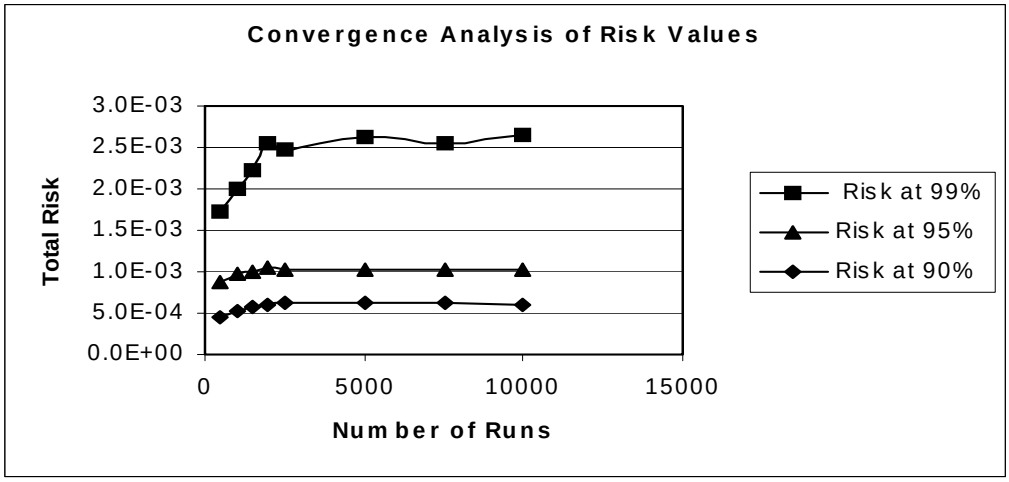

Figure 8-1. Convergence analysis.

8.2.2.1 <u>Air Dispersion Modeling</u>. The ISCST3 model was used to calculate the dispersion of particle and vapor emissions from a waste management unit. This model has many capabilities needed for this assessment, such as the ability to model area sources. For dispersion modeling of this type, ISCST3 is considered a fairly accurate model with error within about a factor of 2. It does not include photochemical reactions or degradation of a chemical in the air, which results in additional model uncertainty. Deposition and associated plume depletion are important for particulates and vapors and were explicitly incorporated into this analysis. Currently, algorithms specifically designed to model the dry deposition of gases have not been verified for the specific compounds in question (primarily volatile organics). In place of algorithms, a transfer coefficient was used to model the dry deposition of gases. A concern with this approach is that the deposition is calculated outside of the model. As a result, the mass is deposited on the ground from the plume and is not subtracted from the air concentrations estimated by ISCST3. This results in a slight nonconservation of mass in the system.

Other uncertainties introduced into the analysis in dispersion modeling are related to agricultural field shape. A square shape was selected because it minimizes the error introduced by not knowing the orientation of the agricultural field to wind direction.

8.2.3 Variable Uncertainty

Variable uncertainty occurs when (1) there is a lack of data about the values used in the equations, (2) the data that are available are not representative of the particular instance being modeled, or (3) variable values cannot be measured precisely and/or accurately because of limitations in measurement technology. Random, or sample, errors are a common source of parameter uncertainty that is especially critical for small sample sizes. More difficult to recognize are nonrandom or systematic errors that result from bias in sampling, experimental design, or choice of assumptions.

8.2.3.1 Agricultural Field Variables. Source characterization required making assumptions about agricultural practices on farms where biosolids may be applied. There is much uncertainty associated with the actual practices employed on farms where biosolids are actually employed. It is not known what area is amended with biosolids and what crops or animals are raised on the amended land or what specific practices are employed. The variables used in this analysis represent the data available on potential agricultural practices. For this reason, substantial uncertainty concerning the variable values for agricultural practices remains.

8.2.3.2 Watershed Universal Soil Loss Equation (USLE) Variables. A combination of region-specific and national default variables was used along with USLE to model soil erosion losses from watersheds to waterbodies. The USLE calculations are particularly sensitive to site-specific values; thus, uncertainty is associated with using regional and national parameter values. Many of the ULSE parameters were based on the regional meteorological and regional soil data used in other parts of the analysis. These include soil erodibility factor (*K*), rainfall erosivity, and slope. Other variables were based on national default values (e.g., cover and management factors) or default relationships with other factors (e.g., length was determined as a function of slope).

8.2.3.3 Biosolids Characteristics. Few data were available on the physical and chemical characteristics of biosolids. To address this lack, assumptions on specific biosolids characteristics were based on general knowledge of biosolids. In this analysis, except for constituent concentration, which was measured, general biosolids characteristics, including default assumptions for bulk density, moisture, and porosity, were used.

8.2.3.4 Exposure Uncertainty. Exposure modeling relies heavily on default assumptions concerning population activity patterns, mobility, dietary habits, body weights, and other factors. As described earlier in the variability section, the probabilistic analysis for the adult and child exposure scenario addressed the possible variability in the exposure modeling by using distributions of values for exposure factors. There are some uncertainties, however, in the data that are used. Although it is possible to study various populations to determine various exposure parameters (e.g., age-specific soil ingestion rates or intake rates for food) or to assess past exposures (epidemiological studies) or current exposures, risk assessment is about prediction. Therefore, long-term exposure monitoring in this context is infeasible. The EFH

(U.S. EPA, 1997a,b,c) provides the current state of the science concerning exposure assumptions, and it is used throughout this document. To the extent that actual exposure scenarios vary from the assumptions in this risk assessment, risks could be underestimated or overestimated. For example, there could be farmers and children who have higher exposures than those predicted; however, it is more likely that actual exposures for most of these individuals would fall within the predicted range and, moreover, would be similar to what was modeled.

8.2.3.5 Human Health Benchmarks. Toxicological benchmarks are designed to be conservative (that is, to potentially overestimate risk) because of the uncertainties and challenges associated with condensing toxicity data into a single quantitative expression.

8.2.3.5.1 *Cancer Slope Factor.* The CSF for TCDD was derived as the 95 percent upper confidence limit of the slope of the dose-response curve using a linear, no-threshold, dose-response model. The CSF, is, therefore, an upper-bound estimate of the cancer risk per unit dose and, for this reason, may overstate the magnitude of the risk. In addition, the use of CSFs in projecting excess individual cancer risk introduces uncertainty stemming from a number of factors, including

- Limited understanding of cancer biology
- Variability in the response of animal models
- Differential response in animal models versus humans
- Difference between animal dosing protocols and human exposure patterns.

A key step in CSF development is high- to low-dose extrapolation. Depending on the model used to fit the data, extrapolations to the low-dose range can vary by several orders of magnitude, reflecting the potential uncertainty associated with the CSF. In addition, uncertainty is introduced in the analysis of dioxins, furans, and PCBs because the TEF scheme is used to relate the toxicity of all congeners to the toxicity of TCDD. There are no other data for use for congener-specific toxicity endpoints. The TEF convention described in the Draft Dioxin Reassessment Document (U.S. EPA, 2000a) was used in this analysis as the appropriate way to represent the concentrations of dioxin-like constituents in all media and risk to receptors attributable to all congeners. The congener-specific health benchmark values have been linked to this single CSF because all congeners are assumed to act by the same mechanism and, therefore, can be evaluated using the TEF convention. The TEF scheme to calculate the TEQ of mixtures is currently the worldwide accepted procedure for evaluating exposure and potential health risk for dioxin-like compounds. As such, use of CSF, which was understandably developed mostly, if not solely, based on data from 2,3,7,8-TCDD, is appropriately applied to TEQ. In addition, dioxin-like congeners occur as a suite of congeners.

8.2.3.5.2 *Human Health Benchmarks and Children*. EPA recognizes that significant uncertainties exist regarding the estimation of lifetime cancer risks in children. EPA estimated the risk of developing cancer from the estimated LADD and the slope of the dose-response curve. A CSF is derived from either human or animal data and is taken as the upper bound on the slope of the dose-response curve in the low-dose region, generally assumed to be linear, expressed as a lifetime excess cancer risk per unit exposure. Individuals exposed to carcinogens in the first few years of life may be at increased risk of developing cancer.

8.2.3.6 Natural Background Exposures. Dioxins are present in the environment as a result of the application of biosolids and from other sources. Thus, receptors potentially receive a "background" exposure that may be greater than the exposure resulting from release of dioxins from biosolids. For national analyses such as this assessment, the inclusion of background concentrations as part of the analysis is not feasible because of the variability of background concentrations nationwide and the lack of data on national background concentrations for each constituent. Not including the exposure an individual may already have to a constituent of concern (i.e., exposure to background concentrations) does not change the "incremental" increase in risk to an individual due to possible exposures to constituents in biosolids.

8.2.3.7 Exposure Factors. For most exposure factors addressed, data analyses involved fitting distributions of data summaries from the EFH (U.S. EPA, 1997a,b,c), in most cases by fitting distributions to selected percentiles. It is assumed that little information is lost by fitting to percentiles versus fitting to raw data. However, some believe that such analyses should always be based on raw data, synthesizing all credible sources.

Three standard two-parameter probability statistical distributions (gamma, lognormal, and Weibull) were used for this analysis. These distributions are special cases of a three-parameter distribution (generalized gamma) that allows for a likelihood ratio test of the fit of the two-parameter models. Other statistical distributions are possible (e.g., U.S. EPA, 2000b), but the technique used in this analysis offered considerable improvement over using a lognormal model in all cases, and it was appropriate for this analysis. In support of this conclusion, a comparison of results showed that the three-parameter generalized gamma distribution did not significantly improve on goodness of fit over the two-parameter distributional forms in 58 of 59 cases at the 5 percent level of significance.

Although they offer significant improvement in objectivity over visual estimation, goodness-of-fit tests used to determine which statistical distribution to use for a particular parameter are themselves subject to some uncertainty that should be considered in their application to exposure factors. One area of concern is uncertainty about how the survey statistics in the EFH (U.S. EPA, 1997a,b,c) were calculated. All of the statistics that have been used to assess goodness of fit assume a random sample, which may or may not be a valid assumption for EFH data. Specifically, many of the EFH data sources are surveys that, in many cases, do not involve purely random samples. Rather, they use clustering and stratification, primarily for economic reasons.

8.3 References

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U.S. EPA (Environmental Protection Agency). 1997b. *Exposure Factors Handbook, Volume II, Food Ingestion Factors.* EPA/600/P-95/002Fa. Washington, DC: U.S. Government Printing Office.

U.S. EPA (Environmental Protection Agency). 1997c. *Exposure Factors Handbook, Volume III, Activity Factors.* EPA/600/P-95/002Fa. Washington, DC: U.S. Government Printing Office.

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U.S. Environmental Protection Agency (EPA). 2000b. *Options for Development of Parametric Probability Distributions for Exposure Factors.* EPA/600/R-00/058. Washington, DC: U.S. Government Printing Office.

9.0 Screening Ecological Risk Assessment of Dioxins, Furans, and Dioxin-like PCBs in Land-Applied Biosolids

9.1 Introduction

This section describes the screening ecological risk assessment (SERA) that was performed to investigate the potential for adverse ecological effects from dioxins in land-applied biosolids. Screening-level ecological risk assessments are designed to provide a high level of confidence in determining a low probability of adverse effects to ecological receptors (U.S. EPA, 2001a). The SERA was not designed or intended to provide definitive estimates of risk; rather, the SERA provides insight into the potential for adverse ecological effects. The SERA was designed to be consistent with EPA's Guidelines for Ecological Risk Assessment (U.S. EPA, 1998).

The SERA was conducted in two phases. In Phase 1, an initial screen was conducted to determine whether the dioxin concentrations in land-applied biosolids warranted further assessment. The purpose of this screen was to provide a simple, efficient indicator of the potential for adverse ecological effects at a high-end exposure. The Phase 2 SERA was based on more realistic, less conservative assumptions regarding the environmental media concentrations, receptor-specific dietary preferences, and ecological benchmarks. The results from Phase 2 are point estimates of potential hazards to a wide variety of mammals and birds, and were intended to inform the ongoing assessment of the ecological risks associated with the agricultural application of biosolids.

The risk metric chosen for the SERA is the hazard quotient (HQ), the ratio of the exposure (in units of dose) to an ecological benchmark. Media concentrations (e.g., sediment, soil) from the human health risk assessment modeling simulations were used to predict exposure doses, and HQs were calculated on a TCDD toxicity equivalence concentration (TEQ) basis. Calculation of HQs has a binary outcome: either the dose is below the protective ecological benchmark ($HQ<1$), or it is equal to or greater than the benchmark ($HQ\geq1$). However, the screening HQ results should be interpreted within the context of the SERA design. For example, a high level of conservatism built into the SERA provides higher confidence to support a conclusion of low potential for adverse ecological effects at an HQ below 1. Conversely, an HQ that is greater than the target HQ of 1.0 may provide sufficient justification for further analysis. The HQ results presented in this section are intended only to provide useful information for the decision-making process; the screening HQ results cannot be used to predict the probability or ecological significance of adverse effects.

The SERA methodology is organized according to EPA's Guidelines for Ecological Risk Assessment (U.S. EPA, 1998) with descriptions of problem formulation analysis and risk characterization provided in Sections 9.2, 9.3, and 9.4, respectively.

9.2 Problem Formulation

The problem formulation process consists of (1) selection of assessment endpoints, (2) development of a conceptual model, and (3) development of an analysis plan (U.S. EPA, 1998). The selection of endpoints and development of the conceptual model are discussed in Sections 9.2.1 and 9.2.2, and development of the analysis plan is briefly described in 9.2.3.

9.2.1 Assessment Endpoint Selection

Assessment endpoints are defined as "explicit expressions of the actual environmental value that is to be protected, functionally defined as an entity and its attributes" (U.S. EPA, 1998). The assessment endpoints serve as critical links between the ecological risk assessment and the management goal. For the biosolids SERA, the management goal was the following:

- Evaluate and characterize the potential for adverse ecological effects on wildlife that may be affected by land application of biosolids.

The assessment endpoints (entities and attributes) are survival, growth, and reproduction of avian and mammalian wildlife species typically associated with terrestrial and waterbody margin habitats adjacent to crop fields and pastures to which biosolids are applied. Population-level risks were not directly assessed because a population-level assessment would require information on a variety of parameters, such as survival, fecundity, immigration, and predator-prey relations. Although models were identified to evaluate the effects of chemical stressors on wildlife species populations, the data needed to support them are not readily available for a national-level assessment, and such an approach was considered beyond the scope of this screening-level analysis. Consequently, the SERA evaluated organism-level endpoints considered highly relevant to the viability of wildlife populations.

This approach assumes that, if individuals are protected from adverse reproductive and developmental effects associated with dioxins, furans, and dioxin-like PCBs in biosolids, protection at a higher level of biological organization (in this case, wildlife populations) may be inferred. The ecological screening assessment addressed effects to mammals and birds, the receptors that are expected to experience the highest exposure to dioxins; the assessment did not address risks to other receptor groups, such as invertebrates and plants primarily because these groups of receptors are known to be relatively insensitive to dioxin-like toxicity. The potential for dioxins to bioaccumulate in wildlife receptors is specifically addressed through analysis of the ingestion pathway. The analysis includes receptors exposed through ingestion of both aquatic and terrestrial food items and thus addresses the potential for bioaccumulation of dioxins from soil, surface water, and sediment. In the case of mammals and birds, studies identifying

Table 9-1. Assessment Endpoints for the Biosolids SERA

Assessment endpoint	**Ecological significance**	**Representative receptors** (entities)	**Characteristic(s)** (attributes)	**Measure of effect** (measurement endpoints)
Survival, growth, and reproduction of mammalian wildlife species	■ Includes upper trophic level consumers ■ Socially valued (e.g., endangered species) ■ Top recipients of bioaccumulative chemicals ■ Represents species with large foraging ranges ■ Represents species with longer life spans	e.g., deer mouse, meadow vole, red fox	Reproductive and developmental success	Chronic or subchronic NOAEL or MATL for developmental and reproductive effects
Survival, growth, and reproduction of avian wildlife species		e.g., red-tailed hawk, belted kingfisher	Reproductive and developmental success	Chronic or subchronic NOAEL or MATL for developmental and reproductive effects
Viable amphibian and reptile wildlife populations		e.g., green frog, eastern newt, northern water snake, eastern box turtle	Reproductive and developmental success	Chronic or subchronic NOAEL or MATL for developmental and reproductive effects
Survival, growth, and reproduction of fish	■ Highly exposed receptors from constant contact with contaminated media ■ Act as vectors to transfer contaminants to terrestrial species	e.g., fish (salmonids),	Growth, survival, and reproductive success	NOAEL for developmental effects

NOAEL - No observed adverse effects level
MATL - Maximum allowable toxicant level

reproductive and developmental effects in laboratory species were extrapolated to representative wildlife species. These endpoints do not reflect true population benchmarks because they do not consider other factors relevant to population dynamics, such as emigration, immigration, carrying capacity, and predator-prey interactions. Nevertheless, the selection of endpoints on reproductive fitness allows for inference on the possible impacts on wildlife populations. The bioaccumulation factors (BAFs) for terrestrial invertebrates used in the analysis were derived from empirical data and assume a linear relationship between the concentration in soil and in food items. However, these values are relatively conservative, and EPA considers them adequate for a screening-level analysis. Congener-specific BSAFs were used to model uptake from sediments. Thus, the BSAFs reflect the differences in bioaccumulative potential among the congeners. However, congener-specific data were not available for soil uptake. Therefore, the TCDD BAF was used for all congeners. EPA considers this approach to be appropriate for a screening assessment.

The representative receptors (entities) selected under each assessment endpoint reflect the desire to represent

- Significance of the receptor to the ecosystem
- Position of the receptor along a continuum of trophic levels
- Susceptibility of the receptor through media and food exposure pathways
- Toxicological sensitivity of the receptor to dioxins, furans, and dioxin-like PCBs.

9.2.2 Development of Conceptual Model

The conceptual model for the assessment describes the exposure scenarios and the relationships between the ecological receptors and the stressors of concern. The conceptual model is developed through analysis of the (1) environmental behavior of constituents, (2) identification of exposure pathways of concern, (3) identification of habitats and receptors of concern, and (4) characterization of ecological effects. Therefore, the conceptual model integrates information related to the constituents to be modeled (e.g., environmental behavior such as bioaccumulation), ecotoxicological effects data for constituents of concern, receptors and ecosystems potentially at risk, and relevant pathways of exposure. Because land application of biosolids may occur throughout the United States, virtually any type of ecosystem and ecological receptor may be exposed to dioxins, furans, and dioxin-like PCBs in biosolids. For screening purposes, the conceptual model included ecological receptors that are representative of either waterbody margin habitats in freshwater systems (e.g., streams, lakes, or ponds) or terrestrial habitats (e.g., forests, crop lands). Previous sections (Sections 3.0 through 5.0) of this report provide extensive details on the agricultural application of biosolids and how these exposure scenarios are developed. To avoid duplicating the discussions in these sections, the description of the conceptual model is intentionally brief with respect to the exposure scenario, application rates of biosolids, and other pertinent information on the site layout. As appropriate, references to previous sections have been provided to allow the reader to quickly identify additional details on the fate and transport modeling of chemical constituents in biosolids.

Because dioxins, furans, and dioxin-like PCBs are persistent, bioaccumulative organics, the conceptual model includes both direct and indirect (i.e., food chain) exposures for ecological receptors. Constituents released from an agricultural application of biosolids may be transported

to surface waterbodies through erosion and runoff and, frequently, are buried in the bed sediment. In addition, constituents may be dispersed and deposited directly onto plants, soils, and surface waterbodies by wet and dry deposition mechanisms. Soils and sediments have been shown to be sinks for environmental releases of dioxin and dioxin-like compounds; therefore, direct contact with these contaminated media may pose potential risks to ecological receptors (e.g., benthic dwellers). The dioxin-like constituents in biosolids have been shown to bioaccumulate in the food chain, and receptors in higher trophic levels may be particularly at risk through food chain exposures. Figure 9-1 presents a graphic representation of the conceptual model.

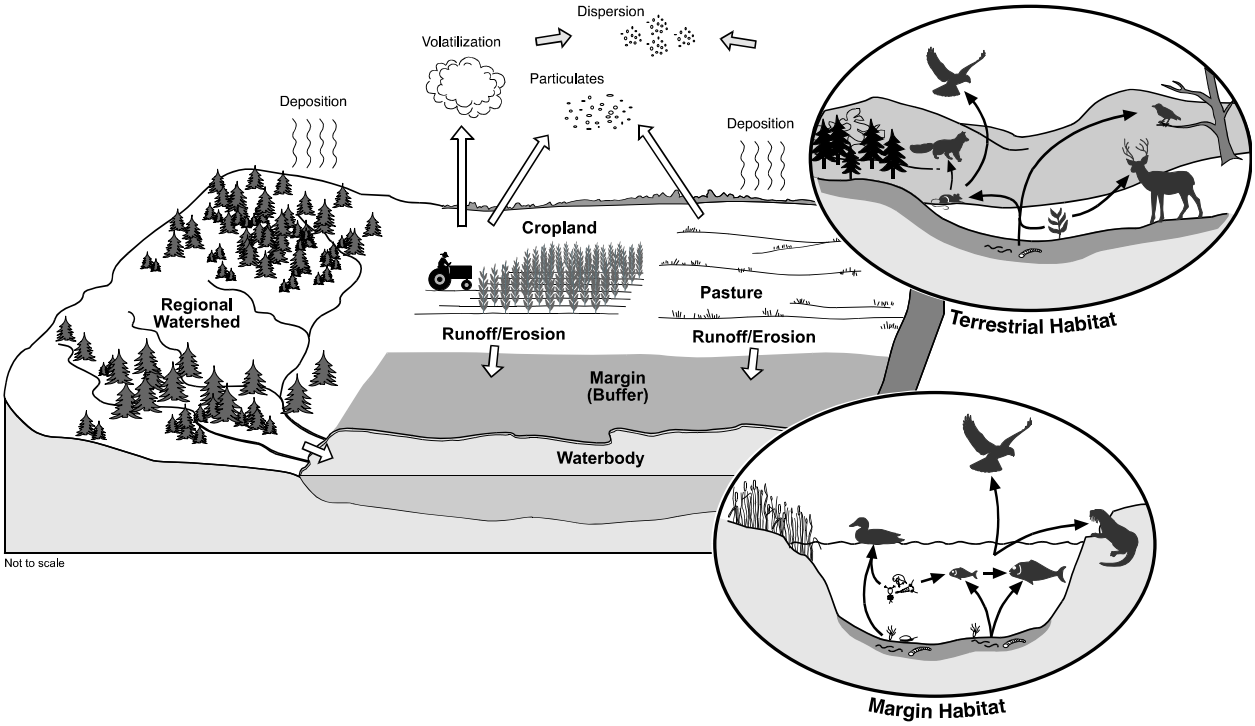

Figure 9-1. Conceptual model for the biosolids SERA.

9.2.2.1 Chemicals of Concern. The SERA addresses the 29 dioxin and PCB congeners modeled in the human health risk assessment, shown in Table 9-2.

9.2.2.2 Environmental Behavior of Chemicals of Concern. Generally, the mobility and fate of dioxins, furans, and dioxin-like PCBs is closely tied to the movement of sediments, particulates, and soils via erosion. For example, in surface water, these chemicals are associated primarily with suspended organic matter, which eventually settles into sediments. In the sediment compartment, dioxins, furans and dioxin-like PCBs are associated with the organic carbon fraction. Concentrations in sediments range from 6.0E-05 to 7.6E-03 mg/kg sediment, with the latter being related to sediments in areas of high industrial activity. In addition to the movement of dioxin via abiotic means, dioxin is also mobile through biotic means.

Table 9-2. Dioxin, Furan, and Dioxin-like PCB Congeners Assessed in the SERA

Polychlorinated dibenzo-p-dioxins and dibenzofurans	
CAS #	**Congener**
1746016	2,3,7,8-TCDD
40321764	1,2,3,7,8- PeCDD
39227286	1,2,3,4,7,8-HxCDD
19408743	1,2,3,7,8,9-HxCDD
35822469	1,2,3,6,7,8-HxCDD
3268879	1,2,3,4,6,7,8-HpCDD
51207319	1,2,3,4,6,7,8,9-OCDD
51207319	2,3,7,8-TCDF
57117416	1,2,3,7,8-PeCDF
57117314	2,3,4,7,8-PeCDF
70648269	1,2,3,4,7,8-HxCDF
57117449	1,2,3,7,8,9-HxCDF
72918219	1,2,3,6,7,8-HxCDF
60851345	2,3,4,6,7,8-HxCDF
67562394	1,2,3,4,6,7,8-HpCDF
55673897	1,2,3,4,7,8,9-HpCDF
39001020	1,2,3,4,6,7,8,9-OCDF

Dioxin-like polychlorinated biphenyls		
IUPAC #	**CAS #**	**Structure**
77	32598133	3,3',4,4'-TCB
81	70362504	3,4,4',5-TCB
105	32598144	2,3,3',4,4'-PeCB
114	74472370	2,3,4,4',5-PeCB
118	31508006	2,3',4,4',5-PeCB
123	65510443	2',3,4,4',5-PeCB
126	57465288	3,3',4,4',5-PeCB
156	38380084	2,3,3',4,4',5-HxCB**

(continued)

Table 9-2. (continued)

Polychlorinated biphenyls		
IUPAC #	**CAS #**	**Structure**
157	52663726	2,3,3',4,4',5'-HxCB**
167	32774166	2,3',4,4',5,5'-HxCB
169	39635319	3,3',4,4',5,5'-HxCB
189	70362504	2,3,3',4,4',5,5'-HpCB

Chemical Abstract Service number.
** These two congeners are co-eluting and are therefore modeled as a single congener.

Concentrations in fish range from below an analytical detection limit of 5.0E-07 mg/kg fish tissue, to 1.0E-04 mg/kg fish tissue (whole body, wet weight). Assuming that the source of the dioxins, furans, and dioxin-like PCBs is exhausted, concentrations in sediment and biota decrease over time as these chemicals are slowly metabolized or transported elsewhere through sediment movement. Similar chemical behavior is observed in terrestrial systems; however, dioxin is adsorbed to organic content in the soil and is somewhat less mobile (Eisler, 1986). The accumulation of dioxins from the soil into plants has been shown to be negligible (U.S. EPA, 2000).

The environmental behavior of chemical contaminants in biosolids is, to some degree, determined by application and management practices. For example, concentration profiles for dioxins, furans, and dioxin-like PCBs applied on a daily basis would likely be very different than the profiles developed for biannual applications. In Section 3.1.3, Figure 3-1 is accompanied by a detailed explanation of the conceptual site model used in the model simulations, and Section 4.0 provides a complete characterization of agriculturally applied biosolids, from the physical characteristics of the biosolids to the properties of the environmental setting (e.g., soil properties). Because biosolids applications occur nationwide, the model simulations produce distributions of media concentrations that capture the variability in climate, soil, and agricultural practices across the contiguous 48 states. To support the modeling simulations described in Sections 4.0 and 5.0, the 48 states were subdivided into 41 climatic regions (see Figure 3-2), and each region was represented by climate data from any reporting meteorological station within the bounds of the region. This implicitly assumes that the meteorological conditions in any region are sufficiently uniform so as to be represented by a single station. As described in Section 4.3.2, these geographic regions were also used as the basis for identifying a representative farm size and a distribution of soil types on the farm. For convenience, several key assumptions on common agricultural practices are presented below.

- Biosolids are applied at a rate of 5 to 10 metric tons per hectare per application (application rates for biosolids were assumed to be uniform nationwide).
- Applications occur once every 2 years.
- Application continues for up to 40 years (20 applications).

- Cropland is tilled to a depth of 20 cm multiple times during the year.
- Pastureland is not tilled; thus, biosolids are assumed to be incorporated into only the top 2 cm of soil.

9.2.2.3 Habitats Potentially at Risk. For agricultural application of biosolids, the SERA addresses two generalized habitat types: a terrestrial habitat and a waterbody margin habitat associated with freshwater systems (e.g., streams, ponds). These habitat types provide a framework for identifying exposure pathways of concern and define the context for receptor species selection.

The terrestrial habitat consists of crop fields and pastures where biosolids are applied. The conceptual layout described in detail in Section 4.3.1 is based on the assumption that farmers apply biosolids to adjacent crop fields and pasture. Thus, ecological receptors may be exposed to contaminants in plants, prey, and soil in the crop field and pasture by feeding and foraging in these areas. The waterbody margin habitat consists of nearby surface waterbodies and their adjacent terrestrial margin. The waterbodies receive chemical loads through runoff and erosion from the agricultural field. The buffer area shown in Figure 3-1 is located between the fields and a nearby surface waterbody; for the purposes of the SERA, it constitutes the terrestrial margin associated with the waterbody. Receptors may be exposed to terrestrial plants and prey and to soil in the buffer area as part of the margin habitat; in addition, receptors may take fish, other aquatic biota, sediment, and drinking water from the receiving waterbody.

In summary, the representative terrestrial and waterbody margin habitats in the SERA are intended to capture the key elements of freshwater and agricultural field systems. However, the actual exposures received by wildlife will be strongly influenced by a variety of habitat characteristics. In margin habitats, the waterbody size, flow rate, bed sediment composition, and the presence and types of aquatic flora and fauna will significantly affect the ecological exposures. Similarly, in terrestrial systems, factors such as regional location, vegetative cover type, soil characteristics, and adequacy of food sources will determine the applied dose to wildlife. Although these habitat characteristics are not explicitly addressed in the SERA, receptors assigned to the two representative habitats are intended to address significant exposure pathways and represent scenarios appropriate for a screening-level analysis.

Figures 9-2 and 9-3 show simplified food webs for exposure in terrestrial and margin habitats. The trophic levels and feeding guilds shown in the figures are defined as follows:

Trophic Levels		Feeding Guilds	
T1:	Species is prey to other receptors, but is not a predator.	Herbivore:	Consumes primarily plant matter.
T2:	Species is both predator and prey to other receptors.	Omnivore:	Can be expected to consume both plant and animal matter.
T3:	Top predators; species are generally assumed not to be prey to other receptors.	Carnivore:	Feeds primarily on animals.

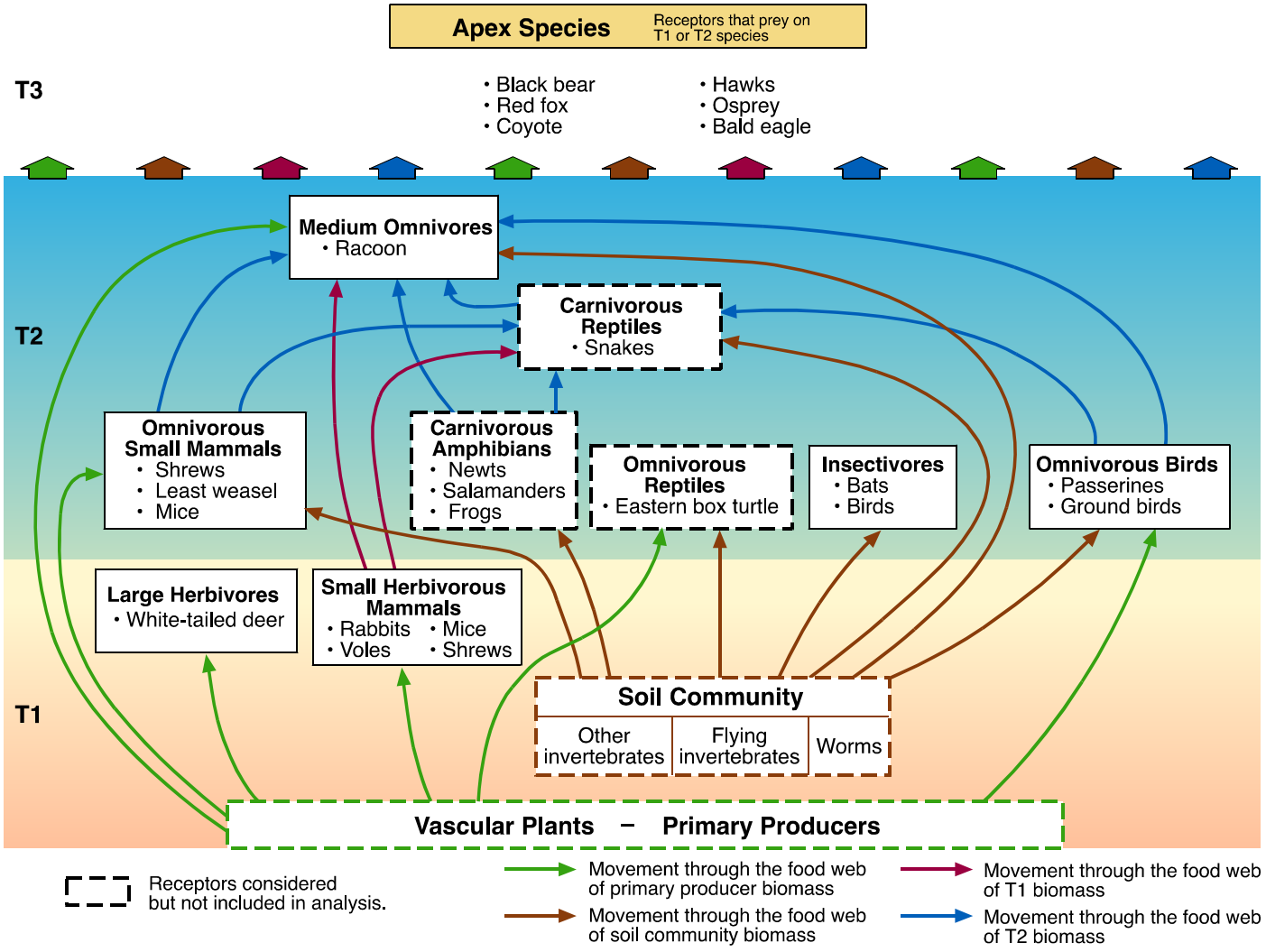

Figure 9-2. Terrestrial food web, including example receptors.

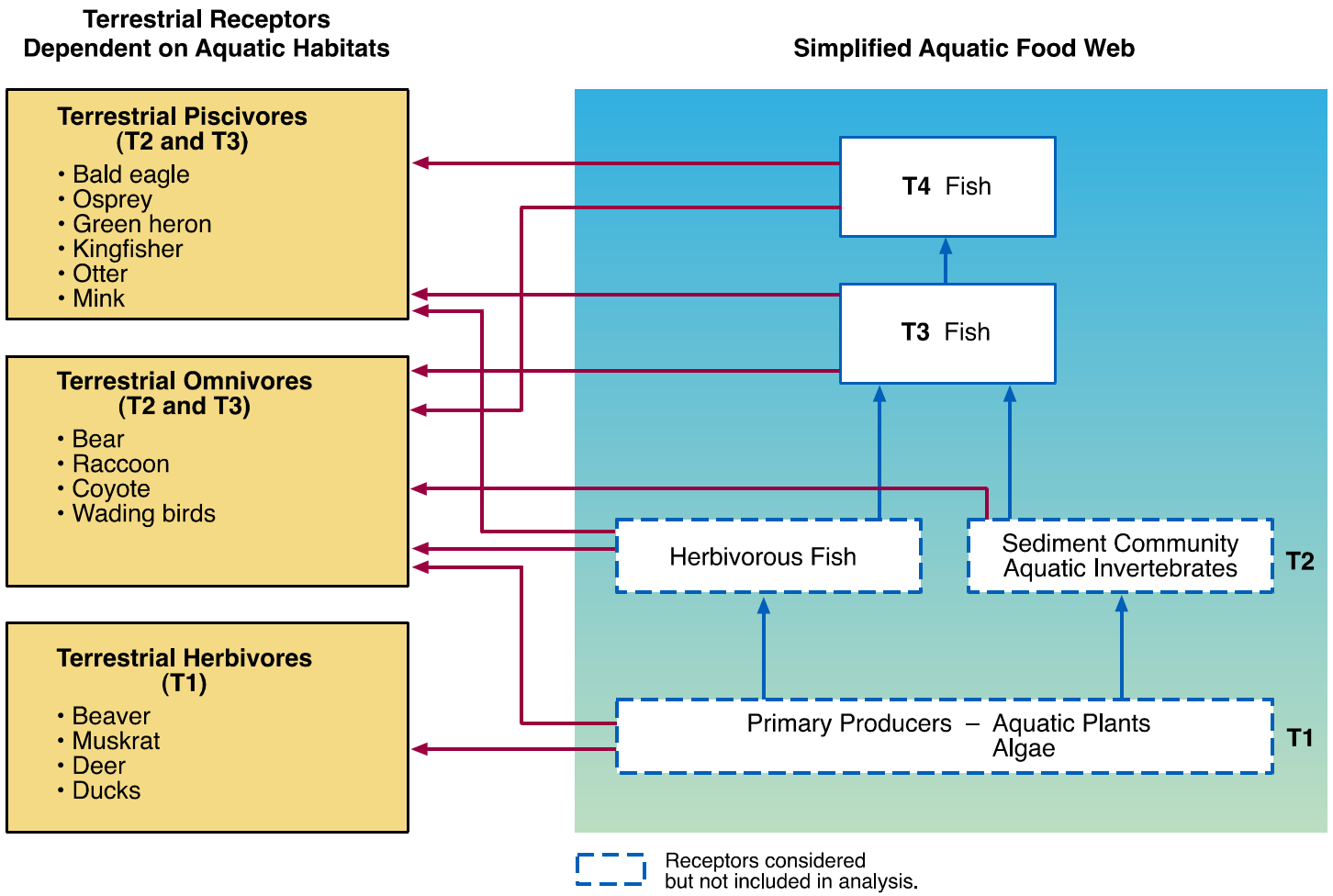

Figure 9-3. Interface between terrestrial receptors and aquatic food web, including example receptors.

The food webs were developed based on generally accepted concepts about food webs and natural community dynamics (Anderson, 1997; Begon and Mortimer, 1981; Caduto, 1990; Davis and Simon, 1995; Kadlec and Knight, 1996; Sample et al., 1997; Schoener, 1989; Schoenly and Cohen, 1991; Suter, 1993; Tanner, 1978; U.S. EPA, 1993a, 1994). Species-specific information was taken from the references listed in Appendix L, Table L-5. The food webs facilitate the selection of receptor species for each habitat type.

9.2.2.4 Selection of Receptors of Concern. Ecological receptors typical of the terrestrial and margin habitats were considered on the basis of (1) trophic levels, taxa, and feeding guilds (e.g., herbivores, carnivores); (2) potential for exposure to dioxins in land-applied biosolids; (3) toxicological sensitivity; and (4) geographical distribution (e.g., avoid narrow ecological niches). Receptors with a high potential for exposure were defined as those documented to feed and forage in agricultural fields or in margin habitats. Because dioxins, furans, and dioxin-like PCB congeners are known to bioaccumulate in fish, small mammals, and soil and sediment invertebrates, receptors whose diets include these items were also assumed to have a high potential for exposure.

Of the representative receptors considered for inclusion in the SERA, adequate ecotoxicological data were identified for mammals, birds, and fish. The primary exposure route of interest for mammals and birds is ingestion, and exposure is expressed in terms of ingestion dose. The primary exposure route of interest for fish is through ingestion, but exposure is expressed in terms of concentration in fish eggs, that is, the exposure for fish is assessed based on a tissue residue approach for a sensitive life stage (eggs) of a sensitive species (i.e., lake trout). The mammalian and avian wildlife species included in the SERA are shown in Table 9-3. The SERA did not include aquatic and terrestrial plants, aquatic invertebrates, or amphibians, because of their demonstrated tolerance to TCDD in laboratory studies (U.S. EPA, 2001b).

The representative species selected for the Phase 2 analysis were not limited to keystone or indicator species. Indicator species imply that a level of significance to total ecosystem structure or function can be ascertained; however, in a screening-level assessment, this cannot be determined with a high level of confidence. The receptors were selected because (1) these species represent a full range of trophic levels and feeding guilds relevant to dioxin exposures through the food web; (2) life-history data, such as dietary habitats and distribution in the contiguous 48 states were available; and (3) toxicological data were identified, suggesting that the species was sensitive to dioxins, furans, and dioxin-like PCBs (e.g., mammals are highly sensitive to dioxins).

9.2.2.5 Identification of Exposure Pathways of Concern. Dioxin, furan, and dioxin-like PCB congeners are persistent, bioaccumulative, and hydrophobic compounds that have been shown to biomagnify in the food web. Typically, these congeners are stored in the fat tissues of organisms and are minimally metabolized over time. Consequently, animals foraging in the terrestrial and margin habitats may be exposed through the food chain, as well as through direct ingestion of contaminated soil, surface water, and sediment. Inhalation was not considered to be a significant route of exposure for dioxins, furans, and dioxin-like PCBs and was not included in the SERA.

Table 9-3. Wildlife Receptors for the Biosolids SERA

Species	Scientific name	Feeding guild[1]	Trophic level[2]	Habitats
American kestrel	*Falco sparverius*	C	T2	terrestrial
American robin	*Turdus migratorius*	O	T2	terrestrial
American woodcock	*Scolopax minor*	O	T2	terrestrial
Bald eagle	*Haliaeetus leucocephalus*	C	T3	margin
Beaver	*Castor canadensis*	H	T1	margin
Belted kingfisher	*Ceryle alcyon*	O	T2	margin
Black bear	*Ursus americanus*	O	T3	terrestrial
Canada goose	*Branta canadensis*	H	T1	terrestrial
Cooper's hawk	*Accipiter cooperi*	C	T3	terrestrial
Coyote	*Canis latrans*	O	T3	terrestrial
Deer mouse	*Peromyscus maniculatus*	O	T2	terrestrial
Eastern cottontail rabbit	*Sylvilagus floridanus*	H	T1	terrestrial
Great blue heron	*Ardea herodias*	O	T2	margin
Green heron	*Butorides virescens*	O	T2	margin
Herring gull	*Larus argentatus*	O	T2	margin
Least weasel	*Mustela nivalis*	C	T2	terrestrial
Lesser scaup	*Aythya affinis*	O	T2	margin
Little brown bat	*Myotis lucifugus*	I	T2	terrestrial
Long-tailed weasel	*Mustela frenata*	C	T2	terrestrial
Mallard	*Anas platyrhynchos*	O	T2	margin
Meadow vole	*Microtus pennsylvanicus*	H	T1	terrestrial
Mink	*Mustela vison*	C	T2	margin
Muskrat	*Ondatra zibethicus*	H	T1	margin
Northern bobwhite	*Colinus virginianus*	O	T2	terrestrial
Osprey	*Pandion haliaetus*	C	T3	margin
Prairie vole	*Microtus ochrogaster*	H	T1	terrestrial
Raccoon	*Procyon lotor*	O	T2	terrestrial, margin
Red fox	*Vulpes vulpes*	O	T3	terrestrial

(continued)

Table 9-3. (continued)

Species	Scientific name	Feeding guild[1]	Trophic level[2]	Habitats
Red-tailed hawk	*Buteo jamaicensis*	C	T3	terrestrial
River otter	*Lutra canadensis*	C	T2	margin
Short-tailed shrew	*Blarina brevicauda*	O	T2	terrestrial
Short-tailed weasel	*Mustela erminea*	C	T2	terrestrial
Tree swallow	*Tachycineta bicolor*	O	T2	terrestrial
Western meadowlark	*Sturnella neglecta*	O	T2	terrestrial
White-tailed deer	*Odocoileus virginianus*	H	T1	terrestrial

[1] Feeding guild: C = carnivore, H = herbivore, I = insectivore, O = omnivore.
[2] Trophic level: T1 = prey, not a predator; T2 = both a predator and prey; T3 = a top predator, not prey.

Receptors are exposed through the ingestion of

- Aquatic prey, such as fish, mussels, and snails
- Terrestrial prey from the waterbody margin or field, such as vegetation and small mammals
- Soil from the contaminated field or buffer
- Water from contaminated waterbodies
- Sediment from contaminated waterbodies.

In addition, receptors that live in close contact with contaminated media (e.g., benthic invertebrates) may receive significant exposures to dioxins, furans, and dioxin-like PCBs. The primary routes of exposure for these receptors include ingestion of contaminated plants and prey, as well as direct contact. However, as indicated in Section 9.2.1, sufficient toxicological data were not identified to develop environmental quality criteria for soil, sediment, or surface water. As a result, direct contact with contaminated media was not included in the SERA.

9.2.2.6 Characterization of Ecological Effects. As indicated in the previous section, the focus for the SERA is on mammalian and avian receptors. Therefore, the effects characterization in this section discusses the relevant studies reviewed in selecting the most appropriate toxicological data to develop the ecological benchmarks for mammals and birds. The effects characterization is based on a review of recently published sources, other literature citations, and EPA publications. In particular, the *Dose-Response Assessment from Recently Published Research of the Toxicity of 2,3,7,8-Tetrachlorodibenzo-p-dioxin and Related Compounds to Aquatic Wildlife-Laboratory Studies* was reviewed to identify appropriate benchmark studies (NCEA, 2001).

9.2.2.6.1 Mammals. TCDD exposures have been associated with a variety of reproductive and developmental effects in mammals. For example, Khera and Ruddick (1973)

assessed the postnatal effect of TCDD on pregnant Wistar rats and observed a dose-related decrease in the average litter size and pup weight at birth in all but the 0.125 μg/kg-d dose. Bowman et al. (1989a, 1989b) studied the reproductive effects of Rhesus monkeys exposed to diets containing 5 ppt and 25 ppt TCDD for 7 and 24 months. The female monkeys exposed to 25 ppt had a significantly lower Index of Overall Reproductive Success (IORS), while the 5 ppt group did not differ from the control. Hochstein et al. (1988) administered TCDD dietary concentrations of 0, 0.001, 0.01, 0.1, 1.0, 10, and 100 ppb to mink for 125 days. While no significant adverse effects were observed on mink fed dietary concentrations of 0.1 ppb or less, mortality was noted in groups fed 1 and 10 ppb.

Murray et al. (1979) exposed three generations of Sprague-Dawley rats to diets containing 0, 0.001, 0.01, or 0.1 μg TCDD/kg-d. At the 0.01 μg/kg-d dose, Murray et al. (1979) observed no effect on fertility among the f_0 rats, but a significant reduction in fertility was observed among the f_1 and f_2 rats. Thus, through three successive generations, the reproductive capacity of rats ingesting TCDD was clearly affected at dose levels of 0.01 and 0.1 μg/kg-d, but not at 0.001 μg/kg-d. This study was selected for benchmark derivation because it consists of a multigenerational exposure scenario that demonstrates a clear dose-response for reproductive effects attributable to TCDD.

The 125-day test performed by Hochstein et al. (1988) was not considered appropriate for deriving a benchmark because the study was subchronic rather than chronic and the perceived endpoints focus more on mortality than reproductive effects. The Murray et al. (1979) study was chosen over the Khera and Ruddick study (as cited in U.S. EPA, 1995) because of a lower reported NOAEL for rats. The reproduction study by Bowman et al. (1989a, 1989b) on Rhesus monkeys (which produced a lower NOAEL) was not selected because the Murray et al. (1979) study incorporated a multigenerational exposure regime and contained stronger dose-response information.

9.2.2.6.2 Birds. TCDD toxicity has been demonstrated in the embryos of many bird species, including domestic chickens (Brunstrom and Lund, 1988), great blue herons (Hart et al., 1991), ring-necked pheasants (Nosek et al., 1993) and double-crested cormorants (Powell et al., 1997). Sublethal responses include subcutaneous edema (Hart et al., 1991), induction of hepatic microsomal ethoxyresorufin-*O*-dealkylase, depressed embryonic growth, brain asymmetry (Custer et al., 1997), short beaks, fatty liver, heart abnormalities, and poorly developed stomachs (Henshel et al., 1997). Egg mortality has also been found in many studies (e.g., Nosek et al., 1993; Powell et al., 1997). Exposure in these studies was usually by injection, either into the yolk, albumin, or air cell.

Effects on adult birds appear to have been much less studied. Nosek et al. (1992) injected ring-necked pheasants (*Phasianus colchicus*) with various doses of TCDD, once a week for 10 weeks. Mortality, egg production, and embryo mortality were recorded. Embryo mortality was increased by exposure of adults to TCDD, with 100 percent egg mortality at a cumulative dose of 10 μg kg^{-1} body weight. However, even at the highest dose, some eggs were produced. Adult mortality only occurred at the highest dose. The weekly dose to the pheasants for 10 weeks by intraperitoneal (ip) injection is at an equivalent rate of 0.14, 0.014, and 0.0014 μg TCDD/kg-d . Assuming 100 percent absorption from ip injection, the ip exposure route may overestimate the absorption rate of TCDD via oral ingestion by a factor of 1 to 5 depending upon

diet composition (Abt, 1993). The avian benchmark used in the analysis is based on data from an injection study. However, as discussed in EPA's Great Lakes Water Quality Initiative Criteria Document (U.S. EPA, 1995), it is generally acknowledged that ip and oral routes of exposure result in similar risks because, in both instances, the chemical is absorbed by the liver, thereby permitting first-pass metabolism. The study by Nosek et al. was considered the most appropriate for use in the screening analysis because the endpoint pertains to reproduction.[1] Furthermore, there is substantial support in the literature for using this study to evaluate ecological risks to birds (e.g., U.S. EPA, 1993b; 1995).

9.2.2.6.3 Fish. Substantial data were available on adverse effects to fish exposed to dioxins, furans, and dioxin-like PCBs. A variety of sources were reviewed to identify appropriate effects concentrations for comparison, as well as to determine which fish species and endpoints were considered most sensitive based on the available data. The *Dose-Response Assessment from Recently Published Research of the Toxicity of 2,3,7,8-Tetrachlorodibenzo-p-dioxin and Related Compounds to Aquatic Life–Laboratory Studies* (NCEA, 2001) was reviewed along with other relevant reports, such as

- *Workshop Report on the Application of 2,3,7,8-TCDD Toxicity Equivalence Factors to Fish and Wildlife* (U.S. EPA, 2001b)
- *A Compendium of Environmental Quality Benchmarks* (MacDonald et al., 1999)
- *Screening Level Ecological Risk Assessment Protocol for Hazardous Waste Combustion Facilities* (U.S. EPA, 1999)
- *Toxicological Benchmarks for Screening Potential Contaminants of Concern for Effects on Aquatic Biota: 1996 Revision* (Suter and Tsao, 1996)
- *Interim Report on Data and Methods for Assessment of 2,3,7,8-Tetrachlorodibenzo-p-dioxin Risks to Aquatic Life and Associated Wildlife* (U.S. EPA, 1993b).

The environmental quality criteria and effects concentrations for 2,3,7,8-TCDD for fish and aquatic life range from 2.0E-11 mg/L from a proposed water quality criterion for Ontario, Canada (MacDonald et al., 1999), to a value of 3.8E-09 mg/L proposed as a screening-level benchmark for fish in the ecological risk assessment protocol for hazardous waste combustion facilities (U.S. EPA, 1999). The Canadian value likely reflects wildlife exposures, as well, so it was of limited value in the SERA because wildlife exposures were estimated in the Phase 2 screening. Suter and Tsao (1996) presented a screening value of 1.0E-08 mg/L for fish, based on EPA Region 4 Water Management Division, Water Quality Standards Unit's Screening List. EPA proposed a low-risk water concentration of 6E-10 mg/L and a high-risk water concentration

[1] It should be noted that the EPA Office of Water established a precedent for using the Nosek study which includes the use of a 10-fold uncertainty factor because the dosing regimen did not allow for the hens to reach steady state, hence the study was considered sub-chronic. The avian benchmark in the sludge SERA did not include this uncertainty factor.

of 1.0E-09 mg/L for fish (U.S. EPA, 1993b); the follow-on dose-response report (NCEA, 2001) provided additional data in support of EPA's proposed benchmark concentrations.

The preponderance of studies on adverse effects to fish report data on reproductive and developmental endpoints. EPA has previously determined that the critical life stage for several fish species was embryo development, that salmonid fish were the most sensitive group tested, and that lake trout were the most sensitive species in that group (USEPA, 2001d). Toxicity was not observed in adult female lake trout exposed to 2,3,7,8-TCDD dissolved in water even at concentrations at which the oocytes were nonviable. Consequently, the no-effects threshold concentration for embryo mortality of 30 ng/kg based on the survival of lake trout sac fry exposed as eggs was selected as an appropriate tissue residue concentration for the SERA. This concentration reflects data on the most sensitive fish species (lake trout) at the most sensitive life stage and, therefore, was considered to be an appropriate benchmark for screening purposes.

9.2.3 Analysis Plan

The analysis plan is the third critical product of the problem-formulation phase. In essence, the analysis plan provides a blueprint for evaluating the potential for adverse ecological effects for the assessment endpoints, receptors, and exposure pathways of concern. The analysis plan can be broken down into two sections: an exposure analysis and an ecological response analysis. As summarized in the introduction, the analysis consisted of a two-phased approach. Phase 1 was designed as a bounding analysis to assess the potential for ecological effects at high-end exposures to mammals and birds. Therefore, the exposure analysis is based on an evaluation of the 50^{th} and 90^{th} percentile, and maximum TEQ concentrations in biosolids. This phase was a highly conservative estimate that is based on the lowest available ecological benchmarks (i.e., NOAELs) and considers only a few highly exposed ecological receptors (e.g., American robin eating 100 percent diet of earthworms). Phase 2 was designed to provide a conservative screen of the potential hazard to an expanded list of mammalian and avian receptors intended to represent general terrestrial and waterbody margin habitats, as well as to fish populations that inhabit the water body in the margin habitat. For the exposure analysis, fate and transport algorithms described in detail in Section 5.0 provide an appropriate tool to estimate concentrations of dioxins, furans, and dioxin-like PCBs in the environmental media and terrestrial plants attributed to each habitat. For the ecological response analysis, the critical ecotoxicological data presented above are used to estimate less conservative ecological benchmarks (i.e., the geometric mean of the NOAEL and lowest observed adverse effects level (LOAEL)) for mammals and birds. The exposure dose predicted using the modeled concentrations of dioxins, furans, and dioxin-like PCBs is compared to the benchmark to generate HQs for the entire list of receptors (see Table 9-3) in the generalized terrestrial and margin habitats. In addition, the no effects threshold for tissue residue in fish eggs was used to evaluate the potential for developmental effects to exposed fish populations.

9.3 Analysis Methods

The analysis phase of the SERA began with a highly conservative approach to determine whether any of the receptors and exposure routes might be of concern. In this phase, the concentrations of dioxins, furans, and dioxin-like PCBs in biosolids were used to predict maximum possible exposure doses to several highly exposed receptors. Risks were estimated

using conservative ecological benchmarks. The congener concentrations in biosolids were obtained from the NSSS 2001 (U.S. EPA, 2001c). As previously suggested, the intent of the Phase 1 estimate was simply to determine whether any further ecological risk analysis was warranted. Phase 2 consisted of a less conservative analysis based on representative exposure scenarios. The values and data sources used for the key input variables in the SERA are shown in Table 9-4 for both phases of the SERA.

The concentrations of dioxins, furans, and dioxin-like PCBs in various media were derived using a conceptual site model (see Figure 3-1) that simulates the application of biosolids based on the available data on biosolids management. The release, fate and transport, and estimation of media concentrations are presented in detail in Section 5.0. The following sections present the methods used in each phase of the analysis.

9.3.1 Phase 1 – Maximum Potential Risk

The Phase 1 analysis was a highly conservative assessment of the maximum possible risks for highly exposed receptors; the intent of this phase was to determine whether further analysis was warranted. Exposure was based on the 50^{th} and 90^{th} percentiles and maximum concentrations in biosolids; HQs were calculated using NOAELs for reproductive endpoints on individual organisms. The Phase 1 receptors shown in Table 9-5 were selected to represent maximally exposed organisms. These receptors are widely distributed across a large portion of the United States and, based on their diet, represent high-end exposures for birds and mammals in terrestrial and waterbody margin habitats. The ingestion route of exposure was assessed using receptor species whose diets consist largely of animals known to accumulate dioxins, furans, and dioxin-like PCBs from soil and sediments.

Phase 1 risk estimates were generated using a simple spreadsheet model with the following steps. These steps are further discussed below.

1. For each receptor, select diet item to maximize exposure.
2. Calculate congener-specific concentrations in diet items.
3. Calculate congener-specific exposure dose for each receptor.
4. Apply TEFs to congener-specific dose estimates; sum to obtain TCDD TEQ.
5. Calculate HQ using receptor-specific TCDD benchmark.

9.3.1.1 <u>Development of Benchmarks for Phase 1</u>. For the SERA, exposure for all 29 congeners in the assessment was expressed in terms of 2,3,7,8-TCDD toxicity equivalence, and risk estimates were based on NOAELs. Benchmark studies for TCDD for mammals and birds were identified in the literature, and species-specific scaled benchmarks were calculated for each mammal and bird receptor. In identifying appropriate studies to develop benchmarks, several study selection criteria were adopted to ensure that (1) the endpoint was highly relevant to the viability of populations, (2) the dose-response information was sufficient to support development of a MATL, and (3) the study had been reviewed and approved by other EPA and federal agencies.

Using the benchmark study identified during the problem formulation (see Section 9.2.2.5), a scaled benchmark was calculated for each receptor species. For mammals, a scaling

factor of 1/4 was used in accordance with the default methodology proposed by EPA for carcinogenicity assessments and reportable quantity documents for adjusting animal data to an equivalent human dose (U.S. EPA, 1992). For birds, research suggests that the cross-species scaling equation used for mammals is not appropriate (Mineau et al., 1996). The scaling equations (page L-6), rationale, and supporting data are presented in Appendix L. Additional details on scaling ecological benchmarks may be found in Sample et al., 1996. Using a database that characterized acute toxicity of pesticides to avian receptors of various body weights, Mineau et al. (1996) concluded that applying mammalian scaling equations may not predict sufficiently protective doses for avian species. Mineau et al. recommended that a scaling factor of 1 provided a better dose estimate for birds. Therefore, a scaling factor of 1 was applied for avian receptors.

Table 9-4. Values and Assumptions for the SERA

Parameter	Phase 1 – maximum potential risk	Phase 2 – deterministic screening
Congeners addressed	All	All
Receptors	Four highly exposed mammals and birds	35 representative mammals and birds; sensitive fish species (lake trout)
Dietary composition	Diets reflecting maximum exposure	Representative diets
Biouptake factors	Fixed values	Fixed values
Percentage of diet taken from contaminated area	100%	100%
Ecological benchmarks	NOAELs from toxicological study species scaled to body weight for mammalian receptor species; NOAELs not scaled for birds Osprey - 1.4E-05 mg/kg-d Robin - 1.4E-05 mg/kg-d Kingfisher - 1.4E-05 mg/kg-d Mink - 8.32E-07 mg/kg-d	MATL, calculated as the geometric means of NOAELs and LOAELs, scaled as in Phase 1 for each mammalian receptor species complete list of receptor-specific benchmarks for mammals and birds presented in Table L No-effects tissue residue threshold for fish eggs - 30 ng/kg in eggs
Media concentrations used to estimate exposure	50^{th} and 90^{th} percentiles and maximum biosolids concentrations	90^{th} percentile modeled media concentrations (see Section 5.0)

Table 9-5. Phase 1 Receptors[1]

Receptor	Description	Pathway	Habitat
Osprey	Piscivorous bird that uses variety of margin habitats (e.g., wetlands, streams); diet consists entirely of fish.	Ingestion	Margin
American robin	Bird found in variety of terrestrial habitats; diet consists largely of earthworms.	Ingestion	Terrestrial
Belted kingfisher	Bird that primarily uses small ponds and streams; diet consists largely of fish.	Ingestion	Margin
Mink	Mammal that uses variety of margin habitats; diet consists largely of fish and invertebrates.	Ingestion	Margin

[1] Sources for species-specific dietary composition data are listed in Appendix L, Table L-5.

9.3.1.2 Estimating Exposure for Phase 1. Exposure was estimated as an applied dose based on species-specific body weights, ingestion rates, and dietary composition. For Phase 1, exposure was maximized by assuming that

- Environmental concentrations are equal to biosolids concentrations
- Each receptor's diet consists entirely of a single food item that significantly bioaccumulates TCDD[2]
- The entire diet comes from contaminated media.

The dietary item for the ingestion pathway for each receptor is shown in Table 9-6.

9.3.1.2.1 Concentrations in Diet Items. The first step in estimating exposure dose is the calculation of congener-specific concentrations in each receptor's selected diet item. Concentrations in worms are a function of the soil concentration, the soil-to-worm BAF, and the congener-specific bioaccumulation equivalency factor (BEF), as given in Equation 9-1. Concentrations in terrestrial prey items (e.g., worms) were calculated using a BAF for TCDD. The soil-to-worm BAF for TCDD was identified in the literature; all BAFs and their respective sources are presented in Appendix L, Table L-1. Congener-specific BEFs were not available for soil-based uptake; therefore, a default BEF of 1 was assumed for all congeners.

[2] For example, although the robin's diet could consist of anywhere from less than 10 percent to 100 percent soil invertebrates, it was conservatively assumed that the robin's entire diet consists of earthworms for Phase 1.

Table 9-6. Selected Diet Items for Phase 1 Receptors

Receptor	Diet item selected to maximize exposure
Osprey	Fish
American robin	Worms
Belted kingfisher	Fish
Mink	Fish

$$C_{worm\,i} = C_{soil\,i} \times BAF \times BEF_i \quad (9\text{-}1)$$

where

$C_{worm\,i}$ = Total concentration of congener *i* in earthworms (mg/kg WW)

$C_{soil\,i}$ = Soil concentration for congener *i* (mg/kg)

BAF = Bioaccumulation factor for TCDD reflecting biouptake from soil into worms (mg/kg WW_{worm} / mg/kg soil)

BEF_i = Bioaccumulation equivalence factor for congener *i* (unitless; default value of 1 was used)

The concentration in fish was calculated as a function of sediment concentration normalized for organic carbon and congener-specific BSAFs for uptake of dioxins from sediment to fish, as shown in Equation 9-2. Congener-specific BSAFs were recommended in EPA's Draft Dioxin Reassessment Document (U.S. EPA, 2000); all BSAFs and their respective sources are presented in Appendix L, Table L-2.

$$C_{fish\,li} = C_{oc_{sediment\,i}} \times BSAF_{li} \quad (9\text{-}2)$$

where

$C_{fish\,li}$ = Lipid-based concentration of congener *i* in fish (mg/kg_l)

$C_{oc\_sediment\,i}$ = Sediment concentration normalized for organic carbon for congener *i* (mg/kg_{oc})

$BSAF_{li}$ = Biota-sediment accumulation factor for congener *i* reflecting biouptake from sediment into fish lipid (kg_{oc}/kg_l).

9.3.1.2.2 Receptor Dose. As given by Equation 9-3, the ingestion exposure dose for Phase 1 receptors was calculated based on species-specific body weights and ingestion rates.

$$Dose_i = \frac{(IR_{diet} \times C_{diet\ i})}{BW} \quad (9\text{-}3)$$

where

$Dose_i$ = Phase 1 exposure dose for congener *i* (mg/kg-d)
$C_{diet\ i}$ = Concentration of congener *i* in fish or earthworms (mg/kg WW)
IR_{diet} = Species-specific ingestion rate (kg WW/d)
BW = Species-specific adult body weight (kg).

Body weights and ingestion rates were taken from the EPA's *Wildlife Exposure Factors Handbook* (U.S. EPA, 1993a). Average adult body weights and adult ingestion rates were used throughout the assessment.

Congener-specific exposure estimates were multiplied by their respective TCDD TEFs to derive a total dose for each receptor in terms of TCDD equivalence (i.e., TEQs). The summation of congener-specific doses is given by Equation 9-4:

$$Dose_{TEQ} = \Sigma Dose_i \times TEF_i \quad (9\text{-}4)$$

where

$Dose_{TEQ}$ = Total dose in toxicity equivalence (mg/kg-d)
$Dose_i$ = Dose for congener *i* (mg/kg-d)
TEF_i = Toxicity equivalence factor for congener *i*.

The TEFs were taken from the WHO consensus TEFs for mammals, fish, and birds (U.S. EPA, 2001b), and are presented in Appendix L, Table L-9.

9.3.1.3 <u>Risk Calculations for Phase 1</u>. The risk metric for the Phase 1 screen was the HQ, calculated as the ratio of the TEQ exposure dose to the species-specific ecological benchmarks based on allometric scaling of the NOAELs. The exposure doses were calculated using the 50th, 90th, and maximum TEQ concentrations in biosolids. The toxicological studies used in benchmark derivation are described in Section 9.2.2.5 on effects characterization. The assumptions, scaling equations, and factors (i.e., factor of 1/4 for mammals and 1 for birds) are presented in Appendix L. See Section 9.4 for a discussion of Phase 1 results.

9.3.2 Phase 2 – Deterministic Screening

The second phase of the analysis was a deterministic screening of fish and an expanded list of mammals and birds intended to represent a broad range of feeding guilds and trophic levels that are typical of the terrestrial and margin habitats. In addition to fish, Phase 2 included

all receptors shown in Table 9-3 and addressed receptors typical of crop fields, pastures, and surface waterbodies. The dietary preferences for mammals and birds were based on information presented in the *Wildlife Exposure Factors Handbook* (U.S. EPA, 1993a), as well as information from the open literature. Consequently, the receptor diet is intended to reflect the documented variability in dietary preferences rather than to maximize exposure (as in Phase 1). The receptor-specific benchmarks were calculated as the geometric mean of the LOAEL and NOAEL—referred to as the MATL—to provide a less conservative benchmark for adverse ecological effects. The exposure and potential ecological risk (expressed as an HQ) is estimated for each receptor in each habitat type assuming that 100 percent of the diet originates on the contaminated area. For mammals and birds, analysis consisted of the following major steps:

1. Assign representative receptors to each habitat type.

2. Establish dietary composition for each receptor based on habitat assignment.

3. Calculate congener-specific concentrations in each diet item.

4. Calculate total exposure dose for each congener for each receptor based on the ingestion of contaminated food and media.

5. Apply TEFs to congener-specific exposure doses to derive total TCDD equivalent exposure.

6. Calculate HQs for each receptor in each habitat.

For fish, the methodology described in *Framework for Application of the Toxicity Equivalence Methodology for Polychlorinated Dioxins, Furans, and Biphenyls in Ecological Risk Assessment* (U.S. EPA, 2003) was used to evaluate the potential for adverse effects to fish populations. The Phase 2 screening analysis for fish involved the development of a spreadsheet to calculate the toxicity equivalence concentration (TEC) in trout eggs for each congener using the congener-specific: (1) sediment concentrations, (2) trout egg biota-sediment accumulation factor (BSAF), and fish TEFs presented in U.S. EPA, 2003. The tissue residue HQ was then calculated as the ratio of the trout egg TEC to the benchmark concentration for fish eggs (30 ng/kg fish egg as presented in NCEA, 2001).

9.3.2.1 Development of Benchmarks for Phase 2. Appropriate studies (e.g., on reproductive fitness) were identified in the literature and in EPA sources, and species-specific benchmarks were calculated using the scaling algorithms described in Appendix L. Although the same studies were used to derive benchmarks in both phases of the SERA, the Phase 2 screen used a less conservative measure of effect, the MATL. As the geometric mean between the NOAEL and LOAEL, the MATL is intended to represent a de minimis level of effect for a wildlife species population. Because the benchmarks are based on effects to individual organisms, a less conservative measure was considered appropriate for the assessment endpoint of population viability. A NOAEL is highly conservative in that it suggests that any toxicological response to a chemical stressor is considered unacceptable. Given the conservative nature of the Phase 2 screen (e.g., 100 percent of diet is contaminated), making inferences about a wildlife population based on a NOAEL for individual organisms would have been overly conservative and inconsistent with management goals for the SERA. Appendix L includes a

detailed description of the benchmark development methods and presents the species-specific benchmark values used in Phase 2.

9.3.2.2 Characterization of Exposure. The 90th percentile congener-specific concentrations in soil, sediment, surface water, and terrestrial plants were used to calculate exposure doses as well as the fish egg TEC. The 90th percentile concentrations were derived from the fate and transport modeling described in Section 5.0 by (1) adjusting the concentrations predicted by the model by the TEFs for mammals and birds, respectively; (2) arranging the TEQ concentrations for mammals and birds in rank order by the soil concentration in the field and pasture for terrestrial habitats, and the sediment concentration for margin habitats; and (3) selecting the 90th percentile set of concentrations based on the TEQ rank order for mammals and birds, respectively, for the terrestrial habitat (driven by soil TEQ concentration) and the margin habitat (driven by sediment concentration). For fish, the 90th percentile sediment concentrations derived from the fate and transport model were used in the TEC calculation.

The concentration profiles (for media and plants) generated in the model simulations are maximum annual average concentrations. To derive these concentrations, the source model (see Section 5.1) generated 3,000 Monte Carlo realizations of a 200-year time series, and the maximum annual average concentration was picked off of these distributions and rank ordered as described in the preceding paragraph. Consequently, "the 90th percentile" represents the 90th percentile from a distribution of maximum annual average concentrations and provides a conservative upper bound of the modeled concentrations.

Exposures were calculated for receptors assigned to the terrestrial (i.e., field/pasture) and margin (i.e., pond/lake/stream) habitats depending on foraging and feeding habits indicated in the ecological exposure factor database. Table 9-7 presents the list of receptors according to their feeding guild, trophic level, and habitat that were evaluated in the Phase 2 screen.

Table 9-7. Receptors Evaluated in Phase 2

Species	Feeding guild	Trophic level	Terrestrial habitat	Margin habitat
American kestrel	C	T2	●	
American robin	O	T2	●	
American woodcock	O	T2	●	
Bald eagle	C	T3		●
Beaver	H	T1		●
Belted kingfisher	O	T2		●
Black bear	O	T3	●	
Canada goose	H	T1	●	

(continued)

Table 9-7. (continued)

Species	Feeding guild	Trophic level	Terrestrial habitat	Margin habitat
Cooper's hawk	C	T3	●	
Coyote	O	T3	●	
Deer mouse	O	T2	●	
Eastern cottontail rabbit	H	T1	●	
Great blue heron	O	T2		●
Green heron	O	T2		●
Herring gull	O	T2		●
Least weasel	C	T2	●	
Lesser scaup	O	T2		●
Little brown bat	I	T2	●	
Long-tailed weasel	C	T2	●	
Mallard	O	T2		●
Meadow vole	H	T1	●	
Mink	C	T2		●
Muskrat	H	T1		●
Northern bobwhite	O	T2	●	
Osprey	C	T3		●
Prairie vole	H	T1	●	
Raccoon	O	T2	●	●
Red fox	O	T3	●	
Red-tailed hawk	C	T3	●	
River otter	C	T2		●
Short-tailed shrew	O	T2	●	
Short-tailed weasel	C	T2	●	
Tree swallow	O	T2	●	
Western meadowlark	O	T2	●	
White-tailed deer	H	T1	●	

Feeding guild: C = carnivore, H = herbivore, I = insectivore, O = omnivore.
Trophic level: T1 = prey, not a predator; T2 = both a predator and prey; T3 = a top predator, not prey.

Appendix L, Tables L-4 and L-5 show the data sources used for habitat assignments, as well as other exposure factor data for each receptor.

9.3.2.2.1 Estimation of Exposure Dose. Exposure doses were estimated in Phase 2 using the same basic approach that was used in Phase 1; however, the receptor diet in Phase 2 was constructed from the exposure factor database, and modeled concentrations in environmental media and terrestrial plants were used rather than the congener concentrations in biosolids. Ingestion exposure doses were calculated in three steps: (1) development of species-specific diets, (2) calculation of concentrations in each category of food (e.g., vegetation, small mammals, small birds), and (3) summation of total exposure dose. For the terrestrial habitat, incidental ingestion of soil (e.g., associated with the ingestion of terrestrial prey, preening, and other behaviors) was assumed to come from the agricultural field and pasture. For the margin habitat, the incidental ingestion of sediment—rather than soil—was evaluated because wildlife assigned to this habitat consume primarily aquatic biota (e.g., fish, sediment invertebrates). These steps are described in the following sections.

Receptor Diets

Dietary composition for Phase 2 was based on species-specific data on foraging and feeding behavior and reflected a year-round adult diet. The receptor diets were constructed to represent variability in feeding habits, rather than to artificially maximize exposure using the range (defined by the minimum and maximum) for each item in the diet. Diet items are grouped in 17 categories, including different types of vegetation (e.g., fruits, forage, grain, roots) and several categories of prey (e.g., small birds, small mammals, invertebrates, fish). For example, the American robin's dietary percentage ranges are as follows (Terres, 1980; U.S. EPA, 1993a; Stokes and Stokes, 1996):

Diet Item	Dietary Percentage Range
Soil invertebrates (other than earthworms)	8 to 93
Fruits	7 to 92
Earthworms	15 to 27
Forage	0 to 24

For the Phase 2 analysis, each receptor's diet was constructed using the midpoint of dietary percentages for each diet item, beginning with the item with highest midpoint value and proceeding through the diet items until a full diet (100 percent) was accumulated. Thus, the robin's diet would consist of 50.5 percent soil invertebrates and 49.5 percent fruits, based on the following dietary percentage midpoints:

Diet Item	Dietary Percentage Midpoint
Soil invertebrates	50.5
Fruits	49.5
Worms	21
Forage	12

The dietary composition used for each receptor species is presented in Appendix L, Tables L-6 and L-7.

Concentrations in Diet Items

Dietary concentrations were calculated separately for terrestrial-based food items (e.g., soil invertebrates, small mammals) and for aquatic-based food items (e.g., fish, sediment invertebrates).

Terrestrial items. Terrestrial items in the diet include vegetation and small prey, and the prey concentrations for each congener are based on soil-to-organism BAFs and the soil concentration. Concentrations in vegetation occur through particle deposition and vapor transfer (U.S. EPA, 2000), and plant concentrations were calculated based on these two transport mechanisms using the methods described in Section 5.0 (U.S. EPA, 2001a). For the ecological assessment, concentrations in all types of vegetation were calculated on a WW basis, as described in Appendix H, Table H3.16.

Concentrations in prey items (e.g., small mammals and birds) were calculated as described in Section 9.3.1.2.1 for Phase 1. BAFs for terrestrial prey items are empirical values that reflect prey tissue concentrations as a function of soil concentrations. That is, the BAF does not represent a biotransfer from one compartment in the food chain to another. In addition, a diet fraction variable was added to the calculation to account for each diet item's contribution to the total diet (Equation 9-5).[3]

$$C_{diet\ i} = \Sigma\ C_{soil\ i} \times BAF_{ij} \times BEF_i \times DietFrac_j \qquad (9\text{-}5)$$

where

$C_{diet\ i}$ = Total concentration of congener *i* in diet (mg/kg WW)

$C_{soil\ i}$ = Soil concentration for congener *i* (mg/kg)

BAF_{ij} = Bioaccumulation factor for congener *i* for food item *j* (mg/kg WW/ mg/kg soil)

BEF_i = Bioaccumulation equivalence factor for congener *i* (unitless; default value of 1 was used)

$DietFrac_j$ = Fraction of item *j* in diet.

Aquatic items. Aquatic items in the diet include T3 and T4 fish, aquatic plants, and benthic invertebrates, primarily filter feeders. Concentrations in these items were calculated as described in Section 9.3.1.2.1 for Phase 1. The dietary fraction was added to the calculation (as

[3] Because soil-to-plant uptake of dioxin-like congeners is negligible, plant concentrations were taken from the multimedia modeling simulation and used directly to calculate $C_{diet\ i}$.

for Phase 2 terrestrial prey) to account for each diet item's contribution to the diet (Equation 9-6).

$$C_{diet\ li} = \Sigma\ C_{oc_{sediment\ i}} \times BSAF_{lij} \times DietFrac_j \quad (9\text{-}6)$$

where

$C_{diet\ li}$ = Lipid-based concentration of congener *i* in diet (mg/kg)

$C_{oc\_sediment\ i}$ = Sediment concentration normalized for organic carbon for congener *i* (mg/kg_{oc}).

$BSAF_{lij}$ = Biota-sediment accumulation factor reflecting biouptake from sediment into lipid tissue of item *j* (kg_{oc}/kg_l)

$DietFrac_j$ = Fraction of item *j* in diet (unitless).

Total Exposure Dose

Each receptor's exposure dose was calculated as a function of its respective ingestion rate, body weight, and the concentrations in the various diet items.[4] In addition to prey and plant items, soil and sediment ingestion, as a fraction of total diet, were also accounted for in both the terrestrial and margin habitats.[5] In addition, exposure through drinking water ingestion was included in predicting the exposure dose for receptors in the margin habitat. For completeness, Equation 9-7 presents the total exposure dose calculation for mammals and birds assigned to the margin habitat. For the terrestrial habitat, the last term representing water ingestion is simply omitted from the equation.

$$Dose_i = \frac{(IR_{diet} \times C_{diet\ i}) + (C_{soil/sed\ i} \times IR_{diet} \times S_{frac}) + (C_{water\ i} \times IR_{water})}{BW} \quad (9\text{-}7)$$

where

$Dose_i$ = Exposure dose for congener *i* (mg/kg-d)
IR_{diet} = Species-specific ingestion rate (kg WW/d)
$C_{diet\ i}$ = Total concentration of congener *i* in diet (mg/kg WW)
$C_{soil/sed\ i}$ = Concentration of congener *i* in soil or sediment (mg/kg)
S_{frac} = Fraction of soil or sediment in the diet (unitless)

[4] Concentrations in lipid tissue of aquatic organisms were converted to whole-body concentrations by adjusting for lipid content in prey.

[5] The assimilation efficiency for dioxin-like chemicals was conservatively assumed to be 1.0 for each congener. Therefore, it was not shown explicitly in this equation.

$C_{water\ i}$	=	Concentration of congener *i* in surface water (mg/L)
IR_{water}	=	Species-specific water ingestion rate (L/d)
BW	=	Species-specific average adult body weight (kg).

Congener-specific doses were summed to derive a single TEQ dose for each receptor in each habitat, as shown in Equation 9-8:

$$Dose_{TEQ} = \Sigma Dose_i \times TEF_i \quad (9\text{-}8)$$

where

$Dose_{TEQ}$	=	Total dose in toxicity equivalence (mg/kg-d)
$Dose_i$	=	Dose for congener *i* (mg/kg-d)
TEF_i	=	Toxicity equivalence factor for congener *i*.

TEFs were taken from the WHO consensus TEFs for mammals, fish, and birds (U.S. EPA, 2001b) and are presented in Appendix L, Table L-9.

9.3.2.3 <u>Hazard Calculations for Phase 2</u>. As with Phase 1, the risk metric for mammals and birds in the Phase 2 screen was the HQ, calculated as the ratio of the TEQ exposure dose to the species-specific ecological benchmarks based on allometric scaling of the MATLs. The exposure doses were calculated using the 90th percentile TEQ concentrations in environmental media for mammals and birds, respectively. The toxicological studies used in deriving the species-specific MATLs were described in Section 9.2.2.5 on effects characterization. The assumptions, scaling equations, and factors (i.e., factor of 1/4 for mammals and 1 for birds) are presented in Appendix L.

The risk metric for fish in the Phase 2 screen was also the HQ; however, the tissue residue approach described in U.S. EPA, 2003 was adopted rather than an exposure dose or environmental criteria (i.e., acceptable chemical concentrations in media) approach. Table 9-8 presents the data and calculations performed to estimate the fish egg TEC. The BSAFs for trout eggs are based on 7% lipid in eggs and 1.4% organic carbon in sediment (U.S. EPA, 2003).

9.4 Results and Risk Characterization

The two phases of the SERA were designed to provide insight into the potential for adverse ecological effects, and the results from each phase support different conclusions and decisions. Phase 1 was a highly conservative screen intended to serve as the estimate for a more refined screening assessment. The HQ results from Phase 1 were used only to indicate that further analysis was warranted. Phase 2 of the SERA was a more refined screen of the potential for adverse effects on wildlife associated with terrestrial and waterbody margin habitats that may be affected by the agricultural application of biosolids. Although both phases of the SERA were deterministic, the Phase 2 hazard estimates were based on more realistic, but less conservative assumptions regarding the environmental media concentrations, receptor-specific dietary preferences, and ecological benchmarks. The HQ results from Phase 2 are point estimates of risk to a wide variety of mammals and birds and were intended to inform the ongoing assessment of the ecological risks associated with the agricultural application of biosolids.

Table 9-8. Data and Calculation of Trout Egg TECs

Congener	90th percentile sediment concentration (ng/kg)	Trout egg BSAF	Trout egg concentration (ng/kg egg)	WHO - TEF/98 fish TEF	Trout egg TEC (ng/kg egg)
2,3,7,8-TCDD	1.51E-02	0.149	2.24E-03	1	2.2E-03
1,2,3,7,8- PeCDD	8.14E-02	0.121	9.85E-03	1	9.8E-03
1,2,3,4,7,8-HxCDD	5.96E-02	0.018	1.07E-03	0.5	5.4E-04
1,2,3,7,8,9-HxCDD	1.56E-01	0.01	1.56E-03	0.01	1.6E-05
1,2,3,6,7,8-HxCDD	3.89E+00	0.007	2.72E-02	0.01	2.7E-04
1,2,3,4,6,7,8-HpCDD	5.44E+01	0.002	1.09E-01	0.001	1.1E-04
1,2,3,4,6,7,8,9-OCDD	3.85E-02	0.0007	2.70E-05	0.0001	2.7E-09
2,3,7,8-TCDF	3.85E-02	0.069	2.66E-03	0.05	1.3E-04
1,2,3,7,8-PeCDF	1.71E-02	0.009	1.54E-04	0.05	7.7E-06
2,3,4,7,8-PeCDF	2.69E-02	0.162	4.35E-03	0.5	2.2E-03
1,2,3,4,7,8-HxCDF	5.97E-02	0.0045	2.68E-04	0.1	2.7E-05
1,2,3,7,8,9-HxCDF	5.73E-02	0.02	1.15E-03	0.1	1.1E-04
1,2,3,6,7,8-HxCDF	3.38E-03	0.007	2.36E-05	0.1	2.4E-06
2,3,4,6,7,8-HxCDF	4.73E-02	0.002	9.46E-05	0.1	9.5E-06
1,2,3,4,6,7,8-HpCDF	9.91E-01	0.001	9.91E-04	0.01	9.9E-06
1,2,3,4,7,8,9-HpCDF	4.85E-02	0.023	1.12E-03	0.01	1.1E-05
1,2,3,4,6,7,8,9-OCDF	3.82E+00	0.001	3.82E-03	0.0001	3.8E-07
3,3',4,4'-TCB	4.30E+00	0.29	1.25E+00	0.0001	1.2E-04
3,4,4',5-TCB	1.75E+00	0.95	1.66E+00	0.0005	8.3E-04
2,3,3',4,4'-PeCB	4.16E+01	2.54	1.06E+02	0.000005	5.3E-04
2,3,4,4',5-PeCB	3.81E+00	5.22	1.99E+01	0.000005	9.9E-05
2,3',4,4',5-PeCB	1.46E+02	4.66	6.79E+02	0.000005	3.4E-03
2',3,4,4',5-PeCB	2.81E+00	3.8	1.07E+01	0.000005	5.3E-05
3,3',4,4',5-PeCB	4.14E-01	4.18	1.73E+00	0.005	8.7E-03
2,3,3',4,4',5-HxCB*	2.13E+01	5.87	1.25E+02	0.000005	6.3E-04
2,3,3',4,4',5'-HxCB*	8.08E+00	7.89	6.38E+01	0.000005	3.2E-04
2,3',4,4',5,5'-HxCB	3.78E-02	2.03	7.67E-02	0.000005	3.8E-07
3,3',4,4',5,5'-HxCB	1.11E+00	5.58	6.20E+00	0.00005	3.1E-04

* These two congeners are co-eluting and are therefore modeled as a single congener

In the Phase 1 analysis, the HQ values varied from a low of 2 (osprey) for the 50th percentile concentration, to a high of 209 (mink) for the maximum concentration. The highest HQs are associated with biosolids concentrations that were used as a surrogate for sediment (i.e., exposures in margin habitats for osprey, belted kingfisher, and mink). As suggested in the problem formulation, a target HQ of 1 for the Phase 1 screen was used as a estimate to determine whether further analysis was warranted. Simply put, HQs greater than 1 in the first phase of the SERA indicated that the second phase of the SERA was necessary. The results of the Phase 1 analysis[6] are presented in Table 9-9.

Table 9-9. Phase 1 Results

Receptor	HQ		
	50th percentile [TEQ] in biosolids	**90th percentile [TEQ] in biosolids**	**Maximum [TEQ] in biosolids**
Osprey	2	11	31
American robin	5	15	166
Belted kingfisher	4	25	72
Mink	36	26	209

As shown in Table 9-10, no HQ values exceeded the target HQ of 1; values range from a minimum of 0.0035 (Canada goose) to a maximum of 0.36 (short-tailed shrew). The median HQ for the receptors assigned to margin habitats was 0.015, and the median HQ for receptors assigned to terrestrial habitats was 0.044. The HQ comparing the no-effects threshold concentration for fish eggs to the total TEC for dioxins, furans, and dioxin-like PCBs was 0.001. The risk results from Phase 2 did not exceed the target HQ of 1.

Table 9-10. Screening Results from Phase 2

Receptor species	HQ - terrestrial habitats	HQ - margin habitats
American kestrel	0.035	not assigned
American robin	0.012	not assigned
American woodcock	0.18	not assigned
Bald eagle	not assigned	0.0028

(continued)

[6] For the mink, the 50th percentile TEQ biosolids concentration results in an HQ that is 1.4 times higher than the HQ for the 90th percentile TEQ biosolids concentration. Although the 90th percentile biosolids are more toxic to mammals than the 50th percentile biosolids, the congeners in the 50th percentile biosolids include higher concentrations of more bioaccumulative congeners. As a result, the predicted hazard associated with fish ingestion is actually higher for the less toxic sludge. That is, the applied dose in fish reflects a stronger potential to bioaccumulate the 50th percentile congener mixture than the 90th percentile congener mixture.

Table 9-10. (continued)

Receptor species	HQ - terrestrial habitats	HQ - margin habitats
Beaver	not assigned	0.025
Belted kingfisher	not assigned	0.009
Black bear	0.081	not assigned
Canada goose	0.0035	not assigned
Cooper's hawk	0.029	not assigned
Coyote	0.22	not assigned
Deer mouse	0.03	not assigned
Eastern cottontail rabbit	0.044	not assigned
Fish	not applicable	0.001
Great blue heron	not assigned	0.0035
Green heron	not assigned	0.0063
Herring gull	not assigned	0.0088
Herring gull	not assigned	0.0088
Least weasel	0.16	not assigned
Lesser scaup	not assigned	0.021
Little brown bat	0.062	not assigned
Long-tailed weasel	0.22	not assigned
Mallard	not assigned	0.01
Meadow vole	0.017	not assigned
Mink	not assigned	0.023
Muskrat	not assigned	0.081
Northern bobwhite	0.013	not assigned
Osprey	not assigned	0.0036
Prairie vole	0.023	not assigned
Raccoon	0.044	0.13
Red fox	0.17	not assigned
Red-tailed hawk	0.019	not assigned

(continued)

Table 9-10. (continued)

Receptor species	HQ - terrestrial habitats	HQ - margin habitats
River otter	not assigned	0.026
Short-tailed shrew	0.36	not assigned
Short-tailed weasel	0.18	not assigned
Tree swallow	0.028	not assigned
Western meadowlark	0.017	not assigned
White-tailed deer	0.061	not assigned

9.4.1 Interpreting Results from the SERA

As described in Section 9.2, the SERA was designed to evaluate the potential for adverse effects to mammals and birds selected to represent species in general terrestrial and waterbody margin habitats. By inference from the measures of effect (e.g., reproductive fitness), the SERA is intended to provide insight into the potential effects on wildlife populations of mammals, birds, and fish, capturing the most significant exposure pathways associated with dioxin and PCB releases into the environment.

For Phase 1 of the SERA, the exceedances of the target HQ clearly indicated that Phase 2 should be conducted. Although the HQ results from Phase 2 are suggestive of a low potential for adverse ecological effects, these results are intended only to inform the ongoing evaluation of potential ecological risks associated with biosolids application. For example, threatened and endangered species and habitats were not included in the analysis because a more site-specific approach would be required to address the co-occurrence of these receptors and their critical habitat with biosolids application sites. Consequently, the screening results do not indicate whether endangered species are at risk. In addition, the potential for adverse ecological effects (as indicated by the HQ results) should not be confused with the ecological significance. Screening results can only suggest the potential for adverse ecological effects; they do not demonstrate that an adverse response will actually occur, nor do they indicate whether those effects will have significant implications for ecosystems and their components.

The results from the Phase 2 screening were compared to the results from an ecological risk assessment of TCDD in pulp and paper sludge (Meyn et al., 1997). The assessment conducted by Meyn et al. evaluated many of the same receptors (e.g., red-tailed hawk, shrew) as those considered in the biosolids SERA and included four scenarios: agricultural fields (row crops), pasture, silviculture, and mine reclamation. The authors used a Monte Carlo approach to characterize the potential risks to wildlife, and determined that shrews were the wildlife species associated with the highest risks from exposure to TCDD in sludge. This finding is consistent with the results from the biosolids SERA; however, the HQs predicted in Meyn et al. were substantially higher (i.e., the 50^{th} percentile HQs for row crops and pastures were 60 and 200, respectively).

The difference between the results presented by Meyn et al. and those presented in Phase 2 can be attributed primarily to differences in the soil concentrations predicted by the respective models, as well as the choice of benchmarks. The 90th percentile TCDD concentrations for the row crop and pasture scenarios in the Meyn study were 54 ng/kg and 72 ng/kg, respectively, as compared to the 90th percentile TEQ soil concentrations predicted for the biosolids SERA, which were 0.9 ng/kg and 4.2, respectively. The benchmarks used by Meyn et al. were NOAELs divided by an interspecies uncertainty factor (UF) of 10, whereas the MATLs used in the SERA address interspecies differences in sensitivity through allometric scaling for mammals, and make no adjustment for difference in sensitivity among avian species (i.e., no uncertainty factor was applied). Considering the differences in soil concentrations and benchmarks, the risk results from the biosolids SERA are consistent with risk estimates presented by Meyn et al. (1997). For example, increasing the HQ results by a factor of 25 to account for differences in soil concentrations,[7] and a factor of 10 to account for the interspecies uncertainty factor, would result in an HQ of approximately 90 for the shrew. This HQ is between the HQ values at the 50th percentile calculated for the row crop and pasture scenarios for shrews presented in Meyn et al.

9.4.2 Silvicultural and Reclamation Site Applications

In addition to agricultural applications, biosolids are applied as a soil amendment to silvicultural operations and to land reclamation projects. In general, reclamation applications of biosolids are not well characterized. These applications can consist of spreading biosolids on reformed land surfaces as an amendment to support revegetation or as fill material deposited in excavations. In the former case, some tilling may occur with landscaping operations; for the latter case, tilling is unlikely. In either case, the dioxins, furans, and dioxin-like PCBs would be expected to bind to soil particles and exhibit fate and transport behavior similar to that in pastures; that is, the biosolids will not be tilled into the soil. While the application rates and frequency are not necessarily comparable, ecological exposures are likely to occur in a manner similar to that for agricultural fields. The terrestrial vertebrates evaluated in Phase 2 of the SERA are likely to be similar to receptors found at reclamation sites for terrestrial and margin habitats. The 50th percentile HQs for the silviculture and mine reclamation scenarios were also 60 and 200 (as with the row crops and pastures as cited above).

For silvicultural application of biosolids, the application rates and frequency are not well characterized; however, it appears that biosolids are probably applied once per site. The concentration profile for soils may be similar to pastures with the exception of reforestation projects where site preparation for new plantings could include tilling of biosolids into the soil. The concentration profile for reforestation projects would tend to be more similar to the agricultural field applications evaluated in the SERA that involve tilling. Twelve of the avian and mammalian species listed in Table 9-3 for the terrestrial habitat are also be expected to feed and forage in forests; therefore, the screening results for the generalized terrestrial habitat are considered relevant to forest habitats. Although there are forest species that are not represented in the agricultural scenario, the major trophic elements are substantially represented.

[7] The factor of 25 was estimated by calculating a simple arithmetic average for the agricultural field and pasture for Meyn study (63 ng/kg) and the biosolids SERA (~2.5 ng/kg), respectively, and dividing.

The HQ results from Phase 2 of the SERA have limited applicability to silvicultural and reclamation site applications. The application of biosolids to the surface may form a litter layer with substantially higher concentrations of dioxins, furans, and dioxin-like PCBs than the concentrations estimated in the model simulations for agricultural fields and pastures. The invertebrate community feeding on the biosolids layer may accumulate relatively high congener concentrations resulting in exposures for mammals and birds that are similar to those evaluated in the Phase 1 screen. Extrapolating from the information presented in Phases 1 and 2 of the SERA, the hazards to receptors feeding on soil invertebrates in a silvicultural application could potentially fall within a range of concern (i.e., an HQ above 1). Although the biosolids SERA provides some indication of the potential for adverse ecological effects associated with the silvicultural and reclamation scenarios, further evaluation will be required to characterize the potential ecological risks.

9.4.3 Uncertainty

In discussing the uncertainties associated with Phase 2 of the SERA, it is important to consider the management goal as the context for identifying key uncertainties and deciding whether these uncertainties are acceptable. Uncertainties do not necessarily diminish the value of the information presented in the SERA. For example, given the goals of the Phase 2 screening assessment, uncertainties that tend to bias the risk results to produce more conservative estimates of the potential for adverse ecological effects may be considered acceptable. Consequently, this discussion is focused on the most significant sources of uncertainty and describes the most likely impact of those uncertainties on the screening risk estimates. The results of the SERA are not intended to provide a final or conclusive statement regarding the ecological risks associated with the agricultural application of biosolids.

- **Ecological effects associated with background concentrations of dioxins, furans, and dioxin-like PCBs are not considered.** The screening results reflect the incremental risk to ecological receptors from exposure to dioxins, furans, and dioxin-like PCBs in biosolids. However, there is some evidence to suggest that ecological damages may be associated with background concentrations of dioxin-like compounds. Section 5.2.2.1 presents soil and sediment concentrations of TCDD-TEQs (based on human health TEFs) for comparison with background concentrations in rural soil (2.5 ng/kg) and sediment (5.8 ng/kg). Based on this information, the aggregate risk (i.e., background and biosolids-related) from TCDD exposure may be higher than the incremental risk attributable to biosolids application.

- **The SERA evaluates only dioxins, furans, and dioxin-like PCBs, implying that other stressors are insignficant.** The SERA did not address other chemical constituents in biosolids, nor did it address other potential stressors (chemical or other) to which wildlife may be exposed. As a result, the predicted screening risks (as represented by the HQ results) may underestimate the potential for adverse ecological effects in a multistressor environment.

- **The agricultural application of biosolids does not adequately represent the silviculture and reclamation scenarios.** As discussed above, there is

considerable uncertainty in extrapolating from the agricultural application of biosolids to other scenarios. This uncertainty suggests that further evaluation of silvicultural and reclamation practices may be required to evaluate the potential for adverse ecological effects in those scenarios.

- **The temporal scale for the assessment is driven by the modeling system and is based on annual concentrations averaged across the area of interest.** Because annual concentrations are used in calculating exposure doses, potentially significant peaks in exposure are not explicitly addressed (e.g., the concentration profile following an application of biosolids). To some degree, the data on bioaccumulation and toxicity support the use of annual averages because they are based on long-term, steady-state situations. Nevertheless, risks to wildlife may be underestimated if peak exposures occur at sensitive life stages.

- **The spatial scale of the assessment assumes that 100 percent of the diet originates from the contaminated area.** For certain receptors (e.g., deer mouse), this assumption is consistent with the relationship between the species home range and the size of the agricultural field and pasture in the conceptual site model. However, for species with much larger home ranges (e.g., coyote), this assumption tends to overestimate the potential hazard associated with biosolids application.

- **Margin habitats are broadly defined in terms of streams, ponds, and lakes.** Defining the margin habitat broadly, rather than simply modeling a small farm pond, has implications with regard to receptor selection, as well as the applicabilty of exposure estimates. For example, concentrations of dioxins, furans, and dioxin-like PCBs in a lake ecosystem attributable to biosolids are likely to be very small and, possibly, negligible. In contrast, the concentration in sediment of a small farm pond may increase substantially from erosion and runoff of soil-bound congeners. The surface water model does not distinguish between these types of waterbodies, and, as a result, the sediment and surface water concentrations would likely overestimate potential exposures for lakes and moderate-sized streams.

- **The measure of effect is at the level of the individual organism; therefore, effects at the population level must be inferred from the endpoint.** Although the endpoints chosen for benchmark development for mammals and birds are highly relevant to population viability, they cannot be used to directly evaluate the potential risks to wildlife species populations. Population-level models have been used by ecologists for decades to evaluate population impacts associated with a variety of stressors. However, parameterizing a population model requires a substantial investment in resources, and there are many difficult decisions to be made regarding the appropriate level of effect for the population (e.g., is a 10 percent reduction in the reproductive fitness of the shrew population acceptable?). Currently, it is not possible to determine whether inference to populations from endpoints relevant to population viability tends to over- or underestimate the potential for adverse ecological effects.

- **Ecological benchmarks in Phase 2 are based on a statistical rather than biological derivation, and data are insufficient to provide defensible adjustment factors to account for interspecies variability.** Although it is widely recognized that using NOAELs in screening analyses tends to produce results that are difficult to interpret, there is no consensus on the most appropriate measure of effect for a SERA. Moreover, the available toxicological data provide little support to develop adjustment factors to account for interspecies variability. As a result, there is significant uncertainty associated with deriving the species-specific ecological benchmarks.

- **It is not possible to verify that reproductive and developmental endpoints are, in all cases, sufficient to protect the assessment endpoints for wildlife populations.** The endpoints for certain wildlife populations (i.e., mammals, birds) were almost exclusively taken from reproductive and developmental studies. Although reproductive and developmental endpoints have been recognized by the Science Advisory Board (SAB) as relevant to population viability, they are not always the critical effect associated with a chemical stressor. The assumption that effects that are relevant to population viability do not occur at lower environmental concentrations limits confidence in the screening HQ results.

- **Uncertainty is inherent in the TEF/TEQ methodology.** Although EPA has determined that the TEF/TEQ methodology used in this analysis reduces the uncertainty associated with risk estimates for AhR agonists relative to those based on a single compound (e.g., TCDD), there may be effects associated with these chemicals that are unrelated to AhR and, therefore, are not accounted for (U.S. EPA, 2001b). Furthermore, EPA points out that use of the TEFs is most appropriate for taxa and endpoints used in developing the TEF values. Uncertainties are introduced with increasing taxonomic and endpoint extrapolation.

- **The selection of terrestrial BAFs is based on regression analyses and empirical data and does not include all of the prey categories.** The terrestrial BAFs were based on empirical data and regression analyses (see Appendix L), and information on small mammals was used to represent terrestrial vertebrates of different sizes. In addition, measures of central tendency—rather than high-end values—were considered appropriate in selecting input values. Although the uncertainty associated with representing terrestrial vertebrates using data on small mammals has not been quantified, using a high-end value for bioaccumulation may have produced HQ results that exceeded the target HQ of 1.

- **The default BEF of 1 assumes that all congeners are accumulated in terrestrial prey at a rate similar to 2,3,7,8-TCDD.** Lacking congener-specific adjustment factors for bioaccumulation, no adjustment was made to account for differences in congener-specific accumulation in terrestrial animals. Based on the BEFs for bioaccumulation in aquatic organisms, the default factor likely overestimates the tissue concentrations in terrestrial prey.

- **The congener-specific BSAFs were recommended for use in risk assessment in the Draft Dioxin Reassessment Document (U.S. EPA, 2000).** The U.S. EPA Office of Research and Development recommends congener-specific values for BSAFs. These recommendations were based on a review of numerous studies from different types of waterbodies and many species of fish. Although there is some uncertainty in applying empirical values to estimate tissue concentrations in fish, this is considered to be a relatively minor source of uncertainty given the exhaustive review conducted by EPA.

Because the ecological analysis was a screening analysis intended only to indicate potential for adverse ecological effects, EPA considers the qualitative uncertainty analysis to be adequate. The uncertainty discussion identifies sources of uncertainty, discusses their implications on the risk outcome, and, where possible, indicates whether the uncertainty is likely to cause an over- or underestimation of risk.

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Appendix A

2001 National Sewage Sludge Survey - Congener Concentration Data

Table A-1. Appendix A 2001 National Sewage Sludge Survey Sampling Data for Dioxins and Furans

Episode	Tier	2,3,7,8-TCDD 1746016 (ng/kg)	1,2,3,7,8,9-HXCDD 19408743 (ng/kg)	OCDD 3268879 (ng/kg)	1,2,3,4,6,7,8-HPCDD 35822469 (ng/kg)	OCDF 39001020 (ng/kg)	1,2,3,4,7,8-HXCDD 39227286 (ng/kg)	1,2,3,7,8-PECDD 40321764 (ng/kg)	2,3,7,8-TCDF 51207319 (ng/kg)	1,2,3,4,7,8,9-HPCDF 55673897 (ng/kg)	2,3,4,7,8-PECDF 57117314 (ng/kg)	1,2,3,7,8-PECDF 57117416 (ng/kg)	1,2,3,6,7,8-HXCDF 57117449 (ng/kg)	1,2,3,6,7,8-HXCDD 57653857 (ng/kg)	2,3,4,6,7,8-HXCDF 60851345 (ng/kg)	1,2,3,4,6,7,8-HPCDF 67562394 (ng/kg)	1,2,3,4,7,8-HXCDF 70648269 (ng/kg)	1,2,3,7,8,9-HXCDF 72918219 (ng/kg)
6338	2	0.8	3.9	934	90	178	1.3	4.1	2.5	2.4	2.4	1.3	3.1	5.9	4.1	48.6	4.3	0.5
6339	3	0.7	3.1	957	86.7	237	1.4	4	1.7	1.9	1.5	1.8	1.9	5.6	1.6	68.4	2.6	1.8
6340	2	1.7	25.6	10600	668	6020	9.1	7.7	5	12.5	3.7	2.3	10	33.7	16.5	357	9.5	0.5
6341	2	0.5	4	1010	95.9	169	1.5	1.7	0.8	2.3	1	0.7	1.8	4.4	1.7	35.2	2.1	0.5
6342	4	1.1	5.4	1800	237	296	1.2	2.7	1.4	1.7	1	0.5	1.6	12.3	1.9	72	1.7	0.5
6343	3	0.3	1.1	1510	80.2	77.8	0.4	0.5	0.4	1	0.3	0.3	0.5	2.5	0.6	16.7	0.6	0.5
6344	3	1.4	13.8	1970	338	147	2.2	2.8	1.7	2.5	1.2	1	2.2	40.8	1.9	47.5	3	0.5
6345	2	14	332	3040	1410	1510	124	92	79.7	418	463	189	618	230	974	2540	500	54.4
6346	1	47.2	49.7	5040	783	1070	9.8	11	6.3	9.1	6.6	5.7	9.7	92.8	12.6	227	24.1	0.6
6347	2	0.7	62.2	4200	639	64.9	3.2	19	4	2.2	4.3	2.2	6.2	264	14.8	98.6	12.8	0.5
6348	3	0.9	6.9	3040	209	554	2.2	5.2	4.9	3.4	1.9	1.1	2.6	10.1	2.8	117	3.1	0.5
6349	1	1.6	16.7	7140	672	462	6.1	7.1	3	8.1	4.8	2.6	7.9	24.9	7.5	146	9	0.2
6350	1	1.8	33.7	12600	1230	844	13.6	11.8	4.6	17.2	4.9	3	13.6	45	11.1	259	12.8	0.5
6351	4	3	21.6	3350	321	201	3.9	9.5	2.5	2.8	1.6	1	2.7	43.1	2.5	62	3.4	0.5
6370	2	0.7	5.8	3630	615	121	1.3	3.1	1.7	1.5	2.3	0.5	1.2	12.4	1.1	28.9	1.9	0.5
6371	1	0.5	2.1	1070	83.3	395	0.6	1.7	1.9	3	0.7	0.6	0.9	5	2.8	38.8	3.8	0.2
6352	1	1.5	22.1	10000	735	2460	8.9	8.6	4.8	43.7	4.9	3.7	11.9	27.1	12.7	227	19.4	1
6353	1	1.4	22.2	13200	1030	1680	7.9	7.6	5.6	30.3	4.8	4	9.6	33.9	7.4	199	17.2	0.9
6354	3	0.25	19.8	2170	184	2100	1	4.5	0.6	3.4	0.8	0.4	1.9	73.5	3.9	319	2.1	0.5
6355	4	2.4	22.8	7790	560	544	8.6	11.8	6.5	7	4	2.5	8.4	28.1	7	145	8.9	0.5
6356	3	0.9	13.3	3400	340	351	5.3	4.8	2.4	5.7	2.4	1.5	5.5	14.8	4.8	120	5.7	0.5
6357	1	0.2	24.5	3780	698	181	3.5	5.5	1.2	4.3	1.4	0.9	3.3	84.7	2.7	63.7	3.7	0.5
6358	4	1.1	12.5	2750	312	266	4.8	6.4	10.6	6.9	7.8	2.7	8.2	14.9	7.9	105	10.2	0.6
6359	3	0.7	2.7	1730	198	184	0.7	1.2	1	1.7	1.1	0.6	1.3	8.5	1.2	34.4	1.9	0.5
6360	3	0.7	5.9	2170	146	277	1.9	3.1	1.4	2.2	1.1	0.6	2.1	7.4	1.8	64.6	2.3	0.5
6361	1	1.1	19.4	11300	946	505	6.8	8.1	4.7	14.8	6	4.3	11.7	30.2	9.4	188	13.9	0.7
6363	4	1	7.5	3930	302	757	2.9	5	2.9	4.1	2.2	1.1	4	15.1	4.3	233	4.9	0.5
6364	4	0.9	6.7	2360	216	327	1.6	4.9	5.1	2	1.6	3.1	2.6	15.5	3.7	116	3.1	3.1
6365	2	1.8	8.7	4620	527	408	2.6	5.1	2.8	3.3	1.8	1	3.3	22	3	94.3	4	0.5
6366	4	0.5	1.9	683	64.7	80.2	0.7	1.8	0.5	0.8	0.4	0.3	0.8	3.3	1	28.3	1	0.5
6367	4	0.4	2.4	588	62.5	190	0.8	2	0.8	1.4	0.7	0.4	1.1	3.4	1.3	39.3	1.4	0.5
6368	3	1.2	14.8	5040	534	267	5.1	4	2.7	4.4	1.6	1.1	4.8	23.8	4.2	88.4	5	0.5
6369	3	2.3	19.6	7560	594	451	7.8	7.7	2.8	9.2	3.5	1.9	10.2	22.8	8	195	10.8	0.5
6372	3	0.9	2.8	1760	93.5	125	0.9	3.4	1.3	0.9	0.7	0.5	1.1	4.1	1.2	42.7	1.4	0.5
6373	2	0.5	3.1	1610	78.1	1660	0.9	4.5	4.3	11.9	1	1.7	1.9	5.1	1.3	62.8	9.1	0.9
6374	2	6.3	1.8	1050	49.1	176	0.7	3.3	9.6	0.7	3.6	2.4	1.1	3.2	1.5	32.4	1.7	0.5
6376	3	1.2	8.3	3180	225	213	2.3	8.2	2.1	2.8	1.4	1	2.7	15	2.7	76.6	2.8	0.5
6377	3	1.9	144	360000	22600	52700	45.1	16.7	2.5	772	4.4	8.6	106	367	29.6	7450	82.6	18.8
6378	3	5.3	6.3	2410	191	942	1.9	4.6	2.8	2.6	1.7	1.2	2.4	13.1	3.2	139	2.8	0.5
6379	3	0.7	3.9	1140	98.5	81.2	1.4	3.7	1.6	1.1	0.9	0.5	1.5	5.6	1.3	33.3	1.8	0.5
6380	4	1	7.4	1420	118	434	1.9	3.8	5.4	1.9	1.5	0.8	2	7.2	2.3	88	2.1	0.5
6381	2	3.2	6.8	2050	162	188	2	2.6	5.3	5.1	3.9	1.8	2.8	6.7	4.8	41.9	2.8	0.3
6382	2	0.35	30.6	1690	196	95	0.5	7.6	1.7	0.5	0.6	0.6	1	115	1.3	25.2	1.2	0.5
6383	4	0.6	2.7	917	77.8	131	1	2.9	0.7	1.4	0.6	0.3	1.1	3.8	1.3	39.7	1.2	0.5
6384	3	0.6	1.9	784	60.1	107	0.8	3.4	0.7	0.7	0.6	0.4	0.8	3.2	1.1	30	1	0.5

(continued)

Table A-1. (continued)

Episode	Tier	2,3,7,8-TCDD 1746016 (ng/kg)	1,2,3,7,8,9-HXCDD 19408743 (ng/kg)	OCDD 3268879 (ng/kg)	1,2,3,4,6,7,8-HPCDD 35822469 (ng/kg)	OCDF 39001020 (ng/kg)	1,2,3,4,7,8-HXCDD 39227286 (ng/kg)	1,2,3,7,8-PECDD 40321764 (ng/kg)	2,3,7,8-TCDF 51207319 (ng/kg)	1,2,3,4,7,8,9-HPCDF 55673897 (ng/kg)	2,3,4,7,8-PECDF 57117314 (ng/kg)	1,2,3,7,8-PECDF 57117416 (ng/kg)	1,2,3,6,7,8-HXCDF 57117449 (ng/kg)	1,2,3,6,7,8-HXCDD 57653857 (ng/kg)	2,3,4,6,7,8-HXCDF 60851345 (ng/kg)	1,2,3,4,6,7,8-HPCDF 67562394 (ng/kg)	1,2,3,4,7,8-HXCDF 70648269 (ng/kg)	1,2,3,7,8,9-HXCDF 72918219 (ng/kg)
6385	3	0.4	9.9	13800	183	25700	0.7	1.6	1.8	14.8	0.9	0.5	5.1	40.3	20.1	3860	4.2	0.5
6387	4	1.4	21.3	2520	225	135	3.6	12.3	1.5	1.7	1	0.6	2	29.8	2.3	54	1.8	0.5
6386	3	0.8	7.8	4570	445	290	2.7	5.3	1	4.7	1.5	0.9	3.1	14.8	2.8	82.8	3.8	0.2
6389	2	4.4	22.8	3640	367	1190	6.7	8.7	10.3	87.8	23.6	13	41.9	22.9	63.2	349	46.5	7.1
6390	2	1.5	4.6	1540	148	197	1.7	10.8	6.4	3.4	1.5	1.3	4.9	8.1	2.4	63.5	2.4	0.5
6391	4	0.6	1.6	538	49	102	0.7	3	0.9	0.6	0.4	0.3	0.7	2.4	0.9	24.4	0.9	0.5
6392	3	1.1	4.2	1700	158	451	1.6	8.3	2.3	1.5	1	0.6	1.5	10.6	2.3	100	1.9	0.5
6393	4	2.2	15.2	7410	649	475	5.9	13.1	1.9	6.1	1.5	1.1	4.5	21.2	5.8	165	4.6	1.7
6394	2	1.4	5.2	607	82.8	119	2.6	3.5	2.2	6.5	6.3	2.8	10.1	8.5	8.8	76.9	13.2	0.5
6395	3	2.1	14.5	2810	349	143	0.75	11.9	5.2	2.2	2.3	1.8	3.8	36.3	4.4	0.75	5.1	0.75
6396	3	1	1.5	695	67.2	106	0.8	4.6	1.9	0.9	0.4	0.3	0.9	3.1	1	39.1	1.2	0.5
6397	3	1.7	9.2	7050	352	396	3.3	10.2	3.2	4.6	1.6	1	3	14.2	3.3	113	5.1	1.65
6375	3	1.1	4.4	2910	209	267	1.4	4.9	3.1	2	1.5	0.5	2.1	9.1	2.1	76.2	2	0.5
6399	2	0.4	1.5	528	50.9	136	0.5	1.5	1	0.7	0.6	0.3	0.8	2.8	1.1	40.3	0.9	0.5
6400	3	1.1	7.2	1870	211	287	2.9	8.1	15.3	2.8	1.9	2.3	3.3	11.6	5.3	124	3.5	0.5
6401	2	0.9	2.9	1150	78.3	178	1.2	4.9	4.6	0.9	0.8	0.7	1.3	4.8	1.3	49.9	1.3	0.5
6402	1	2.2	15.2	6900	599	686	6.3	8.7	7.7	6.3	2.8	1.6	5.9	27.3	5.2	156	6.4	0.2
6403	4	0.4	1.4	393	37.5	60.2	0.6	1.9	0.3	0.6	0.3	0.2	0.6	1.9	0.6	20.2	0.5	0.5
6404	3	0.9	6.1	2030	177	518	1.9	4	3	3.2	2.1	1.4	3.6	9.9	4	112	4.4	1.1
6405	2	0.9	5	1490	148	371	1.4	3.4	2.2	2.8	1.5	1	2.4	7.1	2.4	93	2.8	0.2
6406	2	1.4	9	3400	349	544	3	5.9	3.9	3.9	3	1.7	3.8	18.1	3.9	127	5.3	0.2
6407	2	1.7	30.8	12600	1200	625	7.9	5.8	3.6	11.2	3.3	2.1	5.8	55.1	4.8	170	11.2	0.4
6409	3	0.9	12.5	4230	394	498	5.6	5.5	4.3	7	1.6	1.1	4.4	20.4	3.4	121	4.5	0.5
6410	3	1.2	4.2	1660	144	277	1.3	3.5	1.9	2	1.2	0.8	2	7.6	2.2	74.9	2.4	0.5
6411	3	1.6	21.1	5290	504	674	7.8	9.2	7.9	7.2	4.7	2.6	8	26.6	6.9	173	8.3	0.4
6412	2	0.6	5.4	1260	40.8	26.6	1.1	1.4	1.2	0.5	1	0.6	0.5	2.3	0.5	7	0.5	0.5
6413	1	1.6	4.6	1280	134	169	1.1	2	5.5	1.9	3.9	2.1	2.5	8.5	2.6	43.4	4	0.2
6414	2	0.9	6.5	1950	200	417	2	3.9	2.7	3.3	2.3	1.3	3.8	11.7	3.9	130	6.9	0.5
6415	3	1.6	9.1	2900	287	588	2.4	6.5	7.4	3.2	4.2	4.2	4.9	17.9	4	138	8.4	0.5
6416	4	1.5	7	2370	288	253	1.5	2.8	1.3	2.3	1.1	0.5	2.3	19.8	1.6	82.8	3.8	0.5
6418	2	1.7	22.3	9870	1030	232	7.5	6.4	2.6	8.9	3.8	2.8	8.8	38	7.7	177	15.8	0.3
6419	3	0.5	3.4	2430	180	194	1.2	2.4	1.4	2.5	1.4	0.7	2.1	6	2.4	63.7	3.3	0.5
6420	2	3.6	19.5	6870	526	699	5.9	6.7	4.9	10.3	3.8	2.2	10	22.7	11.6	183	8.6	0.5
6421	3	3.4	40.2	12800	1080	930	16.3	13.4	2.6	21.7	3.7	2.3	16	43.6	12.1	352	15.3	0.4
6423	3	2	16.6	4180	415	311	5.1	6.2	5.7	6.7	2.6	1.6	7.7	20.9	5	132	7.2	0.3
6424	4	5	18.3	7930	655	339	6.5	9.2	3.7	4.5	2.2	1.1	6.7	26.3	8.2	172	6.8	0.9
6425	4	0.7	6.3	5070	183	281	2.3	3.6	1.2	3.1	0.9	0.7	2.6	8	2.1	83.4	3	0.5
6426	4	1.6	8.3	3450	376	258	2.8	3.6	2.3	3.9	1.9	1	3.4	15.2	3.2	91	4.3	0.2
6427	2	1.6	11.7	2660	298	321	3.9	6	3.9	4.8	4.7	2.1	5.7	15.8	5.1	125	7.2	0.5
6428	4	1	14.4	4060	460	423	4.2	5.3	5	3.5	2	1.4	4.5	34	4.3	129	4.8	0.65
6429	2	2.2	30.9	15800	1840	1450	10.1	11.3	5.7	27.6	6.2	4.4	14	61.2	9.9	323	22.8	1.1
6430	4	1.3	16.5	6240	720	330	4.7	4.4	2.9	5.7	2.8	1.5	5.9	31.1	4.9	135	6.1	0.2
6431	2	1.5	17.4	3790	403	585	7	6.4	7.4	11.8	7.1	5.2	15.1	20.2	9.2	279	26.6	0.8
6433	4	1.2	16.9	5590	779	297	3.6	4.9	3.3	4.3	2.4	1.5	4.1	44.3	3.5	102	6	0.2
6434	1	3.1	42.3	10400	1010	929	14.9	14.4	8.8	18.4	8.5	5.4	16.9	52.9	14.7	320	21.6	0.8

(continued)

Table A-1. (continued)

Episode	Tier	2,3,7,8-TCDD 1746016 (ng/kg)	1,2,3,7,8,9-HXCDD 19408743 (ng/kg)	OCDD 3268879 (ng/kg)	1,2,3,4,6,7,8-HPCDD 35822469 (ng/kg)	OCDF 39001020 (ng/kg)	1,2,3,4,7,8-HXCDD 39227286 (ng/kg)	1,2,3,7,8-PECDD 40321764 (ng/kg)	2,3,7,8-TCDF 51207319 (ng/kg)	1,2,3,4,7,8,9-HPCDF 55673897 (ng/kg)	2,3,4,7,8-PECDF 57117314 (ng/kg)	1,2,3,7,8-PECDF 57117416 (ng/kg)	1,2,3,6,7,8-HXCDF 57117449 (ng/kg)	1,2,3,6,7,8-HXCDD 57653857 (ng/kg)	2,3,4,6,7,8-HXCDF 60851345 (ng/kg)	1,2,3,4,6,7,8-HPCDF 67562394 (ng/kg)	1,2,3,4,7,8-HXCDF 70648269 (ng/kg)	1,2,3,7,8,9-HXCDF 72918219 (ng/kg)
6435	3	1.7	24.4	4890	604	473	7.3	11.2	4.6	8.9	6.6	3.6	10	47.6	8.9	179	11.8	0.4
6436	2	0.8	9.7	4190	426	282	3.4	3.5	2.3	4.6	2.4	1.5	3.7	16.2	3.4	71.7	5	0.3
6437	2	12.3	52.4	1120	271	4.5	4.5	85	1.5	0.8	2	1.9	2.2	128	7	28.2	2.5	0.3
6438	2	0.3	1.4	200	21.9	31.3	0.5	0.6	0.4	0.6	0.6	0.4	0.7	1.4	0.8	8.3	1	0.5

Table A-2. Appendix A 2001 National Sewage Sludge Survey Sampling Data for Coplanar Polychlorinated Biphenyls

Episode	Tier	PCB-118 31508006 (ng/kg)	PCB-77 32598133 (ng/kg)	PCB-105 32598144 (ng/kg)	PCB-169 32774166 (ng/kg)	PCB-189 39635319 (ng/kg)	PCB-167 52663726 (ng/kg)	PCB-126 57465288 (ng/kg)	PCB-123 65510443 (ng/kg)	PCB-81 70362504 (ng/kg)	PCB-114 74472370 (ng/kg)	PCB-156 & PCB-157 COELUTE (ng/kg)
6338	2	12300	312	5080	3	166	706	30.4	265	151	355	2320
6339	3	8580	194	3490	8.15	59.3	378	163.5	202	177	225	1320
6340	2	15900	964	6770	0.5	110	778	100	412	294	427	2530
6341	2	4460	24800	1920	450	40.7	230	501	105	85	124	747
6342	4	12000	832	5210	2.5	69.1	473	25.3	396	224	382	1670
6343	3	822	18.3	333	2.5	8.7	48.8	50	22.3	12.4	20.4	170
6344	3	3160	100	1280	2.5	31.3	169	50	96.2	37.5	75.8	553
6345	2	32200	1190	12200	90.8	1440	2740	256	670	465	998	8200
6346	1	14400	13800	6690	30.6	215	1040	114	457	262	580	3170
6347	2	16000	704	7080	4.3	138	843	36.1	377	189	432	2890
6348	3	11800	331	4810	3.7	77.7	574	50	414	138	323	2070
6349	1	18400	676	8030	5.7	340	1160	57.8	411	212	429	3780
6350	1	19200	873	8130	5.7	229	1120	60.6	483	216	519	3580
6351	4	1510	22.4	663	0.5	13.7	101	10	28.7	22.4	41.1	367
6370	2	5850	188	2460	1.5	39.3	281	50	349	89.5	159	933
6371	1	6800	319	2900	2	87.5	383	50	145	87.7	164	1240
6352	1	29700	1220	13200	8.5	1010	2380	93.9	672	277	864	6910
6353	1	15800	1030	7120	6.5	368	1100	71.5	484	320	490	3260
6354	3	3120	153	1240	1.2	22.3	138	8.5	117	36	83.1	512
6355	4	23900	700	10500	5.8	167	1350	68.3	554	392	680	4630
6356	3	9010	499	3890	21	62.9	430	60.4	268	213	257	1390
6357	1	25600	333	10800	2.5	141	1360	29.7	426	561	782	4250
6358	4	63600	13000	39200	11.7	527	2390	381	2140	1980	2500	8000
6359	3	11300	277	4190	4	53.7	439	400	226	170	263	1460
6360	3	6090	160	2520	1.3	37.6	268	11.3	157	66.8	165	978
6361	1	14700	901	5990	3.3	161	623	38.4	312	176	361	2250
6363	4	15300	525	6480	0.5	88.9	710	28.4	363	243	409	2680
6364	4	19500	458	7110	4.9	214	944	490	372	300	427	3200

(continued)

Table A-2. (continued)

Episode	Tier	PCB-118 31508006 (ng/kg)	PCB-77 32598133 (ng/kg)	PCB-105 32598144 (ng/kg)	PCB-169 32774166 (ng/kg)	PCB-189 39635319 (ng/kg)	PCB-167 52663726 (ng/kg)	PCB-126 57465288 (ng/kg)	PCB-123 65510443 (ng/kg)	PCB-81 70362504 (ng/kg)	PCB-114 74472370 (ng/kg)	PCB-156 & PCB-157 COELUTE (ng/kg)
6365	2	1120	51.5	481	0.5	8.2	47.5	10	33.8	18.2	30.7	178
6366	4	6770	279	2670	2.5	34.3	266	50	257	140	182	912
6367	4	6210	360	2490	2.5	63.3	290	50	261	128	180	999
6368	3	870	44.7	359	0.3	7.8	48.8	5.5	21.1	12.5	22.3	151
6369	3	15500	659	6680	4.9	107	832	400	391	146	317	2420
6372	3	8020	229	3480	1.6	55	511	19.6	330	113	225	1520
6373	2	11900	570	4920	2.5	88.6	564	50	413	266	362	1880
6374	2	4300	173	1630	2.5	26.4	178	50	165	104	126	599
6376	3	326	13.9	120	0.5	1.9	12.6	10	12.2	5.1	8.1	42.2
6377	3	5250	222	2180	2.5	41.6	267	18	177	142	161	893
6378	3	232	19.3	87.9	0.5	1.5	8.5	30	9.4	4.5	6.8	25.5
6379	3	22600	519	9880	3.6	153	1200	44.7	497	218	538	4300
6380	4	256	10.6	103	0.5	1.8	8.9	10	7.2	4.9	6.5	30.5
6381	2	8670	496	3640	2.5	131	475	29	231	194	298	1460
6382	2	5750	147	2370	2.5	31.5	273	8.3	133	127	149	909
6383	4	3620	146	1520	1.1	24.5	171	8.7	141	77.2	91.6	615
6384	3	4850	122	1660	2.5	33.9	210	8.3	140	101	100	694
6385	3	18700	214	7910	1	46.6	675	400	309	156	439	2060
6387	4	4360	214	1870	2.2	33.5	205	19.1	133	87.2	120	733
6386	3	4330	197	1820	1.7	35.4	251	13.3	126	66.1	117	807
6389	2	4750	267	1900	8.3	48.3	221	21.3	204	57.1	143	777
6390	2	9750	469	3960	2.5	67.9	459	34.4	420	223	288	1460
6391	4	3360	164	1420	2.5	23.8	149	50	150	62.7	103	533
6392	3	5450	355	2230	2.5	35.6	240	50	182	104	167	858
6393	4	1820	168	1240	4.2	47.7	209	26.7	75.8	23	69	686
6394	2	3340	81.3	1320	2.4	40.2	182	8.6	197	44	91.3	583
6395	3	5310	348	2740	3.8	44.4	306	76	303	100	144	995
6396	3	8880	337	2430	2.9	54.6	390	22.5	308	121	128	1280

(continued)

Table A-2. (continued)

Episode	Tier	PCB-118 31508006 (ng/kg)	PCB-77 32598133 (ng/kg)	PCB-105 32598144 (ng/kg)	PCB-169 32774166 (ng/kg)	PCB-189 39635319 (ng/kg)	PCB-167 52663726 (ng/kg)	PCB-126 57465288 (ng/kg)	PCB-123 65510443 (ng/kg)	PCB-81 70362504 (ng/kg)	PCB-114 74472370 (ng/kg)	PCB-156 & PCB-157 COELUTE (ng/kg)
6397	3	5110	253	2090	2.3	45.6	260	18.1	213	109	142	831
6375	3	870	19.4	327	0.5	5.7	39.3	10	26	18	25.5	139
6399	2	2660	121	1010	2.5	18.8	118	50	187	69.8	64.6	396
6400	3	5760	326	2340	5.9	55	297	36.6	948	79.8	164	1040
6401	2	3480	211	1420	2.5	30.9	180	50	392	66.6	104	601
6402	1	1320	73	551	0.6	14	71.5	7.9	90.5	20.1	36.1	228
6403	4	4210	180	1740	2.5	34.3	210	50	419	75.1	123	729
6404	3	3610	197	1320	10.35	33.8	162	206.5	280	73.3	122	645
6405	2	7880	363	3110	3.8	59.6	347	50	381	88.8	195	1140
6406	2	18700	683	7300	4.9	129	800	43.3	581	401	462	2770
6407	2	42600	3220	21300	9	576	2190	158	1030	692	1400	6800
6409	3	5140	251	1990	3.1	50.4	257	50	421	85.8	141	823
6410	3	7080	286	2840	3	58.8	338	24.1	364	161	180	1140
6411	3	25500	598	10800	4	158	1180	39.9	619	400	653	4100
6412	2	2800	163	1220	2.5	30.1	128	50	66.8	52.4	74.4	435
6413	1	9410	333	4000	2.3	82.2	458	50	213	125	246	1490
6414	2	1140	53.2	464	0.5	12.2	61.9	10	37.7	19	31.6	196
6415	3	33100	1730	15100	2.5	207	1490	72.3	1040	613	986	4930
6416	4	11300	203	4440	0.5	66.4	542	50	301	173	302	1830
6418	2	12800	574	5960	2.5	160	887	58.4	315	334	323	2750
6419	3	5990	234	2630	2.5	46.6	298	50	169	109	153	936
6420	2	23300	816	9120	6.4	665	1910	54	481	443	576	5820
6421	3	9720	493	3810	3	73.5	474	30.9	282	117	250	1480
6423	3	2160	116	847	0.5	15.3	102	7.7	49.8	33.4	53.5	320
6424	4	15200	455	6370	4.1	75.6	662	48.2	424	286	328	2140
6425	4	4660	346	1820	1.9	29.7	214	50	294	56.9	137	784
6426	4	13600	2030	6840	2.9	89.3	550	48.4	407	378	421	1730
6427	2	17300	1030	8290	5.4	140	862	69	476	432	549	2850

(continued)

Table A-2. (continued)

Episode	Tier	PCB-118 31508006 (ng/kg)	PCB-77 32598133 (ng/kg)	PCB-105 32598144 (ng/kg)	PCB-169 32774166 (ng/kg)	PCB-189 39635319 (ng/kg)	PCB-167 52663726 (ng/kg)	PCB-126 57465288 (ng/kg)	PCB-123 65510443 (ng/kg)	PCB-81 70362504 (ng/kg)	PCB-114 74472370 (ng/kg)	PCB-156 & PCB-157 COELUTE (ng/kg)
6428	4	819	18	340	0.55	6.8	43.3	11.5	24	12.3	18.7	163
6429	2	21400	980	8600	5.1	152	967	68.8	543	247	570	3150
6430	4	1580	34.7	629	0.6	14.6	85.3	12	44.7	21.8	35.4	286
6431	2	26200	1150	10600	6.1	213	1370	63.2	513	566	642	4400
6433	4	5230	150	2030	0.9	26.9	211	8.6	99.4	74.9	125	720
6434	1	5280	791	2730	1.1	81.2	228	22.2	141	110	213	684
6435	3	1880	87.7	777	0.6	16.4	90.4	10	39.2	28.3	49.7	292
6436	2	13500	1120	6490	2.5	76.7	497	46.1	342	310	404	1670
6437	2	5630	195	2270	0.5	39.6	260	50	150	96.8	143	947
6438	2	13500	915	6350	3.8	106	672	40.9	354	210	416	2220

Appendix B

2001 National Sewage Sludge Survey - Sample Selection Strategy

MEMORANDUM

TO: Charles White, EPA

FROM: Kathleen Stralka, SAIC WAM

CC: Amit Kumar, SAIC
Dana Greenwood, RTI

DATE: August 10, 2001

REFERENCE: EPA Contract No. 68-C-99-233; Work Assignment No. 2-14
SAIC Project No. 01-0813-08-1657-140

SUBJECT: 2001 NSSS - Survey weights

TD/Dv#: T140806a/D140810a

In response to your technical direction, we transmit information for projecting samples in the 2001 National Sewage Sludge Survey (2001 NSSS) to the Nation.

Stratum (h)	Sample Size(n_h)	Operating POTWs in Sample	Adjusted Stratum (N_h)	Sampling Fraction (n_h/N_h)	Stratum Weight (N_h/N)
1	11	11	27	11/27	27/7201
2	30	30	301	30/301	301/7201
3	36	35	1787	35/1787	1787/7201
4	24	22	5086	22/5086	5086/7201
∑	101	98	7201		1.000

Strata 3 and 4 population sizes reflect adjustments for out-of-business facilities. Please notice that of the 98 POTWs in the 2001 NSSS, only 94 report data for dioxin and furans. The four POTWs that do not report dioxin data are accounted for as follows:

- Stratum 2 - episode 6422 samples were treated as blanks.
- Stratum 3 - No data from Episodes 6388 or 6389
- Stratum 4 - No data from Episode 6417.

The attached file lists the POTWs in the 2001 NSSS according to their stratum.

R165ff01

The primary assumption underlying the statistical sample design of the 2001 NSSS is that the population consists of 7,714 Publicly Owned Treatment Works (POTWs) across four strata. These strata categorize the POTWs according to the average daily flow of influent wastewater. The strata definitions and the strata sizes based on the 1988 population are tabulated below.

Stratum	Stratum Definition	Number of POTWs in the Population Stratum
1	Flow Greater than 100 million gallons per day (MGD)	27
2	10 MGD<Flow ≤100 MGD	301
3	1 MGD<Flow ≤10 MGD	1838
4	Flow ≤1 MGD	5548
Total		7,714

From the POTWs sampled for the 1988 NSSS, a statistical sample of 101 POTWs was drawn to comprise the 2001 NSSS. The sampling fractions for the 2001 NSSS were derived using Bayes Theorem.

Define A_h as the event that a POTW was randomly drawn from the N_h POTWs in stratum h of the 1988 population of POTWs. Define B_h as the event that a POTW was randomly drawn for the 2001 NSSS. The event B/A indicates that a POTW in the 2001 NSSS was randomly selected from the sample of n_h POTWs in the 1988 NSSS to be included in the 2001 NSSS. The event AB is defined as the event that a POTW is in both the 1988 and 2001 NSSS. Thus, using Bayes Theorem,

$P[B_h|A_h]*P[A_h]=P[AB_h]$ applied to stratum 1 yields a sampling fraction ($P[AB_h]$) of 11/27 because $P[B_h|A_h]*P[A_h]$ =11/19*19/27.

Three POTWs from the 1988 NSSS that were drawn for the 2001 NSSS were no longer in business. One of these out-of-business POTWs was in stratum 3. The other two were in stratum 4. Thus, the population stratum size was adjusted to reflected closed POTWs.

Appendix C

Agricultural Parameters

Table C-1. Agricultural Field and Monofill Parameters for Source Partitioning Models and Fate and Transport Model

Parameter Code	Parameter Description	Value	Reference	Land Application Unit Model	Fate and Transport Model
CutOffYr	Operating life (year)	Triangular distribution: min - 1 max - 40 mode - 20	U.S. EPA, 1995 (p. 6)	✓	✓
C_crop	USLE cover factor for the crop (unitless)	0.1	U.S. EPA, 2000	✓	
C_pasture	USLE cover factor for the pasture (unitless)	0.3	U.S. EPA, 2000	✓	
effdust	Dust suppression control efficiency for controlled areas (unitless)	Normal distribution: min - 0 max - 1 mean - 0.5 stdev - 0.3	Best professional judgment, based on information in U.S. EPA, 1989	✓	
ER	Soil enrichment ratio (unitless)	3	U.S. EPA, 2000		✓
fcult_crop	Number of cultivations per application for the crop (unitless)	3	U.S. EPA, 1995 (p. 177)	✓	
fcult_pasture	Number of cultivations per application for the pasture (unitless)	1	U.S. EPA, 1995 (p. 177)	✓	

(continued)

Table C-1. (continued)

Parameter Code	Parameter Description	Value	Reference	Land Application Unit Model	Fate and Transport Model
fd_crop	Frequency of surface disturbance per month for active LAU on the crop (1/mo)	Nappl x fcult_crop / 12 months	Best professional judgment	✓	
fd_pasture	Frequency of surface disturbance per month for active LAU on the pasture (1/mo)	Nappl x fcult_crop / 12 months	Best professional judgment	✓	
fwmu	Fraction of waste in waste management unit (mass fraction)	1	Best professional judgment	✓	
Lc	Roughness ratio (cm/h)	Lognormal distribution: min - 0.0001 max - 0.001 mean - 0.0003 stdev - 0.304	Carsel and Parrish, 1988	✓	
load	Waste loading rate (dry) (Mg/y)	capacity/ CutOffYr	Best professional judgment		
mcW	Volumetric water content (waste on trucks) (volume percent)	Triangular distribution: min - 1 max - 75 mode - 40	Best professional judgment	✓	
mt_crop	Distance vehicle travels on crop surface (m)	(Width of farm / Width of truck) * Length of farm * fcult	U.S. EPA, 1995 (pp. 173, 177)	✓	

(continued)

Table C-1. (continued)

Parameter Code	Parameter Description	Value	Reference	Land Application Unit Model	Fate and Transport Model
mt_pasture	Distance vehicle travels on pasture surface (m)	(Width of farm / Width of truck) * Length of farm * fcult	U.S. EPA, 1995 (pp. 173, 177)	✓	
Nappl	Waste applications per year (1/year)	1/2	Best professional judgment, based on information in U.S. EPA, 1989	✓	
nv_crop	Vehicles per day on the crop (mean annual) (1/d)	fcult_crop/ 365 days	Best professional judgment	✓	
nv_pasture	Vehicles per day on the pasture (mean annual) (1/d)	fcult_pasture/ 365 days	Best professional judgment	✓	
P_crop	USLE erosion control factor for crop (unitless)	0.5	Wanielista and Yousef, 1993	✓	
P_pasture	USLE erosion control factor for pasture (unitless)	1	Wanielista and Yousef, 1993	✓	
Rappl	Wet waste application rate (Mg/m^2-year)	Equal probability: min - 2.5E-04 max - 5.0E-03	U.S. EPA, 1995 (pp. 199-200)	✓	
Runoff_LWS	Runoff from local watershed (m^3/d)	Output from source model (add crop and pasture)			✓

(continued)

Table C-1. (continued)

Parameter Code	Parameter Description	Value	Reference	Land Application Unit Model	Fate and Transport Model
Runoff_RWS	Runoff from regional watershed (m^3/d)	Output from source model			✓
SY	Start time exposure begins (year)	Uniform distribution capped at the operating life of the unit	Best professional judgment	✓	✓
veg	Fraction vegetative cover for inactive source (fraction)	Normal distribution: min - 0.8 max - 1.0 mean - 0.9 stdev - 0.1	Best professional judgment	✓	
vw	Vehicle weight (mean) (Mg)	payload x BDw x2 (payload assumed to be 10 cu yd)	Best professional judgment	✓	
zava	Upper depth average soil concentration (m)	0.01	Best professional judgment	✓	
zavb	Lower depth average soil concentration (m)	0.2	Best professional judgment	✓	
zruf_crop	Roughness height for crop (cm)	1	Best professional judgment, based on information in U.S. EPA, 1989	✓	
zruf_pasture	Roughness height for pasture (cm)	1	Best professional judgment, based on information in U.S. EPA, 1989	✓	

References

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Appendix D

Congener-Specific Parameters for Source Partitioning and Fate and Transport Models

Appendix D

Congener-Specific Parameters for Source Partitioning and Fate and Transport Models

The values for congener-specific data were collected for both the source partitioning model and the fate and transport model. Some parameters are used in both source model and the fate and transport model while others are unique to a particular model. Table D-1 presents the parameters used and which model they are used in.

Table D-1. Congener-Specific Parameters for Source Partitioning and Fate and Transport Models

Parameter	Source Partitioning Model	Fate and Transport Model
Air to plant biotransfer factor (Bv)		✓
Antoine's B constant (AntB)	✓	
Antoine's C constant (AntC)	✓	
Bioconcentration factor for cattle (BCF_cattle)		✓
Bioconcentration factor for eggs (BCF_egg)		✓
Bioconcentration factor for poultry (BCF_poultry)		✓
Biota to sediment accumulation factor (BSAF)		✓
Boiling point (tb)	✓	
Critical pressure (Pc)	✓	
Critical temperature (tc)	✓	
Degradation rate in sediment (kgs)	✓	✓

(continued)

Table D-1. (continued)

Parameter	Source Partitioning Model	Fate and Transport Model
Degradation rate in soil (Ksg)	✓	✓
Degradation rate in surface water (kgw)		✓
Diffusivity in air (Da)	✓	✓
Diffusivity in water (Dw)	✓	✓
Dry deposition velocity (Vdv)		✓
Fraction of wet deposition adhering to plant surface (Fw)		✓
Henry's law constant (HLC)	✓	✓
Hydrolysis (Kh)	✓	✓
Melting point (MP)		✓
Molecular weight (MW)		✓
Organic carbon partition coefficient (Koc)	✓	✓
Plant surface loss coefficient for particulates (KpPar)		✓
Root concentration factor (RCF)		✓
Soil water partition coefficient (Kow)		✓
Solubility (S)	✓	✓
Toxicity equivalency factors (TEF)		✓
Vapor pressure (VP)	✓	✓

The primary source for data collection was the *Exposure and Human Health Reassessment of 2,3,7,8-Tetrachlorodibenzo-p-Dioxin (TCDD) and Related Compounds* (U.S. EPA, 2000). Values for water solubility and vapor pressure were collected from U.S. EPA (1994) and ATSDR (1994) when data were not available in the Draft Dioxin Reassessment. Values for diffusivity in water were calculated based on Equation D-1 provided by *Processes, Coefficients, and Models for Simulating Toxic Organics and Heavy Metals in Surface Waters* (U.S. EPA, 1987):

$$Dw = 0.00022 \times MW^{(-2/3)} \qquad \text{(D-1)}$$

Degradation (soil, sediment, surface water) and hydrolysis rates were assumed to be zero as recommended by the Dioxin Reassessment (U.S. EPA, 2000). Soil water partition coefficients are calculated the model using the following equation:

$$Kd = foc \times K_{OC} \quad \text{(D-2)}$$

Parameters in the fate and transport model that were held constant for all congeners included KpPar, Fw, and Vdv.

Parameter	Definition	Value	Reference
Fw	Fraction of wet deposition adhering to plant surface (unitless)	0.6	U.S. EPA, 1997
KpPar	Plant surface loss coefficient for particulates (1/yr)	18.07	U.S. EPA, 1997
Vdv	Dry deposition velocity (cm/s)	0.2	Koester and Hites, 1992

Within the source model, temperature correction routines were instated for chemical diffusivity in air (D_a), chemical diffusivity in water (D_w), and Henry's law constant (H). The correction routine for D_a was derived from the FSG Method (Lyman et al.,1990, Ch. 17, Eq. 17-12, and the routine for D_w was derived from Eq 17-24 (Hayduk and Laudie) in Lyman et al. (1990). The temperature correction for H used estimates of the heat of vaporization from Lyman et al. (1990), Eq. 13-21. The Haggenmacher method (Lyman et al., 1990, Section 13-5) is used to determine the heat of vaporization at the boiling point. Temperature corrections for partitioning (K_d, K_{oc}), hydrolysis, and solubility were not included in the model. These routines use Antoine's constants B and C, the boiling temperature of the chemical, and the critical temperature and pressure for the chemical. Because there were no values for Antoine's constants or the critical temperature and pressure, default equations were used by the model.

Table D-2. Chemical-Specific Inputs for 2,3,3',4,4',5,5'-HpCB (CAS No. 39635-31-9)

Parameter	Definition	Value	Reference
TEF	Toxicity equivalency factors	0.0001	U.S. EPA, 2000
MW	Molecular weight (g/mol)	395.33	U.S. EPA, 2000
MP	Melting point (degrees C)	162	U.S. EPA, 2000
tb	Boiling point (degrees C)	400	ATSDR, 1998b
S	Water solubility (mg/L)	6.26E-05	U.S. EPA, 2000
VP	Vapor pressure (mm Hg)	1.31E-08	U.S. EPA, 2000
HLC	Henry's Law Constant (atm-m3/mol)	6.65E-05	U.S. EPA, 2000
Da	Diffusivity in air (cm2/s)	4.24E-02	U.S. EPA, 2000
Dw	Diffusivity in water (cm2/s)	4.08E-06	U.S. EPA, 1987
Koc	Organic carbon partition coefficient (unitless)	3.16E+07	U.S. EPA, 2000
Kow	Soil water partition coefficient (mL/g)	5.13E+07	U.S. EPA, 2000
RCF	Root concentration factor (ug/g WW plant)/(ug/mL soil water)	2.61E+04	U.S. EPA, 2000
Bv	Air-to-plant biotransfer factor (ug/g DW plant)/(ug/g air)	1.49E+05	U.S. EPA, 2000
BSAF	Biota-to-sediment accumulation factor (unitless)	2.08	U.S. EPA, 2000
BCF_cattle	Bioconcentration factor for cattle (unitless)	2.3	U.S. EPA, 2000
BCF_poultry	Bioconcentration factor for poultry (unitless)	7.4	U.S. EPA, 2000
BCF_egg	Bioconcentration factor for eggs (unitless)	6.5	U.S. EPA, 2000

Table D-3. Chemical-Specific Inputs for 1,2,3,4,6,7,8-HpCDD (CAS No. 35822-46-9)

Parameter	Definition	Value	Reference
TEF	Toxicity equivalency factors	0.01	U.S. EPA, 2000
MW	Molecular weight (g/mol)	425.31	U.S. EPA, 2000
MP	Melting point (degrees C)	264	U.S. EPA, 2000
tb	Boiling point (degrees C)	507.2	ATSDR, 1998a
S	Water solubility (mg/L)	2.40E-06	U.S. EPA, 2000
VP	Vapor pressure (mm Hg)	5.60E-12	U.S. EPA, 2000
HLC	Henry's Law Constant (atm-m3/mol)	1.26E-05	U.S. EPA, 2000
Da	Diffusivity in air (cm2/s)	4.09E-02	U.S. EPA, 2000
Dw	Diffusivity in water (cm2/s)	3.89E-06	U.S. EPA, 1987
Koc	Organic carbon partition coefficient (unitless)	6.17E+07	U.S. EPA, 2000
Kow	Soil water partition coefficient (mL/g)	1.00E+08	U.S. EPA, 2000
RCF	Root concentration factor (ug/g WW plant)/(ug/mL soil water)	4.37E+04	U.S. EPA, 2000
Bv	Air-to-plant biotransfer factor (ug/g DW plant)/(ug/g air)	9.10E+05	U.S. EPA, 2000
BSAF	Biota-to-sediment accumulation factor (unitless)	0.003	U.S. EPA, 2000
BCF_cattle	Bioconcentration factor for cattle (unitless)	0.48	U.S. EPA, 2000
BCF_poultry	Bioconcentration factor for poultry (unitless)	1.4	U.S. EPA, 2000
BCF_egg	Bioconcentration factor for eggs (unitless)	4.8	U.S. EPA, 2000

Table D-4. Chemical-Specific Inputs for 1,2,3,4,6,7,8-HpCDF (CAS No. 67562-39-4)

Parameter	Definition	Value	Reference
TEF	Toxicity equivalency factors	0.01	U.S. EPA, 2000
MW	Molecular weight (g/mol)	409.31	U.S. EPA, 2000
MP	Melting point (degrees C)	236	U.S. EPA, 2000
tb	Boiling point (degrees C)	500	ATSDR, 1994
S	Water solubility (mg/L)	1.35E-06	U.S. EPA, 2000
VP	Vapor pressure (mm Hg)	3.50E-11	U.S. EPA, 2000
HLC	Henry's Law Constant (atm-m3/mol)	1.41E-05	U.S. EPA, 2000
Da	Diffusivity in air (cm2/s)	4.17E-02	U.S. EPA, 2000
Dw	Diffusivity in water (cm2/s)	3.99E-06	U.S. EPA, 1987
Koc	Organic carbon partition coefficient (unitless)	1.55E+07	U.S. EPA, 2000
Kow	Soil water partition coefficient (mL/g)	2.51E+07	U.S. EPA, 2000
RCF	Root concentration factor (ug/g WW plant)/(ug/mL soil water)	1.51E+04	U.S. EPA, 2000
Bv	Air-to-plant biotransfer factor (ug/g DW plant)/(ug/g air)	8.30E+05	U.S. EPA, 2000
BSAF	Biota-to-sediment accumulation factor (unitless)	0.001	U.S. EPA, 2000
BCF_cattle	Bioconcentration factor for cattle (unitless)	0.55	U.S. EPA, 2000
BCF_poultry	Bioconcentration factor for poultry (unitless)	1	U.S. EPA, 2000
BCF_egg	Bioconcentration factor for eggs (unitless)	3.1	U.S. EPA, 2000

Table D-5. Chemical-Specific Inputs for 1,2,3,4,7,8,9-HpCDF (CAS No. 55673-89-7)

Parameter	Definition	Value	Reference
TEF	Toxicity equivalency factors	0.01	U.S. EPA, 2000
MW	Molecular weight (g/mol)	409.31	U.S. EPA, 2000
MP	Melting point (degrees C)	221	U.S. EPA, 2000
tb	Boiling point (degrees C)	500	ATSDR, 1994
S	Water solubility (mg/L)	1.35E-06	U.S. EPA, 1994
VP	Vapor pressure (mm Hg)	1.07E-10	U.S. EPA, 2000
HLC	Henry's Law Constant (atm-m3/mol)	1.40E-05	U.S. EPA, 2000
Da	Diffusivity in air (cm2/s)	4.17E-02	U.S. EPA, 2000
Dw	Diffusivity in water (cm2/s)	3.99E-06	U.S. EPA, 1987
Koc	Organic carbon partition coefficient (unitless)	6.17E+07	U.S. EPA, 2000
Kow	Soil water partition coefficient (mL/g)	1.00E+08	U.S. EPA, 2000
RCF	Root concentration factor (ug/g WW plant)/(ug/mL soil water)	4.37E+04	U.S. EPA, 2000
Bv	Air-to-plant biotransfer factor (ug/g DW plant)/(ug/g air)	8.30E+05	U.S. EPA, 2000
BSAF	Biota-to-sediment accumulation factor (unitless)	0.035	U.S. EPA, 2000
BCF_cattle	Bioconcentration factor for cattle (unitless)	1.32	U.S. EPA, 2000
BCF_poultry	Bioconcentration factor for poultry (unitless)	0.9	U.S. EPA, 2000
BCF_egg	Bioconcentration factor for eggs (unitless)	2.2	U.S. EPA, 2000

Table D-6. Chemical-Specific Inputs for 2,3,3',4,4',5-HxCB (CAS No. 38380-08-4)

Parameter	Definition	Value	Reference
TEF	Toxicity equivalency factors	0.0005	U.S. EPA, 2000
MW	Molecular weight (g/mol)	360.88	U.S. EPA, 2000
MP	Melting point (degrees C)	129.5	U.S. EPA, 2000
tb	Boiling point (degrees C)	400	ATSDR, 1998b
S	Water solubility (mg/L)	4.10E-04	U.S. EPA, 2000
VP	Vapor pressure (mm Hg)	1.47E-07	U.S. EPA, 2000
HLC	Henry's Law Constant (atm-m3/mol)	8.70E-04	U.S. EPA, 2000
Da	Diffusivity in air (cm2/s)	4.44E-02	U.S. EPA, 2000
Dw	Diffusivity in water (cm2/s)	4.34E-06	U.S. EPA, 1987
Koc	Organic carbon partition coefficient (unitless)	8.91E+06	U.S. EPA, 2000
Kow	Soil water partition coefficient (mL/g)	1.45E+07	U.S. EPA, 2000
RCF	Root concentration factor (ug/g WW plant)/(ug/mL soil water)	9.84E+03	U.S. EPA, 2000
Bv	Air-to-plant biotransfer factor (ug/g DW plant)/(ug/g air)	1.49E+05	U.S. EPA, 2000
BSAF	Biota-to-sediment accumulation factor (unitless)	3.97	U.S. EPA, 2000
BCF_cattle	Bioconcentration factor for cattle (unitless)	2.2	U.S. EPA, 2000
BCF_poultry	Bioconcentration factor for poultry (unitless)	7.4	U.S. EPA, 2000
BCF_egg	Bioconcentration factor for eggs (unitless)	6.5	U.S. EPA, 2000

Table D-7. Chemical-Specific Inputs for 2,3',4,4',5,5'-HxCB (CAS No. 52663-72-6)

Parameter	Definition	Value	Reference
TEF	Toxicity equivalency factors	0.00001	U.S. EPA, 2000
MW	Molecular weight (g/mol)	360.88	U.S. EPA, 2000
MP	Melting point (degrees C)	125	U.S. EPA, 2000
tb	Boiling point (degrees C)	400	ATSDR, 1998b
S	Water solubility (mg/L)	3.61E-04	U.S. EPA, 2000
VP	Vapor pressure (mm Hg)	1.95E-07	U.S. EPA, 2000
HLC	Henry's Law Constant (atm-m3/mol)	1.10E-04	U.S. EPA, 2000
Da	Diffusivity in air (cm2/s)	4.44E-02	U.S. EPA, 2000
Dw	Diffusivity in water (cm2/s)	4.34E-06	U.S. EPA, 1987
Koc	Organic carbon partition coefficient (unitless)	7.59E+06	U.S. EPA, 2000
Kow	Soil water partition coefficient (mL/g)	1.23E+07	U.S. EPA, 2000
RCF	Root concentration factor (ug/g WW plant)/(ug/mL soil water)	8.70E+03	U.S. EPA, 2000
Bv	Air-to-plant biotransfer factor (ug/g DW plant)/(ug/g air)	1.49E+05	U.S. EPA, 2000
BSAF	Biota-to-sediment accumulation factor (unitless)	8.35	U.S. EPA, 2000
BCF_cattle	Bioconcentration factor for cattle (unitless)	2.2	U.S. EPA, 2000
BCF_poultry	Bioconcentration factor for poultry (unitless)	7.4	U.S. EPA, 2000
BCF_egg	Bioconcentration factor for eggs (unitless)	6.5	U.S. EPA, 2000

Table D-8. Chemical-Specific Inputs for 3,3',4,4',5,5'-HxCB (CAS No. 32774-16-6)

Parameter	Definition	Value	Reference
TEF	Toxicity equivalency factors	0.01	U.S. EPA, 2000
MW	Molecular weight (g/mol)	360.88	U.S. EPA, 2000
MP	Melting point (degrees C)	208	U.S. EPA, 2000
tb	Boiling point (degrees C)	400	ATSDR, 1998b
S	Water solubility (mg/L)	3.61E-05	U.S. EPA, 2000
VP	Vapor pressure (mm Hg)	1.81E-07	U.S. EPA, 2000
HLC	Henry's Law Constant (atm-m3/mol)	6.52E-05	U.S. EPA, 2000
Da	Diffusivity in air (cm2/s)	4.44E-02	U.S. EPA, 2000
Dw	Diffusivity in water (cm2/s)	4.34E-06	U.S. EPA, 1987
Koc	Organic carbon partition coefficient (unitless)	1.78E+07	U.S. EPA, 2000
Kow	Soil water partition coefficient (mL/g)	2.88E+07	U.S. EPA, 2000
RCF	Root concentration factor (ug/g WW plant)/(ug/mL soil water)	1.70E+04	U.S. EPA, 2000
Bv	Air-to-plant biotransfer factor (ug/g DW plant)/(ug/g air)	1.49E+05	U.S. EPA, 2000
BSAF	Biota-to-sediment accumulation factor (unitless)	11.85	U.S. EPA, 2000
BCF_cattle	Bioconcentration factor for cattle (unitless)	2.2	U.S. EPA, 2000
BCF_poultry	Bioconcentration factor for poultry (unitless)	6.5	U.S. EPA, 2000
BCF_egg	Bioconcentration factor for eggs (unitless)	7.4	U.S. EPA, 2000

Table D-9. Chemical-Specific Inputs for 1,2,3,4,7,8-HxCDD (CAS No. 39227-28-6)

Parameter	Definition	Value	Reference
TEF	Toxicity equivalency factors	0.1	U.S. EPA, 2000
MW	Molecular weight (g/mol)	390.87	U.S. EPA, 2000
MP	Melting point (degrees C)	273	U.S. EPA, 2000
tb	Boiling point (degrees C)	500	ATSDR, 1998a
S	Water solubility (mg/L)	4.42E-06	U.S. EPA, 2000
VP	Vapor pressure (mm Hg)	3.80E-11	U.S. EPA, 2000
HLC	Henry's Law Constant (atm-m3/mol)	1.07E-05	U.S. EPA, 2000
Da	Diffusivity in air (cm2/s)	4.27E-02	U.S. EPA, 2000
Dw	Diffusivity in water (cm2/s)	4.12E-06	U.S. EPA, 1987
Koc	Organic carbon partition coefficient (unitless)	3.89E+07	U.S. EPA, 2000
Kow	Soil water partition coefficient (mL/g)	6.31E+07	U.S. EPA, 2000
RCF	Root concentration factor (ug/g WW plant)/(ug/mL soil water)	3.06E+04	U.S. EPA, 2000
Bv	Air-to-plant biotransfer factor (ug/g DW plant)/(ug/g air)	5.20E+05	U.S. EPA, 2000
BSAF	Biota-to-sediment accumulation factor (unitless)	0.028	U.S. EPA, 2000
BCF_cattle	Bioconcentration factor for cattle (unitless)	2.69	U.S. EPA, 2000
BCF_poultry	Bioconcentration factor for poultry (unitless)	3.6	U.S. EPA, 2000
BCF_egg	Bioconcentration factor for eggs (unitless)	5.4	U.S. EPA, 2000

Table D-10. Chemical-Specific Inputs for 1,2,3,6,7,8-HxCDD (CAS No. 57653-85-7)

Parameter	Definition	Value	Reference
TEF	Toxicity equivalency factors	0.1	U.S. EPA, 2000
MW	Molecular weight (g/mol)	390.87	U.S. EPA, 2000
MP	Melting point (degrees C)	285	U.S. EPA, 2000
tb	Boiling point (degrees C)	500	ATSDR, 1998a
S	Water solubility (mg/L)	4.40E-06	U.S. EPA, 1994
VP	Vapor pressure (mm Hg)	3.60E-11	U.S. EPA, 2000
HLC	Henry's Law Constant (atm-m3/mol)	1.10E-05	U.S. EPA, 2000
Da	Diffusivity in air (cm2/s)	4.27E-02	U.S. EPA, 2000
Dw	Diffusivity in water (cm2/s)	4.12E-06	U.S. EPA, 1987
Koc	Organic carbon partition coefficient (unitless)	1.23E+07	U.S. EPA, 2000
Kow	Soil water partition coefficient (mL/g)	2.00E+07	U.S. EPA, 2000
RCF	Root concentration factor (ug/g WW plant)/(ug/mL soil water)	1.26E+04	U.S. EPA, 2000
Bv	Air-to-plant biotransfer factor (ug/g DW plant)/(ug/g air)	5.20E+05	U.S. EPA, 2000
BSAF	Biota-to-sediment accumulation factor (unitless)	0.011	U.S. EPA, 2000
BCF_cattle	Bioconcentration factor for cattle (unitless)	2.32	U.S. EPA, 2000
BCF_poultry	Bioconcentration factor for poultry (unitless)	5.6	U.S. EPA, 2000
BCF_egg	Bioconcentration factor for eggs (unitless)	10.2	U.S. EPA, 2000

Table D-11. Chemical-Specific Inputs for 1,2,3,7,8,9-HxCDD (CAS No. 19408-74-3)

Parameter	Definition	Value	Reference
TEF	Toxicity equivalency factors	0.1	U.S. EPA, 2000
MW	Molecular weight (g/mol)	390.87	U.S. EPA, 2000
MP	Melting point (degrees C)	243	U.S. EPA, 2000
tb	Boiling point (degrees C)	500	ATSDR, 1998a
S	Water solubility (mg/L)	4.40E-06	U.S. EPA, 1994
VP	Vapor pressure (mm Hg)	4.90E-11	U.S. EPA, 2000
HLC	Henry's Law Constant (atm-m3/mol)	1.10E-05	U.S. EPA, 2000
Da	Diffusivity in air (cm2/s)	4.27E-02	U.S. EPA, 2000
Dw	Diffusivity in water (cm2/s)	4.12E-06	U.S. EPA, 1987
Koc	Organic carbon partition coefficient (unitless)	1.23E+07	U.S. EPA, 2000
Kow	Soil water partition coefficient (mL/g)	2.00E+07	U.S. EPA, 2000
RCF	Root concentration factor (ug/g WW plant)/(ug/mL soil water)	1.26E+04	U.S. EPA, 2000
Bv	Air-to-plant biotransfer factor (ug/g DW plant)/(ug/g air)	5.20E+05	U.S. EPA, 2000
BSAF	Biota-to-sediment accumulation factor (unitless)	0.013	U.S. EPA, 2000
BCF_cattle	Bioconcentration factor for cattle (unitless)	2.99	U.S. EPA, 2000
BCF_poultry	Bioconcentration factor for poultry (unitless)	2.4	U.S. EPA, 2000
BCF_egg	Bioconcentration factor for eggs (unitless)	4.5	U.S. EPA, 2000

Table D-12. Chemical-Specific Inputs for 1,2,3,4,7,8-HxCDF (CAS No. 70648-26-9)

Parameter	Definition	Value	Reference
TEF	Toxicity equivalency factors	0.1	U.S. EPA, 2000
MW	Molecular weight (g/mol)	374.87	U.S. EPA, 2000
MP	Melting point (degrees C)	225.5	U.S. EPA, 2000
tb	Boiling point (degrees C)	500	ATSDR, 1994
S	Water solubility (mg/L)	8.25E-06	U.S. EPA, 2000
VP	Vapor pressure (mm Hg)	2.40E-10	U.S. EPA, 2000
HLC	Henry's Law Constant (atm-m3/mol)	1.43E-05	U.S. EPA, 2000
Da	Diffusivity in air (cm2/s)	4.36E-02	U.S. EPA, 2000
Dw	Diffusivity in water (cm2/s)	4.23E-06	U.S. EPA, 1987
Koc	Organic carbon partition coefficient (unitless)	6.17E+06	U.S. EPA, 2000
Kow	Soil water partition coefficient (mL/g)	1.00E+07	U.S. EPA, 2000
RCF	Root concentration factor (ug/g WW plant)/(ug/mL soil water)	7.41E+03	U.S. EPA, 2000
Bv	Air-to-plant biotransfer factor (ug/g DW plant)/(ug/g air)	1.62E+05	U.S. EPA, 2000
BSAF	Biota-to-sediment accumulation factor (unitless)	0.007	U.S. EPA, 2000
BCF_cattle	Bioconcentration factor for cattle (unitless)	3.12	U.S. EPA, 2000
BCF_poultry	Bioconcentration factor for poultry (unitless)	4.8	U.S. EPA, 2000
BCF_egg	Bioconcentration factor for eggs (unitless)	7.4	U.S. EPA, 2000

Table D-13. Chemical-Specific Inputs for 1,2,3,6,7,8-HxCDF (CAS No. 57117-44-9)

Parameter	Definition	Value	Reference
TEF	Toxicity equivalency factors	0.1	U.S. EPA, 2000
MW	Molecular weight (g/mol)	374.87	U.S. EPA, 2000
MP	Melting point (degrees C)	232	U.S. EPA, 2000
tb	Boiling point (degrees C)	500	ATSDR, 1994
S	Water solubility (mg/L)	1.77E-05	U.S. EPA, 2000
VP	Vapor pressure (mm Hg)	2.20E-10	U.S. EPA, 2000
HLC	Henry's Law Constant (atm-m3/mol)	7.31E-06	U.S. EPA, 2000
Da	Diffusivity in air (cm2/s)	4.36E-02	U.S. EPA, 2000
Dw	Diffusivity in water (cm2/s)	4.23E-06	U.S. EPA, 1987
Koc	Organic carbon partition coefficient (unitless)	6.17E+06	U.S. EPA, 2000
Kow	Soil water partition coefficient (mL/g)	1.00E+07	U.S. EPA, 2000
RCF	Root concentration factor (ug/g WW plant)/(ug/mL soil water)	7.41E+03	U.S. EPA, 2000
Bv	Air-to-plant biotransfer factor (ug/g DW plant)/(ug/g air)	1.62E+05	U.S. EPA, 2000
BSAF	Biota-to-sediment accumulation factor (unitless)	0.017	U.S. EPA, 2000
BCF_cattle	Bioconcentration factor for cattle (unitless)	2.67	U.S. EPA, 2000
BCF_poultry	Bioconcentration factor for poultry (unitless)	5.3	U.S. EPA, 2000
BCF_egg	Bioconcentration factor for eggs (unitless)	8.2	U.S. EPA, 2000

Table D-14. Chemical-Specific Inputs for 1,2,3,7,8,9-HxCDF (CAS No. 72918-21-9)

Parameter	Definition	Value	Reference
TEF	Toxicity equivalency factors	0.1	U.S. EPA, 2000
MW	Molecular weight (g/mol)	374.87	U.S. EPA, 2000
MP	Melting point (degrees C)	246	U.S. EPA, 2000
tb	Boiling point (degrees C)	500	ATSDR, 1994
S	Water solubility (mg/L)	1.30E-05	U.S. EPA, 1994
VP	Vapor pressure (mm Hg)	3.74E-08	U.S. EPA, 2000
HLC	Henry's Law Constant (atm-m3/mol)	1.10E-05	U.S. EPA, 2000
Da	Diffusivity in air (cm2/s)	4.36E-02	U.S. EPA, 2000
Dw	Diffusivity in water (cm2/s)	4.23E-06	U.S. EPA, 1987
Koc	Organic carbon partition coefficient (unitless)	6.17E+06	U.S. EPA, 2000
Kow	Soil water partition coefficient (mL/g)	1.00E+07	U.S. EPA, 2000
RCF	Root concentration factor (ug/g WW plant)/(ug/mL soil water)	7.41E+03	U.S. EPA, 2000
Bv	Air-to-plant biotransfer factor (ug/g DW plant)/(ug/g air)	1.62E+05	U.S. EPA, 2000
BSAF	Biota-to-sediment accumulation factor (unitless)	0.06	U.S. EPA, 2000
BCF_cattle	Bioconcentration factor for cattle (unitless)	2.67	U.S. EPA, 2000
BCF_poultry	Bioconcentration factor for poultry (unitless)	4.1	U.S. EPA, 2000
BCF_egg	Bioconcentration factor for eggs (unitless)	6.2	U.S. EPA, 2000

Table D-15. Chemical-Specific Inputs for 2,3,4,6,7,8-HxCDF (CAS No. 60851-34-5)

Parameter	Definition	Value	Reference
TEF	Toxicity equivalency factors	0.1	U.S. EPA, 2000
MW	Molecular weight (g/mol)	374.87	U.S. EPA, 2000
MP	Melting point (degrees C)	239	U.S. EPA, 2000
tb	Boiling point (degrees C)	500	ATSDR, 1994
S	Water solubility (mg/L)	1.30E-05	U.S. EPA, 1994
VP	Vapor pressure (mm Hg)	2.00E-10	U.S. EPA, 2000
HLC	Henry's Law Constant (atm-m3/mol)	1.10E-05	U.S. EPA, 2000
Da	Diffusivity in air (cm2/s)	4.36E-02	U.S. EPA, 2000
Dw	Diffusivity in water (cm2/s)	4.23E-06	U.S. EPA, 1987
Koc	Organic carbon partition coefficient (unitless)	6.17E+06	U.S. EPA, 2000
Kow	Soil water partition coefficient (mL/g)	1.00E+07	U.S. EPA, 2000
RCF	Root concentration factor (ug/g WW plant)/(ug/mL soil water)	7.41E+03	U.S. EPA, 2000
Bv	Air-to-plant biotransfer factor (ug/g DW plant)/(ug/g air)	1.62E+05	U.S. EPA, 2000
BSAF	Biota-to-sediment accumulation factor (unitless)	0.057	U.S. EPA, 2000
BCF_cattle	Bioconcentration factor for cattle (unitless)	2.37	U.S. EPA, 2000
BCF_poultry	Bioconcentration factor for poultry (unitless)	2.1	U.S. EPA, 2000
BCF_egg	Bioconcentration factor for eggs (unitless)	3	U.S. EPA, 2000

Table D-16. Chemical-Specific Inputs for 1,2,3,4,6,7,8,9-OCDD (CAS No. 3268-87-9)

Parameter	Definition	Value	Reference
TEF	Toxicity equivalency factors	0.0001	U.S. EPA, 2000
MW	Molecular weight (g/mol)	460.76	U.S. EPA, 2000
MP	Melting point (degrees C)	325	U.S. EPA, 2000
tb	Boiling point (degrees C)	510	ATSDR, 1998a
S	Water solubility (mg/L)	7.40E-08	U.S. EPA, 2000
VP	Vapor pressure (mm Hg)	8.25E-13	U.S. EPA, 2000
HLC	Henry's Law Constant (atm-m3/mol)	6.75E-06	U.S. EPA, 2000
Da	Diffusivity in air (cm2/s)	3.93E-02	U.S. EPA, 2000
Dw	Diffusivity in water (cm2/s)	3.69E-06	U.S. EPA, 1987
Koc	Organic carbon partition coefficient (unitless)	9.77E+07	U.S. EPA, 2000
Kow	Soil water partition coefficient (mL/g)	1.58E+08	U.S. EPA, 2000
RCF	Root concentration factor (ug/g WW plant)/(ug/mL soil water)	6.22E+04	U.S. EPA, 2000
Bv	Air-to-plant biotransfer factor (ug/g DW plant)/(ug/g air)	2.36E+06	U.S. EPA, 2000
BSAF	Biota-to-sediment accumulation factor (unitless)	0.001	U.S. EPA, 2000
BCF_cattle	Bioconcentration factor for cattle (unitless)	0.69	U.S. EPA, 2000
BCF_poultry	Bioconcentration factor for poultry (unitless)	0.3	U.S. EPA, 2000
BCF_egg	Bioconcentration factor for eggs (unitless)	4.3	U.S. EPA, 2000

Table D-17. Chemical-Specific Inputs for 1,2,3,4,6,7,8,9-OCDF (CAS No. 39001-02-0)

Parameter	Definition	Value	Reference
TEF	Toxicity equivalency factors	0.0001	U.S. EPA, 2000
MW	Molecular weight (g/mol)	444.76	U.S. EPA, 2000
MP	Melting point (degrees C)	258	U.S. EPA, 2000
tb	Boiling point (degrees C)	537	ATSDR, 1994
S	Water solubility (mg/L)	1.16E-06	U.S. EPA, 2000
VP	Vapor pressure (mm Hg)	3.75E-12	U.S. EPA, 2000
HLC	Henry's Law Constant (atm-m3/mol)	1.88E-06	U.S. EPA, 2000
Da	Diffusivity in air (cm2/s)	4.00E-02	U.S. EPA, 2000
Dw	Diffusivity in water (cm2/s)	3.78E-06	U.S. EPA, 1987
Koc	Organic carbon partition coefficient (unitless)	3.89E+08	U.S. EPA, 2000
Kow	Soil water partition coefficient (mL/g)	6.31E+08	U.S. EPA, 2000
RCF	Root concentration factor (ug/g WW plant)/(ug/mL soil water)	1.80E+05	U.S. EPA, 2000
Bv	Air-to-plant biotransfer factor (ug/g DW plant)/(ug/g air)	2.28E+06	U.S. EPA, 2000
BSAF	Biota-to-sediment accumulation factor (unitless)	0.001	U.S. EPA, 2000
BCF_cattle	Bioconcentration factor for cattle (unitless)	0.27	U.S. EPA, 2000
BCF_poultry	Bioconcentration factor for poultry (unitless)	0.3	U.S. EPA, 2000
BCF_egg	Bioconcentration factor for eggs (unitless)	1.4	U.S. EPA, 2000

Table D-18. Chemical-Specific Inputs for 2,3,3',4,4'-PeCB (CAS No. 32598-14-4)

Parameter	Definition	Value	Reference
TEF	Toxicity equivalency factors	0.0001	U.S. EPA, 2000
MW	Molecular weight (g/mol)	326.44	U.S. EPA, 2000
MP	Melting point (degrees C)	116.5	U.S. EPA, 2000
tb	Boiling point (degrees C)	380	ATSDR, 1998b
S	Water solubility (mg/L)	1.90E-03	U.S. EPA, 2000
VP	Vapor pressure (mm Hg)	8.28E-07	U.S. EPA, 2000
HLC	Henry's Law Constant (atm-m3/mol)	9.93E-05	U.S. EPA, 2000
Da	Diffusivity in air (cm2/s)	4.67E-02	U.S. EPA, 2000
Dw	Diffusivity in water (cm2/s)	4.64E-06	U.S. EPA, 1987
Koc	Organic carbon partition coefficient (unitless)	6.17E+05	U.S. EPA, 2000
Kow	Soil water partition coefficient (mL/g)	1.00E+06	U.S. EPA, 2000
RCF	Root concentration factor (ug/g WW plant)/(ug/mL soil water)	1.26E+03	U.S. EPA, 2000
Bv	Air-to-plant biotransfer factor (ug/g DW plant)/(ug/g air)	1.49E+05	U.S. EPA, 2000
BSAF	Biota-to-sediment accumulation factor (unitless)	4.18	U.S. EPA, 2000
BCF_cattle	Bioconcentration factor for cattle (unitless)	1.2	U.S. EPA, 2000
BCF_poultry	Bioconcentration factor for poultry (unitless)	7.4	U.S. EPA, 2000
BCF_egg	Bioconcentration factor for eggs (unitless)	6.5	U.S. EPA, 2000

Table D-19. Chemical-Specific Inputs for 2',3,4,4',5-PeCB (CAS No. 65510-44-3)

Parameter	Definition	Value	Reference
TEF	Toxicity equivalency factors	0.0001	U.S. EPA, 2000
MW	Molecular weight (g/mol)	326.44	U.S. EPA, 2000
MP	Melting point (degrees C)	134	U.S. EPA, 2000
tb	Boiling point (degrees C)	380	ATSDR, 1998b
S	Water solubility (mg/L)	1.64E-03	U.S. EPA, 2000
VP	Vapor pressure (mm Hg)	8.78E-07	U.S. EPA, 2000
HLC	Henry's Law Constant (atm-m3/mol)	1.74E-04	U.S. EPA, 2000
Da	Diffusivity in air (cm2/s)	4.67E-02	U.S. EPA, 2000
Dw	Diffusivity in water (cm2/s)	4.64E-06	U.S. EPA, 1987
Koc	Organic carbon partition coefficient (unitless)	3.39E+06	U.S. EPA, 2000
Kow	Soil water partition coefficient (mL/g)	5.50E+06	U.S. EPA, 2000
RCF	Root concentration factor (ug/g WW plant)/(ug/mL soil water)	4.68E+03	U.S. EPA, 2000
Bv	Air-to-plant biotransfer factor (ug/g DW plant)/(ug/g air)	1.49E+05	U.S. EPA, 2000
BSAF	Biota-to-sediment accumulation factor (unitless)	6.4	U.S. EPA, 2000
BCF_cattle	Bioconcentration factor for cattle (unitless)	1.2	U.S. EPA, 2000
BCF_poultry	Bioconcentration factor for poultry (unitless)	7.4	U.S. EPA, 2000
BCF_egg	Bioconcentration factor for eggs (unitless)	6.5	U.S. EPA, 2000

Table D-20. Chemical-Specific Inputs for 2,3',4,4',5-PeCB (CAS No. 31508-00-6)

Parameter	Definition	Value	Reference
TEF	Toxicity equivalency factors	0.0001	U.S. EPA, 2000
MW	Molecular weight (g/mol)	326.44	U.S. EPA, 2000
MP	Melting point (degrees C)	111	U.S. EPA, 2000
tb	Boiling point (degrees C)	380	ATSDR, 1998b
S	Water solubility (mg/L)	1.59E-03	U.S. EPA, 2000
VP	Vapor pressure (mm Hg)	3.14E-07	U.S. EPA, 2000
HLC	Henry's Law Constant (atm-m3/mol)	8.50E-05	U.S. EPA, 2000
Da	Diffusivity in air (cm2/s)	4.67E-02	U.S. EPA, 2000
Dw	Diffusivity in water (cm2/s)	4.64E-06	U.S. EPA, 1987
Koc	Organic carbon partition coefficient (unitless)	8.13E+06	U.S. EPA, 2000
Kow	Soil water partition coefficient (mL/g)	1.32E+07	U.S. EPA, 2000
RCF	Root concentration factor (ug/g WW plant)/(ug/mL soil water)	9.17E+03	U.S. EPA, 2000
Bv	Air-to-plant biotransfer factor (ug/g DW plant)/(ug/g air)	1.49E+05	U.S. EPA, 2000
BSAF	Biota-to-sediment accumulation factor (unitless)	3.59	U.S. EPA, 2000
BCF_cattle	Bioconcentration factor for cattle (unitless)	1.2	U.S. EPA, 2000
BCF_poultry	Bioconcentration factor for poultry (unitless)	7.4	U.S. EPA, 2000
BCF_egg	Bioconcentration factor for eggs (unitless)	6.5	U.S. EPA, 2000

Table D-21. Chemical-Specific Inputs for 2,3,4,4',5-PeCB (CAS No. 74472-37-0)

Parameter	Definition	Value	Reference
TEF	Toxicity equivalency factors	0.0005	U.S. EPA, 2000
MW	Molecular weight (g/mol)	326.44	U.S. EPA, 2000
MP	Melting point (degrees C)	98	U.S. EPA, 2000
tb	Boiling point (degrees C)	380	ATSDR, 1998b
S	Water solubility (mg/L)	2.85E-03	U.S. EPA, 2000
VP	Vapor pressure (mm Hg)	4.18E-07	U.S. EPA, 2000
HLC	Henry's Law Constant (atm-m3/mol)	6.90E-05	U.S. EPA, 2000
Da	Diffusivity in air (cm2/s)	4.67E-02	U.S. EPA, 2000
Dw	Diffusivity in water (cm2/s)	4.64E-06	U.S. EPA, 1987
Koc	Organic carbon partition coefficient (unitless)	2.75E+06	U.S. EPA, 2000
Kow	Soil water partition coefficient (mL/g)	4.47E+06	U.S. EPA, 2000
RCF	Root concentration factor (ug/g WW plant)/(ug/mL soil water)	3.99E+03	U.S. EPA, 2000
Bv	Air-to-plant biotransfer factor (ug/g DW plant)/(ug/g air)	1.49E+05	U.S. EPA, 2000
BSAF	Biota-to-sediment accumulation factor (unitless)	6.4	U.S. EPA, 2000
BCF_cattle	Bioconcentration factor for cattle (unitless)	1.2	U.S. EPA, 2000
BCF_poultry	Bioconcentration factor for poultry (unitless)	7.4	U.S. EPA, 2000
BCF_egg	Bioconcentration factor for eggs (unitless)	6.5	U.S. EPA, 2000

Table D-22. Chemical-Specific Inputs for 3,3',4,4',5-PeCB (CAS No. 57465-28-8)

Parameter	Definition	Value	Reference
TEF	Toxicity equivalency factors	0.1	U.S. EPA, 2000
MW	Molecular weight (g/mol)	326.44	U.S. EPA, 2000
MP	Melting point (degrees C)	160	U.S. EPA, 2000
tb	Boiling point (degrees C)	380	ATSDR, 1998b
S	Water solubility (mg/L)	1.03E-03	U.S. EPA, 2000
VP	Vapor pressure (mm Hg)	2.96E-07	U.S. EPA, 2000
HLC	Henry's Law Constant (atm-m3/mol)	5.40E-05	U.S. EPA, 2000
Da	Diffusivity in air (cm2/s)	4.67E-02	U.S. EPA, 2000
Dw	Diffusivity in water (cm2/s)	4.64E-06	U.S. EPA, 1987
Koc	Organic carbon partition coefficient (unitless)	4.79E+06	U.S. EPA, 2000
Kow	Soil water partition coefficient (mL/g)	7.76E+06	U.S. EPA, 2000
RCF	Root concentration factor (ug/g WW plant)/(ug/mL soil water)	6.10E+03	U.S. EPA, 2000
Bv	Air-to-plant biotransfer factor (ug/g DW plant)/(ug/g air)	1.49E+05	U.S. EPA, 2000
BSAF	Biota-to-sediment accumulation factor (unitless)	3.21	U.S. EPA, 2000
BCF_cattle	Bioconcentration factor for cattle (unitless)	1.2	U.S. EPA, 2000
BCF_poultry	Bioconcentration factor for poultry (unitless)	6.5	U.S. EPA, 2000
BCF_egg	Bioconcentration factor for eggs (unitless)	7.4	U.S. EPA, 2000

Table D-23. Chemical-Specific Inputs for 1,2,3,7,8-PeCDD (CAS No. 40321-76-4)

Parameter	Definition	Value	Reference
TEF	Toxicity equivalency factors	1	U.S. EPA, 2000
MW	Molecular weight (g/mol)	356.42	U.S. EPA, 2000
MP	Melting point (degrees C)	240	U.S. EPA, 2000
tb	Boiling point (degrees C)	500	ATSDR, 1998a
S	Water solubility (mg/L)	1.43E-04	U.S. EPA, 1994
VP	Vapor pressure (mm Hg)	4.40E-10	U.S. EPA, 2000
HLC	Henry's Law Constant (atm-m3/mol)	2.60E-06	U.S. EPA, 2000
Da	Diffusivity in air (cm2/s)	4.47E-02	U.S. EPA, 2000
Dw	Diffusivity in water (cm2/s)	4.38E-06	U.S. EPA, 1987
Koc	Organic carbon partition coefficient (unitless)	2.69E+06	U.S. EPA, 2000
Kow	Soil water partition coefficient (mL/g)	4.37E+06	U.S. EPA, 2000
RCF	Root concentration factor (ug/g WW plant)/(ug/mL soil water)	3.92E+03	U.S. EPA, 2000
Bv	Air-to-plant biotransfer factor (ug/g DW plant)/(ug/g air)	2.39E+05	U.S. EPA, 2000
BSAF	Biota-to-sediment accumulation factor (unitless)	0.083	U.S. EPA, 2000
BCF_cattle	Bioconcentration factor for cattle (unitless)	5.55	U.S. EPA, 2000
BCF_poultry	Bioconcentration factor for poultry (unitless)	6.8	U.S. EPA, 2000
BCF_egg	Bioconcentration factor for eggs (unitless)	6	U.S. EPA, 2000

Table D-24. Chemical-Specific Inputs for 1,2,3,7,8-PeCDF (CAS No. 57117-41-6)

Parameter	Definition	Value	Reference
TEF	Toxicity equivalency factors	0.05	U.S. EPA, 2000
MW	Molecular weight (g/mol)	340.42	U.S. EPA, 2000
MP	Melting point (degrees C)	225	U.S. EPA, 2000
tb	Boiling point (degrees C)	500	ATSDR, 1994
S	Water solubility (mg/L)	2.36E-04	U.S. EPA, 1994
VP	Vapor pressure (mm Hg)	1.70E-09	U.S. EPA, 2000
HLC	Henry's Law Constant (atm-m3/mol)	5.00E-06	U.S. EPA, 2000
Da	Diffusivity in air (cm2/s)	4.57E-02	U.S. EPA, 2000
Dw	Diffusivity in water (cm2/s)	4.51E-06	U.S. EPA, 1987
Koc	Organic carbon partition coefficient (unitless)	3.80E+06	U.S. EPA, 2000
Kow	Soil water partition coefficient (mL/g)	6.17E+06	U.S. EPA, 2000
RCF	Root concentration factor (ug/g WW plant)/(ug/mL soil water)	5.11E+03	U.S. EPA, 2000
Bv	Air-to-plant biotransfer factor (ug/g DW plant)/(ug/g air)	9.75E+04	U.S. EPA, 2000
BSAF	Biota-to-sediment accumulation factor (unitless)	0.02	U.S. EPA, 2000
BCF_cattle	Bioconcentration factor for cattle (unitless)	0.97	U.S. EPA, 2000
BCF_poultry	Bioconcentration factor for poultry (unitless)	18	U.S. EPA, 2000
BCF_egg	Bioconcentration factor for eggs (unitless)	20.5	U.S. EPA, 2000

Table D-25. Chemical-Specific Inputs for 2,3,4,7,8-PeCDF (CAS No. 57117-31-4)

Parameter	Definition	Value	Reference
TEF	Toxicity equivalency factors	0.5	U.S. EPA, 2000
MW	Molecular weight (g/mol)	340.42	U.S. EPA, 2000
MP	Melting point (degrees C)	196	U.S. EPA, 2000
tb	Boiling point (degrees C)	500	ATSDR, 1994
S	Water solubility (mg/L)	2.36E-04	U.S. EPA, 2000
VP	Vapor pressure (mm Hg)	2.60E-09	U.S. EPA, 2000
HLC	Henry's Law Constant (atm-m3/mol)	4.98E-06	U.S. EPA, 2000
Da	Diffusivity in air (cm2/s)	4.57E-02	U.S. EPA, 2000
Dw	Diffusivity in water (cm2/s)	4.51E-06	U.S. EPA, 1987
Koc	Organic carbon partition coefficient (unitless)	1.95E+06	U.S. EPA, 2000
Kow	Soil water partition coefficient (mL/g)	3.16E+06	U.S. EPA, 2000
RCF	Root concentration factor (ug/g WW plant)/(ug/mL soil water)	3.05E+03	U.S. EPA, 2000
Bv	Air-to-plant biotransfer factor (ug/g DW plant)/(ug/g air)	9.75E+04	U.S. EPA, 2000
BSAF	Biota-to-sediment accumulation factor (unitless)	0.144	U.S. EPA, 2000
BCF_cattle	Bioconcentration factor for cattle (unitless)	4.13	U.S. EPA, 2000
BCF_poultry	Bioconcentration factor for poultry (unitless)	7.4	U.S. EPA, 2000
BCF_egg	Bioconcentration factor for eggs (unitless)	7.8	U.S. EPA, 2000

Table D-26. Chemical-Specific Inputs for 2,3,7,8-TCDD (CAS No. 1746-01-6)

Parameter	Definition	Value	Reference
TEF	Toxicity equivalency factors	1	U.S. EPA, 2000
MW	Molecular weight (g/mol)	321.98	U.S. EPA, 2000
MP	Melting point (degrees C)	305	U.S. EPA, 2000
tb	Boiling point (degrees C)	446.5	ATSDR, 1998a
S	Water solubility (mg/L)	1.93E-05	U.S. EPA, 2000
VP	Vapor pressure (mm Hg)	1.50E-09	U.S. EPA, 2000
HLC	Henry's Law Constant (atm-m3/mol)	3.29E-05	U.S. EPA, 2000
Da	Diffusivity in air (cm2/s)	4.70E-02	U.S. EPA, 2000
Dw	Diffusivity in water (cm2/s)	4.68E-06	U.S. EPA, 1987
Koc	Organic carbon partition coefficient (unitless)	3.98E+06	U.S. EPA, 2000
Kow	Soil water partition coefficient (mL/g)	6.31E+06	U.S. EPA, 2000
RCF	Root concentration factor (ug/g WW plant)/(ug/mL soil water)	5.20E+03	U.S. EPA, 2000
Bv	Air-to-plant biotransfer factor (ug/g DW plant)/(ug/g air)	6.55E+04	U.S. EPA, 2000
BSAF	Biota-to-sediment accumulation factor (unitless)	0.09	U.S. EPA, 2000
BCF_cattle	Bioconcentration factor for cattle (unitless)	5.76	U.S. EPA, 2000
BCF_poultry	Bioconcentration factor for poultry (unitless)	8.8	U.S. EPA, 2000
BCF_egg	Bioconcentration factor for eggs (unitless)	7.8	U.S. EPA, 2000

Table D-27. Chemical-Specific Inputs for 2,3,7,8-TCDF (CAS No. 51207-31-9)

Parameter	Definition	Value	Reference
TEF	Toxicity equivalency factors	0.1	U.S. EPA, 2000
MW	Molecular weight (g/mol)	305.98	U.S. EPA, 2000
MP	Melting point (degrees C)	227	U.S. EPA, 2000
tb	Boiling point (degrees C)	500	ATSDR, 1994
S	Water solubility (mg/L)	4.19E-04	U.S. EPA, 2000
VP	Vapor pressure (mm Hg)	1.50E-08	U.S. EPA, 2000
HLC	Henry's Law Constant (atm-m3/mol)	1.44E-05	U.S. EPA, 2000
Da	Diffusivity in air (cm2/s)	4.82E-02	U.S. EPA, 2000
Dw	Diffusivity in water (cm2/s)	4.85E-06	U.S. EPA, 1987
Koc	Organic carbon partition coefficient (unitless)	7.76E+05	U.S. EPA, 2000
Kow	Soil water partition coefficient (mL/g)	1.26E+06	U.S. EPA, 2000
RCF	Root concentration factor (ug/g WW plant)/(ug/mL soil water)	1.50E+03	U.S. EPA, 2000
Bv	Air-to-plant biotransfer factor (ug/g DW plant)/(ug/g air)	4.57E+04	U.S. EPA, 2000
BSAF	Biota-to-sediment accumulation factor (unitless)	0.072	U.S. EPA, 2000
BCF_cattle	Bioconcentration factor for cattle (unitless)	1.25	U.S. EPA, 2000
BCF_poultry	Bioconcentration factor for poultry (unitless)	3.1	U.S. EPA, 2000
BCF_egg	Bioconcentration factor for eggs (unitless)	2.7	U.S. EPA, 2000

Table D-28. Chemical-Specific Inputs for 3,3',4,4'-TeCB (CAS No. 32598-13-3)

Parameter	Definition	Value	Reference
TEF	Toxicity equivalency factors	0.0001	U.S. EPA, 2000
MW	Molecular weight (g/mol)	291.99	U.S. EPA, 2000
MP	Melting point (degrees C)	180	U.S. EPA, 2000
tb	Boiling point (degrees C)	360	ATSDR, 1998b
S	Water solubility (mg/L)	1.00E-03	U.S. EPA, 2000
VP	Vapor pressure (mm Hg)	4.47E-07	U.S. EPA, 2000
HLC	Henry's Law Constant (atm-m3/mol)	1.70E-05	U.S. EPA, 2000
Da	Diffusivity in air (cm2/s)	4.94E-02	U.S. EPA, 2000
Dw	Diffusivity in water (cm2/s)	5.00E-06	U.S. EPA, 1987
Koc	Organic carbon partition coefficient (unitless)	1.95E+06	U.S. EPA, 2000
Kow	Soil water partition coefficient (mL/g)	3.16E+06	U.S. EPA, 2000
RCF	Root concentration factor (ug/g WW plant)/(ug/mL soil water)	3.05E+03	U.S. EPA, 2000
Bv	Air-to-plant biotransfer factor (ug/g DW plant)/(ug/g air)	1.49E+05	U.S. EPA, 2000
BSAF	Biota-to-sediment accumulation factor (unitless)	2.205	U.S. EPA, 2000
BCF_cattle	Bioconcentration factor for cattle (unitless)	5.9	U.S. EPA, 2000
BCF_poultry	Bioconcentration factor for poultry (unitless)	6.5	U.S. EPA, 2000
BCF_egg	Bioconcentration factor for eggs (unitless)	7.4	U.S. EPA, 2000

Table D-29. Chemical-Specific Inputs for 3,4,4',5-TeCB (CAS No. 70362-50-4)

Parameter	Definition	Value	Reference
TEF	Toxicity equivalency factors	0.0001	U.S. EPA, 2000
MW	Molecular weight (g/mol)	291.99	U.S. EPA, 2000
MP	Melting point (degrees C)	160	U.S. EPA, 2000
tb	Boiling point (degrees C)	360	ATSDR, 1998b
S	Water solubility (mg/L)	2.92E-03	U.S. EPA, 2000
VP	Vapor pressure (mm Hg)	7.85E-07	U.S. EPA, 2000
HLC	Henry's Law Constant (atm-m3/mol)	1.28E-04	U.S. EPA, 2000
Da	Diffusivity in air (cm2/s)	4.94E-02	U.S. EPA, 2000
Dw	Diffusivity in water (cm2/s)	5.00E-06	U.S. EPA, 1987
Koc	Organic carbon partition coefficient (unitless)	1.41E+06	U.S. EPA, 2000
Kow	Soil water partition coefficient (mL/g)	2.29E+06	U.S. EPA, 2000
RCF	Root concentration factor (ug/g WW plant)/(ug/mL soil water)	2.40E+03	U.S. EPA, 2000
Bv	Air-to-plant biotransfer factor (ug/g DW plant)/(ug/g air)	1.49E+05	U.S. EPA, 2000
BSAF	Biota-to-sediment accumulation factor (unitless)	1.005	U.S. EPA, 2000
BCF_cattle	Bioconcentration factor for cattle (unitless)	5.9	U.S. EPA, 2000
BCF_poultry	Bioconcentration factor for poultry (unitless)	6.5	U.S. EPA, 2000
BCF_egg	Bioconcentration factor for eggs (unitless)	7.4	U.S. EPA, 2000

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Appendix E

Site Data

Table E-1. Site Parameters Used by Source Partitioning Model and Fate and Transport Model

Parameter Code	Parameter Description	Value	References	Source Model	Fate and Transport Model
AirTemp	Long-term average air temperature (°C)	Met station specific (see Table E-2)	U.S. DOC and U.S. DOE, 1993	✓	
AquTemp	Average vadose zone temperature (°C)	Met station specific (see Table E-2)	Van der Leeden et al., 1990	✓	
CN	SCS curve number (unitless)	Uniform distribution: (see Table E-3)	Wanielista and Yousef, 1993	✓	
ConVs	Settling velocity (m/d)	Uniform distribution: min - 0.05 max - 1	Best professional judgment	✓	
Farm_area	Median area for the crop and pasture combined (m^2)	Met station specific (see Table E-2)	U.S. DOC, 1994	✓	✓
K	USLE soil erodibility factor	Met station specific	Schwarz and Alexander, 1995	✓	✓
LS	USLE length-slope factor	Site-specific (where L in LS = X flow site-specific)	Schwarz and Alexander, 1995	✓	✓
R	USLE rainfall/erosivity factor (1/yr)	Met station specific (see Table E-2)	NCDR, ERL, NWS, 1995		✓
SiteLatitude	Latitude (degrees)	Met station specific (see Table E-2)	U.S. DOC and U.S. DOE, 1993	✓	
T1	Start time exposure begins	Uniform distribution capped at the operating life of the unit		✓	✓
Td	Time period of deposition	Triangular distribution: min = 1 max = 40		✓	✓
uw	Mean annual wind speed (m/s)	Met station specific (see Table E-2)	U.S. DOC and U.S. DOE, 1993		✓
Watershed_area	Area of watershed for a third-order stream	Triangular distribution: min - 2.3E+07 max - 1.11E+08 mode - 5.96E+07	Keup, 1985	✓	✓
Wai_LWS	Imperviousness of watershed area for local watershed (%)	2	Center for Watershed Protection, 1998		✓
Wai_RWS	Imperviousness of watershed area for regional watershed (%)	Uniform distribution: min - 2 max - 20	Center for Watershed Protection, 1998		✓

Table E-2. Values for Met Specific Parameters

MetStation	AirTemp (°C)	AquTemp (°C)	Farm_area (m^2)	R (1/yr)	SiteLatitude (degrees)	uw (m/s)
Albuquerque	13.53	16	1878963	40	35.05	4.012
Asheville	12.6	17	224196.8	225	35.433	3.452
Atlanta	16.38	18	428563.8	310	33.65	3.938
Billings	8.64	9	5025002	20	45.8	4.998
Bismarck	6.15	8	3738501	60	46.767	4.328
Boise	10.89	13	786712.1	20	43.567	3.71
Boulder	10.11	12	2986592	50	40.0167	3.783
Burlington	7.29	9	644262.2	85	44.467	4.075
Casper	7.56	12	3357286	35	42.917	5.628
Charleston	18.18	19	325368.6	360	32.9	3.788
Chicago	9.69	12	718724.6	155	41.983	4.632
Cleveland	9.91	12	441918.5	120	41.417	4.593
Fresno	17.15	18	189393.7	50	36.767	2.791
Grand Island	10.74	12	1142028	130	40.967	5.039
Harrisburg	11.62	12	416018.5	150	40.217	3.078
Hartford	9.92	11	202343.7	150	41.933	3.693
Houston	20.04	24	499788.8	425	29.967	3.604
Huntington	12.8	14	350863.9	140	38.367	2.961
Las Vegas	19.91	23	394974.8	25	36.083	4.547
Little Rock	16.55	18	643857.5	310	34.733	3.138
Los Angeles	16.63	19	97934.33	60	33.933	3.592
Meridian	17.58	19	497765.4	400	32.333	2.689
Miami	24.31	26	160256.2	480	25.8	4.221
Minneapolis	8.3	8	844177.7	140	44.883	4.766

(continued)

Table E-2. (continued)

MetStation	AirTemp (°C)	AquTemp (°C)	Farm_area (m^2)	R (1/yr)	SiteLatitude (degrees)	uw (m/s)
Muskegon	8.63	10	473888.8	100	43.167	4.817
Nashville	15.61	16	382024.8	220	36.117	3.63
New Orleans	20.11	22	367860.8	555	29.983	3.531
Norfolk	15.75	16	394570.1	280	36.9	4.997
Philadelphia	12.24	12	157828	185	39.883	4.188
Phoenix	23.34	21	1374723	50	33.433	2.669
Portland	7.57	9	397402.9	115	43.65	3.918
Raleigh-Durham	14.94	16	345603	280	35.867	3.393
Salem	11.65	12	180490.5	35	44.917	3.295
Salt Lake City	11.12	12	580726.3	35	40.783	4.011
San Francisco	13.26	17	161065.5	50	37.617	4.849
Seattle	11	11	162279.6	35	47.45	3.859
Shreveport	18.18	20	448798.2	360	32.467	3.429
Tampa	22.12	24	271140.5	445	27.967	3.753
Tulsa	15.72	19	744624.6	270	36.2	4.551
Williamsport	9.9	11	514357.6	125	41.25	3.495
Winnemucca	9.58	13	656807.5	15	40.9	3.859

Table E-3. SCS Curve Number Values for Crop and Pasture Based on Hydrologic Group

Hydrologic Group	Crop	Pasture
A	72	39
B	81	61
C	88	74
D	91	80

Table E-4. Median Waterbody Temperatures by HUC Region

HUC Region	Waterbody Temperature (K)
1	287
2	289
3	294
4	287
5	290
6	291
7	288
8	293
9	283
10	286
11	290
12	294
13	289
14	282
15	290
16	282
17	284
18	288

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Appendix F

Source Model for Land Application Units

Table of Contents

Table of Contents (continued)

Figures

Number **Page**

Tables

Number **Page**

F-1.0 Introduction

A source term module was developed for land application units (LAUs) to provide estimates of annual average surface soil constituent concentrations and constituent mass emission rates to air, downslope land, and ground water. These estimates are then used in an integrated, multipathway module linking source term modules with environmental fate and transport and exposure/risk modules. Additionally, LAU source emission modules have been combined with a local watershed module (a "local" watershed is a sheet-flow-only watershed containing the LAU) to provide estimates of constituent mass flux rates from runoff and erosion to a downslope waterbody, as well as surface soil constituent concentrations in downslope buffer areas. Because the LAU source is assumed here to interact hydrologically with the local watershed of which it is an integral part, it is termed a "land-based" unit.

A soil column module was developed to describe the dynamics of constituent mass fate and transport within LAUs and near-surface soils in watershed subareas. It is referred to as the Generic Soil Column Module (GSCM). (The term "soil" is used loosely here to refer to a porous medium, whether it is waste in the LAU or near-surface soil in a watershed subarea.) Governing equations for the GSCM are similar to those used by Jury et al. (1983, 1990) and Shan and Stevens (1995). However, the analytical solution techniques used by these authors were not applicable to the source emission module developed here because of the need to consider the periodic addition of constituent mass and enhanced constituent mass loss rates in the surface soil (e.g., due to runoff, erosion, wind, and mechanical processes). A new solution technique has been developed for use that is computationally efficient and sufficiently flexible to allow consideration of the LAU. Use of the GSCM described here allows:

- Constituent mass balance
- Waste additions/removals to simulate active facilities
- Joint estimation of constituent mass losses due to a variety of mechanisms, including:
  - Volatilization of gas-phase constituent mass from the surface to the air
  - Leaching of aqueous-phase constituent mass by advection or diffusion from the bottom of the WMU or vadose zone

— First-order losses, which can include:

- Abiotic and biodegradation
- Suspension of constituent mass adsorbed to surface particles due to wind action and vehicular activity
- Suspension of constituent mass adsorbed to surface particles due to water erosion
- Surface runoff of aqueous-phase constituent mass.

Section 2 provides a description of the GSCM assumptions, governing equations, boundary conditions, and solution technique. Section 3 describes the application of the GSCM to the land-based LAU and its integration within the holistic local watershed module, including hydrology, soil erosion, and runoff water quality. Sections 4 and 5 describe the specifics of the application and integration for the LAU. Appendix A lists and defines all symbols used in Sections 2 through 6. Appendixes B and C provide supplementary information on determination of H', D_a, and D_w for organic compounds and particulate emission equations.

F-2.0 Generic Soil Column Module

F-2.1 Assumptions

The following assumptions were made in the development of the Generic Soil Column Module used in the LAU:

- The contaminant partitions to three phases: adsorbed (solid), dissolved (liquid), and gaseous (as in Jury et al., 1983, 1990).

$$C_T = \rho_b C_S + \theta_w C_L + \theta_a C_G \quad \text{(F-2-1)}$$

where

C_T = total contaminant concentration in soil (g/m^3 of soil)
ρb = soil dry bulk density (g/cm^3)
Cs = adsorbed phase contaminant concentration in soil (µg/g of dry soil)
θ_w = soil volumetric water content (m^3 soil water/m^3 soil)
C_L = aqueous-phase contaminant concentration soil (g/m^3 of soil water)
θ_a = soil volumetric air content (m^3 soil air/m^3 soil)
C_G = gas-phase contaminant concentration in soil (g/m^3 of soil air).

- The contaminant undergoes reversible, linear equilibrium partitioning between the adsorbed and dissolved phases (as in Jury et al., 1983, 1990).

$$C_S = K_d C_L \quad \text{(F-2-2)}$$

where K_d is the linear equilibrium partitioning coefficient (cm^3/g). For organic contaminants:

$$K_d = foc \cdot K_{oc} \quad \text{(F-2-3)}$$

where foc is the organic carbon fraction in soil and K_{oc} is the equilibrium partition coefficient, normalized to organic carbon. Alternatively, K_d can be specified as an input parameter for inorganic contaminants. (It is implicit in this linear equilibrium partitioning assumption that the sorptive capacity of the soil column solids is considered to be infinite with respect to the total mass of contaminant over the duration of the simulation, i.e., the soil column sorptive capacity does not become exhausted.)

$$C_G = H' C_L \tag{F-2-4}$$

- Contaminant in the dissolved and gaseous phases is assumed to be in equilibrium and to follow Henry's law (as in Jury et al., 1983, 1990).
where H′ is the dimensionless Henry's law coefficient.

- The total contaminant concentration in soil can also be expressed in units of µg of contaminant mass per g of dry soil (µg/g):

$$C_T' = \frac{C_T}{\rho_b} \tag{F-2-5}$$

- Using the linear equilibrium approximations in Equations F-2-2 through F-2-5, C_T can be expressed in terms of C_L, C_S, or C_G:

$$C_T = K_{TL} C_L = \frac{K_{TL}}{K_d} C_S = \frac{K_{TL}}{H'} C_G \tag{F-2-6}$$

where

$$K_{TL} = \rho_b K_d + \theta_w + \theta_a H' \tag{F-2-7}$$

K_{TL} is the dimensionless equilibrium distribution coefficient between the total and aqueous-phase constituent concentrations in soil.

- The total water flux or infiltration rate (I, m/d) is constant in space and time (as in Jury et al., 1983, 1990) and greater than or equal to zero. It is specified as an annual average.

- Material in the soil column (including bulk waste) can be approximated as unconsolidated homogeneous porous media whose basic properties (ρ_b, foc, θ_w, θ_a, and η -- the total soil porosity) are average annual values, constant in space.

- Contaminant mass may be lost from the soil column due to one or more first-order loss processes.
- The total chemical flux is the sum of the vapor flux and the flux of the dissolved solute (as in Jury et al., 1983, 1990).
- The chemical is transported in one dimension through the soil column (as in Jury et al., 1983, 1990).
- The vapor-phase and liquid-phase porosity and tortuosity factors obey the module of Millington and Quirk (1961) (as in Jury et al., 1983, 1990). (See equation F-2-9a below).
- The modeled spatial domain of the soil column remains constant in volume and fixed in space with respect to a vertical reference, e.g., the water table.

F-2.2 Governing Mass Balance Equation

Under the above assumptions, the governing mass fate and transport equation can be written as follows:

$$\frac{\partial C_T}{\partial t} = D_E \frac{\partial^2 C_T}{\partial z^2} - V_E \frac{\partial C_T}{\partial z} - kC_T \qquad \text{(F-2-8)}$$

where k (1/d) is the total first-order loss rate, D_E (m^2/d) is the effective diffusivity in soil calculated as follows:

$$D_E = \frac{(\theta_a^{10/3} D_a H' + \theta_w^{10/3} D_w)\ 8.64}{\eta^2 K_{TL}} \qquad \text{(F-2-9a)}$$

where D_a and D_w (cm^2/s) are air and water diffusivities, respectively, and 8.64 is a conversion factor (m^2-s/cm^2-d). D_E can be considered to be the sum of the effective gaseous and water diffusion coefficients in soil, $D_{E,a}$, and $D_{E,w}$, respectively, where

$$D_{E,a} = \frac{\theta_a^{10/3} D_a H'\ 8.64}{\eta^2 K_{TL}} \qquad \text{(F-2-9b)}$$

$$D_{E,w} = \frac{\theta_w^{10/3} D_w\ 8.64}{\eta^2 K_{TL}} \qquad \text{(F-2-9c)}$$

The effective solute convection velocity (V_E, m/d) is equal to the water flux corrected for the contaminant partitioning to the water phase as follows:

$$V_E = \frac{I}{K_{TL}} \tag{F-2-10}$$

F-2.3 Parameter Estimation Methodologies

- Water content (θ_w) is estimated as a function of the annual average infiltration rate (I, m/d) using (Clapp and Hornberger, 1978):

$$\theta_w = \eta \cdot \left(\frac{I}{0.24 K_{sat}} \right)^{1/(2SM_b+3)} \tag{F-2-11}$$

  where K_{sat} (cm/h) is saturated hydraulic conductivity, SM_b is a unitless exponent specified by soil-type, and 0.24 (h-m/d-cm) is a unit conversion factor.

- Volumetric air content is estimated using:

$$\theta = \eta - \theta_w \ . \tag{F-2-12}$$

- H′, D_a, and D_w can be either estimated as a function of temperature in the soil column (T_{sc}, °C) using the methods described in Appendix B or specified directly as input parameters if preadjusted values are available.

F-2.4 Solution Technique

F-2.4.1 Background

A solution of the complete convective-diffusive-decay concentration module (Equation F-2-8) was undertaken to evaluate, in a soil column of depth z_{sc}

- Total contaminant concentration as a function of time, t, and depth below the surface, z, for an arbitrary chemical

- Contaminant mass fluxes across the upper (z = 0) and lower boundaries (z = z_{sc}) of the soil column.

A numerical solution of Equation F-2-8, with zero concentration boundary condition at the surface and zero gradient lower boundary condition, was first examined as a straightforward explicit finite difference method. This approach resulted in such a high numerical diffusion that it was impossible to distinguish diffusion effects. By subdividing each section into relatively

thinner sections, the numerical diffusion could be reduced to more acceptable levels, but then smaller time steps were required, and the computation time became quite long. In addition, the numerical solution was not stable in the extremes (e.g., high/low V_E or D_E).

An alternative, quasi-analytical approach was developed that allows for relative computational speed and significantly reduces concern about numerical diffusion and lack of stability. The tradeoff is a loss of ability to evaluate short-term trends in concentration and diffusive flux profiles. The method was developed to allow estimation of long-term (i.e., annual average) contaminant concentration profiles and mass fluxes.

The alternative approach developed consists of a superposition of analytic solutions of the three components of the governing equation (Equation 2-8) on the same grid. The solution for the simplified case where the soil column consists of one homogeneous zone, whose properties are uniform in space and time, is described below. Adaptations of the solution technique to account for variations from this simplified case (e.g., more than one homogeneous zone as for a landfill with cover soil zone atop the waste zone) are described in the module-specific sections.

F-2.4.2 Description of Quasi-analytical Approach

A quasi-analytical approach was developed that is a step-wise solution of the three components of the governing equation (Equation F-2-8) on the same grid. Boundary conditions of C_T=0 at both the upper and lower boundaries of the soil column are assumed, although some flexibility exists in specifying the lower boundary condition as discussed below. That is, the following equations are solved individually:

$$\frac{\partial C_T}{\partial t} = D_E \frac{\partial^2 C_T}{\partial z^2} \qquad \text{(F-2-13)}$$

$$\frac{\partial C_T}{\partial t} = - V_E \frac{\partial C_T}{\partial z} \qquad \text{(F-2-14)}$$

$$\frac{\partial C_T}{\partial t} = - k C_T \qquad \text{(F-2-15)}$$

Equations F-2-13 through F-2-15 each have an analytical solution that can be combined to obtain a pure diffusion solution that moves with velocity V_E through the porous medium (Jost, 1960). The solution of the general differential equation then has the form of the solution of the

diffusive portion with its time dependence, translating in space with velocity V_E, and decaying exponentially with time.

The first two solutions for a point source are graphically depicted in Figures F-2-1a and F-2-1b for illustration. If it were possible to compute such point source solutions for each position in the soil column and each time of interest, then the contributions at each point could be added to obtain a global solution because the governing differential equations are linear. That is, each point in the soil column could be treated as if it were the only point for which there is a nonzero concentration.

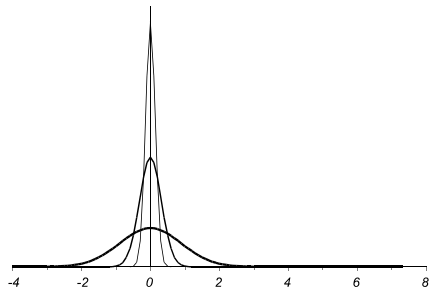

Figure F-2-1a. Development of diffusive spreading from a point source with time, corresponding to times of 0.01, 0.05, and 0.4.

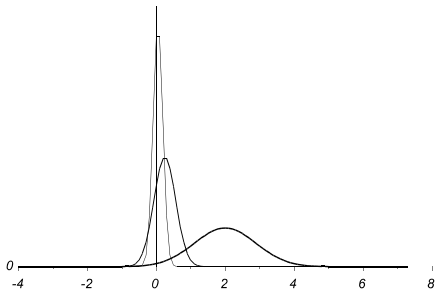

Figure F-2-1b. Diffusive spreading from a point source with a constant velocity to the right at times of 0.01, 0.05, and 0.4.

To make the analysis tractable, instead of a point source, the soil column is divided into layer sources each of depth dz (i.e., a grid). A layer source can be thought of as multiple point sources packed closely together. In such a case, Equation F-2-13 has a solution for one-dimensional diffusion, with the concentration at any point and any time given by

$$C_T(z',t) = \frac{C_{T0}}{2}\left[erf\left(\frac{z' + dz/2}{\sqrt{4D_E t}} \right) + erf\left(\frac{dz/2 - z'}{\sqrt{4D_E t}} \right) \right] \qquad \text{(F-2-16)}$$

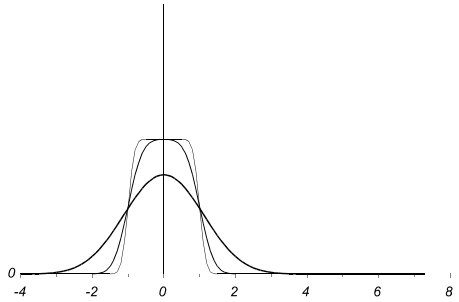

Figure F-2-2a. Development of diffusive spreading from a layer source with time, corresponding to times of 0.01, 0.05, and 0.4.

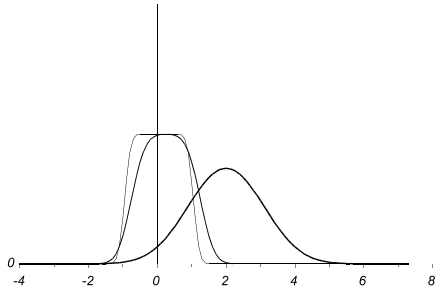

Figure F-2-2b. Diffusive spreading from a layer source with a constant velocity to the right at times of 0.01, 0.05, and 0.4.

for a layer of width dz centered at z′ = 0 (Jost, 1960). The concentration profile is assumed to be initially uniform from z′ = -dz/2 to z′ = +dz/2 and zero everywhere else. With time, the profile spreads outward and the concentration at the origin decreases, as shown in Figure F-2-2a for dz=2. With a positive velocity V_E, the concentration profile also moves down the soil column as illustrated in Figure F-2-2b. The use of layer solutions requires that we assume uniform average concentrations within each layer. Thus, the thickness of the layers determines the spatial resolution available.

The total amount of material, m, in g/m^2 that has passed any ordinate z′ after time t is given by the integral of the concentration from z′ to ∞ with half leaving to the left (negative z′ values) and half to the right (positive z′ values) :

$$m(z',t) = 2\int_{z'}^{\infty} C_T(z,t)dz \qquad \text{(F-2-17)}$$

The integral in Equation (2-17) can be derived as

$$m(z',t) = C_{T0}\sqrt{4D_E t}\left[\int_{(z'-dz/2)/\sqrt{4D_E t}}^{\infty} erfc(y)\,dy - \int_{(z'+dz/2)/\sqrt{4D_E t}}^{\infty} erfc(y)\,dy\right] \qquad \text{(F-2-18)}$$

which is evaluated using the relationship (Abramowitz and Stegun, 1970):

$$\int \mathrm{erfc}(x)dx = x\,\mathrm{erfc}(x) - \frac{1}{\sqrt{\pi}}\exp\left(-x^2\right) + \text{constant} \qquad \text{(F-2-19)}$$

The fraction of the original mass that diffuses past a boundary at z′ in any time period 0 to t, Df(z′,t), is one-half m(z′,t) divided by the amount of mass initially present in g/m^2 in the source layer (C_{T0}·dz):

$$Df(z',t) = 0.5 \cdot \frac{\sqrt{4D_E t}}{dz}\left[\int_{(z'-dz/2)/\sqrt{4D_E t}}^{\infty} erfc(y)\,dy - \int_{(z'+dz/2)/\sqrt{4D_E t}}^{\infty} erfc(y)\,dy\right] \qquad \text{(F-2-20)}$$

The fraction of mass that remains in the original layer of width dz after diffusion in the time period 0 to t, $Df_0(t)$, is:

$$Df_0(t) = 1 - 2 \cdot Df(z' = 0.5dz, t) \qquad \text{(F-2-21)}$$

By means of evaluations at all the layer boundaries (z′=0.5dz, 1.5dz, 2.5dz, ...), the amount of contaminant mass transported to any layer via diffusion after time t can be calculated as the difference between the amount outside the upstream boundary and the amount outside the downstream boundary. For example, the fraction of mass originally present in the source layer that ends up in the layer adjacent to the source layer in time t is Df(z′=0.5dz, t) -Df(z′=1.5dz, t). The integrated amounts of material that have crossed the layer boundaries and the amount that remains in the source layer after time t are given directly by Equations F-2-20 and F-2-21, respectively, and only have to be computed once for fixed time steps and layer thicknesses.

The amount of mass that diffuses from a given layer out the lower boundary of the soil column in time t can be tracked by multiplying Df(z',t), evaluated at the point where, for that layer, z' is at the bottom of the soil column ($z = z_{sc}$) by (C_{T0} ·dz) for that layer. Diffusive losses across the bottom boundary from all the soil column layers are summed to get the total diffusive (aqueous and gaseous phase) loss across the bottom boundary, $M_{lchd}(t)$ (g/m^2) in time t.

Likewise, by summing the total diffusive losses across the upper boundary from each layer, the total diffusive loss out the top of the soil column, $M_0(t)$ (g/m^2), is determined. The volatilization loss from the surface of the soil column, $M_{vol}(t)$ (g/m^2), is assumed to be due to gaseous phase diffusion only and is determined by

$$M_{vol}(t) = M_0(t) \cdot \frac{D_{E,a}}{D_E} \qquad \text{(F-2-22)}$$

where ($D_{E,a}/D_E$) is the fraction of the total diffusive loss from any layer that is due to diffusion in the gaseous phase in the soil. It is assumed that mass is not lost across the top boundary due to diffusion in the aqueous phase in the soil. In order to maintain mass balance, mass calculated to be lost this way is added back into the top layer in the soil, augmenting the total contaminant concentration there by
($M_0(t) \cdot D_{E,w}/D_E$). This method of obtaining $M_{vol}(t)$ is an approximation, justified on the basis of computational efficiency. A more rigorous treatment would include a mathematical transition layer across which diffusion from the soil to the air occurs. However, use of such a transition

layer would require a more computationally intensive solution technique as well as specification of the thickness of the transition layer. Without this approximation (i.e., if $M_{vol}(t) = M_0(t)$), $M_{vol}(t)$ could be greater than zero for non-volatile contaminants ($D_a = H' = 0$) due to the possible contribution to M_0 from the aqueous phase diffusive flux. It is believed that this method of estimating $M_{vol}(t)$ and augmenting the total contaminant concentration in the surface layer, while not theoretically rigorous, does represent a reasonable approximation of what actually occurs. That is, contaminant mass diffuses to the surface in both the aqueous and gaseous phases. While the contaminant mass in the gas phase volatilizes out the surface of the soil column, the contaminant mass in the aqueous phase is left behind, concentrating the contaminant mass in surface soil (approximated here as the surface soil column layer).

To account for decay, Equation F-2-15 is solved readily by the technique of separation of variables (Jost,1960). It has a solution of the form

$$C_T = C_{T0} \exp(-kt) \qquad \text{(F-2-23)}$$

As Equation 2-23 is applied to each layer, the amount of mass lost due to first-order decay in time, t, M_{loss} (g/m^2), can be tracked using:

$$M_{loss}(t) = \left(1 - \exp(-kt)\right) C_{T0} \cdot dz \qquad \text{(F-2-24)}$$

Where multiple first-order loss processes may occur (i.e., $k = \sum k_j$), the fraction of initial mass present lost due to each process j is determined using:

$$M_{loss,j}(t) = \frac{k_j}{k} M_{loss}(t) \qquad \text{(F-2-25)}$$

A potential difficulty with the layer solution is that the convection of material leads to an artificial numerical diffusion because the concentration within each layer can only be expressed as an average value. This component of numerical diffusion can be avoided completely if the contents of each layer are transferred completely to the next layer at the end of each time step by making the time step equal to the layer thickness divided by the effective velocity, V_E.

$$dt = \frac{dz}{V_E} \qquad \text{(F-2-26)}$$

The contaminant mass in the bottom layer is convected out of the lower boundary. Total mass lost due to advection in dt, M_{lcha} (g/m^2), is simply C_{T0} in the lowest soil column layer times dz.

F-2.4.2.1 <u>Boundary Conditions</u>. Zero concentration is assumed at the upper boundary of the soil column. This is consistent with the assumption that the air is a sink for volatilized contaminant mass, but requires the approximate method for estimating $M_{vol}(t)$ described above.

At the lower boundary of the soil column, the flexibility exists with this solution technique to specify a value between zero and one for the ratio (bcm) of the total contaminant concentration in the soil directly below the modeled soil column and in the soil column. A ratio of one (bcm=1) corresponds to a zero gradient boundary condition ($dC_T/dz=0$). A ratio of zero (bcm=0) corresponds to a zero concentration boundary condition ($C_T=0$).

When bcm is equal to zero, diffusive fluxes at the upper and lower boundaries of the soil column are calculated directly as described above. When bcm is greater than zero, a reflection of the soil column is created. The contaminant concentrations in the reflected soil column cells are set equal to bcm times the contaminant concentration in the soil column cell being reflected (i.e., the concentration in the first cell of the reflected soil column is set to bcm times the contaminant concentration in the lowest cell of the actual soil column). The upward diffusive flux from the reflected soil column cells: (1) offsets the diffusive flux out the lower boundary of the soil column, (2) increments the contaminant concentrations in the soil column, and (3) augments the diffusive flux out the upper boundary of the soil column. Hence, when bcm is equal to one (the no diffusion boundary condition), the downward diffusive flux out the bottom boundary of the soil column is completely offset by the upward diffusive flux across the same boundary from the reflected soil column cells.

F-2.4.2.2 <u>Algorithm</u>. The general algorithm for applying the individual solutions to Equations F-2-13 through F-2-15 is as follows for a homogeneous soil column and an averaging time period of 1 year.

1. Specify

   - Lower boundary condition multiplier (bcm)
   - Initial conditions in soil column (C_{T0})
   - Soil column size (z_{sc}) and properties (ρ_b, foc, η, K_{sat}, SM_b)
   - First-order loss rates (k_j)
   - Chemical properties (K_{oc}, H', D_a, D_w)
   - Upper and lower averaging depths (z_{ava}, z_{avb}).

2. Calculate/read K_d. K_d is internally calculated for organics, and read as a user input for metals.

3. Subdivide the soil column into multiple layers of depth, dz, that are an integral fraction of z_{sc}. Calculate the total number of layers, $N_{dz} = z_{sc}/dz$.

4. Get annual average infiltration rate (I) for the year.

5. Calculate θ_w, θ_a, K_{TL}, D_E, V_E.

6. Calculate the time to cross a single layer at velocity V_E (Equation F-2-26). This is the convection-based computing time step, dt. See also note below.

7. Evaluate the fraction of mass that remains in a layer (Equation F-2-23) and that diffuses across layer boundaries z′= 0.5dz, 1.5dz, 2.5dz,... (Equation F-2-22) at t=dt. (These fractions are constant for a fixed dt.)

8. Calculate the amount of mass present in the soil column at the beginning of the year (M_{col1}, g/m^2).

9. Initialize cumulative mass loss variables (M_{vol}, M_{lchd} , M_{lcha}, $M_{loss,j}$).

10. Diffusion. Adjust the concentration profile to reflect diffusive fluxes for one time step. This redistributes material throughout the whole soil column. Increment M_{vol} and M_{lchd}.

11. First-order losses: Allow the concentration profile to decay in each layer (Equation F-2-25) for one time step. Increment mass lost due to all applicable first- order loss processes, j, $M_{loss,j}$ (Equation F-2-23).

12. Convection: Propagate the concentration profile one layer downstream. Increment M_{lcha}.

13. Repeat Steps 10 through 12 until it is time to add and/or remove contaminant mass (go to Step 14) or until the end of the year (go to Step 15).

14. To account for the addition of contaminant mass, update the contaminant concentrations in the affected layers. Track total mass added (M_{add}, g/m^2) and/or removed (M_{rem}, g/m^2). Begin the algorithm again at Step 10.

15. At end of the year, calculate/report:

    - Total mass in the soil column (M_{col2}, g/m^2)
    - Mass balance error for the year (M_{err}, g/m^2):

$$M_{err} = M_{col2} - M_{col1} - M_{add} + M_{rem} + M_{vol} + M_{lcha} + M_{lchd} + \sum_j M_{loss,j} \qquad \text{(F-2-27)}$$

    - Annual average total concentration in surface layer
    - Annual, depth-weighted average total concentration ($z_{ava} \le z \le z_{avb}$)
    - Annual average volatilization flux (J_{vol}, g/m^2/d)

$$J_{vol} = \frac{M_{vol}}{365} \qquad \text{(F-2-28)}$$

    - Annual average leaching flux (J_{lch}, g/m^2/d):

$$J_{lch} = \frac{M_{lchd} + M_{lcha}}{365} \quad \text{(F-2-29)}$$

16. Begin the algorithm again at Step 4 until mass is no longer added to the soil column and mass has been depleted from the soil (i.e., M_{col2} =0).

Note that the convection time step cannot be any greater than the length of time between mass additions or removals (e.g., waste applications in an LAU). For example, if contaminant mass is added every 30 days, this is the maximum time step, regardless of how small the velocity is. When dt is limited in this fashion, the number of time steps required before a convective transfer can take place is determined, and the convective transfer step is performed on an "as-needed" basis. If the calculated convective time step is 60 days, in this example, the convective transfer would occur every other time step. This will result in a temporal distortion of the concentrations within the layers, but over several steps and, by the end of the year, preliminary module runs show that the effects average out.

The primary means by which the performance of the solution algorithm is checked is via the annual mass balance check (Equation F-2-27) to ensure that the change in mass in the system over the year is equal to the difference between mass additions and losses. If M_{err} is greater than 10^{-8} g/m^2, a message is written to the warning file.

F-2.5 Limitations Related to Use of GSCM

The following limitations are noted for the GSCM:

- The GSCM was developed originally for organic contaminants, and assumes that the partition efficient, K_d, is linear and is estimated as the product of K_{oc} and f_{oc}. Partitioning for metals involves complex chemistry, including the dynamic effects of aqueous-phase contaminant concentration, precipitation, dissolution, adsorption/desorption, and the geochemistry of media (e.g., oxidation-reduction conditions) on the value of K_d and the fate and transport behavior of metals in general. This complexity is not modeled by the GSCM for metals partitioning; rather, K_d is externally provided as a randomly sampled value by the chemical properties processor (CPP).

- With organic contaminants, the GSCM is not applicable if nonaqueous phase liquid (NAPL) is present. Similarly, with metals, the presence of a precipitate is not allowed. The presence of NAPL (precipitate) is determined by comparing C_T to the theoretical maximum contaminant concentration in soil without NAPL (precipitate), determined by the aqueous solubility, saturated soil-gas concentration of the contaminant, and the sorptive capacity of the soil. The limit on C_T is estimated using

$$C_T < K_{TL} C_L^{sol} \quad \text{(F-2-30)}$$

where C_L^{sol} (g/m^3) is the aqueous solubility. It is expected that in most circumstances exit levels will be sufficiently low that the presence of NAPL (precipitate) would be precluded.

- The algorithm is being applied to develop source release estimates on an annual average basis, to support estimation of chronic (long-term average) risk estimates. Some of the inputs used (e.g., infiltration) are long-term annual average estimates, while others are annual average. Accordingly, the outputs are not strictly applicable to individual years.

- The module allows consideration of only one contaminant at a time and does not simulate fate and transport of reaction products in its current form. With further module development, it would be possible to track the production of reaction products in each soil column layer and use basically the same algorithm that is used for the parent compound to module the fate of reaction products.

- The solution technique used, sequential solutions to the three-component differential equations of the governing differential equation, allows computational efficiency. However, systematic errors could result from the choice of the order in which these solutions are applied. The size of the error would be dependent on the relative loss rates associated with the three processes. For example, if the first- order loss rate due to degradation were high and losses due to degradation were calculated first, then less contaminant mass would be available for diffusive and advective losses. The current algorithm prioritizes diffusive losses since the diffusion equation is solved first. This is followed by first-order losses and advection in that order.

- As discussed, a boundary condition at the soil/air interface of $C_T = 0$ was assumed in developing this solution technique. This is consistent with the assumption that the air is a sink for volatilized contaminant mass. However, as discussed in Section F-2.4.1, because the diffusion coefficient used in the governing equation (Equation F-2-8) includes diffusion in both the air and aqueous phases of the soil, contaminant mass that is transported upward in the soil column via diffusion can include mass in both the air and aqueous phases. While this is appropriate within the soil where the ratio of air to water is relatively constant, the assumption breaks down at the soil/air interface itself. To account for the fact that contaminant mass in the aqueous phase should not be lost out of the surface of the soil column— which, for example, would lead to nonzero volatilization fluxes for nonvolatile contaminants ($D_a = H' = 0$)— the volatilization flux at the surface is assumed to include only the diffusive flux due to gas-phase diffusion. Mass estimated to be lost from the surface due to aqueous-phase diffusion is added back into the surface soil column layer, augmenting the contaminant concentration there and maintaining mass balance. This is an approximation, justified on the basis of computational efficiency; nonetheless, the approximation should be in reasonable agreement with what actually occurs in nature.

F-3.0 Local Watershed/Soil Column Module

F-3.1 Introduction

The LAU source emissions module is required to provide annual average contaminant mass flux rates from the surface of the LAU and its subsurface interface with the vadose zone, total contaminant concentration in the surface material, and contaminant mass emission rate due to particulate emissions. In addition, because these LAUs are on the land surface, they are integral land areas in their respective watersheds and, consequently, are not only affected by runoff and erosion from upslope land areas, but also affect downslope land areas through runoff and erosion. Indeed, after some period of time during which runoff and erosion has occurred from a LAU, the downslope land areas will have been contaminated and their surface concentrations could approach (or conceivably even exceed long after LAU operation ceases) the residual chemical concentrations in the LAU at that time. Thus, after extensive runoff and erosion from a LAU, the entire downslope surface area can be considered a "source" and it becomes important to consider these "extended source" areas in the risk assessment. It is for this reason that a holistic modeling approach has been taken with the LAU source module to incorporate them into the watershed of which they are a part.

The watershed including an LAU is termed here the "local" watershed, and is illustrated in Figure F-3-1. A local watershed is defined as that drainage area that just contains the LAU (or a portion thereof — there can be multiple local watersheds) in the lateral (perpendicular to runoff flow) direction, and in which runoff occurs as overland flow (sheet flow) only. Thus, a local watershed extends downslope only to the point that runoff flows and eroded soil loads would enter a well-defined drainage channel, e.g., a ditch, stream, lake, or some other waterbody. The sheet-flow-only restriction is based on the assumption that any subareas downslope of the LAU subarea are subject to chemical contamination from the LAU through overland runoff and soil erosion.

Figure F-3-2 illustrates how the local watershed is conceptualized for the combined Local Watershed/Soil Column Module, that is, as a two-dimensional, two-medium system. The dimensions are longitudinal, i.e., downslope or in the direction of runoff flow, and vertical, i.e., through the soil column. The media are the soil column and, during runoff events, the overlying runoff water column. The local watershed is assumed to be made up of, in the longitudinal direction, an arbitrary number of land subareas that may have differing surface or subsurface characteristics, e.g., land uses, soil properties, and chemical concentrations. For example, subarea 2 might be a LAU, subarea 1 would then represent an upslope area, and subareas 3 through N would be downslope buffer areas extending to the waterbody.

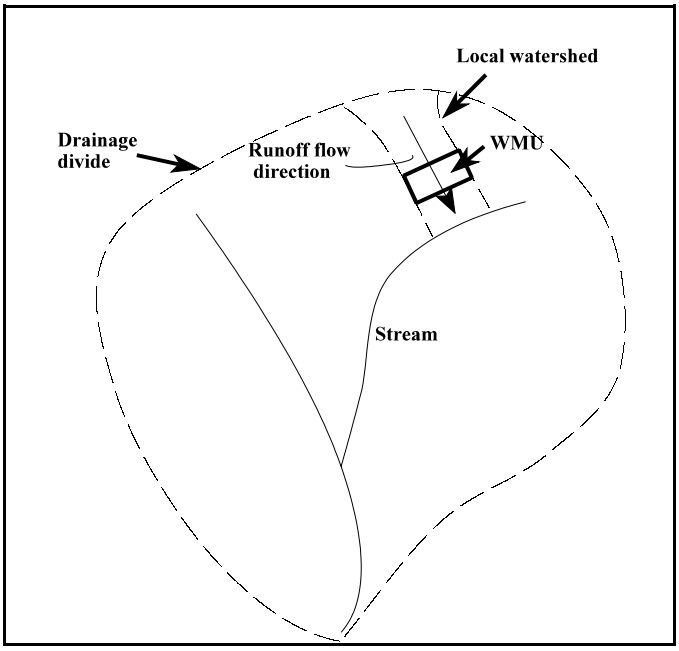

Figure F-3-1. Local watershed containing WMU.

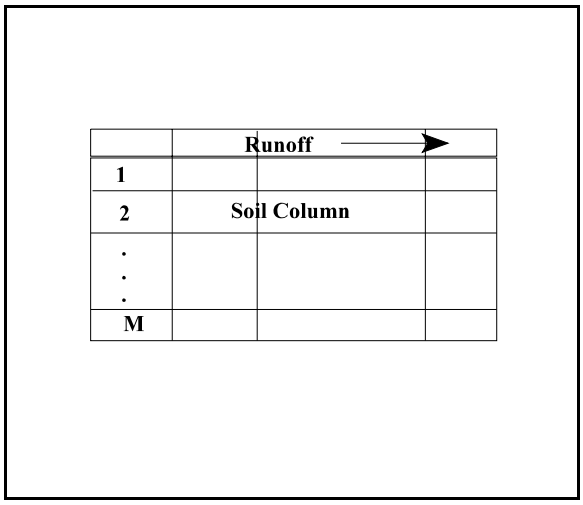

Figure F-3-2b. Cross-section view.

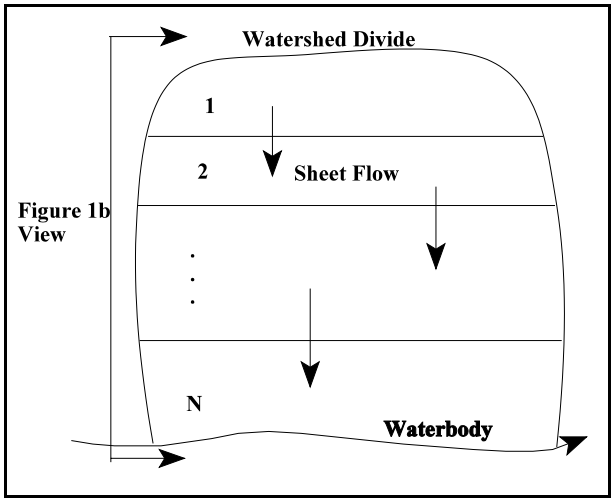

Figure F-3-2a. Local watershed.

F-3.2 Hydrology

F-3.2.1 Overview

Hydrologic modeling is performed to simulate watershed runoff and ground water recharge (termed here "infiltration"). The hydrology module is based on a daily soil moisture water balance performed for the root zone of the soil column. At the end of a given day, t, the soil moisture in the root zone of an arbitrary watershed subarea, i, is updated as

$$SM_{i,t} = SM_{i,t-1} + P_t + RO_{i-1,t} - RO_{i,t} - ET_{i,t} - IN_{i,t} \qquad \text{(F-3-1)}$$

where

$SM_{i,t}$	=	soil moisture (cm) in root zone at end of day t for subarea i
$SM_{i,t-1}$	=	soil moisture (cm) in root zone at end of previous day for subarea i
P_t	=	total precipitation (cm) on day t
$RO_{i-1,t}$	=	storm runoff (cm) on day t coming onto subarea i from i-1
$RO_{i,t}$	=	storm runoff (cm) on day t leaving subarea i
$ET_{i,t}$	=	evapotranspiration (cm) from root zone on day t for subarea i
$IN_{i,t}$	=	infiltration (ground water recharge) on day t (cm) for subarea i.

Precipitation is undifferentiated between rainfall and frozen precipitation; that is, frozen precipitation is treated as rainfall. Runoff, evapotranspiration, and infiltration losses from the root zone are discussed in subsequent sections. The equations presented in these sections refer to "day t and subarea i" in accordance with the above water balance equation (Equation F-3-1).

F-3.2.2 Runoff

F-3.2.2.1 <u>Governing Equations.</u> Daily runoff is based on the Soil Conservation Service's (SCS) widely used "curve number" procedure (USDA, 1986) and is a function of current and antecedent precipitation and land use. Land use is considered empirically by the curve numbers, which are catalogued by land use or cover type (e.g., woods, meadow, impervious surfaces), treatment or practice (e.g., contoured, terraced), hydrologic condition, and hydrologic soil group.

Runoff depth is calculated by the SCS procedure as

$$RO = \frac{(P - Ia)^2}{P - Ia + S} \quad for\ P \geq Ia \qquad \text{(F-3-2)}$$

where

RO	=	runoff depth (cm)
P	=	precipitation depth (cm)
Ia	=	initial abstraction (threshold precipitation depth for runoff to occur) (cm)
S	=	watershed storage (cm).

By experimentation with over 3,000 soil types and cover crops, the SCS developed the following relationships for watershed storage as a function of CN and initial abstraction as a function of storage.

$$S = \frac{2540}{CN} - 25.4 \qquad \text{(F-3-3)}$$

$$Ia = 0.2S \qquad \text{(F-3-4)}$$

Combining Equations F-3-2 and F-3-3 results in

$$RO = \frac{(P - 0.2S)^2}{P + 0.8S} \quad for\ P \geq 0.2S \qquad \text{(F-3-5a)}$$

$$RO = 0 \quad for\ P < 0.2S \qquad \text{(F-3-5b)}$$

where S is given by Equation 3-3. For impervious surfaces (CN = 100), it can be seen that RO = P.

Three antecedent moisture classes (AMCs) have been defined for use in adjusting the SCS curve numbers as shown in Table F-3-1. The growing season is assumed to be June through August (Julian Day 152 to 243) throughout the country.

Table F-3-1. Antecedent Moisture Classes for SCS Curve Number Methodology

AMC Class	Total 5-day Antecedent Rainfall (cm)	
	Dormant Season	Growing Season
I	< 1.3	< 3.6
II	1.3 to 2.8	3.6 to 5.3
III	> 2.8	> 5.3

Source: U.S. EPA et al. (1985).

Curve numbers are typically presented in the literature assuming average antecedent moisture conditions (AMC II) and can be adjusted for drier (AMC I) or wetter (AMC III) conditions as (Chow et al., 1988).

These adjustments have the effect of increasing runoff under wet antecedent conditions and decreasing runoff under dry antecedent conditions, relative to average conditions.

F-3.2.2.2 Implementation. Recall the conceptual module for the local watershed (Figure F-3-2), where the subareas may have different land uses and different curve numbers for each subarea. Equation F-3-5 is nonlinear in the curve number; therefore, the method by which the SCS procedure is applied to multiple subareas can make a significant difference in the resulting cumulative runoff values for downslope subareas. There are essentially two options for implementing the procedure. The first is based on runoff **routing** from each subarea to the next downslope subarea. That is, the runoff depth from subarea 1 would first be calculated from Equation F-3-5. The cumulative runoff depth from subareas 1 and 2 would then be calculated by applying Equation F-3-5 to subarea 2 and adding (routing) the runoff depth from subarea 1. This would be repeated for all subareas. This method is **not** appropriate for the sheet flow assumption of the local watershed and can give much higher cumulative runoff depths (volumes) than would actually occur under the sheet flow assumption. (The implicit assumption of the routing method is that the subareas are not hydrologically connected, e.g., runoff from subarea 1 is captured in a drainage system (non-sheet-flow) and diverted directly to the watershed outlet without passing through/over downslope subareas.)

A different, nonrouting method is appropriate for implementing the SCS procedure for the local (sheet flow) watershed. The method is based on determining composite curve numbers and is analogous to the nonsoil routing implementation of the Universal Soil Loss Equation (USLE) soil erosion module presented in Section 3.3. The methodology used for implementing this method is illustrated by the following pseudo-code.

$$CN(I) = \frac{4.2CN(II)}{10 - 0.058CN(II)} \qquad \text{(F-3-6)}$$

FOR i = 1,...,N (subareas)

$$CN(III) = \frac{23CN(II)}{10 + 0.13CN(II)} \qquad \text{(F-3-7)}$$

$CNeff_i$ = area-weighted composite CN_i for all subareas j, j=1,...,i
Calculate S_i from equation (3.2.2-2) using $CNeff_i$
Calculate RO_i from equation (3.2.2-1) using S_i. (RO_i is the ***average*** runoff depth over all upslope subareas j, j=1,...,i).
Calculate $Q_i = RO_i * WSA_i$ where Q_i is cumulative runoff volume and WSA_i is cumulative area.
IF i = 1 THEN
$H1_i = RO_i$ where $H1_i$ is subarea-specific runoff depth for subarea i, i.e. $RO_i - RO_{i-1}$
ELSE
$H1_i = (Q_i - Q_{i-1})/A_i$ where A_i is subarea-specific surface area
IF $H1_i < 0$ THEN $H1_i = 0$
END IF
NEXT i

F-3.2.3 Evapotranspiration

Potential evapotranspiration (PET) is the demand for soil moisture from evaporation and plant transpiration. When soil moisture is abundant, actual evapotranspiration (ET) equals PET. When soil moisture is limiting, ET will be less than PET. The extent to which it is less under limiting conditions has been expressed as a function of PET, available soil water (AW), and available soil water capacity (AWC) as (Dunne and Leopold, 1978).

$$AWC = (FC - WP)\frac{DRZ}{100} \qquad \text{(F-3-10)}$$

where

f = a functional relationship of the arguments.

and

WP = soil wilting point (% volume), which is the minimum soil moisture content that is available to plants. (Plants can exert a maximum suction of approximately 15 atmospheres. The wilting point is that moisture that would not be available at 15 atmospheres.)

FC = soil field capacity (% volume), which is the maximum soil moisture content that can be held in the soil by capillary or osmotic forces. Soil moisture above the field capacity is readily drained by gravity.

$$ET = \min[PET,\ PET(\frac{SM - WP}{FC - WP})] \qquad \text{(F-3-11)}$$

DRZ = depth of the root zone (cm).

$$ET = PET * f(\frac{AW}{AWC}) \qquad \text{(F-3-8)}$$

$$AW = (SM - WP)\frac{DRZ}{100} \qquad \text{(F-3-9)}$$

The functional relationship in Equation 3-8 is assumed here to be linear, so that ET (cm) is calculated as

PET is estimated as described below.

The more theoretically based modules for daily evapotranspiration (e.g., the Penman-Monteith equation [Monteith, 1965]) rely on the availability of significant daily meteorological data, including temperature gradient between surface and air, solar radiation, windspeed, and relative humidity. All of these variables may not be readily available for all application sites. Therefore, a less data-demanding module, the Hargreaves equation (Shuttleworth, 1975), is proposed. As compared with the most theoretical modules, some accuracy will be sacrificed. Nonetheless, the Hargreaves method, which is primarily temperature-based, has been shown to provide reasonable estimates of evaporation (Jensen, 1990)—presumably because it also includes an implicit link to solar radiation through its latitude parameter (Shuttleworth, 1993).

The Hargreaves equation is

$$PET = 0.0023 S_0 \Delta_T^{0.5} (T + 17.8) * 0.1 \qquad \text{(F-3-12)}$$

where

PET = potential evapotranspiration (cm/d)

T = mean daily air temperature (° C)

Δ_T = difference in mean monthly maximum and mean monthly minimum air temperature

S_0 = water equivalent of extraterrestrial radiation (mm/d) and is given as (Duffie and Beckman, 1980)

$$S_0 = 15.392 d_r (\varpi_s Sin\phi Sin\theta + Cos\phi Cos\theta Sin\varpi_s) \quad \text{(F-3-13)}$$

where

$$d_r = 1 + 0.033 Cos(\frac{2\pi}{365} J) \quad \text{(F-3-14)}$$

and

J = Julian day

ϖ_s = sunset hour angle (radians) given by

$$\varpi_s = Arccos(-Tan\phi Tan\theta) \quad \text{(F-3-15)}$$

ϕ = site latitude (positive for northern hemisphere, negative for southern)

θ = solar declination (radians) given by

$$\theta = 0.4093 Sin(\frac{2\pi}{365} J - 1.405) \quad \text{(F-3-16)}$$

F-3.2.4 Infiltration (Recharge)

Soil moisture in excess of the soil's field capacity (FC), if not used to satisfy ET, is available for gravity drainage from the root zone as infiltration to subroot zones (Dunne and Leopold, 1978). This infiltration rate will, however, be limited by the root zone soil's saturated hydraulic conductivity. Accordingly, infiltration is calculated as

$$IN = \min[Ksat, (SM - FC)\frac{DRZ}{100}] \quad \text{(F-3-17)}$$

where

IN = infiltration rate (cm/d)
Ksat = saturated hydraulic conductivity (cm/d).

In the event that infiltration is limited by Ksat, the hydrology algorithm includes a feedback loop that increases the previously calculated runoff volume by the amount of excess soil moisture, i.e., the water above the field capacity that exceeds Ksat. This adjustment is made to preserve water balance and is based on the assumption that the runoff curve number method, which is only loosely sensitive to soil moisture (through the antecedent precipitation adjustment) has admitted more water into the soil column than can be accommodated by ET, infiltration, and/or increased soil moisture. After the runoff is increased for this excess, the ET, infiltration, and soil moisture are updated to reflect this modification and preserve the water balance.

F-3.3 Soil Erosion

F-3.3.1 General

The Soil Erosion Module is based on the Universal Soil Loss Equation, an empirical methodology (see, e.g., Wischmeier and Smith, 1978) based on measured soil losses for experimental field-scale plots in the United States for some 40,000 storms. The USLE predicts sheet and rill erosion from hillsides upslope of defined drainage channels, such as streams. It does not predict streambank erosion. Let SL (kg/m^2-time) denote the eroded soil flux (unit load) from a hillside area over some time period. SL is predicted by the USLE as the product of six variables:

$$SL = R \times K \times C \times P \times LS \times Sd \quad \text{(F-3-18)}$$

These variables are discussed below.

R is the rainfall factor with units of 1/time. The rainfall factor accounts for the erosive (kinetic) energy of falling raindrops, which is essentially measured by rainfall intensity. The kinetic energy of an individual storm times its maximum 30-minute intensity is sometimes called the erosivity index (EI) factor. R factors have been compiled throughout the United States on a long-term annual average basis. These R factors were developed by cumulating these individual storm EI factors.

$$LS_i = (.045X_i)^b(65.41Sin^2\theta + 4.56Sin\theta + .065) \quad \text{(F-3-19)}$$

K is the soil erodibility factor with units of kg/m^2. Soil erodibility is an experimentally determined property and is a function of soil type, including particle size distribution, organic content, structure, and profile. K values are reported by soil type in the literature.

C is the dimensionless "cropping management" factor that varies between 0 and 1. It accounts for the type of cover (e.g., sod, grass type, fallow) on the soil. C is used to correct the USLE prediction relative to the cover type for which the experimentally determined K values were measured (fallow).

$$\theta = \arctan(S/100) \qquad \text{(F-3-20)}$$

P is the dimensionless practice factor and accounts for the effect of erosion control practices, e.g., contouring or terracing. P is never negative, but could be greater than 1.0 if land practices actually encourage erosion relative to the original experimental plots on which K was measured.

LS is the combined "length-slope"factor and is given by (U.S. EPA, 1985b) as where

X_i = flow distance (m) from the point at which sheet flow originates (the upslope drainage divide) to the point of interest on the hillside.

θ = slope angle (degrees), where θ may be calculated from percent slope, S, as

and b, the exponent, is determined as a function of S as:

b = 0.5, if S > .05
b = 0.4, if .035 <= S <= .045
b = 0.3, if .01 <= S < .035
b = 0.2, if S < .01.

LS increases with increasing flow distance because runoff quantity generally increases with distance. It increases with slope because runoff velocity generally increases with slope.

Sd is the "sediment delivery ratio," which estimates the fraction of onsite eroded soil that reaches a particular downslope or downstream location in the subbasin (Shen and Julien, 1993). The sediment delivery ratio is here used to account for deposition of eroded soil from the local watershed in ditches, gullies, or other depressions. Vanoni (1975) developed the sediment delivery ratio as a function of watershed drainage area. That formulation is

$$Sd = a \times A^{-.125} \qquad \text{(F-3-21)}$$

where

Sd	=	sediment delivery ratio (dimensionless)
A	=	subbasin area (m^2)
a	=	normalized to give Sd = 1.0 for an area of 0.001 mi^2 as per Vanoni (1975). (For area in m^2, a = 2.67.).

F-3.3.2 MUSLE Implementation

The USLE is implemented on a storm event basis, i.e., the "modified" USLE (MUSLE) is used. This implementation requires determining an R value (with units of 1/day) for each daily storm event that specifies the erosivity of that individual storm. Let the storm-event-specific R value be denoted as R_t for storm event t, so that the pseudo-code presented above is applied for a given daily storm event. Several methods have been proposed for estimating R_t and are summarized below. Method 4 is used in this application.

Method 1 — R_t as a Function of Total Daily Precipitation. This method (Richardson et al., 1983) predicts R_t as a function of total daily precipitation by means of a two-parameter regression module (a power function). The parameters were estimated by Richardson et al. from long-term records of daily "erosivity index" (EI, which is operationally equivalent to R) and total daily precipitation for 11 sites, all located east of the Rocky Mountains. (Western sites were not included in the data "... so that the relationships would not be influenced by the complex orographic effects of mountainous terrain.") It was determined that one of the parameters (the exponent) was statistically invariant with respect to site, while the other parameter did vary by site. In addition, the variance of the prediction error was also found to be a predictable function of site location. Thus, tables relating the varying regression parameter and its prediction error variance were generated from the regression data by site. Several methods were considered for correlating those 11 sites to western sites (e.g., correlation by average storm intensity), but were rejected as either too data-intensive or too uncertain.

Method 2 — R_t as a Function of Storm Runoff. This method (used by PRZM) predicts R_t as a function of daily storm event runoff and peak storm runoff (Williams, 1975). Although total runoff from the (daily) storm event is available (from the SCS Curve Number module), the shape and duration of the runoff hydrograph for the storm is not calculated and, thus, the peak runoff from the storm is not available.

Method 3 — R_t Calculated from Hourly Erosivity Index Values. This method (Wischmeier and Smith, 1978) is the most rigorous MUSLE approach. It is not based on regression analysis of presumed correlated independent variables, but rather predicts R_t directly by aggregating hourly EI calculations over the storm's duration. The EI values are calculated from hourly average rainfall intensity data. This is the method that has been used to estimate long-term annual total R values for the classical (annual total) use of the USLE. Because hourly precipitation data are available from the SAMSON files, this method is feasible. Method 4 below is essentially based on this method, although the method allocates the (published) long-term annual R values down to hourly R (and then up to daily R_t) instead of building up the long-term annual R from the hourly data.

Method 4 — R_t Allocated from Published Long-Term Annual Total R Values. Because published values of long-term annual total R values exist in the form of isopleths across the

country, it seems appropriate to use these annual total R data and disaggregate them down to a daily basis for the MUSLE. This is the method used for the LAU. Pseudo-code to implement this method is:

Given: Long-term annual total R, Rann, for a site.
Given: Number of years in the simulation, NYR.
Given: Hourly time series of precipitation amounts for the complete record of NYR years.

1. Compute cumulative R over record, R_{total} = Rann x NYR

2. Compute cumulative precipitation over NYR years, PPT_{total}

3. For each hourly precipitation value in the record, allocate R_{total} to that hour based on the fraction of PPT_{total} represented by the hourly precipitation. Denote an hourly allocation as R_{hour}.

4. For each day of the record, cumulate all R_{hour} values to the daily total. The result is R_t for each day of the NYR record.

F-3.3.3 Spatial Implementation

For the local watershed application, the USLE is applied spatially to a hillside that comprises N subareas (see Figure 3-2a). Pseudo-code for this application is:

LET CSL_i = cumulative soil load (kg/day) for subarea i, i.e. eroded load from subarea i and all upslope subareas j, j = 1,...,i
LET WSA_i = cumulative land area (m^2) upslope of and including subarea i

FOR i=1,...,N
$Keff_i$ = area-weighted K_i for all subareas j, j=1,...,i
$Ceff_i$ = area-weighted C_i for all subareas j, j=1,...,i
$Peff_i$ = area-weighted P_i for all subareas j, j=1,...,i
$CSL_i = R*WSA_i*Keff_i*Ceff_i*Peff_i*LS_i*Sd_i$
NEXT i

The assignment of the sheet-flow distance parameter, X_i, within the LS_i factor (see Equation F-3-19) merits discussion in the context of the "local watershed" conceptual module. This local watershed construct (see Figure F-3-1) was developed to simulate the downslope transport of contaminant due to storm water runoff and soil erosion from the LAU. The use of the USLE equation for estimating soil erosion (and associated chemical load) assumes that runoff is essentially sheet flow and that erosion results from sheet, or, at most, rill (very small channels) erosion; i.e., runoff does not occur in significantly defined drainage channels (e.g., ditches, swales) within the local watershed. The delineation of the sheet-flow-only local watershed is accomplished by geographic information system (GIS) analysis, and a key component of this analysis with respect to the sheet-flow-only assumption is the correct generation of the waterbody network such that the waterbody delineated as lying downslope of the local watershed is in fact the first "defined drainage channel" that the runoff would

encounter. That is, runoff upslope of the GIS-defined waterbody is essentially sheet flow, in accordance with the conceptual module and the underlying assumptions of the USLE. The criterion used for terminating (headwater) the GIS-delineated streams is a tributary drainage area of 700,000 m^2, which has been estimated to coincide with "first-order" stream headwaters. Thus, the 700,000-m^2 criterion provides an upper bound on the area of a local watershed.

The issue here, however, is that within this 700,000-m^2 upper bound there is ample opportunity for the length of the sheet-flow path (measured in the direction of the steepest gradient) of any given local watershed to greatly exceed a distance at which one could reasonably expect to maintain sheet-flow conditions; that is, a ditch or swale (but not necessarily a first-order stream) would have been encountered. That distance is dependent on many factors such as slope, soil type, and runoff intensity, but has been estimated to be no more than approximately one-quarter of a mile (400 m) (Wischmeier and Smith, 1978). Indeed, more recent data (Lightle and Weesies, 1998) have suggested even more restrictive limits that vary nonlinearly with slope, e.g., 30.5 m for a slope of 0.5 percent, 91 m for slope of 2 percent and 15 m for slopes exceeding 17 percent. Thus, to the extent that a GIS-delineated flow path distance greatly exceeds a reasonable maximum sheet-flow-only distance, application of the sheet-flow-only module to that entire local watershed becomes inconsistent with what might actually be occurring at that site. The implications of such an inconsistency are the following:

- Soil erosion (and associated contaminant loss) would be overestimated, because erosion is an increasing function of flow distance (see Equation F-3-19).

- Contamination in a downslope buffer would be overestimated. (The runoff/erosion may instead be channeled directly into the waterbody via a ditch or swale before it reaches the buffer area.)

The obvious solution to this issue is to further disaggregate the local watershed into a series of sublocal watersheds, each defined by a flow distance not exceeding the maximum, and apply the module sequentially to each sublocal watershed. There are a number of difficulties associated with this option, however, including:

- The impracticality of implementation in GIS in an automated manner.

- The increased computational burden.

- Is soil/chemical "piped" directly to the waterbody at the outlet of each sublocal watershed or assumed to be deposited in the ditch or swale? If deposited, when would it finally be transported to the waterbody?

- The inherent uncertainty in spatial resolution of the WMU within the local watershed in the first place.

In short, while this solution is appealing from a conceptual point of view, it is believed to be impractical and, indeed, an inappropriate complexity. The resolution used is to simply limit the flow distance to a reasonable maximum when the GIS-delineated distance exceeds that maximum. The conceptual module corresponding to this approach is that the runoff water itself

may be diverted by swales or ditches, but the soil and chemical being eroded are maintained on the local watershed surface, to be transported downslope over time across the buffer and into the waterbody. This resolution is environmentally conservative with respect to contamination in the buffer. Depending on the actual residence time of a chemical deposited in a swale or ditch within the local watershed, it is not necessarily conservative with respect to chemical loadings to the waterbody. Nonetheless, mass balance is conserved.

F-3.4 Chemical Fate and Transport

F-3.4.1 Runoff Compartment

F-3.4.1.1 Introduction. A module of chemical and suspended solids concentrations in storm event runoff is presented in this section. The module is based on mass balances of solids and chemical in the runoff and the top soil column layer of thickness dz. The soil compartment is external to this module (see Section F-3.4.2) and results from that compartment are called as needed by the software. A simplifying assumption is made that solids and chemical concentrations in the runoff are at instantaneous steady-state during each individual runoff event, but can vary among runoff events, i.e. a quasi-dynamic approach is used. While assumption of instantaneous steady-state for each storm event is not strictly accurate, it was felt appropriate for the following reasons:

- Run time considerations (i.e., maximize the numerical time step).
- Data will not be available at the temporal scale to accurately track within-storm event conditions (e.g., rainfall hyetographs).
- Because of the anticipated relatively small surface areas of the watershed subareas and the associated relatively small runoff volumes, the actual time to steady-state may not differ significantly from the one day or less implicitly assumed here. (A sensitivity analysis was performed using a dynamic form of the runoff compartment module that suggested relatively little difference in soil concentrations as a function of the steady-state versus dynamic assumption.)
- To the extent that the actual time to steady-state would be greater than 1 day, the module is biased toward overestimating downslope concentrations and waterbody loads (i.e., it is risk-conservative).

Figure F-3-3 presents the conceptual Runoff Quality Module showing the two compartments and the fate and transport processes considered. Development of mass balance equations for solids and chemical follow. (It should be noted that hydrolysis, volatilization, and biodegradation processes are not simulated in the runoff compartment. The percentage of time

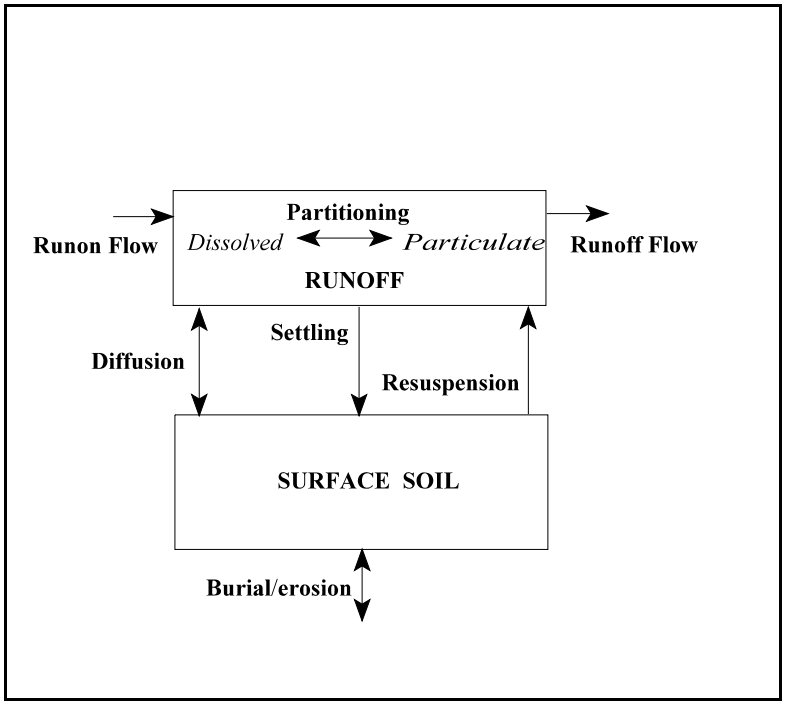

Figure F-3-3. Runoff quality conceptual model.

that runoff is actually occurring will be sufficiently short that any additional losses from these processes should be minimal. In addition, these processes are continuously simulated in the surface layer of the soil column. To also include them in the runoff compartment would be "double-counting.")

F-3.4.1.2 <u>Solids in Runoff Compartment</u>. A steady-state mass balance of solids in the runoff, i.e. suspended solids from erosion, written for arbitrary local watershed subarea i is given by the following equation. (In the subsequent module development, units are presented in general dimensional format, i.e., M(ass)-L(ength)-T(ime), for simplicity of presentation.)

$$0 = Q'_{i-1} m_{1,i-1} - Q'_i m_{1,i} - vs_i A_i m_{1,i} + vr_i A_i m_2 \qquad \text{(F-3-22a)}$$

$$Q'_{i-1} = Q_{i-1} + \frac{CSL_{i-1}}{\rho} \qquad \text{(F-3-22b)}$$

$$Q'_i = Q_i + \frac{CSL_i}{\rho} \qquad \text{(F-3-22c)}$$

where

$m_{1,i}$ = solids concentration (M/L^3) in the subarea i runoff (suspended solids)

m_2 = solids concentration (M/L^3) in the top soil column layer of subarea i
Q_i = runoff flow (L^3/T) leaving subarea i
Q_{i-1} = runon flow (L^3/T) from subarea i-1
A_i = surface area (L^2) of subarea i
vs_i = settling velocity (L/T)
vr_i = resuspension velocity (L/T)
Q'_i = total runoff flow volume (L^3/T) (water plus solids) leaving subarea i
CSL_i = cumulative soil load leaving subarea i (M/T)
ρ = particle density (M/L^3) (i.e., 2.65 g/m^3).

(Note: subscript "1" denotes the runoff compartment while "2" denotes the top soil column layer compartment.) The first term in Equation F-3-22a is the flux of soil across the upslope interface of subarea i. The second term is the flux of soil across the downslope interface. The third term is an internal sink of soil due to settling while the fourth term is an internal source due to resuspension.

3.4.1.3 Solids in Soil Compartment. The GSCM does not consider chemical mass transport among watershed subareas due to soil erosion, because it is based on a single subarea only. Therefore, that transport is considered here. The assumption is made that solids mass transport from or to the soil compartment of any given watershed subarea occurs only in a vertical direction, i.e., no downgradient advection of the top soil column layer itself is considered. (This is analogous to the assumption of a stationary sediment bed in stream/sediment quality modules.) The downslope mass transport of soil occurs due to vertical erosion or resuspension of soil followed by advective transport of the soil in the runoff water as suspended solids. The transport is described in terms of three parameters — settling, resuspension, and burial/erosion velocities. Under the assumption of no advective transport of the soil column layer, the steady-state mass balance equation for the surficial soil layer is

$$0 = vs_i m_{1,i} A_i - vr_i m_{2,i} A_i - vb_i m_{2,i} A_i \qquad \text{(F-3-23)}$$

where

vb_i = burial/erosion velocity (L/T).

The first term of Equation (F-3-23) is a source of soil mass to the surficial soil column layer due to settling from the overlying runoff water. The second term is a sink from resuspension. The third term is either a source or a sink depending on the sign of the burial/erosion velocity as described subsequently.

Consider the solids balances in the runoff and soil compartments, Equations F-3-22 and F-3-23, respectively. These two equations involve three parameters—vs, vr, and vb—and two solids concentrations—m_1 and m_2. Which of these five variables is known for arbitrary subarea i? It can be assumed that the solids concentration in the soil (m_2) is a known value — it is simply the bulk soil density. Consider now the suspended solids concentration in subarea i, $m_{1,i}$. From the Soil Erosion Module, the total solids mass fluxes moving across both the upslope and

downslope interfaces of subarea i are known, and these two fluxes are, respectively, the first two terms on the right side of Equation F-3-22 $m_{1,i}$ can then be determined as

$$m_{1,i} = CSL_i/Q'_i \qquad \text{(F-3-24)}$$

where CSL_i is the cumulative soil load leaving subarea i, as determined by the Soil Erosion Module, and Q'_i is the cumulative runoff flow volume (including solids' volume) leaving subarea i, as determined by the Runoff Quantity Model. Therefore, because the soil concentration (m_2) is assumed to be known and the Soil Erosion and Runoff Quantity modules can be used to determine the suspended solids concentrations (the $m_{1,i}$), Equations F-3-22 and F-3-23 can now be considered as two equations in three unknowns, vs, vr, and vb.

The settling (vs) and resuspension (vr) parameters reflect processes internal to subarea i, while the burial/erosion parameter (vb) reflects net changes across subarea i and is completely determined by the difference in the soil fluxes entering and leaving subarea i. This can be seen by adding the right-hand-sides of Equations F-3-22 and F-3-23 and setting the result to zero. All terms involving vs and vr cancel, and the burial/erosion velocity is then given by

$$vb_i = \frac{CSL_{i-1} - CSL_i}{A_i m_2} \qquad \text{(F-3-25)}$$

where CSL_{i-1} and CSL_i denote the soil fluxes into and out of subarea i, respectively, as discussed above. From Equation 3-25 it can be seen that, if the soil load entering subarea i (CSL_{i-1}) is greater than the soil load leaving (CSL_i), then the burial/erosion velocity is positive and soil is being deposited (buried). Conversely, as will typically be the case, if the load leaving is greater than the load entering, then the burial/erosion velocity will be negative and erosion is occurring in an upward direction.

Consider now vs and vr. With the net soil flux across the subarea having been determined, Equations F-3-22 and F-3-23 are in fact the same equation—the burial velocity term is explicitly shown in Equation F-3-23 and implicitly shown in Equation F-3-22. Thus, either Equation F-3-22 or F-3-23 represents one equation in two unknowns, vs and vr. If one of these is known, the other can be solved for. Of the two, the resuspension velocity would be very difficult to obtain estimates for, while the settling velocity could be assumed similar to, for example, hindered or compaction settling in sludge thickeners. Accordingly, vr as a function of vs (and vb, which is determined as per Equation F-3-25 is given for subarea i by

$$vr_i = vs_i \frac{m_{1,i}}{m_2} - vb_i \qquad \text{(F-3-26)}$$

The settling velocity, vs, is assigned values from a uniform random distribution between the range 0.05 and 1.0 m/d, based on observed settling velocities for "mineral" sludges in sludge thickening experiments.

In summary, because m_2 is assumed known and m_1 is calculated from results of the Soil Erosion and Runoff modules, the solids mass balance equations are used to determine the burial/erosion and resuspension parameters for subsequent use in the chemical (contaminant) model.

F-3.4.1.4 <u>Contaminant in Runoff Compartment</u>. As illustrated in Figure F-3-3, a steady-state mass balance of contaminant in the runoff results in the equation

$$0 = Q'_{i-1}c_{1,i-1} - Q'_i c_{1,i} - vs_i A_i Fp_{1,i} c_{1,i} + vr_i A_i Fp_{2,i} Er_i c_{2,i} + vd_i A_i \left(\frac{Fd_{2,i}}{\Phi_2} c_{2,i} - \frac{Fd_{1,i}}{\Phi_{1,i}} c_{1,i}\right) \quad \text{(F-3-27)}$$

where

$c_{1,i}$ = total contaminant concentration (particulate + dissolved) in runoff in subarea i (M/L^3)

$c_{2,i}$ = total contaminant concentration in soil (M/L^3)

$V_{1,i}$ = subarea-specific (not cumulative) runoff volume for subarea i (L^3)

$Fp_{1,i}$ = fraction particulate in runoff

$Fd_{1,i}$ = fraction dissolved in runoff ($1-Fp_{1,i}$)

vd_i = diffusive exchange velocity (L/T)

Er_i = enrichment ratio

$\Phi_{1,i}$ = is the porosity of the runoff, calculated as

$$\Phi_{1,i} = 1 - \frac{m_{1,i}}{\rho} \quad \text{(F-3-28)}$$

$$\Phi_2 = 1 - \frac{m_2}{\rho} \quad \text{(F-3-29)}$$

where ρ is the density (M/L^3) of suspended solids (e.g., 2.65 g/cm^3).

Φ_2 = soil porosity, calculated as

Note that ϕ_2 is equivalent to porosity (η) in the GSCM.

Equation (F-3-27) can be used to express $c_{1,i}$ as a function of $c_{1,i-1}$ and $c_{2,i}$ as

$$c_{1,i} = \frac{Q'_{i-1}c_{1,i-1} + [vr_iA_iFp_{2,i}Er_i + vd_iA_i(Fd_{2,i}/\Phi_2)]c_{2,i}}{Q'_i + vs_iA_iFp_{1,i} + vd_iA_i(Fd_{1,i}/\Phi_{1,i})} \quad \text{(F-3-30)}$$

where $c_{2,i}$ is determined by the GSCM as described in Section 2. Determination of the individual terms constituting this equation are described below.

$Fp_{1,i}$ is calculated as (Thomann and Mueller, 1987)

$$Fp_{1,i} = \frac{(k_d/\Phi_{1,i})m_{1,i}}{1 + (k_d/\Phi_{1,i})m_{1,i}} \quad \text{(F-3-31)}$$

where

k_d = chemical-specific partition coefficient (L^3/M) (Note: k_d is divided by porosity to attain the porosity-corrected k_d with units of mass per total [liquid plus solids] volume.)

$Fp_{2,i}$ is similarly calculated as

$$Fp_{2,i} = \frac{(k_d/\Phi_2)m_2}{1 + (k_d/\Phi_2)m_2} \quad \text{(F-3-32)}$$

where it can be seen that Fp_2 (and Fd_2) will be constant among all subareas i.

$Fd_{1,i}$ and $Fd_{2,i}$ are then determined as

$$Fd_{1,i} = 1 - Fp_{1,i} \quad \text{(F-3-33)}$$

$$Fd_{2,i} = 1 - Fp_{2,i} \quad \text{(F-3-34)}$$

Under the assumption that resistance to vertical diffusion is much greater in the soil than in the runoff, the diffusive exchange velocity, vd_i, can be expressed as (Thomann and Mueller, 1987, p. 548)

$$vd_i = \frac{Dw}{\Phi_2 Lc} \qquad \text{(F-3-35)}$$

where

Dw = water diffusivity (L^2/T).
Lc = characteristic mixing length (L) over which a concentration gradient exists; assumed to be the depth of the runoff including the solids (H1'):

$$Lc = H1'_i = \frac{Q'_i}{A_i} \qquad \text{(F-3-36)}$$

The enrichment ratio, Er_i, is used to account for preferential erosion of finer soil particles — with higher specific surface areas and more sorbed chemical per unit area — as rainfall intensity decreases. That is, large (highly erosive) runoff events may result in average eroded soil particle sizes and associated sorbed chemical loads that do not differ much from the average sizes/loads in the surficial soil column layer. However, less intense runoff events will erode the finer materials and resulting chemical loads could be significantly higher than represented by the average soil concentration. U.S. EPA et al. (1985) give the storm event-specific enrichment ratio as a power function of sediment discharge flux (M/L^2). This formulation results in:

$$Er_i = \frac{a}{(CSL_i/WSA_i)^{0.2}} \qquad \text{(F-3-37)}$$

where a = 7.39 for CSL_i/WSA_i in kg/ha (U.S. EPA et al., 1985). (CSL_i is the event soil load leaving subarea i and WSA_i is the local watershed surface area from the drainage divide down to and including subarea i.) It should be noted that the enrichment ratio is greater than or equal to 1.0. Should specific values of the sediment discharge (the denominator) result in an enrichment ratio less than 1.0, it is reset to 1.0 in the code.

F-3.4.2 Soil Compartment

The GSCM (see Section F-2.2) is coupled to the Runoff Compartment Module (see Section F-3.4.1) in this section and applied to the several subareas that constitive the sheet flow local watershed of which the LAU or wastepile is an integral part. Continuing the chemical concentration indexing scheme (i.e., subscript “1" denoting runoff compartment, and subscript “2" denoting surficial soil compartment), let the total (dissolved, particulate, and gaseous phase) chemical concentration in the surficial soil column layer of any local watershed subarea i be denoted as $C_{2,i}$. ($C_{2,i}$ is equivalent to C_T in the GSCM description.) From Section F-2.2 (GSCM), the governing differential equation for the surface soil layer of subarea i is

$$\frac{\partial C_{2,i}}{\partial t} = D_E \frac{\partial^2 C_{2,i}}{\partial z^2} - V_E \frac{\partial C_{2,i}}{\partial z} - \Sigma k_j C_{2,i} + ss_i \qquad \text{(F-3-38)}$$

where k_j represents first-order rate constant due to process j not including runoff/erosion processes, i.e., biological decay and hydrolysis and wind/mechanical action. The last term, ss_i, is a source/sink term representing the net effect of runoff and erosion processes on $C_{2,i}$ as illustrated in Figure F-3-3. This term is given by

$$ss_i = \frac{vs_i Fp_{1,i} C_{1,i} - vr_i Fp_{2,i} Er_i C_{2,i} - vd_i \left(\frac{Fd_{2,i}}{\Phi_2} C_{2,i} - \frac{Fd_{1,i}}{\Phi_{1,i}} C_{1,i}\right) - vb_i Fp_2 C_{2,i}}{dz} \qquad \text{(F-3-39)}$$

where vs_i, vr_i, vb_i, and vd_i denote, respectively, the settling, resuspension, burial/erosion and diffusive exchange velocities for subarea i as described in the Runoff Compartment model. Thus, the terms comprising ss_i are, respectively, a source of chemical due to settling from the overlying runoff water, a sink of chemical due to resuspension, and a source or sink (depending on the relative values of $C_{1,i}$ and $C_{2,i}$) due to chemical diffusion from/to the runoff.

(The burial/erosion mechanism introduces a minor mass balance error into the model. The module for surface soil/runoff water fate and transport [Section F-3.4.1] is based on a conceptual module originally developed for use in a stream/sediment application [e.g., Thomann and Mueller, 1987] where the sediment compartment location relative to a reference point below the surface can move vertically ["float"] as burial and erosion occur. In that moving frame of reference, burial/erosion of contaminant does not introduce a mass balance error because, with respect to the modeled sediment, this sink/source of contaminant is **exogenous** to the modeled system, i.e., it is coming from/going to outside of the modeled system. There is internal [endogenous] mass balance consistency within the modeled system. However, the frame of reference is not allowed to float, but is fixed by the elevation of the lower boundary, e.g. top of the vadose zone. Thus, if sorbed chemical is eroded from the surface cell, that surface cell, which is vertically fixed, must have a "source" that is internal to the modeled soil column to compensate for this sink or its internal mass balance is not maintained. The magnitude of this mass balance error is equal to the mass of eroded soil from the surface over the duration of the simulation times its average sorbed chemical concentration. In most cases, this error as a percentage of the total chemical mass in the modeled LAU will be quite small, and that has been confirmed in multiple executions of the module. Conceptually at least, the GSCM could be designed so that, after each runoff event, the surficial soil compartment could decrease or increase in size to accommodate the event's erosion/burial magnitude, while maintaining a fixed vertical reference.

Grouping coefficients of $C_{1,i}$ and $C_{2,i}$, Equation F-3-39 can be rewritten as

$$ss_i = a_i C_{1,i} - b_i C_{2,i} - k_{bu,i} C_{2,i} \qquad \text{(F-3-40a)}$$

where

$$a_i = \frac{vs_t Fp_{1,i} + vd_i \frac{Fd_{1,i}}{\Phi_{1,i}}}{dz} \quad \text{(F-3-40b)}$$

$$b_i = \frac{vr_t Fp_{2,i} Er_i + vd_i \frac{Fd_{2,i}}{\Phi_2}}{dz} \quad \text{(F-3-40c)}$$

$$k_{bu,i} = \frac{vb_i \, Fp_{2,i}}{dz} \quad \text{(F-3-40d)}$$

and $k_{bu,i}$ is the first-order rate constant (1/T) associated with the burial/erosion process.

Using Equation F-3-40, Equation F-3-38 can be rewritten as

$$\frac{\partial C_{2,i}}{\partial t} = D_E \frac{\partial^2 C_{2,i}}{\partial z^2} - V_E \frac{\partial C_{2,i}}{\partial z} - \Sigma k_j C_{2,i} + a_i C_{1,i} - b_i C_{2,i} - k_{bu,i} C_{2,i} \quad \text{(F-3-41)}$$

From Equation F-3-41, it can be seen that $C_{2,i}$ is a function of $C_{1,i}$. Similarly, from Equation F-3-30 of the Runoff Compartment Module, it can be seen that $C_{1,i}$ is a function of $C_{2,i}$. Thus, $C_{2,i}$ and $C_{1,i}$ are jointly determined at any time t by simultaneous solution of their two respective equations.

$C_{2,i}$ at time t can be determined by substitution for $C_{1,i}$. From the Runoff Compartment module (Equation F-3-30). $C_{1,i}$ can be expressed as

$$C_{1,i} = \frac{Q'_{i-1} C_{1,i-1}}{d_{2,i}} + \frac{d_{1,i}}{d_{2,i}} C_{2,i} \quad \text{(F-3-42a)}$$

where

$$d_{1,i} = vr_t A_i Fp_{2,i} Er_i + vd_t A_i \frac{Fd_{2,i}}{\Phi_2} \quad \text{(F-3-42b)}$$

Substituting for $C_{1,i}$ from Equation F-3-42 into Equation F-3-41, the differential equation for $C_{2,i}$ is now

$$d_{2,i} = Q'_i + vs_t A_i Fp_{1,i} + vd_t A_i \frac{Fd_{1,i}}{\Phi_{1,i}} \quad \text{(F-3-42c)}$$

expressed implicitly as a function of $C_{1,i}$ as

$$\frac{\partial C_{2,i}}{\partial t} = D_E \frac{\partial^2 C_{2,i}}{\partial z^2} - V_E \frac{\partial C_{2,i}}{\partial z} - (\Sigma k_j + b_i + k_{bu,i} - \frac{a_i d_{1,i}}{d_{2,i}}) C_{2,i} + \frac{a_i Q'_{i-1} C_{1,i-1}}{d_{2,i}} \qquad \text{(F-3-43)}$$

Once $C_{2,i}$ at time t is determined by solution of Equation F-3-43, the associated value for $C_{1,i}$ can be found from Equation F-3-42, thus completing the simultaneous solution. (The value for
$C_{1,i-1}$, i.e., the runoff concentration in the immediately upslope subarea, will have been determined previously during the simultaneous solution for the i-1 subarea at time t.)

To implement the simultaneous solution, Equation F-3-43 can be simplified to

$$\frac{\partial C_{2,i}}{\partial t} = D_E \frac{\partial^2 C_{2,i}}{\partial z^2} - V_E \frac{\partial C_{2,i}}{\partial z} - k'_i C_{2,i} + ld_{i-1} \qquad \text{(F-3-44a)}$$

where

$$k'_i = \Sigma k_j + k_{ev,i} + k_{bu,i} \qquad \text{(F-3-44b)}$$

$$k_{ev,i} = b_i - a_i \frac{d_{1,i}}{d_{2,i}} \qquad \text{(F-3-44c)}$$

$$ld_{i-1} = \frac{a_i}{d_{2,i}} Q'_{i-1} C_{1,i-1} \qquad \text{(F-3-44d)}$$

$k_{ev,i}$ is the storm event (or runoff and erosion) first-order loss rate, k'_i is the lumped first-order loss rate which includes the effects of abiotic hydrolysis (j=hy), aerobic biodegradation (j=ae), and wind/mechanical activity (j=wd), in addition to runoff and erosion. k_{hy} and k_{ae} are inputs to the module
and k_{wd} is calculated using the methodologies detailed in Appendix F-A. The last term, ld_{i-1} is the run-on load from upslope subareas in $g/m^3/d$.

Recall that in the GSCM, the governing equation is broken up into three component equations—diffusion, convection, and first-order losses (Equations F-2-13 through F-2-15), each solved individually on a grid. In the subsurface layers, the solution technique described in Section 2 is applied directly. However, for the surface soil column layer, the first two-component equations remain the same, while the third is revised to:

$$\frac{\partial C_{2,i}}{\partial t} = - k' C_{2,i} + ld_{i-1} \quad \text{(F-3-45)}$$

which has the following analytical solution for $C_{2,i} = C^0_{2,i}$ at t = 0:

$$C_{2,i} = \begin{cases} C^0_{2,i} \exp(-k'_i t) + ld_{i-1}\left[\frac{1 - \exp(-k'_i t)}{k'_i}\right] & k'_i > 0 \\ C^0_{2,i} + ld_{i-1} t & k'_i = 0 \end{cases} \quad \text{(F-3-46)}$$

To track mass losses, the total mass added to the soil column in subarea i in any time period zero to t due to settling from runoff water, $M_{add,i}$ (M/L^2), is evaluated using

$$M_{add,i} = ld_{i-1} t \, dz \quad \text{(F-3-47)}$$

A mass balance on the soil column in time t gives:

$$\Delta M_i = M_{add,i} - M_{loss,i} \quad \text{(F-3-48)}$$

where ΔM_i (M/L2) is the change in mass in the soil column in subarea i as given by (($C_{2,i}$ - $C°_{2,i}$)*dz) and $M_{loss,i}$ (M/L^2) is the total mass lost from the subarea i soil column in any time

$$M_{loss,i} = \left[C^0_{2,i}(1 - \exp(-k'_i t)) + ld_{i-1}\left(\frac{k'_i t + \exp(-k'_i t) - 1}{k'_i}\right)\right] dz \quad \text{(F-3-49)}$$

period zero to t. By substituting Equation F-3-46 for $C_{2,i}$ and Equation F-3-47 for $M_{add,i}$ and rearranging, the following equation for $M_{loss,i}$ was derived for $k'_i > 0$. For $k'_i = 0$, $M_{loss,i} = 0$.

The total mass lost in any time period zero to t from subarea i soil column can be attributed to specific first-order loss processes, j, $M_i(t)$ (M/L^2) using

$$M_{j,i} = M_{loss,i} \frac{k_j}{k'_i} \quad \text{(F-3-50)}$$

where

j = hy for hydrolysis,
j = ae for aerobic degradation,
j = wd for losses due to wind/mechanical activity,
j = ev for runoff/erosion events, and
j = bu for burial/erosion.

Equation F-3-42a provides the contaminant concentration in the runoff water at time t. The average contaminant concentration in the runoff water ($\bar{C}_{1,i}$) over time 0 to t is determined using:

$$\bar{C}_{1,i} = \frac{Q'_{i-1}\bar{C}_{1,i-1}}{d_{2,i}} + \frac{d_{1,i}}{d_{2,i}}\bar{C}_{2,i} \qquad \text{(F-3-51)}$$

where $\bar{C}_{2,i}$ is the time-weighted average contaminant concentration in the soil compartment over the same time period. Given the short time step (i.e., 1 day) used in the integration of the Local Watershed/Soil Column Module, $\bar{C}_{2,i}$ is approximated using:

$$\bar{C}_{2,i} = \frac{C^0_{2,i} + C_{2,i}}{2} \qquad \text{(F-3-52)}$$

where the 0 superscript denotes concentration at the beginning of the day.

F-3.5 Implementation

F-3.5.1 Overview

An overview of the algorithm implementing the combined Local Watershed/Soil Column Modules is provided in Figure F-3-4a and b. Some additional differences from the GSCM general algorithm (Section F-2.4.1) are noted. In the GSCM, it is assumed that infiltration is constant and convection events occur at regular intervals throughout the entire simulation. (With a convection event, soil column concentrations are propagated downward and M_{lcha} is incremented.) In the Local Watershed/Soil Column Modules, the infiltration rate (I) is allowed

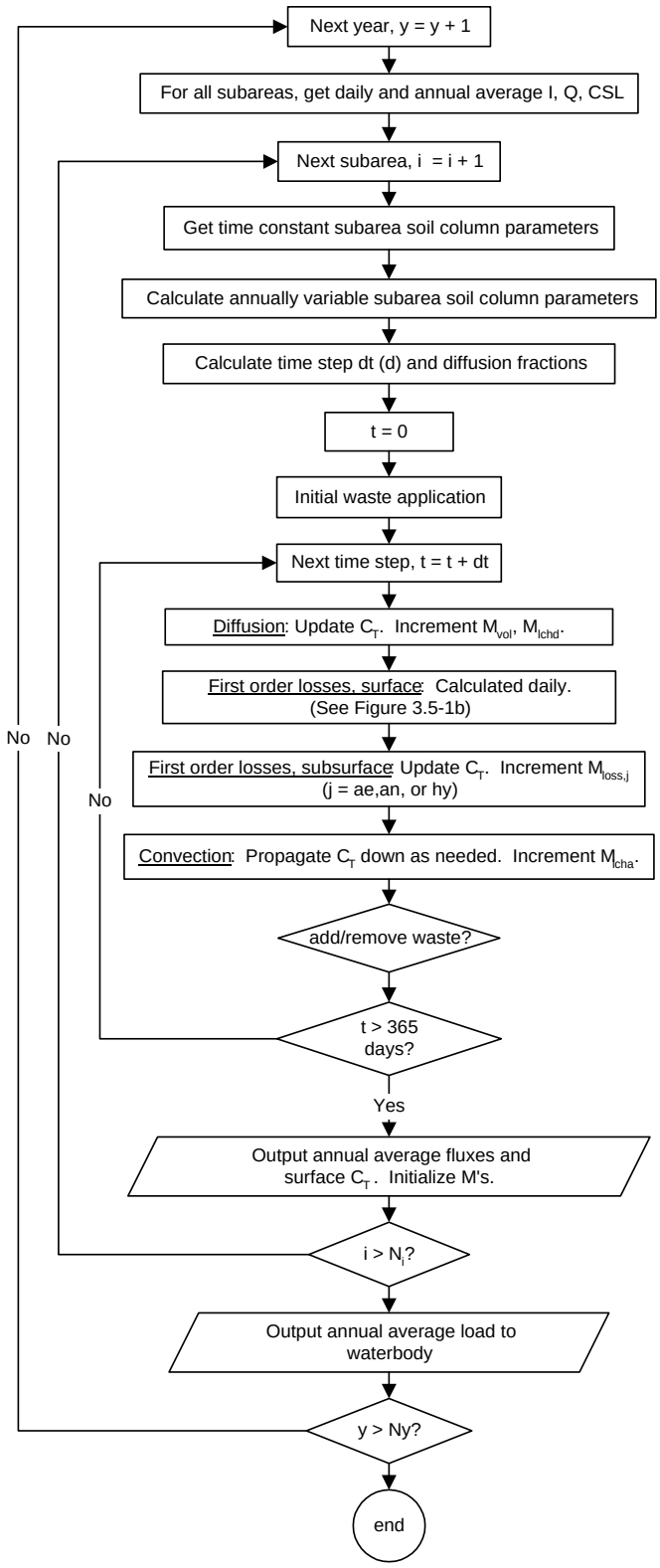

Figure F-3-4a. Overview of algorithm for combined local watershed/soil column module.

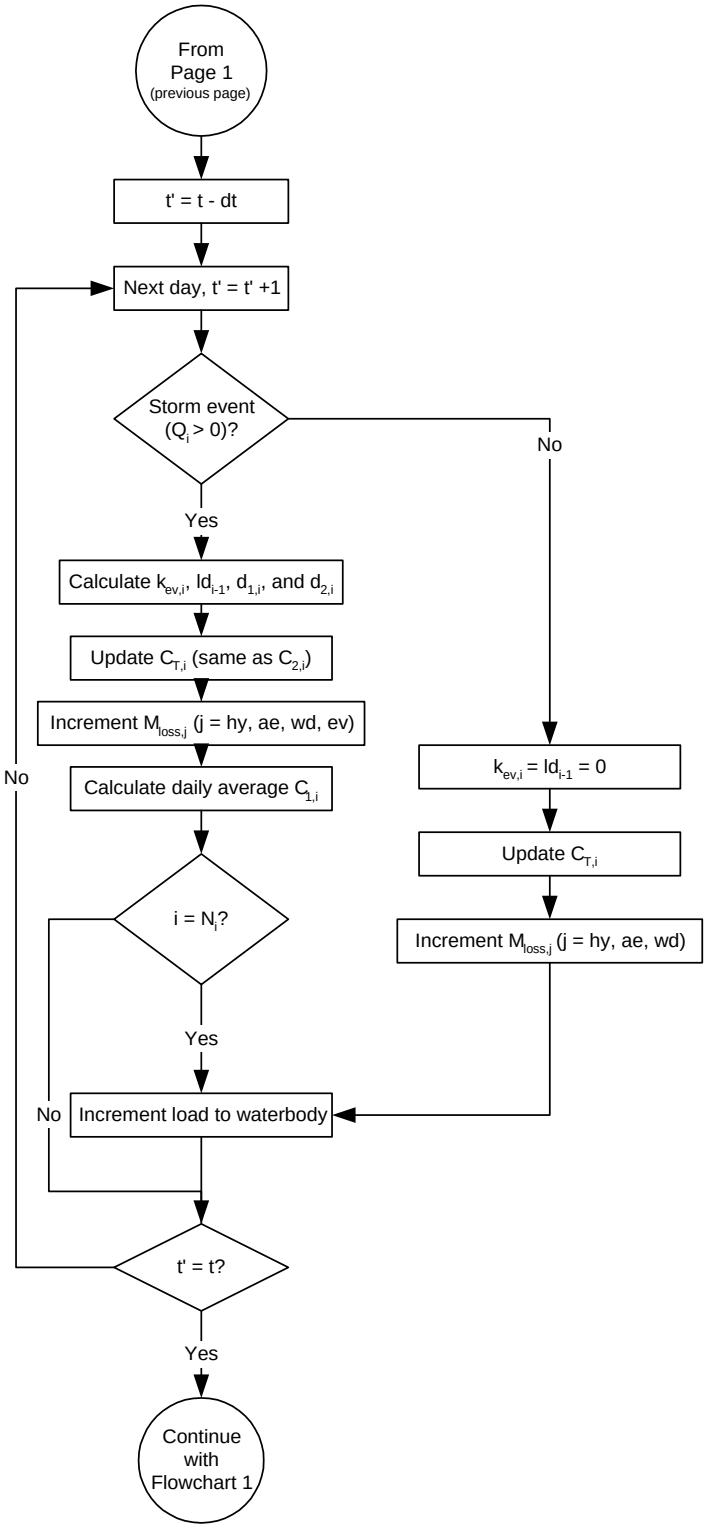

Figure F-3-4b. Detail on calculation of first-order losses in surface layer.

to vary from year to year. As a result, convection events do not occur at regular intervals. To determine the appropriate time to initiate a convection event, at the end of every time step a variable (fadv) tracking the fraction of mass in the bottom soil column layer that would have convected is incremented by ($dt \cdot V_E/dz$). If fadv is sufficiently close to 1, a convection event is initiated and fadv is reset to zero. At the end of the simulation (year = NyrMax), if fadv is greater than zero.

M_{lcha} is incremented by fadv times dz times C_T in the lowest layer and C_T in the lowest layer is adjusted accordingly. Leachate flux for the final year is then calculated using Equation F-2-29.

F-3.5.2 Simulation-Stopping Criterion

For a given local watershed, i, the simulation is stopped in each successive subarea when the amount of contaminant mass in local watershed i and all upslope subareas j ($j < i$) is determined to be insignificant. "Insignificance" is defined by the input parameter TermFrac, and this simulation criterion is implemented as follows:

1. During the years before the end of the operating life of the LAU, the year-end cumulative subarea contaminant mass in each subarea is determined. Here, cumulative subarea mass ($samass_i$) refers to the sum of the contaminant mass in subarea i and all upslope subareas j ($j < i$). The maximum cumulative subarea contaminant mass (max_samass_i) is stored for each subarea.

2. After LAU operation ceases, the year-end cumulative subarea contaminant mass in each subarea is compared to the stored maximum for that subarea. The simulation in subarea i is stopped when

$$samass_i \leq TermFrac * maxsamass_i$$

where "TermFrac" is the user-specified fraction ranging from 0 to 1.0 (unless the NyrMax parameter is reached first, at which point the simulation is automatically stopped). The year the simulation ceases in each local watershed and subarea is stored in an internal two-dimensional array dimensioned on local watershed and subarea.

(Note: As of this writing, computer memory requirements have resulted in an inability to make full use of the above-described TermFrac stopping critierion for highly persistent chemicals. Time series outputs are kept in random access memory [RAM] for postprocessing. When the length of the time series becomes excessive with respect to array sizes and available RAM, memory-cacheing occurs with a concomitant drastic slowdown in run time. To mitigate this problem, it was determined that the length of the time series would be determined by the TermFrac criterion, as described above, or 200 years, whichever comes first.)

F-3.5.3 Leachate Flux Processing

Preliminary module runs indicated that there are many cases where the convective transfer step will occur less than once per year, sometimes even less than once in the entire simulation period. In these cases the leachate flux will be nonzero in the years when a convection event occurs and zero in years when it did not. This is a limitation of the solution technique. In reality, leaching occurs more or less continuously over the time between the modeled convection events. To mitigate this limitation, a leachate flux postprocessing algorithm was developed. The entire simulation ($0 < j \leq$NyrMax) is split into three time periods, where j is used here as the year index:

1. LAU operating years ($0 \leq j \leq y_{op}$)
2. Non-operating years ($y_{op} < j \leq$LeachFluxNY
3. No leachate flux years (LeachFluxNY $< j \leq$NyrMax)

where LeachFLuxNY is the last year there is a positive leachate flux. The processed leachate fluxes (J_{lchp}, $g/m^2/d$) in time periods 1 and 2 are calculated from J_{lch} in each year, j, using:

$$J_{lchp,j} = \frac{I_j}{\bar{I}\,(b-a+1)} \sum_{j=a}^{j=b} J_{lch,j} \qquad \text{(F-3-53)}$$

where, in time period 1, a = 0 and b = y_{op}. In time period 2, a = y_{op} and b = LeachFluxNY. The first term in Equation (F-3-53) is an infiltration-based weight where I_j is the annual average infiltration rate in year j and $\bar{I}$ is the average infiltration rate between years a and b. In time period 3, J_{lchp} is zero.

With use of Equation F-3-53 to estimate the leachate flux, mass is conserved. That is, the total mass lost due to leaching over the course of the simulation is the same using the processed and unprocessed leachate fluxes. However, with the processed leachate flux, a smoother function of leachate flux over time is provided.

F-3.5.4 End-of-Simulation Mass Balance Check

At the end of the simulation, a system-wide mass balance check is performed in the code. The system, in the Local Watershed/Soil Column Modules, includes the LAU subarea and all other subarea "soil columns." The mass balance error (fMerr) is computed as a fraction of the total contaminant mass added to the system from the mass balance equation

$$fMerr = 1 - (fMrem + fMlost) \qquad \text{(F-3-54)}$$

where fMrem is the fraction of total contaminant mass added that remains in the system at the end of the simulation. fMlost is the fraction of the contaminant mass added that was estimated to

have been lost from the system by the end of the simulation. fMlost is the sum of the variables listed and defined in Table 3-2.

Time series outputs are reported as follows:

- *Outputs to Air Module.* All annnual time series outputs to ISCST3 are reported up to and including the last year that there is nonzero VE or CE. Thus, the annual time series outputs to the air model are all the same length.

Table F-3-2. Variables Summarizing Contaminant Mass Losses

Variable	Definition: Fraction of the total mass added lost due to:
fMvol_wmu	Volatilization from the LAU
fMlch_wmu	Leaching from the LAU
fMwnd_wmu	Wind/mechanical action on the LAU surface
fMdeg_wmu	Abiotic and biodegradation within the LAU
fMrmv_wmu[a]	Removal from the LAU
fMvol_sa	Volatilization from the non-LAU subarea soil columns
fMlch_sa	Leaching from the non-LAU subarea soil columns
fMdeg_sa	Abiotic and biodegradation in the non-LAU subarea soil columns
fMswl	Runoff/erosion from the most downslope subarea
fMbur[b]	Burial/erosion in all subareas (see k_{bu} in Equation 3-44d)

[a] Applies only to the WP, which is removed and refreshed regularly. See Section 3.7 for details.
[b] fMbur is the only variable listed that can be negative (indicating a mass gain). This results from the inclusion of a burial/erosion term in linking the runoff and soil compartments. See Figure 3-3 and the discussion of the meaning of the burial/erosion term in Section 3.4.2.

- *Outputs to the Groundwater Model*. The annual time series of LeachFlux for each local watershed is reported up to and including the last year that there is anonzero LeachFlux in any local watershed. This results in the same reported LeachFlux time series length for all local watersheds. After this, all LeachFlux values for all local watersheds will be zero and are not reported. AnnInfil is reported from year one to the last year that meteorological data are available.

F-3.6 Output Summary

Table F-3-3 summarizes the outputs of the combined Local Watershed/Soil Column Module.

- *Outputs to Surface Water*. The annual time series of SWLoadChem are reported up to and including the last year that there is nonzero SWLoadChem in any local

Table F-3-3. Output Summary for the LAU Model

Variable Name[a]		Definition	Units
Documentation	**Code**		
I	AnnInfil	Leachate infiltration rate (annual avg., WMU subarea(s) only)	m/d
J_{vol}	VE	Volatile emission rate	$g/m^2/d$
	VEYR	Year associated with output	Year
	VENY	Number of years in outputs	Unitless
CE30	CE	Constituent mass emission rate-PM30	$g/m^2/d$
	CEYR	Year associated with output	Year
	CENY	Number of years in outputs	Unitless
E30	PE30	Eroded solids mass emission rate-PM30	$g/m^2/d$
	PE30YR	Year associated with output	Year
	PE30NY	Number of years in outputs	Unitless
pmf	PMF	Particulate emission particle size distribution	Mass frac.
	PMFYR	Year associated with output	Year
	PMFNY	Number of years in outputs	Unitless
Q	Runoff	Runoff flow to waterbody	m3/d
J_{lch}	LeachFlux	Leachate contaminant flux	$g/m^2/d$
	LeachFluxYR	Year associated with output	Year
LeachFluxNY	LeachFluxNY	Number of years in outputs	Unitless
	SWLoadChem	Chemical load to waterbody	g/d
	SWLoadChemYr	Year associated with output	year
	SWLoadChemNY	Number of years in outputs	Unitless
CSL	SWLoadSolid	Total suspended solids load to waterbody	g/d
C1	SWConcTot	Total chemical concentration in surface water runoff	mg/L
	SWConcTotYR	Year associated with output	Year
	SWConcTotNY	Number of years in outputs	Unitless
C_T	CTss	Soil concentration in surface soil layer	µg/g
	CTssYR	Year associated with output	Year
	CTssNY	Number of years in outputs	Unitless

(continued)

Table 3-3. (continued)

Variable Name[a]		Definition	Units
Documentation	**Code**		
C_T	CTda	Depth-weighted average soil concentration (from zava to zavb)	µg/g
	CTdaYR	Year associated with output	Year
	CTdaNY	Number of years in outputs	Unitless
	SrcSoil	Flag for soil presence (true)	Logical
	SrcOvl	Flag for overland flow presence (true)	Logical
	SrcLeachMet	Flag for leachate presence when leachate is met-driven (true)	Logical
	SrcLeachSrc	Flag for leachate presence when leachate is not met-driven (false)	Logical
	SrcVE	Flag for volatile emissions presence (true)	Logical
	SrcCE	Flag for chemical sorbed to particulates emissions presence (true)	Logical
	SrcH2O	Flag for surface water presence for eco-exposure (false)	Logical
	NyrMet	Number of years in the available met record	Unitless

[a]Where the variable name is used in the code but not in the documentation, the first column is left blank.

watershed. This results in the same reported SWLoadChem time series length for all local watersheds. SWLoadSolid and Runoff are reported for all local watersheds up to the last year that meteorological data are available.

Outputs to Fate and Transport Model. The annual time series of CTda is reported to the the last year of nonzero CTda in each local watershed and subarea. Thus, the length of the reported time series for CTda in each local watershed and subarea may differ. The same is true for CTss.

F-3.7 Land Application Unit

F-3.7.1 Introduction

Section F-3.4 presented the Local Watershed/Soil Column Module. This section discusses LAU-specific issues in implementation. Figure F-3-5 illustrates the LAU in the local watershed conceptual module.

F-3.7.2 Additional Assumptions

- Waste is applied to the soil surface periodically at even intervals (e.g., quarterly) and then tilled or mixed into the top layer of soil to a depth of z_{till} (m).

- Till zone ($z = 0$ to z_{till}) is completely mixed upon each application of waste to soil.

- The modeled soil column consists of one homogeneous zone, the till zone, consisting of a soil/waste mixture. The till zone properties ($\rho_{b,till}$, $foc_{till,}$) can be estimated as the depth-weighted average of the soil ($\rho_{b,s}$, foc_s) and waste properties ($\rho_{b,w}$, foc_w) according to the depth of soil (d_s, m) and waste (d_w, m) in the till zone. To illustrate, an example using ρ_b is presented below.

$$\rho_{b,till} = \rho_{b,s} \frac{d_s}{z_{till}} + \rho_{b,w} \frac{d_w}{z_{till}} \quad \text{(F-3-55)}$$

$$d_s = z_{till} - d_w \quad \text{(F-3-56)}$$

$$d_w = \frac{W}{\rho_{b,w}} \quad \text{(F-3-57)}$$

$$W = \frac{R_{appl} \cdot sd/100}{N_{appl}} \quad \text{(F-3-58)}$$

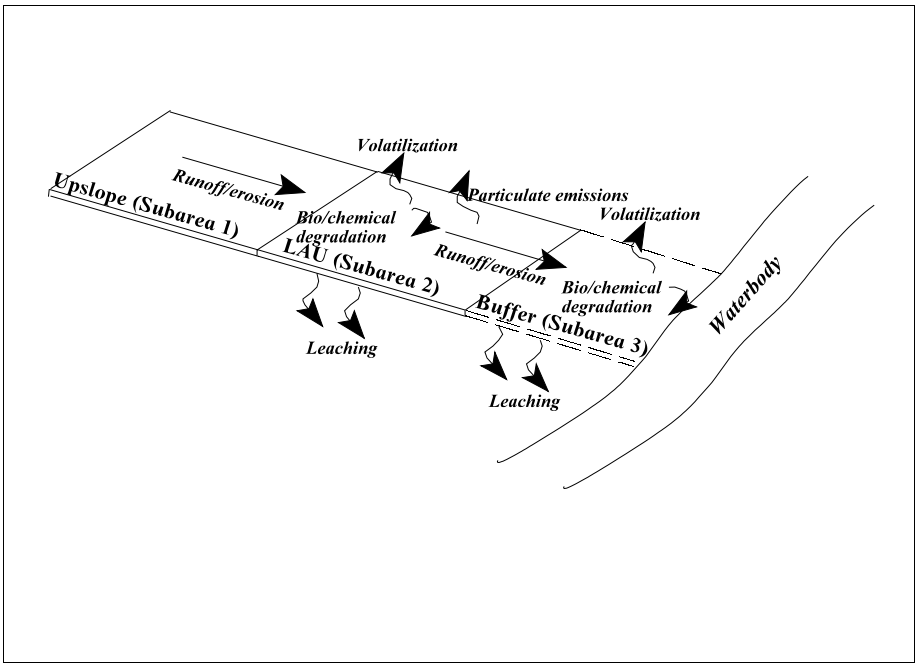

Figure F-3-5. Illustration of LAU in local watershed.

where W is the wet waste mass loading for a single application, determined as where R_{appl} is the wet waste application rate (Mg/m^2-y), sd is the weight percent solids in the waste, N_{appl} is the number of waste applications per year, $\rho b,s$ (g/cm^3) is the dry bulk density of the soil estimated from η_s using Equation (F-3-63), and $\rho_{b,w}$ (g/cm^3) is the dry bulk density.

- The water added to the LAU contained in the wet waste increases the annual average infiltration rate (I) by:

$$+ \frac{R_{appl}\ (1 - sd/100)}{365\,\rho_{H_2O}} \qquad \text{(F-3-59)}$$

- The contaminant mass is concentrated in the solids portion of the waste and is re-partitioned among the solid, aqueous, and gas phases in the soil column.

- The waste added to the till zone does not significantly affect the hydraulic properties of the till zone. Thus, the hydraulic properties of the soil (K_{sat}, SM_b) are used in Equation 2-11 to determine the water content if the till zone. Although the waste may affect the hydraulic properties of the till zone, there is no way of determining this effect theoretically.

- Total porosity of the till zone (η_{till}) is estimated using the following relationship for porous media (Freeze and Cherry, 1979):

$$\eta = 1 - \frac{\rho_b}{2.65} \qquad \text{(F-3-60)}$$

- Waste applications do not result in significant buildup of the soil surface, nor does erosion significantly degrade the soil surface (i.e., the distance from the site

surface (z = 0) to a fixed point below the surface is constant). As a result, there is no naturally occurring limit to the modeled C_T other than the limit for NAPLs. In other words, the modeled contaminant concentration in the till zone could exceed the contaminant concentration in the waste. Indeed, this is physically possible for highly immobile constituents if the waste matrix is organic and decomposes, leaving behind the constituent to concentrate over multiple applications.

- The land application unit is operated for y_{op} years.
- The first-order chemical and biological loss processes in the till zone include aerobic biodegradation (k_{ae}, 1/d) and hydrolysis (k_{hy}, 1/d).
- The first-order loss rate due to wind erosion and other surface disturbances (k_{wd}, 1/d) is applied to the surface layer of the till zone only and is calculated each year as an annual average with consideration of losses from an active LAU due to wind erosion, vehicular activity on the surface of the LAU, and tilling operations. The particulate emission loss rate from an inactive LAU includes wind erosion only. Appendix F-A outlines the estimation procedures for k_{wd}.
- The annual average infiltration rate (I, m/d) is determined using the method described in Section F-3.2.4 (note that I is the same as IN in Section F-3.2.4) with consideration of the properties of the till zone only.
- As described in Section F-3.4, the topmost soil column layer in the GSCM developed for the LAU serves as the soil compartment in the watershed/soil column algorithm (see Figure F-3-3). For the purposes of applying the watershed/ soil column algorithm, it is assumed that the appropriate depth for the soil column surface layer (dz) is 0.01 m. In the LAU module, dz = 0.01 m is used for the entire till zone.

F-3.7.3 Initial Conditions

The simulation starts immediately following the first application of waste, at which time the till zone is well-mixed. Initial conditions are

$$C_T\Big|_{z,t=0} = \frac{W \cdot C'_{T,w} \cdot f_{wmu}}{z_{till}} \qquad \text{(F-3-61)}$$

where $C'_{T,w}$ is the initial total contaminant concentration in the dry waste, calculated by dividing the total mass-based concentration in the wet waste (input by the user as CTPwaste in the LAU code) by sd/100.

$$C_T\Big|_{z,t=j\cdot t_{bet}} = \frac{W \cdot C'_{T,w} \cdot f_{wmu}}{z_{till}} + \overline{C}_T^{\,z}(z_{till}, j \cdot t_{bet}) \qquad \text{(F-3-62)}$$

During the operating lifetime of the LAU ($t \leq 365y_{op}$), with each application of waste the initial condition in the till zone is reset to account for the contaminant mass added as well as any contaminant mass remaining in the till zone from previous applications.

$$t_{bet} = \frac{365}{N_{appl}} \qquad \text{(F-3-63)}$$

where j is the waste application counter index = 1,2,3..., $\bar{C}_T^{\,z}(z,t)$ (g/m^3) is the depth-weighted average total contaminant concentration at time t averaged over a depth of z, and t_{bet} is the time between applications:

F-4.0 References

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Appendix F-A

Symbols, Units, and Definitions

Appendix F-A

Symbols, Units, and Definitions

(Symbols listed in Tables in Appendix F-C, Particulate Emission Equations are not repeated here.)

Table F-A-1. Symbols, Units, and Definitions

Symbol	Units	Definition
η_j	---	total porosity where j is a subscript indicating waste, w; waste/soil mixture in the till zone, till; and soil, s.
η	---	total porosity
θ_a	---	soil volumetric air content
$\theta_{a,j}$	---	soil volumetric air content where j is a subscript indicating waste, w; waste/soil mixture in the till zone, till; and soil, s.
θ_w	---	soil volumetric water content
$\theta_{w,j}$	---	soil volumetric water content where j is a subscript indicating waste, w; waste/soil mixture in the till zone, till; and soil, s.
ρ_b	g/cm^3	soil dry bulk density. Same as m2. (Note: $g/cm^3 = Mg/m^3$)
$\rho_{b,j}$	g/cm^3	dry bulk density where j is a subscript indicating waste, w; waste/soil mixture in the till zone, till; and soil, s.
$\rho_{b,w}^{wet}$	g/cm^3	wet bulk density of LAU waste
A	m^2	area of WMU
a_i	1/d	calculated parameter (equation 3.4.2-3b) for subarea i
bcm	---	lower coil column boundary condition multiplier

(continued)

Table F-A-1. (continued)

Symbol	Units	Definition
b_i	1/d	calculated parameter (equation 3.4.2-3c) for subarea i
C'_T	µg/g	total mass-based contaminant concentration in dry soil
$C'_{T,W}$	µg/g	total mass-based contaminant concentration in incoming dry waste
$C_{2,i}$	g/m^3	contaminant concentration in surface soil grid space in subarea i (equivalent to C_T)
C_G	g/m^3	contaminant concentration in gaseous phase in soil
C_L	g/m^3	contaminant concentration in aqueous phase in soil
C_L^{sol}	g/m^3	contaminant aqueous solubility
CN	unitless	SCS runoff module Curve Number parameter
C_S	µg/g	contaminant concentration in adsorbed phase in soil
$CSL_{i,t}$	kg	cumulative soil load leaving subarea i, day t
C_T	g/m^3	total volume-based contaminant concentration in soil
C_{T0}	g/m^3	initial total volume-based contaminant concentration in soil
$d_{1,i}$	m^3/d	calculated parameter (equation 3.4.2-5b) for subarea i
$d_{2,i}$	m^3/d	calculated parameter (equation 3.4.2-5c) for subarea i
D_a	cm^2/s	diffusivity in air
D_E	m^2/d	effective diffusivity in soil
$D_{E,a}$	m^2/d	effective diffusivity in soil air
$D_{E,w}$	m^2/d	effective diffusivity in soil water
Df	---	fraction of original mass in soil column grid space that diffuses past a boundary in time, t.
Df_0	---	fraction of original mass in soil column grid space that remains after time, t.
DRZ	cm	depth of the root zone
d_s	m	thickness of soil in unmixed LAU till zone
dt	d	length of time step in GSCM solution algorithm
d_w	m	thickness of waste in unmixed LAU till zone

(continued)

Table F-A-1. (continued)

Symbol	Units	Definition
D_w	cm^2/s	diffusivity in water
dz	m	soil column grid size in GSCM solution algorithm
ER_i	unitless	erosion chemical enrichment ratio for subarea i
$ET_{i,t}$	cm/day	evapotranspiration from root zone on day t for subarea i
FC_i	cm	soil moisture field capacity for subarea i
foc	---	organic carbon fraction in soil
foc_j	---	organic carbon fraction where j is a subscript indicating waste, w; waste/soil mixture in the till zone, till; and soil, s.
h	m	height of wastepile
H´	---	dimensionless Henry's Law constant
I	m/d	average annual water infiltration rate
$IN_{i,t}$	cm/day	daily infiltration for subarea i, day t
J_{lch}	$g/m^2/d$	annual average leachate flux at lower soil column boundary
J_{vol}	$g/m^2/d$	annual average volatilization flux at upper soil column boundary
k	1/d	total first-order loss rate
$k_{bu,i}$	m/d	first order rate constant due to burial/erosion for subarea i
K_d	cm^3/g	soil-water partition coefficient
k_j	1/d	annual average first order loss rate due to process j, where j indicates hydrolysis, h; aerobic biodegradation, ae; anaerobic biodegradation, an; storm events in subarea i, ev,i; and wind/mechanical activity, wd.
K_{oc}	cm^3/g	equilibrium partition coefficient normalized to organic carbon
K_{sat}	cm/hr	saturated hydraulic conductivity
K_{TL}	---	equilibrium distribution coefficient between the total (g/m^3) and aqueous phase (g/m^3) contaminant concentrations in soil
L	Mg/yr	bulk waste mass loading rate into WMU
ld_{i-1}	$g/m^3/d$	run-on load to subarea i from subarea i-1
L´	Mg/yr	bulk waste loading rate adjusted for mass losses due to unloading

(continued)

Table F-A-1. (continued)

Symbol	Units	Definition
$m1_i$	g/m3	suspended solids concentration in runoff water, subarea i
m	g/m2	total amount of material from soil column grid space that has passed a boundary at time, t
M_{col1}	g/m^2	total mass in soil column at start of year
M_{col2}	g/m^2	total mass in soil column at end of year
M_i	g/m^2	annual contaminant mass loss due to process i, where i is a subscript indicating: ■ total diffusive loss at the surface, 0; ■ gas phase diffusive losses (volatilization) at the surface, vol; ■ aqueous phase leaching due to diffusion, lchd; ■ aqueous phase leaching due to advection, lcha; ■ first order loss process j where j is as defined in k_j.
M_{add}	g/m^2	annual mass added to soil column
M_{rem}	g/m^2	annual mass removed from soil column
N_{appl}	1/y	number of LAU applications per year
N_{dz}	---	total number of grid spaces of depth dz in soil column
N_{ly}	---	assumed number of waste layers in LF cell
PET_i	cm/day	potential evapotranspiration for day t
P_t	cm	total precipitation on day t
$Q_{i,t}$	m3/day	runoff flow volume (water only) leaving subarea i, day t
$Q'_{i,t}$	m3/day	total runoff flow volume (including solids) leaving subarea i, day t
R_{appl}	Mg/m^2-y	LAU waste application rate
Sd	unitless	sediment delivery ratio for subarea/watershed i
$RO_{i,t}$	cm	stormwater runoff depth leaving subarea i, day t
sd	w/w, %	weight percent of solids in raw waste applied to LAU
SM_b	---	unitless soil-specific exponent in equation (2.3-1)
$SM_{i,t}$	cm	soil moisture in root zone at end of day t for subarea i
t	d	time since start of simulation

(continued)

Table F-A-1. (continued)

Symbol	Units	Definition
t_{bet}	d	time between WP refresh or LAU waste application
vb_i	m/d	burial/erosion velocity for subarea i
vd_i	m/d	diffusive exchange velocity between runoff and surficial soil
vr_i	m/d	stormwater runoff resuspension velocity for subarea i
$\bar{C}_T^z$	g/m^3	depth-weighted average C_T at time, t
V_E	m/d	effective solute velocity in soil
W	Mg/m^2	average mass of waste added per LAU application
WP_i	cm	soil moisture wilting point for subarea i
y_{op}	yr	last year of operation of LAU or WP
z	m	distance down from soil surface
z_{sc}	m	total depth of soil column
z_{till}	m	distance from soil surface to bottom of LAU till (mixing) zone

Appendix F-B

Determination H′, D_a, and D_w for Organic Compounds

Appendix F-B

Determination H′, D_a, and D_w for Organic Compounds and Outputs

F-B.1 Introduction

For organic compounds, the dimensionless Henry's law coefficent (H′) and air and water diffusivities (D_a and D_w, cm^2/s, respectively) are calculated as a function of system temperature given user-input reference values and temperatures. H′ is determined from the dimensionless Henry's Law Coefficient (H'^r) at temperature $T^r_{H'}$ (K). D_a and D_w are determined from air (D_a^r) and water (D_w^r) diffusivities (cm^2/s) at temperature t^r_D (°C). The methodologies used are described in this Appendix. Here, the convention is used where T is temperature in Kelvin and t is temperature in degrees centigrade.

F-B.2 Air Diffusivity (D_a)

The reference air diffusivity (D_a^r) is adjusted using the following equation which was derived from the Fuller, Schettler, and Giddings (FSG) Method for estimating air diffusivities of organic compounds in Lyman et al. (1990, Eq. 17-12):

$$D_a = D_a^r \left[\frac{T}{T_D^r}\right]^{1.75} \qquad \text{(F-B.2-1)}$$

In the module, D_a is converted from cm^2/s to m^2/d by multiplying by 8.64.

F-B.3 Water Diffusivity (D_w)

The reference water diffusivity (D_w^r) is adjusted using the following equation which was derived from the Hayduk and Laudie Method for estimating water diffusivities of organic compounds in Lyman et al. (1990, Eq, 17-24):

$$D_w = \frac{\eta_w(t_D^r)}{\eta_w(t)} D_w^r \qquad \text{(F-B.3-1)}$$

where η_w (cp) is the viscosity of water as a function of temperature, t, in degrees centigrade, t^r is the temperature for which D_w^r was specified. Values for η_w are provided in the program and were obtained from Lyman at al. (1990, Table 17-7) for t=0 to 30°C in one degree increments. In the module, D_w is converted from cm^2/s to m^2/d by multiplying by 8.64.

F-B.4 Dimensionless Henry's Law Coefficient (H′)

The algorithm used to adjust the dimensionless Henry's law coefficient, H′, as a function of temperature, T, is based on the Claussius-Clayperon equation and consideration of temperature effects on solubility (Dzombak et al., 1993) and is presented below:

$$H' = H'^{r} \cdot \exp\left[\frac{\Delta H_V(T_{H'}^r)}{R\ T_{H'}^r} - \frac{\Delta H_V(T)}{R\ T} \right] \qquad \text{(F-B.4-1)}$$

where H'^r is the dimensionless Henry's law coefficient at reference temperature $T_{H'}^r$ (K), R is the gas constant (1.9872 cal/mol-K), and $\Delta H_v(T)$ (cal/mol) is the molar heat of vaporization as a function of temperature T (K). $\Delta H_v(T)$ is estimated using Eq. 13-21 and Table 13-7 in Lyman et al. (1990):

$$\Delta H_V = \Delta H_{VB} \left[\frac{1 - T/T_c}{1 - T_b/T_c} \right]^n \qquad \text{(F-B.4-2a)}$$

where

$$n = \begin{cases} 0.30 & \frac{T_b}{T_c} < 0.57 \\ 0.74\left(\frac{T_b}{T_c}\right) - 0.116 & 0.57 \le \frac{T_b}{T_c} \le 0.71 \\ 0.41 & \frac{T_b}{T_c} > 0.71 \end{cases} \qquad \text{(F-B.4-2b)}$$

where T_c (K) is the critical temperature and T_b(K) is the boiling point of the compound of interest ΔH_{VB} (cal/mol) is the molar heat of vaporization at the normal boiling point and is estimated using the method of Haggenmacher (Lyman et al., 1990, Section 13-5):

$$\Delta H_{VB} = \frac{2.303\ B\ R\ T_b^2\ (z_g - z_l)}{(t_b + C)^2} \qquad \text{(F-B.4-3a)}$$

where

$$z_g - z_l = \sqrt{1 - \frac{1/P_c}{(T_b/T_c)^3}} \qquad \text{(F-B.4-3b)}$$

where T_c (K) is the critical temperature, P_c (atm) is the critical pressure, B (˚C or K) and C (˚C). are Antoine's constants. Antoine's constants have been calculated for many compounds, especially hydrocarbons, and are tabulated in the literature (e.g., Reid et al., 1977). Some caution is required in specifying values for the Antoine's constants, because in some tabulations, the conversion factor to natural log (2.303) is included in the value of B. To check, if the value for methane is 405.42 (˚C or K) use the values for B directly. If it is about 930 (˚C or K), divide all values given for B by 2.303. Also, if Antoine's constants are presented in the literature in K, B should not be changed and C should be converted to ˚C by adding 273.2. Note that this is not the usual way to convert from K to ˚C, but is necessary to maintain the constancy of the term B/(t+C) in Antoine's relationship since temeperature,t, is assumed to be in ˚C.

In the code, if T_c is unavailable, T_c is estimated as 1.5Tb (Lyman et al., 1990, p. 14-13). If P_c is unavailable, but B and C are available, (z_g-z_l) is approximated as one (Lyman et al., 1990, Table 14-6). If B and C are unavailable, Trouton's rule is used to estimate ΔH_{VB} (Lyman et al. (1990):

$$\Delta H_{VB} = 21 \frac{cal}{mole - K} T_b \qquad \text{(F-B.4-4)}$$

F-B.5 References

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Appendix F-C

Particulate Emission Equations

Appendix F-C

Particulate Emission Equations

F-C.1 Introduction

The nonwastewater source modules have been designed to provide estimates of the annual average, area-normalized emission rate of contaminant mass adsorbed to particulate matter less than 30 μm in diameter, CE30 (g of contaminant/m^2/d), as well as annual average particle size distribution information in the form of the mass fractions of the total particulate emissions in four aerodynamic particle size categories—30 to 15 μm, 15 to 10 μm, 10 to 2.5 μm, and <2.5 μm.

A variety of release mechanisms are considered. The inventory of release mechanisms considered is different for each WMU, but includes, in general, wind erosion, vehicular activity, unloading operations, tilling, and spreading/compacting operations. The mechanisms considered for each WMU are summarized in Table F-C-1.

This appendix describes the algorithms and assumptions used to estimate annually for each mechanism of release:

- $E30_i$ (g of particulates ≤ 30 μm in diameter/m^2/d), the annual average PM_{30} emission rate due to release mechanism i, where mechanisms of release considered for each WMU are summarized in Table F-C-1

- Particle size range mass fractions, the mass fractions of $E30_i$ in the aerodynamic particle size categories identified above.

For each WMU:

- $\Sigma E30_i$ (g/m_2/d), the total annual average PM_{30} emission rate due to all release mechanisms

- Annual average particle size range mass fractions of the total annual average PM_{30} emission rate

Table F-C-1. Summary of Mechanisms of Release of Particulate Emissions for Each WMU

Mechanism of Release	$E30_i$ Subscript	WMU Type[a,b]						Algorithm Reference
		LAU		LF cell[c]		WP		
		Active	Inact.	Active	Inact.[d]	Active	Inact.	
Wind erosion from open area	wd	X	X	X	X			Cowherd et al. (1985)
Wind erosion from wastepile	wp					X	X	U.S. EPA (1985)
Vehicular activity	ve	X		X		X		U.S. EPA (1995)
Unloading	un			X		X		U.S. EPA (1995)
Spreading/compacting or tilling	sc	X		X		X		U.S. EPA (1985)

[a] X = Mechanism of release is considered in modeling the WMU.
[b] Active = Operating WMU.
Inact. = Inactive WMU where no additional contaminant mass is being added.
[c] For a description of how results for whole LF are obtained from LF cell results, see Section 4.5.
[d] Inactive (full) and uncovered landfill cell. Assume no emissions from a covered LF cell.

- CE30 ($g/m^2/d$), the annual average emission rate of contaminant as PM_{30}
- Annual average first-order loss rate from the soil surface due to contaminant mass losses caused by particulate emissions, k_{wd} (1/d).

F-C.2 Particulate Emission Rate ($E30_i$) Algorithms and Particle Size Range Mass Fractions

F-C.2.1 Wind Erosion from Open Fields ($E30_{wd}$)

The algorithm for the estimation of PM_{30} emissions due to wind erosion from an open field is based on the procedure developed by Cowherd et al. (1985). It was adapted for implementation in a computer code and is presented in detail here. $E30_{wd}$ is estimated in the LAU and LF source emission modules. The user-specified input parameters are summarized in Table F-C-2.

To account for the fact that active and inactive WMUs can differ in the degree of vegetation (veg´), surface roughness height (z'_0), and frequency of disturbances per month (fd´), different values are assigned to these parameters in the equations presented below according to whether the WMU is active or inactive. The value assignments are summarized in Table F-C-3 where veg, z_0, and fd are user input values.

Table F-C-2. Input Parameter Units and Definitions for $E30_{wd}$

Symbol	Units	Definition
asdm	mm	Mode of the aggregate size distribution
Lc	---	Ratio of the silhouette area of roughness elements too large to be included in sieving to total base area
veg	---	Fraction of surface covered with vegetation (inactive WMU)
z_0	cm	Surface roughness height (inactive WMU)
S	w/w, %	Silt content of surface material
U^+	m/s	Observed or probable fastest mile of wind between disturbances
PE	---	Thornthwaite Precipitation Evaporation Index
u	m/s	Mean annual windspeed
p	d/yr	Mean number of days per year with $\geq$0.01 in precipitation
fd	1/mo	Frequency of disturbance per month where a disturbance is defined as an action that exposes fresh surface material (inactive WMU)

Table F-C-3. Active/Inactive WMU Assignments for veg′, z'_0, fd′

Symbol	Units	Active WMU	Inactive WMU
veg′	---	0.0	veg
z'_0	cm	1.0	z_0
fd′	1/mo	fd	0.0

Step 1: Calculate U_{*t}

Calculate the threshold friction velocity, U_{*t} (m/s), the threshold windspeed for the onset of wind erosion:

$$U_{*t} = 0.650 \cdot cf \cdot (asdm)^{0.425} \quad \text{(F-C-1a)}$$

where

$$cf = \begin{cases} 1.0 & Lc < 2x10^{-4} \\ 1.05 + 50.18Lc - 647.89Lc^2 + 6863.50Lc^3 & 2x10^{-4} \le Lc \le 1x10^{-1} \end{cases} \quad \text{(F-C-1b)}$$

Table F-C-2 provides definitions of asdm and Lc. Lc is measured by inspection of a representative 1-m^2 transect of the site surface. Lc can range from zero to 0.1. High Lc ($\geq 2x10^{-4}$) increases the threshold friction velocity, which results in a relatively low or zero particulate emission rate due to wind erosion. Low Lc ($<2x10^{-4}$) is indicative of a bare surface with homogeneous finely divided material (e.g., an agricultural field). Such surfaces have a relatively low threshold friction velocity and increased particulate emissions. Equations (F-C-1a) and (F-C-1b) were derived from Cowherd et al. (1985, Figures 3-4 and 3-5).

Step 2: Calculate U_t

U_t (m/s) is the threshold wind velocity at a height of 7.0 m (7.0 m is the typical weather station anemometer height). It is calculated using Cowherd et al. (1985, Equation, 4-3, with z = 700 cm):

$$U_t = \frac{U_{*t}}{0.4} \ln\left(\frac{700}{z'_0}\right) \qquad z'_0 < 700 \quad \text{(F-C-2)}$$

where z'_0 is the roughness height in cm. Values for z'_0 for various surface conditions are provided in Cowherd et al. (1985, Figure 3-6).

Step 3: Calculate $E30_{wd}$

$E30_{wd}$ is the annual average emission rate of particulate matter less than 30 μm in diameter per unit area of the contaminated surface. Note that the methodology developed in Cowherd et al. (1985) was developed for estimation of emission rate of particulate matter less than 10 μm (or $E10_{wd}$). $E30_{wd}$ can be approximated from $E10_{wd}$ with knowledge of the ratio between PM_{30} and PM_{10} for wind erosion. Cowherd (1998) advises that a good first approximation of this ratio is provided by the particle size multiplier information presented in U.S. EPA (1995) for wind erosion from open fields where PM_{30}/PM_{10} is equal to 2. Therefore, a factor of 2 has been incorporated into Cowherd et al.'s (1985) equations for $E10_{wd}$ to allow estimation of $E30_{wd}$.

For sites with limited erosion potential ($U_{*t} > 0.75$ m/s)

The following equation was derived by using Cowherd et al. (1985, Equations 4-1 to 4-3), applying a factor of 2 as discussed above and converting units to g/m^2/d :

$$E30_{wd} = \begin{cases} \dfrac{11.12(U^+ - U_t)(1 - veg')fd'}{(PE/50)^2} \cdot \dfrac{24}{10^3} & U^+ \geq U_t \\ 0 & U^+ < U_t \end{cases} \qquad \text{(F-C-3)}$$

Data for mean annual U^+ and PE for locations throughout the United States can be found in climatic atlases (e.g., U.S. Department of Commerce, 1968) and Cowherd et al. (1985, Figure 4-2), respectively. Cowherd et al. (1985) advise that, in the worst case, fd should be assumed to be 30 per month.

For sites with unlimited erosion potential ($U_{*t} \leq 0.75$ m/s)

When U_{*t} is less than 0.75 m/s, the site is considered to have unlimited erosion potential and $E30_{wd}$ is calculated using Cowherd et al. (1985, Equation 4-4) with a factor of 2 applied as discussed above.

$$E30_{wd} = 0.072\ (1 - veg')\left(\frac{u}{U_t}\right)^3 g(x) \cdot 24\ \frac{h}{d} \qquad \text{(F-C-4a)}$$

where

$$x = 0.886\ \frac{U_t}{u} \qquad \text{(F-C-4b)}$$

$$g(x) = \begin{cases} 1.91 & 0 \leq x < 0.5 \\ 2.2 - 0.6x & 0.5 \leq x \leq 1.0 \\ 2.9 - 1.3x & 1.0 < x \leq 2.0 \\ 0.18\,(8x^3 + 12x)\exp(-x^2) & x > 2.0 \end{cases} \qquad \text{(F-C-4c)}$$

where g(x) was derived from Cowherd et al. (1985, Figure 4-3). Data for u for locations throughout the United States can be found in climatic atlases (e.g., U.S. Department of Commerce, 1968).

Step 4: Apply Particle Size Range Mass Fractions

Particle size range mass fractions allow estimation of the fraction of the PM_{30} emitted that is in specific size fractions. As mentioned above, Cowherd (1998) suggests using the particle size multipliers provided for wind erosion from industrial fields in U.S. EPA (1995). The U.S. EPA (1995) distribution was adapted to get the fraction of the emissions in the designated size categories as presented in Table F-C-4.

Table F-C-4. Aerodynamic Particle Size Range Mass Fractions for $E30_{wd}$ and $E30_{wp}$

30 μm -15 μm	15 μm -10 μm	10 μm -2.5 μm	≤2.5 μm
0.4	0.10	0.3	0.2

F-C2.2 Vehicular Activity ($E30_{ve}$)

To estimate $E30_{ve}$ ($g/m^2/d$), the quantity of particulate emissions from vehicular travel on the surface of the WMU, the following equation was used:

$$E30_{ve} = 1.36\left(\frac{S}{12}\right)\left(\frac{vs}{48}\right)\left(\frac{vw}{2.7}\right)^{0.7}\left(\frac{nw}{4}\right)^{0.5}\left(\frac{365-p}{365}\right)\cdot nv\cdot\left(1-eff_{dust}\right)\cdot\frac{mt}{A} \quad \text{(F-C-5)}$$

where parameter definitions are provided in Table F-C-5. Equation F-C-5 was derived from an empirical equation presented in U.S. EPA (1995; Equation 1, p. 13.2.2-1) for the kilograms of size-specific particulate emissions emitted per vehicle kilometer traveled on unpaved roads. (In this application, the EPA parameter "fraction of waste on unpaved roads" is one since travel is on the surface of the WMU.) The first six terms of Equation F-C-5 are equivalent to the U.S. EPA (1995) equation after application of the 0.80 particle size multiplier for PM_{30}. EPA's equation has been adapted here to provide emissions normalized to the contaminated surface area and to account for the control of emissions with a dust control efficiency factor of eff_{dust}.

The particle size multipliers for $E30_{ve}$ are presented in Table F-C-6. These have been adapted for the size categories of interest from the particle size multiplier information presented in U.S. EPA (1995).

Table F-C-5. Parameter Units and Definitions for $E30_{ve}$

Symbol	Units	Definition
S	w/w,%	Silt content of roadway (4.3-20)[a, b]
vs	km/h	Mean vehicle speed (21-64)
vw	Mg	Mean vehicle weight (2.7-142)
nw	—	Mean number of wheels per vehicle (4-13)
nv	1/d	Mean annual number of vehicles per day
eff_{dust}	—	Dust suppression control efficiency
A	m^2	Contaminated surface area
mt	m	Meters traveled per vehicle (nv) on contaminated surface
p	d/y	Mean number of days per year with ≥0.01 in precipitation

[a] Silt is defined as particles less than 75 μm in diameter. Silt content is determined by the percent of loose dry surface material that passes through a 200-mesh screen using the ASTM-C-136 method (U.S. EPA, 1985).

[b] Values in parentheses are the ranges of source conditions that were tested in developing the U.S. EPA (1995, Equation 1, p. 13.2.1-1).

Table F-C-6. Aerodynamic Particle Size Range Mass Fractions for $E30_{ve}$

30 μm -15 μm	15 μm -10 μm	10 μm -2.5 μm	≤2.5 μm
0.38	0.17	0.33	0.12

F-C.2.3 Unloading Operations ($E30_{un}$)

The equation for estimating $E30_{un}$ ($g/m^2/d$), the PM_{30} emission rate due to unloading operations at wastepiles and landfills, was adapted from U.S. EPA. (1995, Equation 1, p. 13.2.4-3). The EPA equation was adapted by multiplying it by the average annual loading rate (L, Mg/yr), normalizing the emissions for the contaminated surface area, and applying the particle size multiplier for <30 μm.

$$E30_{un} = (0.0012) \cdot \frac{\left(\frac{u}{2.2}\right)^{1.3}}{\left(\frac{mcW}{2}\right)^{1.4}} \cdot \frac{L}{A} \cdot \frac{10^3 \text{g}}{\text{kg}} \frac{\text{yr}}{365\text{d}} \qquad \text{(F-C-6)}$$

Parameter definitions are provided in Table F-C-7. The particle size range mass fractions were developed from information provided in U.S. EPA (1995) and are presented in Table F-C-8.

Table F-C-7. Parameter Units and Definitions for $E30_{un}$

Symbol	Units	Definition
u	m/s	Mean annual wind speed (0.6-6.7)
mcW	volume %	Waste moisture content (0.25-4.8)
L	Mg/yr	Annual average waste loading rate

Note: Values in parentheses are the ranges of source conditions that were tested in developing the U.S. EPA (1995) equation.

Table F-C-8. Aerodynamic Particle Size Range Mass Fractions for $E30_{un}$

30 μm -15 μm	15 μm -10 μm	10 μm -2.5 μm	≤2.5 μm
0.35	0.18	0.32	0.15

F-C.2.4 Spreading/Compacting or Tilling Operations ($E30_{sc}$)

The equation for estimating $E30_{sc}$ ($g/m^2/d$), the rate of PM_{30} emissions due to spreading and compacting or tilling operations, was adapted from an equation in U.S. EPA (1985, Equation 1, p. 11.2.2-1) that was developed for estimating emissions due to agricultural tilling in units of kilogram of particulate emissions per hectare per tilling (or spreading/ compacting) event. The first two terms in Equation F-C-7 represent the EPA equation with the particle size multiplier for <30 μm applied.

$$E30_{sc} = (1.77)\ S^{0.6} \cdot N_{op} \cdot \frac{10^3\ g}{kg} \cdot \frac{ha}{10^4\ m^2} \qquad \text{(F-C-7)}$$

Parameter definitions are provided in Table F-C-9. The particle size range mass fractions were developed from information provided in U.S. EPA (1985) and are presented in Table F-C-10.

F-C.3 Particle Size Range Mass Fractions for Total PM_{30} Emission Rate

Particle size range mass fractions characterizing the total annual average PM_{30} emission rate ($E30_i$ summed over all applicable mechanisms) is determined annually by applying the mechanism-specific mass fractions to the $E30_i$ estimates to obtain size-specific emission rate

Table F-C-9. Parameter Units and Definitions for $E30_{sc}$

Symbol	Units	Definition
S	w/w, %	Silt content of surface material (1.7-88)[a, b]
N_{op}[c]	1/d	Number of tilling (or spreading and compacting) operations per day
fcult	---	Number of cultivations per application

[a] Silt is defined as particles less than 75 μm in diameter. Silt content is determined by the percent of loose dry surface material that passes through a 200-mesh screen using the ASTM-C-136 method (U.S. EPA, 1985).
[b] Values in parentheses are the ranges of source conditions that were tested in developing the U.S. EPA (1985) equation.
[c] For the LAU, Nop = (Nappl/365 x fcult).

Table F-C-10. Aerodynamic Particle Size Range Mass Fractions for $E30_{sc}$

30 μm -15 μm	15 μm -10 μm	10 μm -2.5 μm	≤2.5 μm
0.24	0.12	0.34	0.30

estimates $E_{i,j}$ ($g/m^2/d$) where subscript j identifies the particle size range (j= 1 indicates 30-15 μm; 2, 15-10 μm; 3, 10-2.5 μm; and 4, <2.5 μm). The total particle size range mass fraction, pmf_j, is calculated as:

$$pmf_j = \frac{\sum_i E_{i,j}}{\sum_i E30_i} \qquad \text{(F-C-8)}$$

F-C.4 Annual Average Constituent Emission Rate (CE30) Equations

The amount of mass lost due to wind and mechanical disturbances, $M_{loss,wd}$ (g/m^2), estimated using Equation F-2-24 and accumulated throughout the simulated year is used to estimate CE30 ($g/m^2/d$), the annual average, area-normalized emission rate of contaminant mass adsorbed to particulate matter less than 30 μm in diameter.

$$CE30 = \frac{M_{loss,wd}}{365} \qquad \text{(F-C-9)}$$

Equation F-C-10 is directly applicable to the LAU during both the inactive and active years, the WP during the inactive years, and the inactive (full) LF cell. For the first year of the LF cell and the active years of the WP, the raw waste losses due to particulate emissions during unloading waste are added to the CE30 estimate. The increment is equal to

$$+ E30un \cdot C'_{T,W} \cdot fwmu \cdot 10^{-6} \frac{g}{\mu g} \qquad \text{(F-C-10)}$$

F-C.5 Estimation of First Order Loss Rate (k_{wd})

$$\frac{\partial C_T}{\partial t} = -k_{wd} C_T \qquad \text{(F-C-11)}$$

An equation for k_{wd} was derived by performing a mass balance on the surface layer of the "soil" column to a depth of dz (the depth of the surface soil column cell) and considering losses due to wind and mechanical activity only:

where:

$$k_{wd} = \frac{1}{dz} \cdot \frac{K_d}{K_{TL}} \cdot \frac{g}{10^6 \mu g} \cdot \Sigma_i E30_i \qquad i \neq un \qquad \text{(F-C-12)}$$

The processes indicated by subscript i that are included for each WMU are summarized in Table F-C-1. Only processes acting on the surface layer are included in the summation of $E30_i$. Therefore, the unloading of raw waste (i=un) is excluded.

F-C.6 References

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Appendix D

Modifications to LAU Source Partition Model Programs

Appendix F-D

Modifications to LAU Source Partition Model Programs

Several coding modifications were made to the LAU source model to enable it to be used for this analysis. Those modifications are summarized below.

F-D.1 LAU Model for Crop Agricultural Field

F-D.1.1 Temperature Correction

The temperature correction routines were revised so that they were performed internal to the program. Routines for internal temperature corrections had been developed and these internal routines were re-instated for the sewage sludge application. These routines are: chemical diffusivity in air (Da), chemical diffusivity in water (Dw), and Henry's law constant (H). The correction routine for Da was derived from the FSG Method (Lyman, 1990, Ch. 17, eq. 17-12), and the routine for Dw was derived from Equation 17-24 (Hayduk and Laudie) in Lyman et al. (1990). The temperature correction for H used estimates of the heat of vaporization from Lyman et al. (1990, eq. 13-21). The Haggenmacher method (Lyman et al., 1990, Sect. 13-5) is used to get the heat of vaporization at the boiling point. Temperature corrections for partitioning (Kd, Koc), hydrolysis, and solubility were not included in the sewage sludge source models.

The temperature correction routines introduced several new input variables to the model: Antoine's constants B and C, the boiling temperature of the chemical, and the critical temperature and pressure for the chemical. Changes were made to the program executables and the data dictionary files to read these data into the program.

F-D.1.2 AP42 Changes to Vehicular Activity Particulate Emissions

One of the particulate emissions equations was modified to reflect a 1998 update by EPA (URL: www.epa.gov/ttn/chief/ap42/ch13) to the equation previously used the LAU. The equation that was updated is presented as equation F-C-6 in this appendix. That equation predicts the daily flux of particulate emissions of 30 um of less particles resulting from vehicular traffic on the surface of the LAU, i.e. variable "E30ve". The updated equation is

$$E30ve = 2.819(S/12)^{0.8}(vw/3)^{0.5}((365-p)/365)nv(1-effdust)(mt/A)$$

where the variables and units are as described in F-C-9.

F-D.2 LAU Model for Pasture Agricultural Field

F-D.2.1 Temperature Correction

Code changes to enable internal temperature corrections were identical to those described above for the crop agricultural field.

F-D.2.2 AP42 Changes to Vehicular Activity Particulate Emissions

Code changes to update the vehicular activity particulate emissions calculations were identical to those described above for the crop agricultural field.

F-D.2.3 Changes to Include Waste Lying on Soil Surface

The most significant change to the LAU Module to configure it for the pasture agricultural field was a set of modifications that together reflect the conceptual scenario that sludge applied to the pasture is not tilled into the soil, but rather spread on the soil surface and mixed with the top 2 cm of soil through natural means. The code changes to effect this scenario performed the following steps:

1. The modeled depth of the "soil column" (variable zZ1WMU) was increased by this depth. The new "soil column" then consisted of the actual soil underneath the spread sludge (0.2 m) plus the depth of the sludge layer lying on top.

2. A sludge application now reflects an updating of the above-soil-surface model layers, rather than a "tilling" into the soil depth.

F-D.2.4 Shortcoming of the LAU Pasture Model

It is noted here that a shortcoming of the LAU model used to simulate the pasture scenario is that the modeled "soil column" now consists of two zones with nonhomogeneous physical properties – the sludge zone lying of top of the soil, and the underlying soil zone. The LAU model was not designed to accommodate different zones; indeed, the single zone soil column's properties (percent silt, bulk density, and fraction organic carbon) are estimated as a weighted average of the soil properties and the waste properties, because they are mixed together. Although the pasture's complete soil column in fact consists of these two different zones, the properties of the sludge (assumed to resemble silt) were used for the entire soil column in the simulation due to this model limitation. Thus, to the extent that the underlying soil is different from silt, some error is introduced into the results by this simplifying assumption. Despite this limitation, the LAU model was considered the most appropriate model to be used for the pasture simulation.

Appendix G

Air Dispersion and Deposition Modeling Input Files

Appendix G

Air Dispersion and Deposition Modeling Input Files

Using PCRAMMET

PCRAMMET is a preprocessor program that integrates surface and upper air meteorological data into an input file for ISCST3. PCRAMMET calculates hourly stability values from surface observations, interpolates hourly mixing height values from twice-daily upper air data, and calculates parameters for wet and dry deposition/depletion calculations. PCRAMMET output can be selected as unformatted or ASCII format (U.S. EPA, 1995c). ISCST3 requires that meteorological data be in ASCII format when multiple-year meteorological data are used.

PCRAMMET input files were set up in an automated fashion. In addition to the surface and upper air data, PCRAMMET requires the input of the following meteorological parameters (U.S. EPA, 1995c):

- Minimum Monin-Obukhov length (m)
- Anemometer height (m)
- Roughness length (m), surface meteorological station
- Roughness length (m), area around facility
- Noontime albedo
- Bowen ratio
- Anthropogenic heat flux (W/m^2)
- Fraction net radiation absorbed by the ground.

Anemometer height was collected from the local climatic data summaries (NOAA, 1983). When anemometer height was not available, the station was assigned the most common anemometer height from the other stations. This value was 6.1 m.

Land use information is required for determining a number of PCRAMMET inputs. To obtain this information, a GIS was used to determine the land use within a 3-km radius around each meteorological station by using GIRAS spatial data with Anderson land use codes (Anderson et al., 1976). Table G-1 shows how the Anderson land use codes were related to PCRAMMET land use codes.

A weighted average, based on the land use percentages for a 3-km radius around each meteorological station, was used to estimate the Bowen ratio, minimum Monin-Obukhov length, the noontime albedo, the roughness height at the meteorological station, and the fraction of net radiation absorbed by the ground.

- The Bowen ratio is a measure of the amount of moisture at the surface around a meteorological station. The wetness of a location was determined based on the annual average precipitation amount. The range of values is provided in Table G-2 as a function of land use type, season, and moisture condition. For this analysis, the annual average values were applied.

- The minimum Monin-Obukhov length, a measure of the atmospheric stability at a meteorological station, was correlated with the land use classification, as shown in Table G-3.

- Noontime albedo values also were correlated with land use around a meteorological station, as shown in Table G-4.

- The surface roughness length is a measure of the height of obstacles to the wind flow. It is not equal to the physical dimensions of the obstacles but is generally proportional to them. Surface roughness length data are shown in Table G-5, along with their corresponding land use. The roughness height was assumed to be the same at the meteorological station and at the LAU site in order to avoid creating a separate meteorological input file for every facility modeled.

- During daytime hours, the heat flux into the ground is parameterized as a fraction of the net radiation incident on the ground. This fraction varies based on land use. A value of 0.15 was used for rural locations. Suburban and urban locations were given values of 0.22 and 0.27, respectively (U.S. EPA, 1995c).

Anthropogenic heat flux for a meteorological station can usually be neglected in areas outside of highly urbanized locations; however, in areas with high population densities or energy use, such as an industrial facility, this flux may not always be negligible (U.S. EPA, 1995c). For this analysis, anthropogenic heat flux was assumed to be zero for all meteorological stations because little information was available to assume any anthropogenic heat flux value for most locations.

Table G-1. Relation Between Anderson Land Use Codes and PCRAMMET Land Use Codes

Anderson Code and Description[a]	RAMMET Type and Description[b]
51 Streams and canals	1 Water surface
52 Lakes	1 Water surface
53 Reservoirs	1 Water surface
54 Bays and estuaries	1 Water surface
41 Deciduous forest land	2 Deciduous forest
61 Forested wetland	2 Deciduous forest
42 Evergreen forest land	3 Conifuerous forest
43 Mixed forest land	4 Mixed forest
62 Nonforested wetland	5 Swamp (nonforested)
84 Wet tundra	5 Swamp (nonforested)
21 Cropland and pasture	6 Agricultural
22 Orchards-groves-vineyards-nurseries-ornamental	6 Agricultural
23 Confined feeding operations	6 Agricultural
24 Other agricultural land	6 Agricultural
31 Herbaceous rangeland	7 Rangeland (grassland)
32 Shrub and brush rangeland	7 Rangeland (grassland)
33 Mixed rangeland	7 Rangeland (grassland)
11 Residential	9 Urban
12 Commercial and services	9 Urban
13 Industrial	9 Urban
14 Transportation-communication-utilities	9 Urban
15 Industrial and commercial complexes	9 Urban
16 Mixed urban or built-up land	9 Urban
17 Other urban or built-up land	9 Urban
71 Dry salt flats	10 Desert shrubland
72 Beaches	10 Desert shrubland

(continued)

Table G-1. (continued)

Anderson Code and Description[a]	RAMMET Type and Description[b]
73 Sandy areas not beaches	10 Desert shrubland
74 Bare exposed rock	10 Desert shrubland
75 Strip mines-quarries-gravel pits	10 Desert shrubland
76 Transitional areas	10 Desert shrubland
81 Shrub and brush tundra	10 Desert shrubland
82 Herbaceous tundra	10 Desert shrubland
83 Bare ground	10 Desert shrubland
85 Mixed tundra	10 Desert shrubland
91 Perennial snowfields	10 Desert shrubland
92 Glaciers	10 Desert shrubland

[a] Anderson codes from Anderson et al. (1976).
[b] RAMMET codes from U.S. EPA (1995c).

Table G-2. Daytime Bowen Ratio by Land Use and Season

	Spring			Summer			Autumn			Winter			Annual Average		
Land Use Type	**Dry**	**Wet**	**Avg.**	**Dry**	**Wet**	**Avg.**	**Dry**	**Wet**	**Avg.**	**Dry**	**Wet**	**Avg.**	**Dry**	**Wet**	**Avg.**
Water surface	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	2.0	0.3	1.5	0.575	0.15	0.45
Deciduous forest	1.5	0.3	0.7	0.6	0.2	0.3	2.0	0.4	1.0	2.0	0.5	1.5	1.53	0.35	0.875
Coniferous forest	1.5	0.3	0.7	0.6	0.2	0.3	1.5	0.3	0.8	2.0	0.3	1.5	1.4	0.275	0.825
Swamp	0.2	0.1	0.1	0.2	0.1	0.1	0.2	0.1	0.1	2.0	0.5	1.5	0.65	0.2	0.45
Cultivated land (agricultural)	1.0	0.2	0.3	1.5	0.3	0.5	2.0	0.4	0.7	2.0	0.5	1.5	1.63	0.35	0.75
Grassland	1.0	0.3	0.4	2.0	0.4	0.8	2.0	0.5	1.0	2.0	0.5	1.5	1.75	0.425	0.825
Urban	2.0	0.5	1.0	4.0	1.0	2.0	4.0	1.0	2.0	2.0	0.5	1.5	3.0	0.75	1.6
Desert shrub land	5.0	1.0	3.0	6.0	5.0	4.0	10.0	2.0	6.0	10.0	2.0	6.0	7.75	2.5	4.75

Source: U.S. EPA, 1995c. Averages computed for this effort.

Table G-3. Minimum Monin-Obukhov Length (Stable Conditions)

Urban Land Use Classification	Length (m)
Agriculture (open)	2
Residential	25
Compact residential/industrial	50
Commercial (19-40 story buildings) (> 40 story buildings)	100 150

Source: U.S. EPA, 1995c.

Table G-4. Albedo Values of Natural Ground Covers for Land Use Types and Seasons

Land Use Type	Spring	Summer	Autumn	Winter	Annual Average
Water surface	0.12	0.1	0.14	0.2	0.14
Deciduous forest	0.12	0.12	0.12	0.5	0.22
Coniferous forest	0.12	0.12	0.12	0.35	0.18
Swamp	0.12	0.14	0.16	0.3	0.18
Cultivated land (agricultural)	0.14	0.2	0.18	0.6	0.28
Grassland	0.18	0.18	0.20	0.6	0.29
Urban	0.14	0.16	0.18	0.35	0.21
Desert shrub land	0.3	0.28	0.28	0.45	0.33

Source: U.S. EPA, 1995c. Average values computed for this analysis.

Table G-5. Surface Roughness Length for Land Use Types and Seasons (meters)

Land Use Type	Spring	Summer	Autumn	Winter	Annual Average
Water surface	0.0001	0.0001	0.0001	0.0001	0.0001
Deciduous forest	1.0	1.3	0.8	0.5	0.9
Coniferous forest	1.3	1.3	1.3	1.3	1.3
Swamp	0.2	0.2	0.2	0.05	0.16
Cultivated land (agricultural)	0.03	0.2	0.05	0.01	0.07
Grassland	0.05	0.2	0.01	0.001	0.04
Urban	1.0	1.0	1.0	1.0	1.0
Desert shrubland	0.3	0.3	0.3	0.15	0.26

Source: U.S. EPA, 1995c. Average values computed for this analysis.

4.3.2.1 Meteorological Data. Five years of representative meteorological data were processed for this analysis. The data gathered included surface data, upper-air data, and precipitation data. These observational data were used as Industrial Source Complex, Short-Term Model, version 3 (ISCST3), inputs.

Surface Data. Hourly surface meteorological data used in air dispersion modeling were processed from the Solar and Meteorological Surface Observation Network (SAMSON) CD-ROM (U.S. DOC and U.S. DOE, 1993). Variables included

- Temperature
- Pressure
- Wind direction
- Windspeed
- Opaque cloud cover
- Ceiling height
- Current weather
- Hourly precipitation.

Upper-Air Data. Twice-daily mixing-height data were calculated from upper-air data contained in the radiosonde data of the North America CD-ROM set (NCDC, 1997). This set contains upper-air data from 1946 through 1996 for most upper-air stations in the United States. The upper-air data were combined with the SAMSON data to create the mixing-height files. EPA's Support Center for Regulatory Air Models (SCRAM) bulletin board was also used to obtain mixing-height data (if available) when mixing-height data could not be successfully calculated from the radiosonde data. The mixing heights used in this risk assessment were variable and were based on hourly ceiling height observations used in the ISCST3 air model.

Filling in Missing Data. Missing surface data were identified using a program called SQAQC, which searched for incidents of missing data on the observation indicator, opaque cloud cover, temperature, station pressure, wind direction and speed, and ceiling height. Years that were missing 10 percent or more of the data were discarded (Atkinson and Lee, 1992). Verification (quality control or QC) checks were performed on the SQAQC program by applying it to station data where the missing data were known and by intentionally degrading surface meteorological files and then running SQAQC to detect the missing values.

Missing surface data were filled in by a program called METFIX. This program fills in up to 5 consecutive hours of data for cloud cover, ceiling height, temperature, pressure, wind direction, and windspeed. For single missing values, the program follows the objective procedures developed by Atkinson and Lee (1992). For two to five consecutive missing values, other rules were developed because the subjective methods provided by Atkinson and Lee (1992) rely on professional judgment and could not be programmed. The METFIX program flagged files where missing data exceeded five consecutive values. In the few cases where this occurred and the missing data did not constitute 10 percent of the file, they were filled in manually according to procedures set forth in Atkinson and Lee (1992). If more than 10 percent of the data were missing, the station was discarded and another station in the climatic region was selected.

All upper-air files were checked for missing data using a program called QAQC. QAQC produces a log file containing occurrences of missing mixing height. Verification (QC) checks were performed on the QAQC program by applying it to station data where the missing data were known and by intentionally degrading existing mixing height files and then running QAQC to detect the missing values.

Missing mixing heights were filled in by running the files through another program written to interpolate one to five consecutive missing values. According to Atkinson and Lee (1992), if there are one to five consecutive missing values, the values should be filled in subjectively using professional judgment. Again, programming these subjective procedures was not feasible, and the program used simple linear interpolation to fill in these values automatically. Information from Atkinson and Lee (1992) was used to determine which files should be discarded (i.e., files missing more than five consecutive missing values or missing 10 percent or more of the data). After the missing mixing heights were filled in for all upper-air files, they were checked once more for missing data using the QAQC program.

4.3.2.2 Climate Data. Meteorological stations selected for purposes of air dispersion modeling also provided long-term climatic data that were necessary for fate and transport modeling. For each of the 41 stations, the following climate data were compiled:

- Mean annual wind direction
- Mean annual windspeed
- Average temperature
- Average annual runoff
- Universal Soil Loss Equation (USLE) rainfall/erosivity factor.

```
CO STARTING
  TITLEONE  Albuquerque
  TITLETWO  464.3 ACRES
  MODELOPT  TOXICS RURAL CONC DDEP WDEP DRYDPLT WETDPLT
  AVERTIME  ANNUAL
  SAVEFILE  23050.SAP
  POLLUTID  PART
  TERRHGTS  FLAT
  ERRORFIL  ERRORS.OUT
  RUNORNOT  RUN
CO FINISHED

SO STARTING

SO LOCATION 1C     AREA    -1174.35   -400    0.00
SO LOCATION 1P     AREA    0   -400    0.00

**          SRCID    QS       HS     XINIT   YINIT   ROTATE   SZINIT

SO SRCPARAM 1C    1.0E-3      0.0    1174.35  800   0.0
SO PARTDIAM 1C    22.5     12.5     6.3     1.3
SO MASSFRAX 1C     0.4      0.1     0.3     0.2
SO PARTDENS 1C       1        1       1       1
SO PARTSLIQ 1C    6.7E-4  6.7E-4  4.5E-4  6.0E-5
SO PARTSICE 1C    2.2E-4  2.2E-4  1.5E-4  2.0E-5

SO SRCPARAM 1P    1.0E-3      0.0    1174.35  800   0.0
SO PARTDIAM 1P    22.5     12.5     6.3     1.3
SO MASSFRAX 1P     0.4      0.1     0.3     0.2
SO PARTDENS 1P       1        1       1       1
SO PARTSLIQ 1P    6.7E-4  6.7E-4  4.5E-4  6.0E-5
SO PARTSICE 1P    2.2E-4  2.2E-4  1.5E-4  2.0E-5

SO SRCGROUP 1 1C
SO SRCGROUP 2 1P
SO SRCGROUP ALL

SO FINISHED

RE STARTING
RE GRIDCART  ONSITE STA
RE GRIDCART  ONSITE XYINC   -1174.35  11  234.87  -400  11  80
RE GRIDCART  ONSITE END
RE INCLUDED  23050.REC
RE FINISHED

ME STARTING
ME INPUTFIL  23050H.MET
ME ANEMHGHT  7 METERS
ME SURFDATA  23050  1985
ME UAIRDATA  23050  1985
ME FINISHED

OU STARTING
  RECTABLE  ALLAVE FIRST
  MAXTABLE  ALLAVE  10
  PLOTFILE  ANNUAL 1 23050_1C.PLP
  PLOTFILE  ANNUAL 2 23050_1P.PLP
  PLOTFILE  ANNUAL ALL 23050.PLP
OU FINISHED
```

```
CO STARTING
  TITLEONE  Asheville
  TITLETWO  55.4 ACRES
  MODELOPT  TOXICS RURAL CONC DDEP WDEP DRYDPLT WETDPLT
  AVERTIME  ANNUAL
  SAVEFILE  03812.SAP
  POLLUTID  PART
  TERRHGTS  FLAT
  ERRORFIL  ERRORS.OUT
  RUNORNOT  RUN
CO FINISHED

SO STARTING

SO LOCATION 1C     AREA    -236.75   -236.75    0.00
SO LOCATION 1P     AREA    0   -236.75    0.00

**          SRCID    QS       HS     XINIT   YINIT   ROTATE   SZINIT

SO SRCPARAM 1C    1.0E-3      0.0    236.75  473.49   0.0
SO PARTDIAM 1C    22.5     12.5     6.3     1.3
SO MASSFRAX 1C     0.4      0.1     0.3     0.2
SO PARTDENS 1C       1        1       1       1
SO PARTSLIQ 1C    6.7E-4  6.7E-4  4.5E-4  6.0E-5
SO PARTSICE 1C    2.2E-4  2.2E-4  1.5E-4  2.0E-5

SO SRCPARAM 1P    1.0E-3      0.0    236.75  473.49   0.0
SO PARTDIAM 1P    22.5     12.5     6.3     1.3
SO MASSFRAX 1P     0.4      0.1     0.3     0.2
SO PARTDENS 1P       1        1       1       1
SO PARTSLIQ 1P    6.7E-4  6.7E-4  4.5E-4  6.0E-5
SO PARTSICE 1P    2.2E-4  2.2E-4  1.5E-4  2.0E-5

SO SRCGROUP 1 1C
SO SRCGROUP 2 1P
SO SRCGROUP ALL

SO FINISHED

RE STARTING
RE GRIDCART  ONSITE STA
RE GRIDCART  ONSITE XYINC   -236.75  11  47.35  -236.75  11  47.35
RE GRIDCART  ONSITE END
RE INCLUDED  03812.REC
RE FINISHED

ME STARTING
ME INPUTFIL  03812H.MET
ME ANEMHGHT  6.1 METERS
ME SURFDATA  03812  1985
ME UAIRDATA  13723  1985
ME FINISHED

OU STARTING
  RECTABLE  ALLAVE FIRST
  MAXTABLE  ALLAVE  10
  PLOTFILE  ANNUAL 1 03812_1C.PLP
  PLOTFILE  ANNUAL 2 03812_1P.PLP
  PLOTFILE  ANNUAL ALL 03812.PLP
OU FINISHED
```

```
CO STARTING
  TITLEONE  Atlanta
  TITLETWO  105.9 ACRES
  MODELOPT  TOXICS RURAL CONC DDEP WDEP DRYDPLT WETDPLT
  AVERTIME  ANNUAL
  SAVEFILE  13874.SAP
  POLLUTID  PART
  TERRHGTS  FLAT
  ERRORFIL  ERRORS.OUT
  RUNORNOT  RUN
CO FINISHED

SO STARTING

SO LOCATION 1C     AREA    -327.32   -327.32    0.00
SO LOCATION 1P     AREA    0   -327.32    0.00

**          SRCID    QS       HS     XINIT   YINIT   ROTATE   SZINIT

SO SRCPARAM 1C    1.0E-3      0.0    327.32  654.65   0.0
SO PARTDIAM 1C    22.5     12.5     6.3     1.3
SO MASSFRAX 1C     0.4      0.1     0.3     0.2
SO PARTDENS 1C       1        1       1       1
SO PARTSLIQ 1C    6.7E-4  6.7E-4  4.5E-4  6.0E-5
SO PARTSICE 1C    2.2E-4  2.2E-4  1.5E-4  2.0E-5

SO SRCPARAM 1P    1.0E-3      0.0    327.32  654.65   0.0
SO PARTDIAM 1P    22.5     12.5     6.3     1.3
SO MASSFRAX 1P     0.4      0.1     0.3     0.2
SO PARTDENS 1P       1        1       1       1
SO PARTSLIQ 1P    6.7E-4  6.7E-4  4.5E-4  6.0E-5
SO PARTSICE 1P    2.2E-4  2.2E-4  1.5E-4  2.0E-5

SO SRCGROUP 1 1C
SO SRCGROUP 2 1P
SO SRCGROUP ALL

SO FINISHED

RE STARTING
RE GRIDCART  ONSITE STA
RE GRIDCART  ONSITE XYINC   -327.32  11  65.46  -327.32  11  65.46
RE GRIDCART  ONSITE END
RE INCLUDED  13874.REC
RE FINISHED

ME STARTING
ME INPUTFIL  13874H.MET
ME ANEMHGHT  6.1 METERS
ME SURFDATA  13874  1986
ME UAIRDATA  13873  1986
ME FINISHED

OU STARTING
  RECTABLE  ALLAVE FIRST
  MAXTABLE  ALLAVE  10
  PLOTFILE  ANNUAL 1 13874_1C.PLP
  PLOTFILE  ANNUAL 2 13874_1P.PLP
  PLOTFILE  ANNUAL ALL 13874.PLP
OU FINISHED
```

```
CO STARTING
  TITLEONE  Billings
  TITLETWO  1241.7 ACRES
  MODELOPT  TOXICS RURAL CONC DDEP WDEP DRYDPLT WETDPLT
  AVERTIME  ANNUAL
  SAVEFILE  24033.SAP
  POLLUTID  PART
  TERRHGTS  FLAT
  ERRORFIL  ERRORS.OUT
  RUNORNOT  RUN
CO FINISHED

SO STARTING

SO LOCATION 1C     AREA    -3140.63   -400    0.00
SO LOCATION 1P     AREA    0   -400    0.00

**          SRCID    QS       HS     XINIT   YINIT   ROTATE   SZINIT

SO SRCPARAM 1C    1.0E-3      0.0    3140.63  800   0.0
SO PARTDIAM 1C    22.5     12.5     6.3     1.3
SO MASSFRAX 1C     0.4      0.1     0.3     0.2
SO PARTDENS 1C       1        1       1       1
SO PARTSLIQ 1C    6.7E-4  6.7E-4  4.5E-4  6.0E-5
SO PARTSICE 1C    2.2E-4  2.2E-4  1.5E-4  2.0E-5

SO SRCPARAM 1P    1.0E-3      0.0    3140.63  800   0.0
SO PARTDIAM 1P    22.5     12.5     6.3     1.3
SO MASSFRAX 1P     0.4      0.1     0.3     0.2
SO PARTDENS 1P       1        1       1       1
SO PARTSLIQ 1P    6.7E-4  6.7E-4  4.5E-4  6.0E-5
SO PARTSICE 1P    2.2E-4  2.2E-4  1.5E-4  2.0E-5

SO SRCGROUP 1 1C
SO SRCGROUP 2 1P
SO SRCGROUP ALL

SO FINISHED

RE STARTING
RE GRIDCART  ONSITE STA
RE GRIDCART  ONSITE XYINC   -3140.63  11  628.13  -400  11  80
RE GRIDCART  ONSITE END
RE INCLUDED  24033.REC
RE FINISHED

ME STARTING
ME INPUTFIL  24033H.MET
ME ANEMHGHT  7.6 METERS
ME SURFDATA  24033  1986
ME UAIRDATA  24143  1986
ME FINISHED

OU STARTING
  RECTABLE  ALLAVE FIRST
  MAXTABLE  ALLAVE  10
  PLOTFILE  ANNUAL 1 24033_1C.PLP
  PLOTFILE  ANNUAL 2 24033_1P.PLP
  PLOTFILE  ANNUAL ALL 24033.PLP
OU FINISHED
```

```
CO STARTING
  TITLEONE  Bismarck
  TITLETWO  923.8 ACRES
  MODELOPT  TOXICS RURAL CONC DDEP WDEP DRYDPLT WETDPLT
  AVERTIME  ANNUAL
  SAVEFILE  24011.SAP
  POLLUTID  PART
  TERRHGTS  FLAT
  ERRORFIL  ERRORS.OUT
  RUNORNOT  RUN
CO FINISHED

SO STARTING

SO LOCATION 1C     AREA    -2336.56   -400    0.00
SO LOCATION 1P     AREA    0   -400    0.00

**          SRCID    QS       HS     XINIT   YINIT   ROTATE   SZINIT

SO SRCPARAM 1C    1.0E-3      0.0    2336.56  800   0.0
SO PARTDIAM 1C    22.5     12.5     6.3     1.3
SO MASSFRAX 1C     0.4      0.1     0.3     0.2
SO PARTDENS 1C       1        1       1       1
SO PARTSLIQ 1C    6.7E-4  6.7E-4  4.5E-4  6.0E-5
SO PARTSICE 1C    2.2E-4  2.2E-4  1.5E-4  2.0E-5

SO SRCPARAM 1P    1.0E-3      0.0    2336.56  800   0.0
SO PARTDIAM 1P    22.5     12.5     6.3     1.3
SO MASSFRAX 1P     0.4      0.1     0.3     0.2
SO PARTDENS 1P       1        1       1       1
SO PARTSLIQ 1P    6.7E-4  6.7E-4  4.5E-4  6.0E-5
SO PARTSICE 1P    2.2E-4  2.2E-4  1.5E-4  2.0E-5

SO SRCGROUP 1 1C
SO SRCGROUP 2 1P
SO SRCGROUP ALL

SO FINISHED

RE STARTING
RE GRIDCART  ONSITE STA
RE GRIDCART  ONSITE XYINC   -2336.56  11  467.31  -400  11  80
RE GRIDCART  ONSITE END
RE INCLUDED  24011.REC
RE FINISHED

ME STARTING
ME INPUTFIL  24011H.MET
ME ANEMHGHT  6.1 METERS
ME SURFDATA  24011  1984
ME UAIRDATA  24011  1984
ME FINISHED

OU STARTING
  RECTABLE  ALLAVE FIRST
  MAXTABLE  ALLAVE  10
  PLOTFILE  ANNUAL 1 24011_1C.PLP
  PLOTFILE  ANNUAL 2 24011_1P.PLP
  PLOTFILE  ANNUAL ALL 24011.PLP
OU FINISHED
```

```
CO STARTING
  TITLEONE  Boise
  TITLETWO  194.4 ACRES
  MODELOPT  TOXICS RURAL CONC DDEP WDEP DRYDPLT WETDPLT
  AVERTIME  ANNUAL
  SAVEFILE  24131.SAP
  POLLUTID  PART
  TERRHGTS  FLAT
  ERRORFIL  ERRORS.OUT
  RUNORNOT  RUN
CO FINISHED

SO STARTING

SO LOCATION 1C     AREA    -491.7   -400    0.00
SO LOCATION 1P     AREA    0   -400    0.00

**          SRCID    QS       HS     XINIT   YINIT   ROTATE   SZINIT

SO SRCPARAM 1C    1.0E-3      0.0    491.7  800   0.0
SO PARTDIAM 1C    22.5     12.5     6.3     1.3
SO MASSFRAX 1C     0.4      0.1     0.3     0.2
SO PARTDENS 1C       1        1       1       1
SO PARTSLIQ 1C    6.7E-4  6.7E-4  4.5E-4  6.0E-5
SO PARTSICE 1C    2.2E-4  2.2E-4  1.5E-4  2.0E-5

SO SRCPARAM 1P    1.0E-3      0.0    491.7  800   0.0
SO PARTDIAM 1P    22.5     12.5     6.3     1.3
SO MASSFRAX 1P     0.4      0.1     0.3     0.2
SO PARTDENS 1P       1        1       1       1
SO PARTSLIQ 1P    6.7E-4  6.7E-4  4.5E-4  6.0E-5
SO PARTSICE 1P    2.2E-4  2.2E-4  1.5E-4  2.0E-5

SO SRCGROUP 1 1C
SO SRCGROUP 2 1P
SO SRCGROUP ALL

SO FINISHED

RE STARTING
RE GRIDCART  ONSITE STA
RE GRIDCART  ONSITE XYINC   -491.7  11  98.34  -400  11  80
RE GRIDCART  ONSITE END
RE INCLUDED  24131.REC
RE FINISHED

ME STARTING
ME INPUTFIL  24131H.MET
ME ANEMHGHT  6.1 METERS
ME SURFDATA  24131  1978
ME UAIRDATA  24131  1978
ME FINISHED

OU STARTING
  RECTABLE  ALLAVE FIRST
  MAXTABLE  ALLAVE  10
  PLOTFILE  ANNUAL 1 24131_1C.PLP
  PLOTFILE  ANNUAL 2 24131_1P.PLP
  PLOTFILE  ANNUAL ALL 24131.PLP
OU FINISHED
```

```
CO STARTING
  TITLEONE  Boulder
  TITLETWO  738 ACRES
  MODELOPT  TOXICS RURAL CONC DDEP WDEP DRYDPLT WETDPLT
  AVERTIME  ANNUAL
  SAVEFILE  94018.SAP
  POLLUTID  PART
  TERRHGTS  FLAT
  ERRORFIL  ERRORS.OUT
  RUNORNOT  RUN
CO FINISHED

SO STARTING

SO LOCATION 1C     AREA    -1866.62   -400    0.00
SO LOCATION 1P     AREA    0   -400    0.00

**          SRCID    QS       HS     XINIT   YINIT   ROTATE   SZINIT

SO SRCPARAM 1C    1.0E-3      0.0    1866.62  800   0.0
SO PARTDIAM 1C    22.5     12.5     6.3     1.3
SO MASSFRAX 1C     0.4      0.1     0.3     0.2
SO PARTDENS 1C       1        1       1       1
SO PARTSLIQ 1C    6.7E-4  6.7E-4  4.5E-4  6.0E-5
SO PARTSICE 1C    2.2E-4  2.2E-4  1.5E-4  2.0E-5

SO SRCPARAM 1P    1.0E-3      0.0    1866.62  800   0.0
SO PARTDIAM 1P    22.5     12.5     6.3     1.3
SO MASSFRAX 1P     0.4      0.1     0.3     0.2
SO PARTDENS 1P       1        1       1       1
SO PARTSLIQ 1P    6.7E-4  6.7E-4  4.5E-4  6.0E-5
SO PARTSICE 1P    2.2E-4  2.2E-4  1.5E-4  2.0E-5

SO SRCGROUP 1 1C
SO SRCGROUP 2 1P
SO SRCGROUP ALL

SO FINISHED

RE STARTING
RE GRIDCART  ONSITE STA
RE GRIDCART  ONSITE XYINC   -1866.62  11  373.32  -400  11  80
RE GRIDCART  ONSITE END
RE INCLUDED  94018.REC
RE FINISHED

ME STARTING
ME INPUTFIL  94018H.MET
ME ANEMHGHT  6.1 METERS
ME SURFDATA  94018  1986
ME UAIRDATA  23062  1986
ME FINISHED

OU STARTING
  RECTABLE  ALLAVE FIRST
  MAXTABLE  ALLAVE  10
  PLOTFILE  ANNUAL 1 94018_1C.PLP
  PLOTFILE  ANNUAL 2 94018_1P.PLP
  PLOTFILE  ANNUAL ALL 94018.PLP
OU FINISHED
```

```
CO STARTING
  TITLEONE  Burlington
  TITLETWO  159.2 ACRES
  MODELOPT  TOXICS RURAL CONC DDEP WDEP DRYDPLT WETDPLT
  AVERTIME  ANNUAL
  SAVEFILE  14742.SAP
  POLLUTID  PART
  TERRHGTS  FLAT
  ERRORFIL  ERRORS.OUT
  RUNORNOT  RUN
CO FINISHED

SO STARTING

SO LOCATION 1C     AREA    -402.66   -400    0.00
SO LOCATION 1P     AREA    0   -400    0.00

**          SRCID    QS       HS     XINIT   YINIT   ROTATE   SZINIT

SO SRCPARAM 1C    1.0E-3      0.0    402.66  800   0.0
SO PARTDIAM 1C    22.5     12.5     6.3     1.3
SO MASSFRAX 1C     0.4      0.1     0.3     0.2
SO PARTDENS 1C       1        1       1       1
SO PARTSLIQ 1C    6.7E-4  6.7E-4  4.5E-4  6.0E-5
SO PARTSICE 1C    2.2E-4  2.2E-4  1.5E-4  2.0E-5

SO SRCPARAM 1P    1.0E-3      0.0    402.66  800   0.0
SO PARTDIAM 1P    22.5     12.5     6.3     1.3
SO MASSFRAX 1P     0.4      0.1     0.3     0.2
SO PARTDENS 1P       1        1       1       1
SO PARTSLIQ 1P    6.7E-4  6.7E-4  4.5E-4  6.0E-5
SO PARTSICE 1P    2.2E-4  2.2E-4  1.5E-4  2.0E-5

SO SRCGROUP 1 1C
SO SRCGROUP 2 1P
SO SRCGROUP ALL

SO FINISHED

RE STARTING
RE GRIDCART  ONSITE STA
RE GRIDCART  ONSITE XYINC   -402.66  11  80.53  -400  11  80
RE GRIDCART  ONSITE END
RE INCLUDED  14742.REC
RE FINISHED

ME STARTING
ME INPUTFIL  14742H.MET
ME ANEMHGHT  6.1 METERS
ME SURFDATA  14742  1985
ME UAIRDATA  14735  1985
ME FINISHED

OU STARTING
  RECTABLE  ALLAVE FIRST
  MAXTABLE  ALLAVE  10
  PLOTFILE  ANNUAL 1 14742_1C.PLP
  PLOTFILE  ANNUAL 2 14742_1P.PLP
  PLOTFILE  ANNUAL ALL 14742.PLP
OU FINISHED
```

```
CO STARTING
  TITLEONE  Casper
  TITLETWO  829.6 ACRES
  MODELOPT  TOXICS RURAL CONC DDEP WDEP DRYDPLT WETDPLT
  AVERTIME  ANNUAL
  SAVEFILE  24089.SAP
  POLLUTID  PART
  TERRHGTS  FLAT
  ERRORFIL  ERRORS.OUT
  RUNORNOT  RUN
CO FINISHED

SO STARTING

SO LOCATION 1C     AREA    -2098.3   -400    0.00
SO LOCATION 1P     AREA    0   -400    0.00

**          SRCID    QS       HS     XINIT   YINIT   ROTATE   SZINIT

SO SRCPARAM 1C    1.0E-3      0.0    2098.3  800   0.0
SO PARTDIAM 1C    22.5     12.5     6.3     1.3
SO MASSFRAX 1C     0.4      0.1     0.3     0.2
SO PARTDENS 1C       1        1       1       1
SO PARTSLIQ 1C    6.7E-4  6.7E-4  4.5E-4  6.0E-5
SO PARTSICE 1C    2.2E-4  2.2E-4  1.5E-4  2.0E-5

SO SRCPARAM 1P    1.0E-3      0.0    2098.3  800   0.0
SO PARTDIAM 1P    22.5     12.5     6.3     1.3
SO MASSFRAX 1P     0.4      0.1     0.3     0.2
SO PARTDENS 1P       1        1       1       1
SO PARTSLIQ 1P    6.7E-4  6.7E-4  4.5E-4  6.0E-5
SO PARTSICE 1P    2.2E-4  2.2E-4  1.5E-4  2.0E-5

SO SRCGROUP 1 1C
SO SRCGROUP 2 1P
SO SRCGROUP ALL

SO FINISHED

RE STARTING
RE GRIDCART  ONSITE STA
RE GRIDCART  ONSITE XYINC   -2098.3  11  419.66  -400  11  80
RE GRIDCART  ONSITE END
RE INCLUDED  24089.REC
RE FINISHED

ME STARTING
ME INPUTFIL  24089H.MET
ME ANEMHGHT  6.1 METERS
ME SURFDATA  24089  1985
ME UAIRDATA  24021  1985
ME FINISHED

OU STARTING
  RECTABLE  ALLAVE FIRST
  MAXTABLE  ALLAVE  10
  PLOTFILE  ANNUAL 1 24089_1C.PLP
  PLOTFILE  ANNUAL 2 24089_1P.PLP
  PLOTFILE  ANNUAL ALL 24089.PLP
OU FINISHED
```

```
CO STARTING
  TITLEONE  Charleston
  TITLETWO  80.4 ACRES
  MODELOPT  TOXICS RURAL CONC DDEP WDEP DRYDPLT WETDPLT
  AVERTIME  ANNUAL
  SAVEFILE  13880.SAP
  POLLUTID  PART
  TERRHGTS  FLAT
  ERRORFIL  ERRORS.OUT
  RUNORNOT  RUN
CO FINISHED

SO STARTING

SO LOCATION 1C     AREA    -285.21   -285.21    0.00
SO LOCATION 1P     AREA    0   -285.21    0.00

**          SRCID    QS       HS     XINIT   YINIT   ROTATE   SZINIT

SO SRCPARAM 1C    1.0E-3      0.0    285.21  570.41   0.0
SO PARTDIAM 1C    22.5     12.5     6.3     1.3
SO MASSFRAX 1C     0.4      0.1     0.3     0.2
SO PARTDENS 1C       1        1       1       1
SO PARTSLIQ 1C    6.7E-4  6.7E-4  4.5E-4  6.0E-5
SO PARTSICE 1C    2.2E-4  2.2E-4  1.5E-4  2.0E-5

SO SRCPARAM 1P    1.0E-3      0.0    285.21  570.41   0.0
SO PARTDIAM 1P    22.5     12.5     6.3     1.3
SO MASSFRAX 1P     0.4      0.1     0.3     0.2
SO PARTDENS 1P       1        1       1       1
SO PARTSLIQ 1P    6.7E-4  6.7E-4  4.5E-4  6.0E-5
SO PARTSICE 1P    2.2E-4  2.2E-4  1.5E-4  2.0E-5

SO SRCGROUP 1 1C
SO SRCGROUP 2 1P
SO SRCGROUP ALL

SO FINISHED

RE STARTING
RE GRIDCART  ONSITE STA
RE GRIDCART  ONSITE XYINC   -285.21  11  57.04  -285.21  11  57.04
RE GRIDCART  ONSITE END
RE INCLUDED  13880.REC
RE FINISHED

ME STARTING
ME INPUTFIL  13880H.MET
ME ANEMHGHT  6.1 METERS
ME SURFDATA  13880  1984
ME UAIRDATA  13880  1984
ME FINISHED

OU STARTING
  RECTABLE  ALLAVE FIRST
  MAXTABLE  ALLAVE  10
  PLOTFILE  ANNUAL 1 13880_1C.PLP
  PLOTFILE  ANNUAL 2 13880_1P.PLP
  PLOTFILE  ANNUAL ALL 13880.PLP
OU FINISHED
```

```
CO STARTING
  TITLEONE  Chicago
  TITLETWO  177.6 ACRES
  MODELOPT  TOXICS RURAL CONC DDEP WDEP DRYDPLT WETDPLT
  AVERTIME  ANNUAL
  SAVEFILE  94846.SAP
  POLLUTID  PART
  TERRHGTS  FLAT
  ERRORFIL  ERRORS.OUT
  RUNORNOT  RUN
CO FINISHED

SO STARTING

SO LOCATION 1C     AREA    -449.2   -400    0.00
SO LOCATION 1P     AREA    0   -400    0.00

**          SRCID    QS       HS     XINIT   YINIT   ROTATE   SZINIT

SO SRCPARAM 1C    1.0E-3      0.0    449.2  800   0.0
SO PARTDIAM 1C    22.5     12.5     6.3     1.3
SO MASSFRAX 1C     0.4      0.1     0.3     0.2
SO PARTDENS 1C       1        1       1       1
SO PARTSLIQ 1C    6.7E-4  6.7E-4  4.5E-4  6.0E-5
SO PARTSICE 1C    2.2E-4  2.2E-4  1.5E-4  2.0E-5

SO SRCPARAM 1P    1.0E-3      0.0    449.2  800   0.0
SO PARTDIAM 1P    22.5     12.5     6.3     1.3
SO MASSFRAX 1P     0.4      0.1     0.3     0.2
SO PARTDENS 1P       1        1       1       1
SO PARTSLIQ 1P    6.7E-4  6.7E-4  4.5E-4  6.0E-5
SO PARTSICE 1P    2.2E-4  2.2E-4  1.5E-4  2.0E-5

SO SRCGROUP 1 1C
SO SRCGROUP 2 1P
SO SRCGROUP ALL

SO FINISHED

RE STARTING
RE GRIDCART  ONSITE STA
RE GRIDCART  ONSITE XYINC   -449.2  11  89.84  -400  11  80
RE GRIDCART  ONSITE END
RE INCLUDED  94846.REC
RE FINISHED

ME STARTING
ME INPUTFIL  94846H.MET
ME ANEMHGHT  6.1 METERS
ME SURFDATA  94846  1984
ME UAIRDATA  14842  1984
ME FINISHED

OU STARTING
  RECTABLE  ALLAVE FIRST
  MAXTABLE  ALLAVE  10
  PLOTFILE  ANNUAL 1 94846_1C.PLP
  PLOTFILE  ANNUAL 2 94846_1P.PLP
  PLOTFILE  ANNUAL ALL 94846.PLP
OU FINISHED
```

```
CO STARTING
  TITLEONE  Cleveland
  TITLETWO  109.2 ACRES
  MODELOPT  TOXICS RURAL CONC DDEP WDEP DRYDPLT WETDPLT
  AVERTIME  ANNUAL
  SAVEFILE  14820.SAP
  POLLUTID  PART
  TERRHGTS  FLAT
  ERRORFIL  ERRORS.OUT
  RUNORNOT  RUN
CO FINISHED

SO STARTING

SO LOCATION 1C     AREA    -332.38   -332.38    0.00
SO LOCATION 1P     AREA    0   -332.38    0.00

**          SRCID    QS       HS     XINIT   YINIT   ROTATE   SZINIT

SO SRCPARAM 1C    1.0E-3      0.0    332.38  664.77   0.0
SO PARTDIAM 1C    22.5     12.5     6.3     1.3
SO MASSFRAX 1C     0.4      0.1     0.3     0.2
SO PARTDENS 1C       1        1       1       1
SO PARTSLIQ 1C    6.7E-4  6.7E-4  4.5E-4  6.0E-5
SO PARTSICE 1C    2.2E-4  2.2E-4  1.5E-4  2.0E-5

SO SRCPARAM 1P    1.0E-3      0.0    332.38  664.77   0.0
SO PARTDIAM 1P    22.5     12.5     6.3     1.3
SO MASSFRAX 1P     0.4      0.1     0.3     0.2
SO PARTDENS 1P       1        1       1       1
SO PARTSLIQ 1P    6.7E-4  6.7E-4  4.5E-4  6.0E-5
SO PARTSICE 1P    2.2E-4  2.2E-4  1.5E-4  2.0E-5

SO SRCGROUP 1 1C
SO SRCGROUP 2 1P
SO SRCGROUP ALL

SO FINISHED

RE STARTING
RE GRIDCART  ONSITE STA
RE GRIDCART  ONSITE XYINC   -332.38  11  66.48  -332.38  11  66.48
RE GRIDCART  ONSITE END
RE INCLUDED  14820.REC
RE FINISHED

ME STARTING
ME INPUTFIL  14820H.MET
ME ANEMHGHT  6.1 METERS
ME SURFDATA  14820  1985
ME UAIRDATA  14733  1985
ME FINISHED

OU STARTING
  RECTABLE  ALLAVE FIRST
  MAXTABLE  ALLAVE  10
  PLOTFILE  ANNUAL 1 14820_1C.PLP
  PLOTFILE  ANNUAL 2 14820_1P.PLP
  PLOTFILE  ANNUAL ALL 14820.PLP
OU FINISHED
```

```
CO STARTING
  TITLEONE  Fresno
  TITLETWO  46.8 ACRES
  MODELOPT  TOXICS RURAL CONC DDEP WDEP DRYDPLT WETDPLT
  AVERTIME  ANNUAL
  SAVEFILE  93193.SAP
  POLLUTID  PART
  TERRHGTS  FLAT
  ERRORFIL  ERRORS.OUT
  RUNORNOT  RUN
CO FINISHED

SO STARTING

SO LOCATION 1C     AREA    -217.6   -217.6    0.00
SO LOCATION 1P     AREA    0   -217.6    0.00

**          SRCID    QS       HS     XINIT   YINIT   ROTATE   SZINIT

SO SRCPARAM 1C    1.0E-3      0.0    217.6  435.19   0.0
SO PARTDIAM 1C    22.5     12.5     6.3     1.3
SO MASSFRAX 1C     0.4      0.1     0.3     0.2
SO PARTDENS 1C       1        1       1       1
SO PARTSLIQ 1C    6.7E-4  6.7E-4  4.5E-4  6.0E-5
SO PARTSICE 1C    2.2E-4  2.2E-4  1.5E-4  2.0E-5

SO SRCPARAM 1P    1.0E-3      0.0    217.6  435.19   0.0
SO PARTDIAM 1P    22.5     12.5     6.3     1.3
SO MASSFRAX 1P     0.4      0.1     0.3     0.2
SO PARTDENS 1P       1        1       1       1
SO PARTSLIQ 1P    6.7E-4  6.7E-4  4.5E-4  6.0E-5
SO PARTSICE 1P    2.2E-4  2.2E-4  1.5E-4  2.0E-5

SO SRCGROUP 1 1C
SO SRCGROUP 2 1P
SO SRCGROUP ALL

SO FINISHED

RE STARTING
RE GRIDCART  ONSITE STA
RE GRIDCART  ONSITE XYINC   -217.6  11  43.52  -217.6  11  43.52
RE GRIDCART  ONSITE END
RE INCLUDED  93193.REC
RE FINISHED

ME STARTING
ME INPUTFIL  93193H.MET
ME ANEMHGHT  6.1 METERS
ME SURFDATA  93193  1985
ME UAIRDATA  23230  1985
ME FINISHED

OU STARTING
  RECTABLE  ALLAVE FIRST
  MAXTABLE  ALLAVE  10
  PLOTFILE  ANNUAL 1 93193_1C.PLP
  PLOTFILE  ANNUAL 2 93193_1P.PLP
  PLOTFILE  ANNUAL ALL 93193.PLP
OU FINISHED
```

```
CO STARTING
  TITLEONE  Harrisburg
  TITLETWO  102.8 ACRES
  MODELOPT  TOXICS RURAL CONC DDEP WDEP DRYDPLT WETDPLT
  AVERTIME  ANNUAL
  SAVEFILE  14751.SAP
  POLLUTID  PART
  TERRHGTS  FLAT
  ERRORFIL  ERRORS.OUT
  RUNORNOT  RUN
CO FINISHED

SO STARTING

SO LOCATION 1C     AREA    -322.5   -322.5    0.00
SO LOCATION 1P     AREA    0   -322.5    0.00

**          SRCID    QS       HS     XINIT   YINIT   ROTATE   SZINIT

SO SRCPARAM 1C    1.0E-3      0.0    322.5  644.99   0.0
SO PARTDIAM 1C    22.5     12.5     6.3     1.3
SO MASSFRAX 1C     0.4      0.1     0.3     0.2
SO PARTDENS 1C       1        1       1       1
SO PARTSLIQ 1C    6.7E-4  6.7E-4  4.5E-4  6.0E-5
SO PARTSICE 1C    2.2E-4  2.2E-4  1.5E-4  2.0E-5

SO SRCPARAM 1P    1.0E-3      0.0    322.5  644.99   0.0
SO PARTDIAM 1P    22.5     12.5     6.3     1.3
SO MASSFRAX 1P     0.4      0.1     0.3     0.2
SO PARTDENS 1P       1        1       1       1
SO PARTSLIQ 1P    6.7E-4  6.7E-4  4.5E-4  6.0E-5
SO PARTSICE 1P    2.2E-4  2.2E-4  1.5E-4  2.0E-5

SO SRCGROUP 1 1C
SO SRCGROUP 2 1P
SO SRCGROUP ALL

SO FINISHED

RE STARTING
RE GRIDCART  ONSITE STA
RE GRIDCART  ONSITE XYINC   -322.5  11  64.5  -322.5  11  64.5
RE GRIDCART  ONSITE END
RE INCLUDED  14751.REC
RE FINISHED

ME STARTING
ME INPUTFIL  14751H.MET
ME ANEMHGHT  6.7 METERS
ME SURFDATA  14751  1985
ME UAIRDATA  93734  1985
ME FINISHED

OU STARTING
  RECTABLE  ALLAVE FIRST
  MAXTABLE  ALLAVE  10
  PLOTFILE  ANNUAL 1 14751_1C.PLP
  PLOTFILE  ANNUAL 2 14751_1P.PLP
  PLOTFILE  ANNUAL ALL 14751.PLP
OU FINISHED
```

```
CO STARTING
  TITLEONE  Hartford
  TITLETWO  50 ACRES
  MODELOPT  TOXICS RURAL CONC DDEP WDEP DRYDPLT WETDPLT
  AVERTIME  ANNUAL
  SAVEFILE  14740.SAP
  POLLUTID  PART
  TERRHGTS  FLAT
  ERRORFIL  ERRORS.OUT
  RUNORNOT  RUN
CO FINISHED

SO STARTING

SO LOCATION 1C     AREA    -224.91   -224.91    0.00
SO LOCATION 1P     AREA    0   -224.91    0.00

**          SRCID    QS       HS     XINIT   YINIT   ROTATE   SZINIT

SO SRCPARAM 1C    1.0E-3      0.0    224.91  449.83   0.0
SO PARTDIAM 1C    22.5     12.5     6.3     1.3
SO MASSFRAX 1C     0.4      0.1     0.3     0.2
SO PARTDENS 1C       1        1       1       1
SO PARTSLIQ 1C    6.7E-4  6.7E-4  4.5E-4  6.0E-5
SO PARTSICE 1C    2.2E-4  2.2E-4  1.5E-4  2.0E-5

SO SRCPARAM 1P    1.0E-3      0.0    224.91  449.83   0.0
SO PARTDIAM 1P    22.5     12.5     6.3     1.3
SO MASSFRAX 1P     0.4      0.1     0.3     0.2
SO PARTDENS 1P       1        1       1       1
SO PARTSLIQ 1P    6.7E-4  6.7E-4  4.5E-4  6.0E-5
SO PARTSICE 1P    2.2E-4  2.2E-4  1.5E-4  2.0E-5

SO SRCGROUP 1 1C
SO SRCGROUP 2 1P
SO SRCGROUP ALL

SO FINISHED

RE STARTING
RE GRIDCART  ONSITE STA
RE GRIDCART  ONSITE XYINC   -224.91  11  44.98  -224.91  11  44.98
RE GRIDCART  ONSITE END
RE INCLUDED  14740.REC
RE FINISHED

ME STARTING
ME INPUTFIL  14740H.MET
ME ANEMHGHT  6.1 METERS
ME SURFDATA  14740  1985
ME UAIRDATA  14735  1985
ME FINISHED

OU STARTING
  RECTABLE  ALLAVE FIRST
  MAXTABLE  ALLAVE  10
  PLOTFILE  ANNUAL 1 14740_1C.PLP
  PLOTFILE  ANNUAL 2 14740_1P.PLP
  PLOTFILE  ANNUAL ALL 14740.PLP
OU FINISHED
```

```
CO STARTING
  TITLEONE  Houston
  TITLETWO  123.5 ACRES
  MODELOPT  TOXICS RURAL CONC DDEP WDEP DRYDPLT WETDPLT
  AVERTIME  ANNUAL
  SAVEFILE  12960.SAP
  POLLUTID  PART
  TERRHGTS  FLAT
  ERRORFIL  ERRORS.OUT
  RUNORNOT  RUN
CO FINISHED

SO STARTING

SO LOCATION 1C     AREA    -353.48   -353.48    0.00
SO LOCATION 1P     AREA    0   -353.48    0.00

**          SRCID    QS       HS     XINIT   YINIT   ROTATE   SZINIT

SO SRCPARAM 1C    1.0E-3      0.0    353.48  706.96   0.0
SO PARTDIAM 1C    22.5     12.5     6.3     1.3
SO MASSFRAX 1C     0.4      0.1     0.3     0.2
SO PARTDENS 1C       1        1       1       1
SO PARTSLIQ 1C    6.7E-4  6.7E-4  4.5E-4  6.0E-5
SO PARTSICE 1C    2.2E-4  2.2E-4  1.5E-4  2.0E-5

SO SRCPARAM 1P    1.0E-3      0.0    353.48  706.96   0.0
SO PARTDIAM 1P    22.5     12.5     6.3     1.3
SO MASSFRAX 1P     0.4      0.1     0.3     0.2
SO PARTDENS 1P       1        1       1       1
SO PARTSLIQ 1P    6.7E-4  6.7E-4  4.5E-4  6.0E-5
SO PARTSICE 1P    2.2E-4  2.2E-4  1.5E-4  2.0E-5

SO SRCGROUP 1 1C
SO SRCGROUP 2 1P
SO SRCGROUP ALL

SO FINISHED

RE STARTING
RE GRIDCART  ONSITE STA
RE GRIDCART  ONSITE XYINC   -353.48  11  70.7  -353.48  11  70.7
RE GRIDCART  ONSITE END
RE INCLUDED  12960.REC
RE FINISHED

ME STARTING
ME INPUTFIL  12960H.MET
ME ANEMHGHT  6.1 METERS
ME SURFDATA  12960  1985
ME UAIRDATA  3937  1985
ME FINISHED

OU STARTING
  RECTABLE  ALLAVE FIRST
  MAXTABLE  ALLAVE  10
  PLOTFILE  ANNUAL 1 12960_1C.PLP
  PLOTFILE  ANNUAL 2 12960_1P.PLP
  PLOTFILE  ANNUAL ALL 12960.PLP
OU FINISHED
```

```
CO STARTING
  TITLEONE  Huntington
  TITLETWO  86.7 ACRES
  MODELOPT  TOXICS RURAL CONC DDEP WDEP DRYDPLT WETDPLT
  AVERTIME  ANNUAL
  SAVEFILE  03860.SAP
  POLLUTID  PART
  TERRHGTS  FLAT
  ERRORFIL  ERRORS.OUT
  RUNORNOT  RUN
CO FINISHED

SO STARTING

SO LOCATION 1C     AREA    -296.17   -296.17    0.00
SO LOCATION 1P     AREA    0   -296.17    0.00

**          SRCID    QS       HS     XINIT   YINIT   ROTATE   SZINIT

SO SRCPARAM 1C    1.0E-3      0.0    296.17  592.34   0.0
SO PARTDIAM 1C    22.5     12.5     6.3     1.3
SO MASSFRAX 1C     0.4      0.1     0.3     0.2
SO PARTDENS 1C       1        1       1       1
SO PARTSLIQ 1C    6.7E-4  6.7E-4  4.5E-4  6.0E-5
SO PARTSICE 1C    2.2E-4  2.2E-4  1.5E-4  2.0E-5

SO SRCPARAM 1P    1.0E-3      0.0    296.17  592.34   0.0
SO PARTDIAM 1P    22.5     12.5     6.3     1.3
SO MASSFRAX 1P     0.4      0.1     0.3     0.2
SO PARTDENS 1P       1        1       1       1
SO PARTSLIQ 1P    6.7E-4  6.7E-4  4.5E-4  6.0E-5
SO PARTSICE 1P    2.2E-4  2.2E-4  1.5E-4  2.0E-5

SO SRCGROUP 1 1C
SO SRCGROUP 2 1P
SO SRCGROUP ALL

SO FINISHED

RE STARTING
RE GRIDCART  ONSITE STA
RE GRIDCART  ONSITE XYINC   -296.17  11  59.23  -296.17  11  59.23
RE GRIDCART  ONSITE END
RE INCLUDED  03860.REC
RE FINISHED

ME STARTING
ME INPUTFIL  03860H.MET
ME ANEMHGHT  6.1 METERS
ME SURFDATA  03860  1984
ME UAIRDATA  3860  1984
ME FINISHED

OU STARTING
  RECTABLE  ALLAVE FIRST
  MAXTABLE  ALLAVE  10
  PLOTFILE  ANNUAL 1 03860_1C.PLP
  PLOTFILE  ANNUAL 2 03860_1P.PLP
  PLOTFILE  ANNUAL ALL 03860.PLP
OU FINISHED
```

```
CO STARTING
  TITLEONE  Las Vegas
  TITLETWO  97.6 ACRES
  MODELOPT  TOXICS RURAL CONC DDEP WDEP DRYDPLT WETDPLT
  AVERTIME  ANNUAL
  SAVEFILE  23169.SAP
  POLLUTID  PART
  TERRHGTS  FLAT
  ERRORFIL  ERRORS.OUT
  RUNORNOT  RUN
CO FINISHED

SO STARTING

SO LOCATION 1C     AREA    -314.24   -314.24    0.00
SO LOCATION 1P     AREA    0   -314.24    0.00

**          SRCID    QS       HS     XINIT   YINIT   ROTATE   SZINIT

SO SRCPARAM 1C    1.0E-3      0.0    314.24  628.47   0.0
SO PARTDIAM 1C    22.5     12.5     6.3     1.3
SO MASSFRAX 1C     0.4      0.1     0.3     0.2
SO PARTDENS 1C       1        1       1       1
SO PARTSLIQ 1C    6.7E-4  6.7E-4  4.5E-4  6.0E-5
SO PARTSICE 1C    2.2E-4  2.2E-4  1.5E-4  2.0E-5

SO SRCPARAM 1P    1.0E-3      0.0    314.24  628.47   0.0
SO PARTDIAM 1P    22.5     12.5     6.3     1.3
SO MASSFRAX 1P     0.4      0.1     0.3     0.2
SO PARTDENS 1P       1        1       1       1
SO PARTSLIQ 1P    6.7E-4  6.7E-4  4.5E-4  6.0E-5
SO PARTSICE 1P    2.2E-4  2.2E-4  1.5E-4  2.0E-5

SO SRCGROUP 1 1C
SO SRCGROUP 2 1P
SO SRCGROUP ALL

SO FINISHED

RE STARTING
RE GRIDCART  ONSITE STA
RE GRIDCART  ONSITE XYINC   -314.24  11  62.85  -314.24  11  62.85
RE GRIDCART  ONSITE END
RE INCLUDED  23169.REC
RE FINISHED

ME STARTING
ME INPUTFIL  23169H.MET
ME ANEMHGHT  6.1 METERS
ME SURFDATA  23169  1986
ME UAIRDATA  3160  1986
ME FINISHED

OU STARTING
  RECTABLE  ALLAVE FIRST
  MAXTABLE  ALLAVE  10
  PLOTFILE  ANNUAL 1 23169_1C.PLP
  PLOTFILE  ANNUAL 2 23169_1P.PLP
  PLOTFILE  ANNUAL ALL 23169.PLP
OU FINISHED
```

```
CO STARTING
  TITLEONE  Lincoln
  TITLETWO  282.2 ACRES
  MODELOPT  TOXICS RURAL CONC DDEP WDEP DRYDPLT WETDPLT
  AVERTIME  ANNUAL
  SAVEFILE  14935.SAP
  POLLUTID  PART
  TERRHGTS  FLAT
  ERRORFIL  ERRORS.OUT
  RUNORNOT  RUN
CO FINISHED

SO STARTING

SO LOCATION 1C     AREA    -713.77   -400    0.00
SO LOCATION 1P     AREA    0   -400    0.00

**          SRCID    QS       HS     XINIT   YINIT   ROTATE   SZINIT

SO SRCPARAM 1C    1.0E-3      0.0    713.77  800   0.0
SO PARTDIAM 1C    22.5     12.5     6.3     1.3
SO MASSFRAX 1C     0.4      0.1     0.3     0.2
SO PARTDENS 1C       1        1       1       1
SO PARTSLIQ 1C    6.7E-4  6.7E-4  4.5E-4  6.0E-5
SO PARTSICE 1C    2.2E-4  2.2E-4  1.5E-4  2.0E-5

SO SRCPARAM 1P    1.0E-3      0.0    713.77  800   0.0
SO PARTDIAM 1P    22.5     12.5     6.3     1.3
SO MASSFRAX 1P     0.4      0.1     0.3     0.2
SO PARTDENS 1P       1        1       1       1
SO PARTSLIQ 1P    6.7E-4  6.7E-4  4.5E-4  6.0E-5
SO PARTSICE 1P    2.2E-4  2.2E-4  1.5E-4  2.0E-5

SO SRCGROUP 1 1C
SO SRCGROUP 2 1P
SO SRCGROUP ALL

SO FINISHED

RE STARTING
RE GRIDCART  ONSITE STA
RE GRIDCART  ONSITE XYINC   -713.77  11  142.75  -400  11  80
RE GRIDCART  ONSITE END
RE INCLUDED  14935.REC
RE FINISHED

ME STARTING
ME INPUTFIL  14935H.MET
ME ANEMHGHT  6.1 METERS
ME SURFDATA  14935  1986
ME UAIRDATA  94918  1986
ME FINISHED

OU STARTING
  RECTABLE  ALLAVE FIRST
  MAXTABLE  ALLAVE  10
  PLOTFILE  ANNUAL 1 14935_1C.PLP
  PLOTFILE  ANNUAL 2 14935_1P.PLP
  PLOTFILE  ANNUAL ALL 14935.PLP
OU FINISHED
```

```
CO STARTING
  TITLEONE  Little Rock
  TITLETWO  159.1 ACRES
  MODELOPT  TOXICS RURAL CONC DDEP WDEP DRYDPLT WETDPLT
  AVERTIME  ANNUAL
  SAVEFILE  13963.SAP
  POLLUTID  PART
  TERRHGTS  FLAT
  ERRORFIL  ERRORS.OUT
  RUNORNOT  RUN
CO FINISHED

SO STARTING

SO LOCATION 1C     AREA    -402.41   -400    0.00
SO LOCATION 1P     AREA    0   -400    0.00

**          SRCID    QS       HS     XINIT   YINIT   ROTATE   SZINIT

SO SRCPARAM 1C    1.0E-3      0.0    402.41  800   0.0
SO PARTDIAM 1C    22.5     12.5     6.3     1.3
SO MASSFRAX 1C     0.4      0.1     0.3     0.2
SO PARTDENS 1C       1        1       1       1
SO PARTSLIQ 1C    6.7E-4  6.7E-4  4.5E-4  6.0E-5
SO PARTSICE 1C    2.2E-4  2.2E-4  1.5E-4  2.0E-5

SO SRCPARAM 1P    1.0E-3      0.0    402.41  800   0.0
SO PARTDIAM 1P    22.5     12.5     6.3     1.3
SO MASSFRAX 1P     0.4      0.1     0.3     0.2
SO PARTDENS 1P       1        1       1       1
SO PARTSLIQ 1P    6.7E-4  6.7E-4  4.5E-4  6.0E-5
SO PARTSICE 1P    2.2E-4  2.2E-4  1.5E-4  2.0E-5

SO SRCGROUP 1 1C
SO SRCGROUP 2 1P
SO SRCGROUP ALL

SO FINISHED

RE STARTING
RE GRIDCART  ONSITE STA
RE GRIDCART  ONSITE XYINC   -402.41  11  80.48  -400  11  80
RE GRIDCART  ONSITE END
RE INCLUDED  13963.REC
RE FINISHED

ME STARTING
ME INPUTFIL  13963H.MET
ME ANEMHGHT  6.1 METERS
ME SURFDATA  13963  1984
ME UAIRDATA  13963  1984
ME FINISHED

OU STARTING
  RECTABLE  ALLAVE FIRST
  MAXTABLE  ALLAVE  10
  PLOTFILE  ANNUAL 1 13963_1C.PLP
  PLOTFILE  ANNUAL 2 13963_1P.PLP
  PLOTFILE  ANNUAL ALL 13963.PLP
OU FINISHED
```

```
CO STARTING
  TITLEONE  Los Angeles
  TITLETWO  24.2 ACRES
  MODELOPT  TOXICS RURAL CONC DDEP WDEP DRYDPLT WETDPLT
  AVERTIME  ANNUAL
  SAVEFILE  23174.SAP
  POLLUTID  PART
  TERRHGTS  FLAT
  ERRORFIL  ERRORS.OUT
  RUNORNOT  RUN
CO FINISHED

SO STARTING

SO LOCATION 1C     AREA    -156.47   -156.47    0.00
SO LOCATION 1P     AREA    0   -156.47    0.00

**          SRCID    QS       HS     XINIT   YINIT   ROTATE   SZINIT

SO SRCPARAM 1C    1.0E-3      0.0    156.47  312.94   0.0
SO PARTDIAM 1C    22.5     12.5     6.3     1.3
SO MASSFRAX 1C     0.4      0.1     0.3     0.2
SO PARTDENS 1C       1        1       1       1
SO PARTSLIQ 1C    6.7E-4  6.7E-4  4.5E-4  6.0E-5
SO PARTSICE 1C    2.2E-4  2.2E-4  1.5E-4  2.0E-5

SO SRCPARAM 1P    1.0E-3      0.0    156.47  312.94   0.0
SO PARTDIAM 1P    22.5     12.5     6.3     1.3
SO MASSFRAX 1P     0.4      0.1     0.3     0.2
SO PARTDENS 1P       1        1       1       1
SO PARTSLIQ 1P    6.7E-4  6.7E-4  4.5E-4  6.0E-5
SO PARTSICE 1P    2.2E-4  2.2E-4  1.5E-4  2.0E-5

SO SRCGROUP 1 1C
SO SRCGROUP 2 1P
SO SRCGROUP ALL

SO FINISHED

RE STARTING
RE GRIDCART  ONSITE STA
RE GRIDCART  ONSITE XYINC   -156.47  11  31.29  -156.47  11  31.29
RE GRIDCART  ONSITE END
RE INCLUDED  23174.REC
RE FINISHED

ME STARTING
ME INPUTFIL  23174H.MET
ME ANEMHGHT  9.1 METERS
ME SURFDATA  23174  1985
ME UAIRDATA  23230  1985
ME FINISHED

OU STARTING
  RECTABLE  ALLAVE FIRST
  MAXTABLE  ALLAVE  10
  PLOTFILE  ANNUAL 1 23174_1C.PLP
  PLOTFILE  ANNUAL 2 23174_1P.PLP
  PLOTFILE  ANNUAL ALL 23174.PLP
OU FINISHED
```

```
CO STARTING
  TITLEONE  Meridian
  TITLETWO  123 ACRES
  MODELOPT  TOXICS RURAL CONC DDEP WDEP DRYDPLT WETDPLT
  AVERTIME  ANNUAL
  SAVEFILE  13865.SAP
  POLLUTID  PART
  TERRHGTS  FLAT
  ERRORFIL  ERRORS.OUT
  RUNORNOT  RUN
CO FINISHED

SO STARTING

SO LOCATION 1C     AREA    -352.76   -352.76    0.00
SO LOCATION 1P     AREA    0   -352.76    0.00

**          SRCID    QS       HS     XINIT   YINIT   ROTATE   SZINIT

SO SRCPARAM 1C    1.0E-3      0.0    352.76  705.52   0.0
SO PARTDIAM 1C    22.5     12.5     6.3     1.3
SO MASSFRAX 1C     0.4      0.1     0.3     0.2
SO PARTDENS 1C       1        1       1       1
SO PARTSLIQ 1C    6.7E-4  6.7E-4  4.5E-4  6.0E-5
SO PARTSICE 1C    2.2E-4  2.2E-4  1.5E-4  2.0E-5

SO SRCPARAM 1P    1.0E-3      0.0    352.76  705.52   0.0
SO PARTDIAM 1P    22.5     12.5     6.3     1.3
SO MASSFRAX 1P     0.4      0.1     0.3     0.2
SO PARTDENS 1P       1        1       1       1
SO PARTSLIQ 1P    6.7E-4  6.7E-4  4.5E-4  6.0E-5
SO PARTSICE 1P    2.2E-4  2.2E-4  1.5E-4  2.0E-5

SO SRCGROUP 1 1C
SO SRCGROUP 2 1P
SO SRCGROUP ALL

SO FINISHED

RE STARTING
RE GRIDCART  ONSITE STA
RE GRIDCART  ONSITE XYINC   -352.76  11  70.55  -352.76  11  70.55
RE GRIDCART  ONSITE END
RE INCLUDED  13865.REC
RE FINISHED

ME STARTING
ME INPUTFIL  13865H.MET
ME ANEMHGHT  6.1 METERS
ME SURFDATA  13865  1986
ME UAIRDATA  3940  1986
ME FINISHED

OU STARTING
  RECTABLE  ALLAVE FIRST
  MAXTABLE  ALLAVE  10
  PLOTFILE  ANNUAL 1 13865_1C.PLP
  PLOTFILE  ANNUAL 2 13865_1P.PLP
  PLOTFILE  ANNUAL ALL 13865.PLP
OU FINISHED
```

```
CO STARTING
  TITLEONE  Miami
  TITLETWO  39.6 ACRES
  MODELOPT  TOXICS RURAL CONC DDEP WDEP DRYDPLT WETDPLT
  AVERTIME  ANNUAL
  SAVEFILE  12839.SAP
  POLLUTID  PART
  TERRHGTS  FLAT
  ERRORFIL  ERRORS.OUT
  RUNORNOT  RUN
CO FINISHED

SO STARTING

SO LOCATION 1C     AREA    -200.16   -200.16    0.00
SO LOCATION 1P     AREA    0   -200.16    0.00

**          SRCID    QS       HS     XINIT   YINIT   ROTATE   SZINIT

SO SRCPARAM 1C    1.0E-3      0.0    200.16  400.32   0.0
SO PARTDIAM 1C    22.5     12.5     6.3     1.3
SO MASSFRAX 1C     0.4      0.1     0.3     0.2
SO PARTDENS 1C       1        1       1       1
SO PARTSLIQ 1C    6.7E-4  6.7E-4  4.5E-4  6.0E-5
SO PARTSICE 1C    2.2E-4  2.2E-4  1.5E-4  2.0E-5

SO SRCPARAM 1P    1.0E-3      0.0    200.16  400.32   0.0
SO PARTDIAM 1P    22.5     12.5     6.3     1.3
SO MASSFRAX 1P     0.4      0.1     0.3     0.2
SO PARTDENS 1P       1        1       1       1
SO PARTSLIQ 1P    6.7E-4  6.7E-4  4.5E-4  6.0E-5
SO PARTSICE 1P    2.2E-4  2.2E-4  1.5E-4  2.0E-5

SO SRCGROUP 1 1C
SO SRCGROUP 2 1P
SO SRCGROUP ALL

SO FINISHED

RE STARTING
RE GRIDCART  ONSITE STA
RE GRIDCART  ONSITE XYINC   -200.16  11  40.03  -200.16  11  40.03
RE GRIDCART  ONSITE END
RE INCLUDED  12839.REC
RE FINISHED

ME STARTING
ME INPUTFIL  12839H.MET
ME ANEMHGHT  7 METERS
ME SURFDATA  12839  1972
ME UAIRDATA  12839  1972
ME FINISHED

OU STARTING
  RECTABLE  ALLAVE FIRST
  MAXTABLE  ALLAVE  10
  PLOTFILE  ANNUAL 1 12839_1C.PLP
  PLOTFILE  ANNUAL 2 12839_1P.PLP
  PLOTFILE  ANNUAL ALL 12839.PLP
OU FINISHED
```

```
CO STARTING
  TITLEONE  Minneapolis
  TITLETWO  208.6 ACRES
  MODELOPT  TOXICS RURAL CONC DDEP WDEP DRYDPLT WETDPLT
  AVERTIME  ANNUAL
  SAVEFILE  14922.SAP
  POLLUTID  PART
  TERRHGTS  FLAT
  ERRORFIL  ERRORS.OUT
  RUNORNOT  RUN
CO FINISHED

SO STARTING

SO LOCATION 1C     AREA    -527.61   -400    0.00
SO LOCATION 1P     AREA    0   -400    0.00

**          SRCID    QS       HS     XINIT   YINIT   ROTATE   SZINIT

SO SRCPARAM 1C    1.0E-3      0.0    527.61  800   0.0
SO PARTDIAM 1C    22.5     12.5     6.3     1.3
SO MASSFRAX 1C     0.4      0.1     0.3     0.2
SO PARTDENS 1C       1        1       1       1
SO PARTSLIQ 1C    6.7E-4  6.7E-4  4.5E-4  6.0E-5
SO PARTSICE 1C    2.2E-4  2.2E-4  1.5E-4  2.0E-5

SO SRCPARAM 1P    1.0E-3      0.0    527.61  800   0.0
SO PARTDIAM 1P    22.5     12.5     6.3     1.3
SO MASSFRAX 1P     0.4      0.1     0.3     0.2
SO PARTDENS 1P       1        1       1       1
SO PARTSLIQ 1P    6.7E-4  6.7E-4  4.5E-4  6.0E-5
SO PARTSICE 1P    2.2E-4  2.2E-4  1.5E-4  2.0E-5

SO SRCGROUP 1 1C
SO SRCGROUP 2 1P
SO SRCGROUP ALL

SO FINISHED

RE STARTING
RE GRIDCART  ONSITE STA
RE GRIDCART  ONSITE XYINC   -527.61  11  105.52  -400  11  80
RE GRIDCART  ONSITE END
RE INCLUDED  14922.REC
RE FINISHED

ME STARTING
ME INPUTFIL  14922H.MET
ME ANEMHGHT  6.4 METERS
ME SURFDATA  14922  1986
ME UAIRDATA  14926  1986
ME FINISHED

OU STARTING
  RECTABLE  ALLAVE FIRST
  MAXTABLE  ALLAVE  10
  PLOTFILE  ANNUAL 1 14922_1C.PLP
  PLOTFILE  ANNUAL 2 14922_1P.PLP
  PLOTFILE  ANNUAL ALL 14922.PLP
OU FINISHED
```

```
CO STARTING
  TITLEONE  Muskegon
  TITLETWO  117.1 ACRES
  MODELOPT  TOXICS RURAL CONC DDEP WDEP DRYDPLT WETDPLT
  AVERTIME  ANNUAL
  SAVEFILE  14840.SAP
  POLLUTID  PART
  TERRHGTS  FLAT
  ERRORFIL  ERRORS.OUT
  RUNORNOT  RUN
CO FINISHED

SO STARTING

SO LOCATION 1C     AREA    -344.2   -344.2    0.00
SO LOCATION 1P     AREA    0   -344.2    0.00

**          SRCID    QS       HS     XINIT   YINIT   ROTATE   SZINIT

SO SRCPARAM 1C    1.0E-3      0.0    344.2  688.4   0.0
SO PARTDIAM 1C    22.5     12.5     6.3     1.3
SO MASSFRAX 1C     0.4      0.1     0.3     0.2
SO PARTDENS 1C       1        1       1       1
SO PARTSLIQ 1C    6.7E-4  6.7E-4  4.5E-4  6.0E-5
SO PARTSICE 1C    2.2E-4  2.2E-4  1.5E-4  2.0E-5

SO SRCPARAM 1P    1.0E-3      0.0    344.2  688.4   0.0
SO PARTDIAM 1P    22.5     12.5     6.3     1.3
SO MASSFRAX 1P     0.4      0.1     0.3     0.2
SO PARTDENS 1P       1        1       1       1
SO PARTSLIQ 1P    6.7E-4  6.7E-4  4.5E-4  6.0E-5
SO PARTSICE 1P    2.2E-4  2.2E-4  1.5E-4  2.0E-5

SO SRCGROUP 1 1C
SO SRCGROUP 2 1P
SO SRCGROUP ALL

SO FINISHED

RE STARTING
RE GRIDCART  ONSITE STA
RE GRIDCART  ONSITE XYINC   -344.2  11  68.84  -344.2  11  68.84
RE GRIDCART  ONSITE END
RE INCLUDED  14840.REC
RE FINISHED

ME STARTING
ME INPUTFIL  14840H.MET
ME ANEMHGHT  6.1 METERS
ME SURFDATA  14840  1977
ME UAIRDATA  14826  1977
ME FINISHED

OU STARTING
  RECTABLE  ALLAVE FIRST
  MAXTABLE  ALLAVE  10
  PLOTFILE  ANNUAL 1 14840_1C.PLP
  PLOTFILE  ANNUAL 2 14840_1P.PLP
  PLOTFILE  ANNUAL ALL 14840.PLP
OU FINISHED

CO STARTING
```

```
  TITLEONE  Nashville
  TITLETWO  94.4 ACRES
  MODELOPT  TOXICS RURAL CONC DDEP WDEP DRYDPLT WETDPLT
  AVERTIME  ANNUAL
  SAVEFILE  13897.SAP
  POLLUTID  PART
  TERRHGTS  FLAT
  ERRORFIL  ERRORS.OUT
  RUNORNOT  RUN
CO FINISHED

SO STARTING

SO LOCATION 1C     AREA    -309.04   -309.04    0.00
SO LOCATION 1P     AREA    0   -309.04    0.00

**          SRCID    QS       HS     XINIT   YINIT   ROTATE   SZINIT

SO SRCPARAM 1C    1.0E-3      0.0    309.04  618.08   0.0
SO PARTDIAM 1C    22.5     12.5     6.3     1.3
SO MASSFRAX 1C     0.4      0.1     0.3     0.2
SO PARTDENS 1C       1        1       1       1
SO PARTSLIQ 1C    6.7E-4  6.7E-4  4.5E-4  6.0E-5
SO PARTSICE 1C    2.2E-4  2.2E-4  1.5E-4  2.0E-5

SO SRCPARAM 1P    1.0E-3      0.0    309.04  618.08   0.0
SO PARTDIAM 1P    22.5     12.5     6.3     1.3
SO MASSFRAX 1P     0.4      0.1     0.3     0.2
SO PARTDENS 1P       1        1       1       1
SO PARTSLIQ 1P    6.7E-4  6.7E-4  4.5E-4  6.0E-5
SO PARTSICE 1P    2.2E-4  2.2E-4  1.5E-4  2.0E-5

SO SRCGROUP 1 1C
SO SRCGROUP 2 1P
SO SRCGROUP ALL

SO FINISHED

RE STARTING
RE GRIDCART  ONSITE STA
RE GRIDCART  ONSITE XYINC   -309.04  11  61.81  -309.04  11  61.81
RE GRIDCART  ONSITE END
RE INCLUDED  13897.REC
RE FINISHED

ME STARTING
ME INPUTFIL  13897H.MET
ME ANEMHGHT  7.6 METERS
ME SURFDATA  13897  1984
ME UAIRDATA  13897  1984
ME FINISHED

OU STARTING
  RECTABLE  ALLAVE FIRST
  MAXTABLE  ALLAVE  10
  PLOTFILE  ANNUAL 1 13897_1C.PLP
  PLOTFILE  ANNUAL 2 13897_1P.PLP
  PLOTFILE  ANNUAL ALL 13897.PLP
OU FINISHED
```

```
CO STARTING
  TITLEONE  New Orleans
  TITLETWO  90.9 ACRES
  MODELOPT  TOXICS RURAL CONC DDEP WDEP DRYDPLT WETDPLT
  AVERTIME  ANNUAL
  SAVEFILE  12916.SAP
  POLLUTID  PART
  TERRHGTS  FLAT
  ERRORFIL  ERRORS.OUT
  RUNORNOT  RUN
CO FINISHED

SO STARTING

SO LOCATION 1C     AREA    -303.26   -303.26    0.00
SO LOCATION 1P     AREA    0   -303.26    0.00

**          SRCID    QS       HS     XINIT   YINIT   ROTATE   SZINIT

SO SRCPARAM 1C    1.0E-3      0.0    303.26  606.52   0.0
SO PARTDIAM 1C    22.5     12.5     6.3     1.3
SO MASSFRAX 1C     0.4      0.1     0.3     0.2
SO PARTDENS 1C       1        1       1       1
SO PARTSLIQ 1C    6.7E-4  6.7E-4  4.5E-4  6.0E-5
SO PARTSICE 1C    2.2E-4  2.2E-4  1.5E-4  2.0E-5

SO SRCPARAM 1P    1.0E-3      0.0    303.26  606.52   0.0
SO PARTDIAM 1P    22.5     12.5     6.3     1.3
SO MASSFRAX 1P     0.4      0.1     0.3     0.2
SO PARTDENS 1P       1        1       1       1
SO PARTSLIQ 1P    6.7E-4  6.7E-4  4.5E-4  6.0E-5
SO PARTSICE 1P    2.2E-4  2.2E-4  1.5E-4  2.0E-5

SO SRCGROUP 1 1C
SO SRCGROUP 2 1P
SO SRCGROUP ALL

SO FINISHED

RE STARTING
RE GRIDCART  ONSITE STA
RE GRIDCART  ONSITE XYINC   -303.26  11  60.65  -303.26  11  60.65
RE GRIDCART  ONSITE END
RE INCLUDED  12916.REC
RE FINISHED

ME STARTING
ME INPUTFIL  12916H.MET
ME ANEMHGHT  6.1 METERS
ME SURFDATA  12916  1985
ME UAIRDATA  3937  1985
ME FINISHED

OU STARTING
  RECTABLE  ALLAVE FIRST
  MAXTABLE  ALLAVE  10
  PLOTFILE  ANNUAL 1 12916_1C.PLP
  PLOTFILE  ANNUAL 2 12916_1P.PLP
  PLOTFILE  ANNUAL ALL 12916.PLP
OU FINISHED
```

```
CO STARTING
  TITLEONE  Norfolk
  TITLETWO  97.5 ACRES
  MODELOPT  TOXICS RURAL CONC DDEP WDEP DRYDPLT WETDPLT
  AVERTIME  ANNUAL
  SAVEFILE  13737.SAP
  POLLUTID  PART
  TERRHGTS  FLAT
  ERRORFIL  ERRORS.OUT
  RUNORNOT  RUN
CO FINISHED

SO STARTING

SO LOCATION 1C     AREA    -314.07   -314.07    0.00
SO LOCATION 1P     AREA    0   -314.07    0.00

**          SRCID    QS       HS     XINIT   YINIT   ROTATE   SZINIT

SO SRCPARAM 1C    1.0E-3      0.0    314.07  628.15   0.0
SO PARTDIAM 1C    22.5     12.5     6.3     1.3
SO MASSFRAX 1C     0.4      0.1     0.3     0.2
SO PARTDENS 1C       1        1       1       1
SO PARTSLIQ 1C    6.7E-4  6.7E-4  4.5E-4  6.0E-5
SO PARTSICE 1C    2.2E-4  2.2E-4  1.5E-4  2.0E-5

SO SRCPARAM 1P    1.0E-3      0.0    314.07  628.15   0.0
SO PARTDIAM 1P    22.5     12.5     6.3     1.3
SO MASSFRAX 1P     0.4      0.1     0.3     0.2
SO PARTDENS 1P       1        1       1       1
SO PARTSLIQ 1P    6.7E-4  6.7E-4  4.5E-4  6.0E-5
SO PARTSICE 1P    2.2E-4  2.2E-4  1.5E-4  2.0E-5

SO SRCGROUP 1 1C
SO SRCGROUP 2 1P
SO SRCGROUP ALL

SO FINISHED

RE STARTING
RE GRIDCART  ONSITE STA
RE GRIDCART  ONSITE XYINC   -314.07  11  62.81  -314.07  11  62.81
RE GRIDCART  ONSITE END
RE INCLUDED  13737.REC
RE FINISHED

ME STARTING
ME INPUTFIL  13737H.MET
ME ANEMHGHT  10.1 METERS
ME SURFDATA  13737  1986
ME UAIRDATA  93739  1986
ME FINISHED

OU STARTING
  RECTABLE  ALLAVE FIRST
  MAXTABLE  ALLAVE  10
  PLOTFILE  ANNUAL 1 13737_1C.PLP
  PLOTFILE  ANNUAL 2 13737_1P.PLP
  PLOTFILE  ANNUAL ALL 13737.PLP
OU FINISHED
```

```
CO STARTING
  TITLEONE  Philadelphia
  TITLETWO  39 ACRES
  MODELOPT  TOXICS RURAL CONC DDEP WDEP DRYDPLT WETDPLT
  AVERTIME  ANNUAL
  SAVEFILE  13739.SAP
  POLLUTID  PART
  TERRHGTS  FLAT
  ERRORFIL  ERRORS.OUT
  RUNORNOT  RUN
CO FINISHED

SO STARTING

SO LOCATION 1C     AREA    -198.64   -198.64    0.00
SO LOCATION 1P     AREA    0   -198.64    0.00

**          SRCID    QS       HS     XINIT   YINIT   ROTATE   SZINIT

SO SRCPARAM 1C    1.0E-3      0.0    198.64  397.28   0.0
SO PARTDIAM 1C    22.5     12.5     6.3     1.3
SO MASSFRAX 1C     0.4      0.1     0.3     0.2
SO PARTDENS 1C       1        1       1       1
SO PARTSLIQ 1C    6.7E-4  6.7E-4  4.5E-4  6.0E-5
SO PARTSICE 1C    2.2E-4  2.2E-4  1.5E-4  2.0E-5

SO SRCPARAM 1P    1.0E-3      0.0    198.64  397.28   0.0
SO PARTDIAM 1P    22.5     12.5     6.3     1.3
SO MASSFRAX 1P     0.4      0.1     0.3     0.2
SO PARTDENS 1P       1        1       1       1
SO PARTSLIQ 1P    6.7E-4  6.7E-4  4.5E-4  6.0E-5
SO PARTSICE 1P    2.2E-4  2.2E-4  1.5E-4  2.0E-5

SO SRCGROUP 1 1C
SO SRCGROUP 2 1P
SO SRCGROUP ALL

SO FINISHED

RE STARTING
RE GRIDCART  ONSITE STA
RE GRIDCART  ONSITE XYINC   -198.64  11  39.73  -198.64  11  39.73
RE GRIDCART  ONSITE END
RE INCLUDED  13739.REC
RE FINISHED

ME STARTING
ME INPUTFIL  13739H.MET
ME ANEMHGHT  6.1 METERS
ME SURFDATA  13739  1981
ME UAIRDATA  93734  1981
ME FINISHED

OU STARTING
  RECTABLE  ALLAVE FIRST
  MAXTABLE  ALLAVE  10
  PLOTFILE  ANNUAL 1 13739_1C.PLP
  PLOTFILE  ANNUAL 2 13739_1P.PLP
  PLOTFILE  ANNUAL ALL 13739.PLP
OU FINISHED
```

```
CO STARTING
  TITLEONE  Phoenix
  TITLETWO  339.7 ACRES
  MODELOPT  TOXICS RURAL CONC DDEP WDEP DRYDPLT WETDPLT
  AVERTIME  ANNUAL
  SAVEFILE  23183.SAP
  POLLUTID  PART
  TERRHGTS  FLAT
  ERRORFIL  ERRORS.OUT
  RUNORNOT  RUN
CO FINISHED

SO STARTING

SO LOCATION 1C     AREA    -859.2   -400    0.00
SO LOCATION 1P     AREA    0   -400    0.00

**          SRCID    QS       HS     XINIT   YINIT   ROTATE   SZINIT

SO SRCPARAM 1C    1.0E-3      0.0    859.2  800   0.0
SO PARTDIAM 1C    22.5     12.5     6.3     1.3
SO MASSFRAX 1C     0.4      0.1     0.3     0.2
SO PARTDENS 1C       1        1       1       1
SO PARTSLIQ 1C    6.7E-4  6.7E-4  4.5E-4  6.0E-5
SO PARTSICE 1C    2.2E-4  2.2E-4  1.5E-4  2.0E-5

SO SRCPARAM 1P    1.0E-3      0.0    859.2  800   0.0
SO PARTDIAM 1P    22.5     12.5     6.3     1.3
SO MASSFRAX 1P     0.4      0.1     0.3     0.2
SO PARTDENS 1P       1        1       1       1
SO PARTSLIQ 1P    6.7E-4  6.7E-4  4.5E-4  6.0E-5
SO PARTSICE 1P    2.2E-4  2.2E-4  1.5E-4  2.0E-5

SO SRCGROUP 1 1C
SO SRCGROUP 2 1P
SO SRCGROUP ALL

SO FINISHED

RE STARTING
RE GRIDCART  ONSITE STA
RE GRIDCART  ONSITE XYINC   -859.2  11  171.84  -400  11  80
RE GRIDCART  ONSITE END
RE INCLUDED  23183.REC
RE FINISHED

ME STARTING
ME INPUTFIL  23183H.MET
ME ANEMHGHT  10.1 METERS
ME SURFDATA  23183  1986
ME UAIRDATA  23160  1986
ME FINISHED

OU STARTING
  RECTABLE  ALLAVE FIRST
  MAXTABLE  ALLAVE  10
  PLOTFILE  ANNUAL 1 23183_1C.PLP
  PLOTFILE  ANNUAL 2 23183_1P.PLP
  PLOTFILE  ANNUAL ALL 23183.PLP
OU FINISHED
```

```
CO STARTING
  TITLEONE  Portland
  TITLETWO  98.2 ACRES
  MODELOPT  TOXICS RURAL CONC DDEP WDEP DRYDPLT WETDPLT
  AVERTIME  ANNUAL
  SAVEFILE  14764.SAP
  POLLUTID  PART
  TERRHGTS  FLAT
  ERRORFIL  ERRORS.OUT
  RUNORNOT  RUN
CO FINISHED

SO STARTING

SO LOCATION 1C     AREA    -315.2   -315.2    0.00
SO LOCATION 1P     AREA    0   -315.2    0.00

**          SRCID    QS       HS     XINIT   YINIT   ROTATE   SZINIT

SO SRCPARAM 1C    1.0E-3      0.0    315.2  630.4   0.0
SO PARTDIAM 1C    22.5     12.5     6.3     1.3
SO MASSFRAX 1C     0.4      0.1     0.3     0.2
SO PARTDENS 1C       1        1       1       1
SO PARTSLIQ 1C    6.7E-4  6.7E-4  4.5E-4  6.0E-5
SO PARTSICE 1C    2.2E-4  2.2E-4  1.5E-4  2.0E-5

SO SRCPARAM 1P    1.0E-3      0.0    315.2  630.4   0.0
SO PARTDIAM 1P    22.5     12.5     6.3     1.3
SO MASSFRAX 1P     0.4      0.1     0.3     0.2
SO PARTDENS 1P       1        1       1       1
SO PARTSLIQ 1P    6.7E-4  6.7E-4  4.5E-4  6.0E-5
SO PARTSICE 1P    2.2E-4  2.2E-4  1.5E-4  2.0E-5

SO SRCGROUP 1 1C
SO SRCGROUP 2 1P
SO SRCGROUP ALL

SO FINISHED

RE STARTING
RE GRIDCART  ONSITE STA
RE GRIDCART  ONSITE XYINC   -315.2  11  63.04  -315.2  11  63.04
RE GRIDCART  ONSITE END
RE INCLUDED  14764.REC
RE FINISHED

ME STARTING
ME INPUTFIL  14764H.MET
ME ANEMHGHT  6.1 METERS
ME SURFDATA  14764  1985
ME UAIRDATA  14764  1985
ME FINISHED

OU STARTING
  RECTABLE  ALLAVE FIRST
  MAXTABLE  ALLAVE  10
  PLOTFILE  ANNUAL 1 14764_1C.PLP
  PLOTFILE  ANNUAL 2 14764_1P.PLP
  PLOTFILE  ANNUAL ALL 14764.PLP
OU FINISHED

CO STARTING
```

```
  TITLEONE  Raleigh-Durham
  TITLETWO  85.4 ACRES
  MODELOPT  TOXICS RURAL CONC DDEP WDEP DRYDPLT WETDPLT
  AVERTIME  ANNUAL
  SAVEFILE  13722.SAP
  POLLUTID  PART
  TERRHGTS  FLAT
  ERRORFIL  ERRORS.OUT
  RUNORNOT  RUN
CO FINISHED

SO STARTING

SO LOCATION 1C     AREA    -293.94   -293.94    0.00
SO LOCATION 1P     AREA    0   -293.94    0.00

**          SRCID    QS       HS     XINIT   YINIT   ROTATE   SZINIT

SO SRCPARAM 1C    1.0E-3      0.0    293.94  587.88   0.0
SO PARTDIAM 1C    22.5     12.5     6.3     1.3
SO MASSFRAX 1C     0.4      0.1     0.3     0.2
SO PARTDENS 1C       1        1       1       1
SO PARTSLIQ 1C    6.7E-4  6.7E-4  4.5E-4  6.0E-5
SO PARTSICE 1C    2.2E-4  2.2E-4  1.5E-4  2.0E-5

SO SRCPARAM 1P    1.0E-3      0.0    293.94  587.88   0.0
SO PARTDIAM 1P    22.5     12.5     6.3     1.3
SO MASSFRAX 1P     0.4      0.1     0.3     0.2
SO PARTDENS 1P       1        1       1       1
SO PARTSLIQ 1P    6.7E-4  6.7E-4  4.5E-4  6.0E-5
SO PARTSICE 1P    2.2E-4  2.2E-4  1.5E-4  2.0E-5

SO SRCGROUP 1 1C
SO SRCGROUP 2 1P
SO SRCGROUP ALL

SO FINISHED

RE STARTING
RE GRIDCART  ONSITE STA
RE GRIDCART  ONSITE XYINC   -293.94  11  58.79  -293.94  11  58.79
RE GRIDCART  ONSITE END
RE INCLUDED  13722.REC
RE FINISHED

ME STARTING
ME INPUTFIL  13722H.MET
ME ANEMHGHT  6.1 METERS
ME SURFDATA  13722  1986
ME UAIRDATA  13723  1986
ME FINISHED

OU STARTING
  RECTABLE  ALLAVE FIRST
  MAXTABLE  ALLAVE  10
  PLOTFILE  ANNUAL 1 13722_1C.PLP
  PLOTFILE  ANNUAL 2 13722_1P.PLP
  PLOTFILE  ANNUAL ALL 13722.PLP
OU FINISHED
```

```
CO STARTING
  TITLEONE  Salem
  TITLETWO  44.6 ACRES
  MODELOPT  TOXICS RURAL CONC DDEP WDEP DRYDPLT WETDPLT
  AVERTIME  ANNUAL
  SAVEFILE  24232.SAP
  POLLUTID  PART
  TERRHGTS  FLAT
  ERRORFIL  ERRORS.OUT
  RUNORNOT  RUN
CO FINISHED

SO STARTING

SO LOCATION 1C     AREA    -212.42   -212.42    0.00
SO LOCATION 1P     AREA    0   -212.42    0.00

**          SRCID    QS       HS     XINIT   YINIT   ROTATE   SZINIT

SO SRCPARAM 1C    1.0E-3      0.0    212.42  424.84   0.0
SO PARTDIAM 1C    22.5     12.5     6.3     1.3
SO MASSFRAX 1C     0.4      0.1     0.3     0.2
SO PARTDENS 1C       1        1       1       1
SO PARTSLIQ 1C    6.7E-4  6.7E-4  4.5E-4  6.0E-5
SO PARTSICE 1C    2.2E-4  2.2E-4  1.5E-4  2.0E-5

SO SRCPARAM 1P    1.0E-3      0.0    212.42  424.84   0.0
SO PARTDIAM 1P    22.5     12.5     6.3     1.3
SO MASSFRAX 1P     0.4      0.1     0.3     0.2
SO PARTDENS 1P       1        1       1       1
SO PARTSLIQ 1P    6.7E-4  6.7E-4  4.5E-4  6.0E-5
SO PARTSICE 1P    2.2E-4  2.2E-4  1.5E-4  2.0E-5

SO SRCGROUP 1 1C
SO SRCGROUP 2 1P
SO SRCGROUP ALL

SO FINISHED

RE STARTING
RE GRIDCART  ONSITE STA
RE GRIDCART  ONSITE XYINC   -212.42  11  42.48  -212.42  11  42.48
RE GRIDCART  ONSITE END
RE INCLUDED  24232.REC
RE FINISHED

ME STARTING
ME INPUTFIL  24232H.MET
ME ANEMHGHT  6.1 METERS
ME SURFDATA  24232  1986
ME UAIRDATA  24232  1986
ME FINISHED

OU STARTING
  RECTABLE  ALLAVE FIRST
  MAXTABLE  ALLAVE  10
  PLOTFILE  ANNUAL 1 24232_1C.PLP
  PLOTFILE  ANNUAL 2 24232_1P.PLP
  PLOTFILE  ANNUAL ALL 24232.PLP
OU FINISHED
```

```
CO STARTING
  TITLEONE  Salt Lake City
  TITLETWO  143.5 ACRES
  MODELOPT  TOXICS RURAL CONC DDEP WDEP DRYDPLT WETDPLT
  AVERTIME  ANNUAL
  SAVEFILE  24127.SAP
  POLLUTID  PART
  TERRHGTS  FLAT
  ERRORFIL  ERRORS.OUT
  RUNORNOT  RUN
CO FINISHED

SO STARTING

SO LOCATION 1C     AREA    -381.03   -381.03    0.00
SO LOCATION 1P     AREA    0   -381.03    0.00

**          SRCID    QS       HS     XINIT   YINIT   ROTATE   SZINIT

SO SRCPARAM 1C    1.0E-3      0.0    381.03  762.05   0.0
SO PARTDIAM 1C    22.5     12.5     6.3     1.3
SO MASSFRAX 1C     0.4      0.1     0.3     0.2
SO PARTDENS 1C       1        1       1       1
SO PARTSLIQ 1C    6.7E-4  6.7E-4  4.5E-4  6.0E-5
SO PARTSICE 1C    2.2E-4  2.2E-4  1.5E-4  2.0E-5

SO SRCPARAM 1P    1.0E-3      0.0    381.03  762.05   0.0
SO PARTDIAM 1P    22.5     12.5     6.3     1.3
SO MASSFRAX 1P     0.4      0.1     0.3     0.2
SO PARTDENS 1P       1        1       1       1
SO PARTSLIQ 1P    6.7E-4  6.7E-4  4.5E-4  6.0E-5
SO PARTSICE 1P    2.2E-4  2.2E-4  1.5E-4  2.0E-5

SO SRCGROUP 1 1C
SO SRCGROUP 2 1P
SO SRCGROUP ALL

SO FINISHED

RE STARTING
RE GRIDCART  ONSITE STA
RE GRIDCART  ONSITE XYINC   -381.03  11  76.21  -381.03  11  76.21
RE GRIDCART  ONSITE END
RE INCLUDED  24127.REC
RE FINISHED

ME STARTING
ME INPUTFIL  24127H.MET
ME ANEMHGHT  6.1 METERS
ME SURFDATA  24127  1986
ME UAIRDATA  24127  1986
ME FINISHED

OU STARTING
  RECTABLE  ALLAVE FIRST
  MAXTABLE  ALLAVE  10
  PLOTFILE  ANNUAL 1 24127_1C.PLP
  PLOTFILE  ANNUAL 2 24127_1P.PLP
  PLOTFILE  ANNUAL ALL 24127.PLP
OU FINISHED
```

```
CO STARTING
  TITLEONE  San Francisco
  TITLETWO  39.8 ACRES
  MODELOPT  TOXICS RURAL CONC DDEP WDEP DRYDPLT WETDPLT
  AVERTIME  ANNUAL
  SAVEFILE  23234.SAP
  POLLUTID  PART
  TERRHGTS  FLAT
  ERRORFIL  ERRORS.OUT
  RUNORNOT  RUN
CO FINISHED

SO STARTING

SO LOCATION 1C     AREA    -200.66   -200.66    0.00
SO LOCATION 1P     AREA    0   -200.66    0.00

**          SRCID    QS       HS     XINIT   YINIT   ROTATE   SZINIT

SO SRCPARAM 1C    1.0E-3      0.0    200.66  401.33   0.0
SO PARTDIAM 1C    22.5     12.5     6.3     1.3
SO MASSFRAX 1C     0.4      0.1     0.3     0.2
SO PARTDENS 1C       1        1       1       1
SO PARTSLIQ 1C    6.7E-4  6.7E-4  4.5E-4  6.0E-5
SO PARTSICE 1C    2.2E-4  2.2E-4  1.5E-4  2.0E-5

SO SRCPARAM 1P    1.0E-3      0.0    200.66  401.33   0.0
SO PARTDIAM 1P    22.5     12.5     6.3     1.3
SO MASSFRAX 1P     0.4      0.1     0.3     0.2
SO PARTDENS 1P       1        1       1       1
SO PARTSLIQ 1P    6.7E-4  6.7E-4  4.5E-4  6.0E-5
SO PARTSICE 1P    2.2E-4  2.2E-4  1.5E-4  2.0E-5

SO SRCGROUP 1 1C
SO SRCGROUP 2 1P
SO SRCGROUP ALL

SO FINISHED

RE STARTING
RE GRIDCART  ONSITE STA
RE GRIDCART  ONSITE XYINC   -200.66  11  40.13  -200.66  11  40.13
RE GRIDCART  ONSITE END
RE INCLUDED  23234.REC
RE FINISHED

ME STARTING
ME INPUTFIL  23234H.MET
ME ANEMHGHT  10.1 METERS
ME SURFDATA  23234  1985
ME UAIRDATA  23230  1985
ME FINISHED

OU STARTING
  RECTABLE  ALLAVE FIRST
  MAXTABLE  ALLAVE  10
  PLOTFILE  ANNUAL 1 23234_1C.PLP
  PLOTFILE  ANNUAL 2 23234_1P.PLP
  PLOTFILE  ANNUAL ALL 23234.PLP
OU FINISHED
```

```
CO STARTING
  TITLEONE  Seattle
  TITLETWO  40.1 ACRES
  MODELOPT  TOXICS RURAL CONC DDEP WDEP DRYDPLT WETDPLT
  AVERTIME  ANNUAL
  SAVEFILE  24233.SAP
  POLLUTID  PART
  TERRHGTS  FLAT
  ERRORFIL  ERRORS.OUT
  RUNORNOT  RUN
CO FINISHED

SO STARTING

SO LOCATION 1C     AREA    -201.42   -201.42    0.00
SO LOCATION 1P     AREA    0   -201.42    0.00

**          SRCID    QS       HS     XINIT   YINIT   ROTATE   SZINIT

SO SRCPARAM 1C    1.0E-3      0.0    201.42  402.84   0.0
SO PARTDIAM 1C    22.5     12.5     6.3     1.3
SO MASSFRAX 1C     0.4      0.1     0.3     0.2
SO PARTDENS 1C       1        1       1       1
SO PARTSLIQ 1C    6.7E-4  6.7E-4  4.5E-4  6.0E-5
SO PARTSICE 1C    2.2E-4  2.2E-4  1.5E-4  2.0E-5

SO SRCPARAM 1P    1.0E-3      0.0    201.42  402.84   0.0
SO PARTDIAM 1P    22.5     12.5     6.3     1.3
SO MASSFRAX 1P     0.4      0.1     0.3     0.2
SO PARTDENS 1P       1        1       1       1
SO PARTSLIQ 1P    6.7E-4  6.7E-4  4.5E-4  6.0E-5
SO PARTSICE 1P    2.2E-4  2.2E-4  1.5E-4  2.0E-5

SO SRCGROUP 1 1C
SO SRCGROUP 2 1P
SO SRCGROUP ALL

SO FINISHED

RE STARTING
RE GRIDCART  ONSITE STA
RE GRIDCART  ONSITE XYINC   -201.42  11  40.28  -201.42  11  40.28
RE GRIDCART  ONSITE END
RE INCLUDED  24233.REC
RE FINISHED

ME STARTING
ME INPUTFIL  24233H.MET
ME ANEMHGHT  6.1 METERS
ME SURFDATA  24233  1986
ME UAIRDATA  94240  1986
ME FINISHED

OU STARTING
  RECTABLE  ALLAVE FIRST
  MAXTABLE  ALLAVE  10
  PLOTFILE  ANNUAL 1 24233_1C.PLP
  PLOTFILE  ANNUAL 2 24233_1P.PLP
  PLOTFILE  ANNUAL ALL 24233.PLP
OU FINISHED
```

```
CO STARTING
  TITLEONE  Shreveport
  TITLETWO  110.9 ACRES
  MODELOPT  TOXICS RURAL CONC DDEP WDEP DRYDPLT WETDPLT
  AVERTIME  ANNUAL
  SAVEFILE  13957.SAP
  POLLUTID  PART
  TERRHGTS  FLAT
  ERRORFIL  ERRORS.OUT
  RUNORNOT  RUN
CO FINISHED

SO STARTING

SO LOCATION 1C     AREA    -334.96   -334.96    0.00
SO LOCATION 1P     AREA    0   -334.96    0.00

**          SRCID    QS       HS     XINIT   YINIT   ROTATE   SZINIT

SO SRCPARAM 1C    1.0E-3      0.0    334.96  669.92   0.0
SO PARTDIAM 1C    22.5     12.5     6.3     1.3
SO MASSFRAX 1C     0.4      0.1     0.3     0.2
SO PARTDENS 1C       1        1       1       1
SO PARTSLIQ 1C    6.7E-4  6.7E-4  4.5E-4  6.0E-5
SO PARTSICE 1C    2.2E-4  2.2E-4  1.5E-4  2.0E-5

SO SRCPARAM 1P    1.0E-3      0.0    334.96  669.92   0.0
SO PARTDIAM 1P    22.5     12.5     6.3     1.3
SO MASSFRAX 1P     0.4      0.1     0.3     0.2
SO PARTDENS 1P       1        1       1       1
SO PARTSLIQ 1P    6.7E-4  6.7E-4  4.5E-4  6.0E-5
SO PARTSICE 1P    2.2E-4  2.2E-4  1.5E-4  2.0E-5

SO SRCGROUP 1 1C
SO SRCGROUP 2 1P
SO SRCGROUP ALL

SO FINISHED

RE STARTING
RE GRIDCART  ONSITE STA
RE GRIDCART  ONSITE XYINC   -334.96  11  66.99  -334.96  11  66.99
RE GRIDCART  ONSITE END
RE INCLUDED  13957.REC
RE FINISHED

ME STARTING
ME INPUTFIL  13957H.MET
ME ANEMHGHT  6.1 METERS
ME SURFDATA  13957  1986
ME UAIRDATA  3951  1986
ME FINISHED

OU STARTING
  RECTABLE  ALLAVE FIRST
  MAXTABLE  ALLAVE  10
  PLOTFILE  ANNUAL 1 13957_1C.PLP
  PLOTFILE  ANNUAL 2 13957_1P.PLP
  PLOTFILE  ANNUAL ALL 13957.PLP
OU FINISHED
```

```
CO STARTING
  TITLEONE  Tampa
  TITLETWO  67 ACRES
  MODELOPT  TOXICS RURAL CONC DDEP WDEP DRYDPLT WETDPLT
  AVERTIME  ANNUAL
  SAVEFILE  12842.SAP
  POLLUTID  PART
  TERRHGTS  FLAT
  ERRORFIL  ERRORS.OUT
  RUNORNOT  RUN
CO FINISHED

SO STARTING

SO LOCATION 1C     AREA    -260.36   -260.36    0.00
SO LOCATION 1P     AREA    0   -260.36    0.00

**          SRCID    QS       HS     XINIT   YINIT   ROTATE   SZINIT

SO SRCPARAM 1C    1.0E-3      0.0    260.36  520.71   0.0
SO PARTDIAM 1C    22.5     12.5     6.3     1.3
SO MASSFRAX 1C     0.4      0.1     0.3     0.2
SO PARTDENS 1C       1        1       1       1
SO PARTSLIQ 1C    6.7E-4  6.7E-4  4.5E-4  6.0E-5
SO PARTSICE 1C    2.2E-4  2.2E-4  1.5E-4  2.0E-5

SO SRCPARAM 1P    1.0E-3      0.0    260.36  520.71   0.0
SO PARTDIAM 1P    22.5     12.5     6.3     1.3
SO MASSFRAX 1P     0.4      0.1     0.3     0.2
SO PARTDENS 1P       1        1       1       1
SO PARTSLIQ 1P    6.7E-4  6.7E-4  4.5E-4  6.0E-5
SO PARTSICE 1P    2.2E-4  2.2E-4  1.5E-4  2.0E-5

SO SRCGROUP 1 1C
SO SRCGROUP 2 1P
SO SRCGROUP ALL

SO FINISHED

RE STARTING
RE GRIDCART  ONSITE STA
RE GRIDCART  ONSITE XYINC   -260.36  11  52.07  -260.36  11  52.07
RE GRIDCART  ONSITE END
RE INCLUDED  12842.REC
RE FINISHED

ME STARTING
ME INPUTFIL  12842H.MET
ME ANEMHGHT  6.7 METERS
ME SURFDATA  12842  1986
ME UAIRDATA  12842  1986
ME FINISHED

OU STARTING
  RECTABLE  ALLAVE FIRST
  MAXTABLE  ALLAVE  10
  PLOTFILE  ANNUAL 1 12842_1C.PLP
  PLOTFILE  ANNUAL 2 12842_1P.PLP
  PLOTFILE  ANNUAL ALL 12842.PLP
OU FINISHED
```

```
CO STARTING
  TITLEONE  Tulsa
  TITLETWO  184 ACRES
  MODELOPT  TOXICS RURAL CONC DDEP WDEP DRYDPLT WETDPLT
  AVERTIME  ANNUAL
  SAVEFILE  13968.SAP
  POLLUTID  PART
  TERRHGTS  FLAT
  ERRORFIL  ERRORS.OUT
  RUNORNOT  RUN
CO FINISHED

SO STARTING

SO LOCATION 1C     AREA    -465.39   -400    0.00
SO LOCATION 1P     AREA    0   -400    0.00

**          SRCID    QS       HS     XINIT   YINIT   ROTATE   SZINIT

SO SRCPARAM 1C    1.0E-3      0.0    465.39  800   0.0
SO PARTDIAM 1C    22.5     12.5     6.3     1.3
SO MASSFRAX 1C     0.4      0.1     0.3     0.2
SO PARTDENS 1C       1        1       1       1
SO PARTSLIQ 1C    6.7E-4  6.7E-4  4.5E-4  6.0E-5
SO PARTSICE 1C    2.2E-4  2.2E-4  1.5E-4  2.0E-5

SO SRCPARAM 1P    1.0E-3      0.0    465.39  800   0.0
SO PARTDIAM 1P    22.5     12.5     6.3     1.3
SO MASSFRAX 1P     0.4      0.1     0.3     0.2
SO PARTDENS 1P       1        1       1       1
SO PARTSLIQ 1P    6.7E-4  6.7E-4  4.5E-4  6.0E-5
SO PARTSICE 1P    2.2E-4  2.2E-4  1.5E-4  2.0E-5

SO SRCGROUP 1 1C
SO SRCGROUP 2 1P
SO SRCGROUP ALL

SO FINISHED

RE STARTING
RE GRIDCART  ONSITE STA
RE GRIDCART  ONSITE XYINC   -465.39  11  93.08  -400  11  80
RE GRIDCART  ONSITE END
RE INCLUDED  13968.REC
RE FINISHED

ME STARTING
ME INPUTFIL  13968H.MET
ME ANEMHGHT  7 METERS
ME SURFDATA  13968  1984
ME UAIRDATA  13967  1984
ME FINISHED

OU STARTING
  RECTABLE  ALLAVE FIRST
  MAXTABLE  ALLAVE  10
  PLOTFILE  ANNUAL 1 13968_1C.PLP
  PLOTFILE  ANNUAL 2 13968_1P.PLP
  PLOTFILE  ANNUAL ALL 13968.PLP
OU FINISHED
```

```
CO STARTING
  TITLEONE  Williamsport
  TITLETWO  127.1 ACRES
  MODELOPT  TOXICS RURAL CONC DDEP WDEP DRYDPLT WETDPLT
  AVERTIME  ANNUAL
  SAVEFILE  14778.SAP
  POLLUTID  PART
  TERRHGTS  FLAT
  ERRORFIL  ERRORS.OUT
  RUNORNOT  RUN
CO FINISHED

SO STARTING

SO LOCATION 1C     AREA    -358.59   -358.59    0.00
SO LOCATION 1P     AREA    0   -358.59    0.00

**          SRCID    QS       HS     XINIT   YINIT   ROTATE   SZINIT

SO SRCPARAM 1C    1.0E-3      0.0    358.59  717.19   0.0
SO PARTDIAM 1C    22.5     12.5     6.3     1.3
SO MASSFRAX 1C     0.4      0.1     0.3     0.2
SO PARTDENS 1C       1        1       1       1
SO PARTSLIQ 1C    6.7E-4  6.7E-4  4.5E-4  6.0E-5
SO PARTSICE 1C    2.2E-4  2.2E-4  1.5E-4  2.0E-5

SO SRCPARAM 1P    1.0E-3      0.0    358.59  717.19   0.0
SO PARTDIAM 1P    22.5     12.5     6.3     1.3
SO MASSFRAX 1P     0.4      0.1     0.3     0.2
SO PARTDENS 1P       1        1       1       1
SO PARTSLIQ 1P    6.7E-4  6.7E-4  4.5E-4  6.0E-5
SO PARTSICE 1P    2.2E-4  2.2E-4  1.5E-4  2.0E-5

SO SRCGROUP 1 1C
SO SRCGROUP 2 1P
SO SRCGROUP ALL

SO FINISHED

RE STARTING
RE GRIDCART  ONSITE STA
RE GRIDCART  ONSITE XYINC   -358.59  11  71.72  -358.59  11  71.72
RE GRIDCART  ONSITE END
RE INCLUDED  14778.REC
RE FINISHED

ME STARTING
ME INPUTFIL  14778H.MET
ME ANEMHGHT  6.1 METERS
ME SURFDATA  14778  1979
ME UAIRDATA  94823  1979
ME FINISHED

OU STARTING
  RECTABLE  ALLAVE FIRST
  MAXTABLE  ALLAVE  10
  PLOTFILE  ANNUAL 1 14778_1C.PLP
  PLOTFILE  ANNUAL 2 14778_1P.PLP
  PLOTFILE  ANNUAL ALL 14778.PLP
OU FINISHED
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CO STARTING
  TITLEONE  Winnemucca
  TITLETWO  162.3 ACRES
  MODELOPT  TOXICS RURAL CONC DDEP WDEP DRYDPLT WETDPLT
  AVERTIME  ANNUAL
  SAVEFILE  24128.SAP
  POLLUTID  PART
  TERRHGTS  FLAT
  ERRORFIL  ERRORS.OUT
  RUNORNOT  RUN
CO FINISHED

SO STARTING

SO LOCATION 1C     AREA    -410.5   -400    0.00
SO LOCATION 1P     AREA    0   -400    0.00

**          SRCID    QS       HS     XINIT   YINIT   ROTATE   SZINIT

SO SRCPARAM 1C    1.0E-3      0.0    410.5  800   0.0
SO PARTDIAM 1C    22.5     12.5     6.3     1.3
SO MASSFRAX 1C     0.4      0.1     0.3     0.2
SO PARTDENS 1C       1        1       1       1
SO PARTSLIQ 1C    6.7E-4  6.7E-4  4.5E-4  6.0E-5
SO PARTSICE 1C    2.2E-4  2.2E-4  1.5E-4  2.0E-5

SO SRCPARAM 1P    1.0E-3      0.0    410.5  800   0.0
SO PARTDIAM 1P    22.5     12.5     6.3     1.3
SO MASSFRAX 1P     0.4      0.1     0.3     0.2
SO PARTDENS 1P       1        1       1       1
SO PARTSLIQ 1P    6.7E-4  6.7E-4  4.5E-4  6.0E-5
SO PARTSICE 1P    2.2E-4  2.2E-4  1.5E-4  2.0E-5

SO SRCGROUP 1 1C
SO SRCGROUP 2 1P
SO SRCGROUP ALL

SO FINISHED

RE STARTING
RE GRIDCART  ONSITE STA
RE GRIDCART  ONSITE XYINC   -410.5  11  82.1  -400  11  80
RE GRIDCART  ONSITE END
RE INCLUDED  24128.REC
RE FINISHED

ME STARTING
ME INPUTFIL  24128H.MET
ME ANEMHGHT  6.1 METERS
ME SURFDATA  24128  1984
ME UAIRDATA  24128  1984
ME FINISHED

OU STARTING
  RECTABLE  ALLAVE FIRST
  MAXTABLE  ALLAVE  10
  PLOTFILE  ANNUAL 1 24128_1C.PLP
  PLOTFILE  ANNUAL 2 24128_1P.PLP
  PLOTFILE  ANNUAL ALL 24128.PLP
OU FINISHED
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Appendix H

Direct and Indirect Exposure Equations

Table H-1.1. ADDmat - Average Daily Dose of Dioxin (2,3,7,8-TCDD) Consumed by Mother (mg/kg-d)

ADDmat

$$ADDmat = ADDoral + ADDinhal$$

$$ADDinhal = \frac{Risk_{inhal} \times AT}{ED_i \times CSFInhal}$$

$$ADDoral = \frac{Risk_{oral} \times AT}{ED \times CSFOral}$$

Name	Description	Location
ADDinhal	Average daily dose due to inhalation (mg/kg-d)	Calculated
ADDoral	Average daily dose due to oral ingestion (mg/kg-d)	Calculated
AT	Averaging time (yr)	See Appendix J
CSFInhal	Inhalation cancer slope factor (mg/kg/d)-1	See Section 2
CSFOral	Oral cancer slope factor (mg/kg/d)-1	See Section 2
ED	Exposure duration for oral ingestion (yr)	See Appendix J
EDi	Exposure duration for inhalation (yr)	See Appendix J
Risk_Inhal	Cancer risk due to inhalation (unitless)	Calculated in Table H-3.16
Risk_Oral	Cancer risk due to oral ingestion (unitless)	Calculated in Table H-3.17

Source: Back calculated from risk values.

Table H-1.2. Cmilkfat - Concentration of Dioxin (2,3,7,8-TCDD) in Maternal Milk Fat (mg/kg)

Cmilkfat

$$Cmilkfat = \frac{ADDmat \times f_{am} \times f_f}{\frac{0.693}{t_{halfb}} \times f_{fm}}$$

Name	Description	Location
0.693	Constant LN(2) (unitless)	
ADDmat	Average daily dose of dioxin (2,3,7,8-TCDD) consumed by mother (mg/kg-d)	Calculated in Table H-1.1
f_am	Fraction of ingested contaminant absorbed by mother (unitless)	See Appendix J
f_f	Proportion of contaminant stored in maternal fat (unitless)	See Appendix J
f_fm	Fraction of mother's weight that is fat (unitless)	See Appendix J
t_halfb	Biological half-life of contaminant in lactating women (d)	See Appendix J

Source: Based on U.S. EPA, 1998.

Table H-1.3. IngBM - Infant Breast Milk Exposure Calculated for Dioxin (2,3,7,8-TCDD) (mg/kg-day)

IngBM

$$IngBM = \frac{(C_{milkfat} \times f_{mbm} + C_{aqueous} \times (1 - f_{mbm})) \times f_{ai} \times CR_{bm} \times 0.001}{BW_{infant}}$$

Name	Description	Location
0.001	Units conversion factor (kg/mL)	
BW_infant	Body weight of infant (kg)	See Appendix J
C_aqueous	Concentration in aqueous phase of maternal milk (mg/kg)	See Appendix J
Cmilkfat	Concentration of contaminant in maternal milk fat (mg/kg)	Calculated in Table H-1.2
CR_bm	Ingestion rate of breast milk (mL/d)	See Appendix J
f_ai	Fraction of ingested contaminant absorbed by the infant (unitless)	See Appendix J
f_mbm	Fraction of fat in maternal breastmilk (unitless)	See Appendix J

Source: Based on U.S. EPA, 1998.

Table H-2.1. Cair - Total (Vapor + Particulate) Air Concentration (mg/m3)

Cair

$$Cair = Q \times (F_v \times Cyv + (1 - F_v) \times Cyp) \times 0.001$$

Name	Description	Location
0.001	Conversion factor (mg/ug)	
Cyp	Normalized particulate air concentration (ug-s-m2/g-m3)	See Appendix G
Cyv	Normalized vapor phase air concentration (ug-s-m2/g-m3)	See Appendix G
Fv	Fraction of air concentration in vapor phase (unitless)	See Appendix D
Q	Emission rate from source (g/s-m2)	Calculated by Source Model

Source: U.S. EPA, 1998.

Table H-2.2. Csed - Concentration of Dioxin on Sediment Settling to Bottom (mg/kg)

Csed
$$Csed = Cssed \times \frac{foc_{bs}}{foc_{sw}}$$

Name	Description	Location
Cssed	Concentration of dioxin on suspended sediment (mg/kg)	Calculated in Table H-2.6
foc_bs	Fraction of organic carbon in bottom sediment (unitless)	See Appendix I
foc_sw	Fraction of organic carbon in suspended sediment (unitless)	See Appendix I

Source: U.S. EPA, 2000.

Table H-2.3. Csoil_1F - Average Soil Concentration Over Time Period of Exposure, T2<=Td (mg/kg)

Csoil_1F

$$Csoil_{1F} = \frac{(Csoil_{t2} + Csoil_{t1})}{2}$$

Name	Description	Location
Csoil_t1	Soil concentration at first year of exposure, T1(mg/kg)	Calculated in Table H-2.5
Csoil_t2	Soil concentration at last year of exposure, T2 (mg/kg)	Calculated in Table H-2.5

Source: Equation was used to estimate the average concentration over the exposure duration.

Table H-2.4. Csoil_2F - Average Soil Concentration OverTime Period of Exposure, T2>Td (mg/kg)

Csoil_2F

$$Csoil_{td2} = \frac{(Csoil_{t2} + Csoil_{td})}{2}$$

$$Csoil_{td1} = \frac{(Csoil_{td} + Csoil_{t1})}{2}$$

$$Csoil_{2F} = Csoil_{td1} \times \frac{(Td - T1)}{ED} + Csoil_{td2} \times \frac{(T2 - Td)}{ED}$$

Name	Description	Location
Csoil_t1	Soil concentration at first year of exposure, T1 (mg/kg)	Calculated in Table H-2.5
Csoil_t2	Soil concentration at last year of exposure, T2 (mg/kg)	Calculated in Table H-2.5
Csoil_td	Soil concentration at last year of deposition, Td (mg/kg)	Calculated in Table H-2.5
Csoil_td1	Average soil concentration from the first year of exposure to the last year of deposition (mg/kg)	Calculated in Table H-2.5
Csoil_td2	Average soil concentration from last year of deposition to the last year of exposure (mg/kg)	Calculated in Table H-2.5
ED	Exposure duration (yr)	See Appendix J
T1	The time at which exposure begins (yr)	See Appendix E
T2	The time at which exposure ends, T1 + ED (yr)	Calculated
Td	The length of time the unit is operational (yr)	See Appendix E

Source: Equations were used to calculate the average concentration over the period of exposure while biosolids were applied and the average concentration after biosolids application ceased. These two concentrations were then time-weighted to determine the average concentration over the exposure duration.

Table H-2.5. Csoil_t - Soil Concentration at Time, T (mg/kg)

Csoil_t

$$Csoil_t = Csoil_i + \frac{Dep + Load}{SoilR + K_s \times Mass} \times 1 - e^{\left(-\frac{SoilR}{Mass} + K_s\right) \times T}$$

Name	Description	Location
Csoil_i	Initial soil concentration (mg/kg)	Calculated
Dep	Deposition term for soil (mg/yr)	Calculated in Table H-2.9
K_s	Soil loss constant (1/yr)	Calculated
Load	Mass of contaminant loaded to soil (mg/yr)	Calculated in Table H-2.18
Mass	Mass of soil (kg)	Calculated in Table H-2.21
SoilR	Mass of soil removed from site (kg/yr)	Calculated in Table H-2.23
T	The time for which the soil concentration is being calculated (yr)	

Source: Equation was based on the equation in U.S. EPA, 2000 with values for deposition load added into the equation.

Note: Depending on the value of T this equation is used to calculate Csoil_t1, Csoil_t2 or Csoil_td. The Value for T is determined in either Csoil_1F or Csoil_2F.

Table H-2.6. Cssed - Concentration of Dioxin on Suspended Sediment (mg/kg)

Cssed

$$Cssed = \frac{Lt}{\frac{Vfx}{Kd_{sw}} + (Fs \times ERw) + \frac{foc_{bs}}{foc_{sw}} \times (1 - Fs) \times ERw}$$

Name	Description	Location
ERw	Total watershed annual soil erosion (kg/yr)	Calculated in Table H-2.12
foc_bs	Fraction of organic carbon in bottom sediment (unitless)	See Appendix I
foc_sw	Fraction of organic carbon in suspended sediment (unitless)	See Appendix I
Fs	Fraction of annual erosion remaining as suspended material (unitless)	Calculated in Table H-2.13
Kd_sw	Soil-water partition coefficient in suspended sediment (L/kg)	Calculated in Table H-2.15
Lt	Loading term for dioxin in waterbody (mg/yr)	Calculated in Table H-2.20
Vfx	Waterbody annual flow mixing volume (L/yr)	Calculated in Table H-2.24

Source: U.S. EPA, 2000.

Table H-2.7. Cvapor - Vapor Air Concentration - Could be Farm, Waterbody or Watershed (mg/m3)

Cvapor

$$Cvapor = Q \times F_v \times Cyv \times 0.001$$

Name	Description	Location
0.001	Conversion factor (mg/ug)	
Cyv	Normalized vapor phase air concentration (ug-s-m2/g-m3)	See Appendix G
Fv	Fraction of air concentration in vapor phase (unitless)	See Appendix D
Q	Emission rate from source (g/s-m2)	Calculated by Source Model

Source: U.S. EPA, 1998.

Table H-2.8. Cw - Concentration of Dioxin in the Waterbody (mg/kg)

Cw

$$Cw = TSS \times Cssed \times 1000000$$

Name	Description	Location
Cssed	Concentration of dioxin on suspended sediment (mg/kg)	Calculated in Table H-2.6
TSS	Total suspended solids (mg/L)	See Appendix I

Source: Best professional judgement

Table H-2.9. Dep - Deposition Term for Soil (mg/yr)

Dep

$$Dydv = 0.31536 \times Cyv \times Vdv$$

$$Dep = 1000 \times Q \times Area \times (F_v \times (Dydv + Dywv) + (1 - F_v) \times (Dydp + Dywp))$$

Name	Description	Location
0.31536	Unit conversion factor (m-g-s/cm-ug-yr)	
1000	Units conversion (mg/g)	
Area	Area of deposition (m2)	See Appendix E
Cyv	Normalized vapor phase air concentration (ug-s-m2/g-m3)	See Appendix G
Dydp	Normalized annual average dry deposition from particle phase (s-m2/m2-yr)	See Appendix G
Dydv	Normalized annual dry deposition from vapor phase (s-m2/m2-yr)	Calculated
Dywp	Normalized annual average wet deposition from particle phase(s-m2/m2-yr)	See Appendix G
Dywv	Normalized annual average wet deposition from vapor phase (s-m2/m2-yr)	See Appendix G
Fv	Fraction of air concentration in vapor phase (unitless)	See Appendix D
Q	Emission rate from source (g/s-m2)	Calculated by Source Model
Vdv	Dry deposition velocity (cm/s)	See Appendix D

Source: U.S. EPA, 1998.

Table H-2.10. Di - Deposition Term for Impervious Surfaces (g/m2-yr)

Di

$$Dydv = 0.31536 \times Cyv \times Vdv$$

$$Di = Q \times (F_v \times (Dydv + Dywv) + (1 - F_v) \times (Dydp + Dywp))$$

Name	Description	Location
0.31536	Unit conversion factor (m-g-s/cm-ug-yr)	
Cyv	Normalized vapor phase air concentration (ug-s-m2/g-m3)	See Appendix G
Dydp	Normalized annual average dry deposition from particle phase (s-m2/m2-yr)	See Appendix G
Dydv	Normalized annual dry deposition from vapor phase (s-m2/m2-yr)	Calculated
Dywp	Normalized annual average wet deposition from particle phase(s-m2/m2-yr)	See Appendix G
Dywv	Normalized annual average wet deposition from vapor phase (s-m2/m2-yr)	See Appendix G
Fv	Fraction of air concentration in vapor phase (unitless)	See Appendix D
Q	Emission rate from source (g/s-m2)	Calculated by Source Model
Vdv	Dry deposition velocity (cm/s)	See Appendix D

Source: U.S. EPA, 1998.

Table H-2.11. Dw - Deposition Term for Water (g/m2-yr)

Dw

$$Dw = Q \times ((F_v \times Dywv) + ((1 - F_v) \times (Dydp + Dywp)))$$

Name	Description	Location
Dydp	Normalized annual average dry deposition from particle phase (s-m2/m2-yr)	See Appendix G
Dywp	Normalized annual average wet deposition from particle phase(s-m2/m2-yr)	See Appendix G
Dywv	Normalized annual average wet deposition from vapor phase (s-m2/m2-yr)	See Appendix G
Fv	Fraction of air concentration in vapor phase (unitless)	See Appendix D
Q	Emission rate from source (g/s-m2)	Calculated by Source Model

Source: U.S. EPA, 1998.

Table H-2.12. ERw - Total Watershed Annual Soil Erosion (kg/yr)

ERw

$$ERw = (Area_{RWS} \times X_e \times SD_{RWS}) + (Area_{LWS} \times X_e \times SD_{LWS})$$

Name	**Description**	**Location**
Area_LWS	Area of the local watershed (m2)	See Appendix E
Area_RWS	Area of the regional watershed (m2)	See Appendix E
SD_LWS	Sediment delivery ratio from local watershed (unitless)	Calculated in Table H-2.22
SD_RWS	Sediment delivery ratio from regional watershed (unitless)	Calculated in Table H-2.22
Xe	Universal Soil Loss Equation (kg/m2-yr)	Calculated in Table H-2.25

Table H-2.13. Fs - Fraction of Annual Erosion Remaining as Suspended Material (unitless)

Fs

$$Fs = \left(Tss \times \frac{Vfx}{ERw} \right) \times 1E-06$$

Name	Description	Location
1E-06	Conversion factor (kg/mg)	
ERw	Total watershed annual soil erosion (kg/yr)	Calculated in Table H-2.12
TSS	Total suspended solids (mg/L)	See Appendix I
Vfx	Waterbody annual flow mixing volume (L/yr)	Calculated in Table H-2.24

Source: U.S. EPA, 2000.

Table H-2.14. KdSoil - Soil-Water Partition Coefficient (mL/g)

KdSoil

$$KdSoil = Koc \times foc$$

Name	Description	Location
foc	Fraction organic carbon (unitless)	See Appendix I
Koc	Organic carbon partition coefficient (ml/g)	See Appendix D

Source: U.S. EPA, 1998.

Table H-2.15. Kdsw - Soil-Water Partition Coefficient for Suspended Sediment (mL/g)

Kdsw
$Kdsw = Koc \times foc$

Name	**Description**	**Location**
foc	Fraction organic carbon (unitless)	See Appendix I
Koc	Organic carbon partition coefficient (ml/g)	See Appendix D

Source: U.S. EPA, 1998.

Table H-2.16. Ldep - Total (Wet and Dry) Particle and Wet Vapor Phase Deposition Load to Waterbody (g/yr)

Ldep

$$Ldep = D_W \times Waw$$

Name	Description	Location
Dw	Deposition term for water (g/m2-yr)	Calculated in Table H-2.11
Waw	Area of the waterbody (m2)	Calculated

Source: U.S. EPA, 1998.

Table H-2.17. Le - Erosion Load to Waterbody (g/yr)

Le

$$Wai = Wat \times \frac{PI}{100}$$

$$L_e = X_e \times (Wat - Wai) \times SD \times ER \times Csoil \times 0.001$$

Name	Description	Location
0.001	Conversion factor (g/mg)	
100	Conversion factor from percent to a fraction (unitless)	
Csoil	Concentration of contaminant in soil (mg/kg)	Calculated in Tables H-2.3, H-2.4
ER	Soil enrichment ratio (unitless)	See Appendix C
PI	Percent impervious (percent)	See Appendix E
SD	Sediment delivery ratio (unitless)	Calculated in Table H-2.22
Wai	Impervious watershed area (m2)	Calculated
Wat	Total watershed area (m2)	See Appendix E
Xe	Universal Soil Loss Equation (kg/m2-yr)	Calculated in Table H-2.25

Source: U.S. EPA, 2000.

Table H-2.18. Loss - Loss Term from Soil (mg/yr)

Loss

$$Loss = (Lri + Le) \times 1000$$

Name	Description	Location
1000	Conversion factor (1000 mg/g)	
Le	Erosion loss from soil (g/yr)	Calculated in Table H-2.17
Lri	Impervious runoff load from soil (g/yr)	Calculated in Table H-2.19

Source: Equivalent of the term "load" in other equations.

Table H-2.19. Lri - Impervious Runoff Load from Soil (g/yr)

Lri

$$Wai = Wat \times \frac{PI}{100}$$

$$Lri = D_i \times Wai$$

Name	Description	Location
100	Conversion factor from percent to a fraction (unitless)	
Di	Deposition term for impervious surfaces (g/m2-yr)	Calculated in Table H-2.10
PI	Percent impervious (percent)	See Appendix E
Wai	Impervious watershed area (m2)	Calculated
Wat	Total watershed area (m2)	See Appendix E

Source: U.S. EPA, 1998.

Table H-2.20. Lt - Loading Term for Dioxin in Waterbody (mg/yr)

Lt
$Lt = Load_{LWS} + Load_{RWS} + (Ldep \times 1000)$

Name	Description	Location
1000	Conversion factor (mg/g)	
Ldep	Total (wet and dry) particle and wet vapor phase deposition load to waterbody (g/yr)	Calculated in Table H-2.16
Load_LWS	Total loading from local watershed (mg/yr)	Calculated in Table H-2.18
Load_RWS	Total loading from regional watershed (mg/yr)	Calculated in Table H-2.18

Source: U.S. EPA, 2000.

Table H-2.21. Mass - Mass of Soil (kg)

Mass

$$Wai = Wat \times \frac{PI}{100}$$

$$Mass = (Wat - Wai) \times Z \times BD \times 10$$

Name	Description	Location
10	Conversion factor (cm2/m2)(kg/g)	
100	Conversion factor from percent to a fraction (unitless)	
BD	Soil bulk density (g/cm3)	See Appendix E
PI	Percent impervious (percent)	See Appendix E
Wai	Impervious watershed area (m2)	Calculated
Wat	Total area receiving deposition (m2)	See Appendix E
Z	Mixing depth of the soil (cm)	See Appendix I

Table H-2.22. SedDelivery - Sediment Delivery Ratio (unitless)

SedDelivery

$$AreaSM = \frac{Area}{2590000}$$

$$SD = A \times (AreaSM)^{-B}$$

Name	Description	Location
2590000	Conversion factor (m2/sq miles)	
A	A = 1.2 if the area ranges from 10 to 100 square miles (unitless)	
	Empirical intercept coefficient related to the size of the area (unitless)	
	A = 2.1 if the area is less than or equal to 0.1 square miles (unitless)	
	A = 1.9 if the area ranges from 0.1 to 1 square miles (unitless)	
	A = 1.4 if the area ranges from 1 to 10 square miles (unitless)	
	A = 0.6 for all other cases (unitless)	
Area	Area receiving pollutant deposition (m2)	See Appendix E
AreaSM	Area receiving pollutant deposition, area / 2590000 (sq miles)	Calculated
B	Empirical slope coefficient related to the power of the drainage area (unitless), (B = 0.125)	

Source: U.S. EPA, 1998.

Table H-2.23. SoilR - Mass of Soil Removed from Exposure Site (kg/yr)

SoilR

$$Wai = Wat \times \frac{PI}{100}$$

$$SoilR = X_e \times (Wat - Wai) \times SD \times ER$$

Name	Description	Location
100	Conversion factor from percent to a fraction (unitless)	
ER	Soil enrichment ratio (unitless)	See Appendix C
PI	Percent impervious (percent)	See Appendix E
SD	Sediment delivery ratio (unitless)	Calculated in Table H-2.22
Wai	Impervious watershed area (m2)	Calculated
Wat	Total watershed area (m2)	See Appendix E
Xe	Universal Soil Loss Equation (kg/m2-yr)	Calculated in Table H-2.25

Source: U.S. EPA, 2000.

Table H-2.24. Vfx - Waterbody Annual Flow Mixing Volume (L/yr)

Vfx

$$Baseflow = a \times Waw^{b}$$

$$Vfx = (Runoff_{RWS} + Runoff_{LWS} + Baseflow) \times 365 \times 1000$$

Name	Description	Location
1000	Conversion factor (L/m3)	
365	Conversion factor (days/yr)	
a	Parameter from regression analysis, based on HUC region (m/d)	
b	Parameter from regression analysis, based on HUC region (unitless)	
Baseflow	30Q2 Flow rate (m3/d)	Calculated
Runoff_LWS	Runoff from local watershed (m3/day)	Calculated by Source Model
Runoff_RWS	Runoff from regional watershed (m3/day)	Calculated by Source Model
Waw	Area of the waterbody (m2)	Calculated

Source: Baseflow - U.S. EPA, 1999.

Table H-2.25. Xe - Universal Soil Loss Equation (kg/m2-yr)

Xe

$$X_e = R \times K \times LS \times C \times P \times \frac{907.18}{4047}$$

Name	Description	Location
4047	Conversion factor (m2/acres)	
907.18	Conversion factor (kg/short tons)	
C	USLE cover management factor (unitless)	See Appendix C
K	USLE soil erodibility factor (short tons/acre)	See Appendix E
LS	USLE length-slope factor (unitless)	See Appendix E
P	USLE supporting practice factor (unitless)	See Appendix C
R	USLE rainfall/erosivity factor (1/yr)	See Appendix E

Source: U.S. EPA, 1998.

Table H-3.1. Abeef - Concentration in Beef Due to Plant and Soil Ingestion (mg/kg - WW)

Abeef

$$Abeef = C_{fat} \times 0.2$$

$$C_{fat} = (BCF_{cattle} \times FF) \times (DF_{beef_{soil}} \times B_s \times Csoil + DF_{beef_{forage}} \times P_{forage} + DF_{beef_{feed}} \times P_{feed})$$

Name	Description	Location
0.2	Fraction of fat in beef (unitless)	
B_s	Bioavailability of contaminant on the soil vehicle relative to the vegetative vehicle (unitless)	See Appendix I
BCF_cattle	Bioconcentration ratio of contaminant as determined from cattle vegetative intake (pasture grass or feed) (unitless)	See Appendix D
C_fat	Concentration of dioxin (2,3,7,8-TCDD) in beef fat (mg/kg)	Calculated
Csoil	Average contaminant soil concentration (mg/kg)	Calculated in Tables H-2.3, H-2.4
DF_beef_feed	Fraction of cattle diet that is feed (unitless)	See Appendix I
DF_beef_forage	Fraction of cattle diet that is pasture grass (unitless)	See Appendix I
DF_beef_soil	Fraction of cattle diet that is soil (unitless)	See Appendix I
FF	Feedlot factor for beef fat calculation (<=1 for beef fat and =1 for milk fat) (unitless)	See Appendix I
P_feed	Average concentration of contaminant in feed (mg/kg)	Calculated
P_forage	Average concentration of contaminant on pasture grass (mg/kg)	Calculated

Source: U.S. EPA, 2000.

Note: Fries and Paustenbach used the same bioconcentration for beef fat and milk fat.The dioxin reassessment provides a range of fat content from 18-22%. The value used above is the mean of 20%.

Table H-3.2. Aeggs - Concentration in Eggs Due to Grain Uptake from Chickens (mg/kg - WW)

Aeggs

$$Aeggs = C_{fat} \times 0.1$$

$$C_{fat} = BCF_{egg} \times (DF_{poultry_{soil}} \times B_s \times Csoil + DF_{poultry_{forage}} \times P_{forage} + DF_{poultry_{feed}} \times P_{feed})$$

Name	Description	Location
0.1	Fraction of fat in eggs (unitless)	
B_s	Bioavailability of contaminant on the soil vehicle relative to the vegetative vehicle (unitless)	See Appendix I
BCF_egg	Bioconcentration ratio of contaminant developed for chicken vegetative intake (unitless)	See Appendix D
C_fat	Concentration of dioxin (2,3,7,8-TCDD) in egg fat (mg/kg)	Calculated
Csoil	Average contaminant soil concentration (mg/kg)	Calculated in Tables H-2.3, H-2.4
DF_poultry_feed	Fraction of chicken diet that is feed (unitless)	See Appendix I
DF_poultry_forage	Fraction of chicken diet that is incidental vegetation while free ranging (unitless)	See Appendix I
DF_poultry_soil	Fraction of chicken diet that is soil (unitless)	See Appendix I
P_feed	Average concentration of contaminant in feed (mg/kg)	Calculated
P_forage	Average concentration of contaminant on free range vegetation (mg/kg)	Calculated

Source: U.S. EPA, 2000.

Table H-3.3. Amilk - Concentration in Milk Due to Plant and Soil Ingestion (mg/kg - WW)

Amilk

$$Amilk = C_{fat} \times 0.04$$

$$C_{fat} = (BCF_{cattle} \times FF) \times (DF_{dairy_{soil}} \times B_s \times Csoil + DF_{dairy_{forage}} \times P_{forage} + DF_{dairy_{feed}} \times P_{feed})$$

Name	Description	Location
0.04	Fraction of fat in milk (unitless)	
B_s	Bioavailability of contaminant on the soil vehicle relative to the vegetative vehicle (unitless)	See Appendix I
BCF_cattle	Bioconcentration ratio of contaminant as determined from cattle vegetative intake (pasture grass or feed) (unitless)	See Appendix D
C_fat	Concentration of dioxin (2,3,7,8-TCDD) in milk fat (mg/kg)	Calculated
Csoil	Average contaminant soil concentration (mg/kg)	Calculated in Tables H-2.3, H-2.4
DF_dairy_feed	Fraction of cattle diet that is feed (unitless)	See Appendix I
DF_dairy_forage	Fraction of cattle diet that is pasture grass (unitless)	See Appendix I
DF_dairy_soil	Fraction of cattle diet that is soil (unitless)	See Appendix I
FF	Feedlot factor for beef fat calculation (<=1 for beef fat and =1 for milk fat) (unitless)	See Appendix I
P_feed	Average concentration of contaminant in feed (mg/kg)	Calculated
P_forage	Average concentration of contaminant on pasture grass (mg/kg)	Calculated

Source: U.S. EPA, 2000.

Table H-3.4. Apoultry - Concentration in Poultry Meat Due to Grain Uptake from Chickens (mg/kg - WW)

Apoultry

$$Apoultry = C_{fat} \times 0.1$$

$$C_{fat} = BCF_{poultry} \times (DF_{poultry_{soil}} \times B_s \times Csoil + DF_{poultry_{forage}} \times P_{forage} + DF_{poultry_{feed}} \times P_{feed})$$

Name	Description	Location
0.1	Fraction of fat in poultry (unitless)	
B_s	Bioavailability of contaminant on the soil vehicle relative to the vegetative vehicle (unitless)	See Appendix I
BCF_poultry	Bioconcentration ratio of contaminant developed for chicken vegetative intake (unitless)	See Appendix D
C_fat	Concentration of dioxin (2,3,7,8-TCDD) in chicken fat (mg/kg)	Calculated
Csoil	Average contaminant soil concentration (mg/kg)	Calculated in Tables H-2.3, H-2.4
DF_poultry_feed	Fraction of chicken diet that is feed (unitless)	See Appendix I
DF_poultry_forage	Fraction of chicken diet that is incidental vegetation while free ranging (unitless)	See Appendix I
DF_poultry_soil	Fraction of chicken diet that is soil (unitless)	See Appendix I
P_feed	Average concentration of contaminant in feed (mg/kg)	Calculated
P_forage	Average concentration of contaminant on free range vegetation (mg/kg)	Calculated

Source: U.S. EPA, 2000.

Table H-3.5. Cfish - Concentration in Fish (mg/kg)

Cfish

$$Cfish = Cfish_{lipid} \times LF$$

$$Cfish_{lipid} = BASF \times Csed$$

Name	Description	Location
BSAF	Biota sediment accumulation factor (unitless)	See Appendix D
Cfish_lipid	Concentration of contaminant in fish lipid (mg/kg)	Calculated
Csed	Concentration in sediment settling to bottom (mg/kg)	Calculated in Table H-2.2
LF	Lipid fraction (unitless)	See Appendix I

Source: U.S. EPA, 1998.

Table H-3.6. Dp - Deposition Term for Plants (mg/m2-yr)

Dp

$$D_p = 1000 \times Q \times (1 - F_v) \times (Dydp + (F_w \times Dywp))$$

Name	**Description**	**Location**
1000	Conversion factor (mg/g)	
Dydp	Normalized annual average dry deposition from particle phase (s-m2/m2-yr)	See Appendix G
Dywp	Normalized annual average wet deposition from particle phase(s-m2/m2-yr)	See Appendix G
Fv	Fraction of air concentration in vapor phase (unitless)	See Appendix D
Fw	Fraction of wet deposition adhering to plant surface (unitless)	See Appendix D
Q	Emission rate from source (g/s-m2)	Calculated by Source Model

Source: U.S. EPA, 1997.

Table H-3.7. Iag - Daily Intake of Contaminant from Consumption of Above-Ground Produce (mg/kg BW/d)

Iag

$$Iag = I_{exfruit} + I_{exveg}$$

$$I_{exveg} = \frac{CR_{exveg}}{1000} \times F_{exveg} \times P_{exveg} \times (1 - L_{exveg})$$

$$I_{exfruit} = \frac{CR_{exfruit}}{1000} \times F_{exfruit} \times P_{exfruit} \times (1 - L_{exfruit})$$

Name	Description	Location
1000	Unit conversion (g/kg)	
CR_exfruit	Daily human consumption rate of exposed fruit (g WW/kg BW/day)	See Appendix J
CR_exveg	Daily human consumption rate of exposed vegetables (g WW/kg BW/day)	See Appendix J
F_exfruit	Fraction of exposed fruit grown in contaminated soil (unitless)	See Appendix J
F_exveg	Fraction of exposed vegetables grown in contaminated soil (unitless)	See Appendix J
I_exfruit	Daily intake of contaminant from consumption of exposed fruit (mg/kg BW/d)	Calculated
I_exveg	Daily intake of contaminant from consumption of exposed vegetables (mg/kg BW/d)	Calculated
L_exfruit	Food preparation loss for exposed fruit (unitless)	See Appendix J
L_exveg	Food preparation loss for exposed vegetables (unitless)	See Appendix J
P_exfruit	Exposed fruit concentration (mg/kg)	Calculated
P_exveg	Exposed vegetable concentration (mg/kg)	Calculated

Source: U.S. EPA, 1998.

Table H-3.8. Ianimal - Daily Intake of Contaminant from Ingestion of ith Animal Tissue Group (mg/kg BW/d)

Ianimal

$$I_{animal} = A_i \times F_i \times L_i \times \frac{CR_i}{1000}$$

Name	Description	Location
1000	Unit conversion (g/kg)	
Ai	Concentration of contaminant in ith animal tissue group (mg/kg WW)	Calculated in Tables H-3.1, H-3.2, H-3.3, H-3.4
CRi	Daily human consumption rate of ith animal tissue group (g WW/kg BW/day)	See Appendix J
Fi	Fraction of animal tissue that is contaminated (unitless)	See Appendix J
Li	Contaminant loss factor (unitless)	See Appendix J

Source: U.S. EPA, 1998.

Table H-3.9. Ibg - Daily Intake of Contaminant from Consumption of Below-Ground Produce (mg/kg-d)

Ibg

$$I_{bg} = \frac{CR_{bg}}{1000} \times Pr_{bg} \times F_{bg} \times (1 - L_{bg})$$

Name	Description	Location
1000	Unit conversion (g/kg)	
CR_bg	Daily human consumption rate of below ground vegetables (g WW/kg BW/day)	See Appendix J
F_bg	Fraction of below ground vegetables grown in contaminated soil (unitless)	See Appendix J
L_bg	Food preparation loss for root vegetables (unitless)	See Appendix J
Prbg	Below ground vegetable concentration in whole weight (mg/kg WW)	Calculated in Table H-3.13

Source: U.S. EPA, 1998.

Table H-3.10. Ifish - Daily Intake of Contaminant from Consumption of Fish (mg/kg-d)

Ifish

$$Ifish = \frac{Cfish \times CR_{fish} \times F_{fish}}{BW \times 1000}$$

$$Cfish = (F_{T3} \times C_{fishT3F}) + (F_{T4} \times C_{fishT4F})$$

Name	Description	Location
1000	Unit conversion (g/kg)	
BW	Body weight (kg)	See Appendix J
C_fishT3F	Concentration of contaminant in T3 fish (mg/kg)	Calculated
C_fishT4F	Concentration of contaminant in T4 fish (mg/kg)	Calculated
Cfish	Concentration of contaminant in fish (mg/kg)	Calculated in Table H-3.5
CRf	Consumption rate of fish (g WW/day)	See Appendix J
F_fish	Fraction of fish intake from contaminated source (unitless)	See Appendix J
F_T3	Fraction of trophic level 3 intake, 0.36 (unitless)	
F_T4	Fraction of trophic level 4 intake, 0.64 (unitless)	

Source: U.S. EPA, 1998.

Table H-3.11. Isoil - Daily Intake of Contaminant from Incidental Ingestion of Soil (mg/kg-d)

Isoil

$$I_{soil} = \frac{C_{soil} \times CR_s \times F_{soil}}{BW}$$

Name	Description	Location
BW	Body weight (kg)	See Appendix J
CRs	Soil ingestion rate (kg/day)	See Appendix J
Csoil	Concentration of contaminant in soil (mg/kg)	Calculated in Tables H-2.3, H-2.4
Fsoil	Fraction of contaminated soil that is ingested (unitless)	See Appendix J

Source: U.S. EPA, 1998.

Table H-3.12. Pd - Vegetative Concentration Due to Direct Deposition (mg/kg - DW)

Pd

$$Pd = \frac{(Dp \times Rp)}{(Yp \times KpPar)}$$

Name	Description	Location
Dp	Deposition term for plants (mg/m2-yr)	Calculated in Table H-3.6
KpPar	Plant surface loss coefficient, particulate (1/yr)	See Appendix D
Rp	Interception fraction - above-ground vegetables (fraction)	See Appendix I
Yp	Crop yield (kg DW/m2)	See Appendix I

Source: U.S. EPA, 2000.

Table H-3.14. Pr - Above-ground vegetation concentration due to root uptake (mg/kg - DW)

Pr

$$Pr = Csoil \times Br$$

Name	Description	Location
Br	Soil-to-plant bioconcentration factor (ug/g DW plant / ug/g soil)	
Csoil	Soil concentration due to deposition to soil (mg/kg)	Calculated

Source: U.S. EPA, 1998. In this analysis Br was set to 0.

Table H-3.13. Prbg - Concentration in Below-Ground Vegetation Due to Root Uptake (mg/kg - WW)

Prbg

$$Pr_{bg} = \frac{C_{soil} \times RCF \times VG_{bg}}{Kd}$$

Name	Description	Location
Csoil	Concentration of contaminant in soil (mg/kg)	Calculated in Tables H-2.3, H-2.4
RCF	Root concentration factor (ug/g - WW plant) / (ug/mL soil water)	See Appendix D
VGbg	Empirical correction factor for below ground vegetables (unitless)	See Appendix I

Source: U.S. EPA, 1998.

Table H-3.15. Pv - Vegetative Concentration Due to Air-to-Plant Transfer (mg/kg - DW)

Pv

$$Pv = \frac{C_{vapor} \times Bv \; x \; VG_{ag} \times 1000}{1200}$$

Name	Description	Location
1000	Conversion factor (g/kg)	
1200	Rho_air is the density of air (g/m3)	
Bv	Air-to-plant biotransfer factor (ug/g DW plant / ug/g air)	See Appendix D
Cvapor	Concentration of vapor (mg/m3)	Calculated in Table H-2.7
VGag	Empirical correction factor for above ground vegetables (unitless)	See Appendix I

Source: U.S. EPA, 1998.

Table H-3.16. Pveg - Total Concentration in Above-Ground Vegetation (mg/kg - WW or DW)

Pveg

$$Pveg_{WW} = (Pd_{veg} + Pv_{veg} + Pr_{veg}) \times \frac{(100 - MAF)}{100}$$

$$Pveg_{DW} = (Pd_{veg} + Pv_{veg} + Pr_{veg})$$

Name	Description	Location
MAF	Plant tissue-specific moisture adjustment factor to convert DW concentration into WW (percent)	
Pd_veg	Vegetative concentration due to direct deposition (mg/kg - DW)	Calculated in Table H-3.12
Pr	Above-ground vegetation concentration due to root uptake, zero for dioxins (mg/kg - DW)	Calculated in Table H-3.13
Pv_veg	Vegetative concentration due to air-to-plant transfer (mg/kg - DW)	Calculated in Table H-3.14

Source: U.S. EPA, 1998.

Note: For exposed vegetataion MAF is 92, for exposed fruit MAF is 85, and for protected fruit MAF is 90. Dry weight is used for forage and feed. Wet weight is used for exposed vegetataion, exposed fruit, and protected fruit

Table H-3.17. Risk_Air - Risk Due to Inhalation (unitless)

Risk_Air

$$Risk_{Air} = TEF \times \frac{(C_{air} \times B_{ri} \times ED_i \times EF_i \times CSFInhal)}{(AT \times 365 \times BW)}$$

Name	Description	Location
365	Conversion factor (days/yr)	
AT	Averaging time (yr)	See Appendix J
Bri	Breathing rate (m3/d)	See Appendix J
BW	Body weight (kg)	See Appendix J
Cair	Concentration of contaminant in air (mg/m3)	Calculated in Table H-2.1
CSFInhal	Inhalation cancer slope factor (mg/kg/d)-1	See Section 2
EDi	Exposure duration for inhalation (yr)	See Appendix J
EFi	Exposure frequency (d/yr)	See Appendix J
TEF	Toxicity equivalency factor (unitless)	See Appendix D

Note: For adults with an ED greater than 50, AT is the ED plus 20. For children with an ED greater than 70, AT is the ED. Otherwise the AT is set to 70 years.

Table H-3.18. Risk_Oral - Risk Due to Ingestion (unitless)

Risk_Oral

$$Risk_{Oral} = TEF \times \frac{(I \times ED \times EF \times CSFOral)}{(AT \times 365)}$$

Name	Description	Location
365	Conversion factor (days/yr)	
AT	Averaging time (yr)	See Appendix J
CSFOral	Oral cancer slope factor (mg/kg/d)-1	See Section 2
ED	Exposure duration for oral ingestion (yr)	See Appendix J
EF	Exposure frequency (d/yr)	See Appendix J
TEF	Toxicity equivalency factor (unitless)	See Appendix D

Note: For adults with an ED greater than 50, AT is the ED plus 20. For children with an ED greater than 70, AT is the ED. Otherwise the AT is set to 70 years.

Appendix I

Variables for Aboveground Fate and Transport

Table I-1. Waterbody and Soil Parameters with Constant Values

Parameter Code	Parameter Description	Value
foc_bs	Fraction organic carbon for bed sediments (unitless)	0.04
foc_sw	Fraction organic carbon for suspended sediments (unitless)	0.075
bsc	Bed sediment concentration (kg/L)	1
bsp	Bed sediment porosity (cm^3/cm^3)	0.6
db	Depth of upper benthic layer (m)	0.03
dw	Depth of water column (m)	0.18
dz	Waterbody depth (m)	0.21
G	Gas phase transfer coefficient (m/yr)	36500
U	Velocity of the stream (m/s)	0.5
TSS	Total suspended solids in water column (mg/L)	10
Zt	Mixing depth of soil - tilled (cm) - pasture	20 2
Zu	Mixing depth of soil - untilled (cm)	1

Source: U.S. EPA (Environmental Protection Agency). 1998. *Methodology for Assessing Health Risks Associated with Multiple Pathways of Exposure to Combustor Emissions. Update to EPA/600/6-90/003 Methodology for Assessing Health Risks Associated with Indirect Exposure to Combustor Emissions.* EPA 600/R-98/137. Washington, DC: U.S. Government Printing Office.

Table I-2. Biota Parameters for Farm Food Chain Algorithms

Parameter Code	Parameter Description	Parameter Type	Value
Rp	Interception fraction (unitless)	Exposed fruit Exposed vegetables Forage Feed	0.48 0.48 0.35 0.62
VG	Empirical correction factor (unitless)	Exposed fruit Exposed vegetables Belowground roots Forage Feed	0.01 0.01 0.25 1.00 0.50
Yp	Crop yield (kg DW/m^2)	Exposed fruit Exposed vegetables Forage Feed	1.17 1.17 0.15 0.63
DF_beef	Fraction of diet from contaminated source for beef cattle (unitless)	Soil Forage Feed	0.04 0.48 0.48
DF_dairy	Fraction of diet from contaminated source for dairy cattle (unitless)	Soil Forage Feed	0.02 0.08 0.90
DF_poultry	Fraction of diet from contaminated source for poultry (unitless)	Soil Forage Feed	0.10 0.05 0
LF	Lipid fraction for fish (unitless)	Trophic Level 3 Trophic Level 4	0.0182 0.031
FF	Fraction of diet from feed lot for cattle (unitless)		1.00
Bs	Bioavailability for soil (unitless)		0.65

Source: U.S. EPA (Environmental Protection Agency). 2000. *Exposure and Human Health Reassessment of 2,3,7,8-Tetrachlorodibenzo-p-Dioxin (TCDD) and Related Compounds. Part I: Estimating Exposure to Dioxin-Like Compounds. Volume 4: Site-Specific Assessment Procedures.* Draft. Exposure Assessment and Risk Characterization Group, Office of Research and Development, Washington, DC. September.

Appendix J

Human Exposure Factors

Appendix J

Human Exposure Factors

Exposure factors are data that quantify human behavior patterns (e.g., ingestion rates of beef and fruit) and characteristics (e.g., body weight) that affect their exposure to environmental contaminants. These data can be used to construct realistic assumptions concerning an individual's exposure to and subsequent intake of a contaminant in the environment. The exposure factors data also enable the U.S. Environmental Protection Agency (EPA) to differentiate the exposures of individuals who have different lifestyles (e.g., a resident vs. a farmer and a child vs. an adult). The derivation and values used for the human exposure factors in this risk assessment are described here and the exposure factors selected for the probabilistic and deterministic analyses are presented.

J.1 Exposure Parameters Used in Probabilistic Analysis

J.1.1 Introduction

The general methodology for collecting human exposure data for the probabilistic analysis relied on the *Exposure Factors Handbook* (U.S. EPA, 1997a), which was used in one of three ways:

1. When *Exposure Factors Handbook* (EFH) percentile data were adequate (most input variables), maximum likelihood estimation was used to fit selected parametric models (gamma, lognormal, Weibull, and generalized gamma) to the EFH data. The chi-square measure of goodness of fit was then used to choose the best distribution. Parameter uncertainty information (e.g., for averages, standard deviations) also was derived using the asymptotic normality of the maximum likelihood estimate or a regression approach.

2. For a few variable conditions when percentile data were not adequate for statistical model fitting, models were selected on the basis of results for other age cohorts or, if no comparable information was available, by assuming lognormal as a default distribution and reasonable coefficients of variation (CVs).

3. Other variables for which data were not adequate for either 1 or 2 above were fixed at EFH-recommended mean values or according to established EPA policy.

Table J-1 summarizes all of the parameters used in the probabilistic analysis. Both fixed variables and the values used to define distributed data are provided.

J.1.2 Exposure Parameter Distribution Methodology

Exposure parameter distributions were developed for use in the Monte Carlo analysis. For most variables for which distributions were developed, exposure factor data from the EFH were analyzed to fit selected parametric models (i.e., gamma, lognormal, Weibull). Steps in the development of distributions included preparing data, fitting models, assessing fit, and preparing parameters to characterize distributional uncertainty in the model inputs.

For many exposure factors, EFH data include sample sizes and estimates of the following parameters for specific receptor types and age groups: mean, standard deviation, standard error, and percentiles corresponding to a subset of the following probabilities–0.01, 0.02, 0.05, 0.10, 0.15, 0.25, 0.50, 0.75, 0.85, 0.90, 0.95, 0.98, and 0.99. These percentile data were used as a basis for fitting distributions where available. Although in no case are all of these percentiles actually provided for a single factor, seven or more are typically present in the EFH data. Therefore, using the percentiles is a fuller use of the available information than simply fitting data based on the method of moments (e.g., selecting models that agree with the data mean and standard deviation). For some factors, certain percentiles were not used in the fitting process because sample sizes were too small to justify their use. Percentiles were used only if at least one data point was in the tail of the distribution. If the EFH data repeated a value across several adjacent percentiles, only one value (the most central or closest to the median) was used in most cases (e.g., if both the 98^{th} and 99^{th} percentiles had the same value, only the 98^{th} value was used).

The EFH does not use standardized age cohorts across exposure factors. Different exposure factors have data reported for different age categories. Therefore, to obtain the percentiles for fitting the four standardized age cohorts (i.e., ages 1 to 5, 6 to 11, 12 to 19, and more than 20), each EFH cohort-specific value for a given exposure factor was assigned to one of these four cohorts. When multiple EFH cohorts fit into a single cohort, the EFH percentiles were averaged within each cohort (e.g., data on 1- to 2- and 3- to 5-year-olds were averaged for the 1- to 5-year old cohort). If sample sizes were available, weighted averages were used, with weights proportional to sample sizes. If sample sizes were not available, equal weights were assumed (i.e., the percentiles were simply averaged).

Because the EFH data are always positive and almost always skewed to the right (i.e., have a long right tail), three two-parameter probability models commonly used to characterize such data (gamma, lognormal, and Weibull) were selected. In addition, a three-parameter model (generalized gamma) was used that unifies them[1] and allows for a likelihood ratio test of the fit of the two-parameter models. However, only the two-parameter models were selected for use in the analysis because the three-parameter generalized gamma model did not significantly improve the goodness of fit over the two-parameter models. This simple setup constitutes a considerable improvement over the common practice of using a lognormal model in which adequate EFH data were available to support maximum likelihood estimation. However, in a few cases (e.g.,

[1] Gamma, Weibull, and lognormal distributions are all special cases of the generalized gamma distribution.

Table J-1. Summary of Exposure Parameters used in Probabilistic Analysis

Parameter	Units	Variable Type	Constants	Mean (or shape)	Std Dev (or scale)	Minimum	Maximum	Reference
Averaging time for carcinogens	yr	Constant	7.00E+01					U.S. EPA (1989) (RAGS)
Body weight (adult)	kg	Lognormal		7.12E+01	1.33E+01	1.50E+01	3.00E+02	U.S. EPA (1997a); Tbl 7-2, 7-4, 7-5
Body weight (child 1)	kg	Lognormal		1.55E+01	2.05E+00	4.00E+00	5.00E+01	U.S. EPA (1997b); Tbl 7-3, 7-6, 7-7
Body weight (child 2)	kg	Lognormal		3.07E+01	5.96E+00	6.00E+00	2.00E+02	U.S. EPA (1997a); Tbl 7-3, 7-6, 7-7
Body weight (child 3)	kg	Lognormal		5.82E+01	1.02E+01	1.30E+01	3.00E+02	U.S. EPA (1997a); Tbl 7-3, 7-6, 7-7
Body weight (infant)	kg	Gamma		5.42E+01	1.70E-01	2.00E+00	2.60E+01	U.S. EPA (1997a); Tbl 7-3, 7-6, 7-7
Consumption rate: beef (adult farmer)	g WW/kg-d	Lognormal		2.50E+00	2.69E+00	0.00E+00	2.30E+01	U.S. EPA (1997b); Tbl 13-36
Consumption rate: beef (child 1 farmer)	g WW/kg-d	Lognormal		3.88E+00	4.71E+00	0.00E+00	3.60E+01	U.S. EPA (1997b); Tbl 13-36
Consumption rate: beef (child 2 farmer)	g WW/kg-d	Lognormal		3.88E+00	4.71E+00	0.00E+00	3.60E+01	U.S. EPA (1997b); Tbl 13-36
Consumption rate: beef (child 3 farmer)	g WW/kg-d	Gamma		2.47E+00	7.10E-01	0.00E+00	1.00E+01	U.S. EPA (1997b); Tbl 13-36
Consumption rate: breast milk (infant)	mL/d	Triangle		6.88E+02	6.88E+02	0.00E+00	1.38E+03	U.S. EPA (1997b); Tbl 14-16
Consumption rate: egg (adult farmer)	g WW/kg-d	Gamma		1.64E+00	4.88E-01	0.00E+00	1.30E+01	U.S. EPA (1997b); Tbl 11-7, 13-43; USDA (1997)
Consumption rate: egg (child 1 farmer)	g WW/kg-d	Gamma		1.88E+00	8.39E-01	0.00E+00	1.00E+01	U.S. EPA (1997b); Tbl 11-7, 13-43; USDA (1997)
Consumption rate: egg (child 2 farmer)	g WW/kg-d	Gamma		1.88E+00	4.93E-01	0.00E+00	6.00E+00	U.S. EPA (1997b); Tbl 11-7, 13-43; USDA (1997)
Consumption rate: egg (child 3 farmer)	g WW/kg-d	Gamma		1.88E+00	3.34E-01	0.00E+00	4.00E+00	U.S. EPA (1997b); Tbl 11-7, 13-43; USDA (1997)
Consumption rate: exposed fruit (adult farmer)	g WW/kg-d	Lognormal		2.36E+00	3.33E+00	0.00E+00	3.10E+01	U.S. EPA (1997b); Tbl 13-61

(continued)

Table J-1. (continued)

Parameter	Units	Variable Type	Constants	Mean (or shape)	Std Dev (or scale)	Minimum	Maximum	Reference
Consumption rate: exposed fruit (child 1 farmer)	g WW/kg-d	Gamma		1.43E+00	1.58E+00	0.00E+00	1.60E+01	U.S. EPA (1997b); Tbl 13-61
Consumption rate: exposed fruit (child 2 farmer)	g WW/kg-d	Lognormal		2.78E+00	5.12E+00	0.00E+00	3.60E+01	U.S. EPA (1997b); Tbl 13-61
Consumption rate: exposed fruit (child 3 farmer)	g WW/kg-d	Lognormal		1.54E+00	2.44E+00	0.00E+00	1.80E+01	U.S. EPA (1997b); Tbl 13-61
Consumption rate: exposed fruit (adult home gardener)	g WW/kg-d	Lognormal		1.57E+00	2.30E+00	0.00E+00	2.60E+01	U.S. EPA (1997b); Tbl 13-61
Consumption rate: exposed fruit (child 1 home gardener)	g WW/kg-d	Gamma		1.43E+00	1.58E+00	0.00E+00	1.60E+01	U.S. EPA (1997b); Tbl 13-61
Consumption rate: exposed fruit (child 2 home gardener)	g WW/kg-d	Lognormal		2.78E+00	5.12E+00	0.00E+00	3.60E+01	U.S. EPA (1997b); Tbl 13-61
Consumption rate: exposed fruit (child 3 home gardener)	g WW/kg-d	Lognormal		1.54E+00	2.44E+00	0.00E+00	1.80E+01	U.S. EPA (1997b); Tbl 13-61
Consumption rate: exposed vegetables (adult farmer)	g WW/kg-d	Lognormal		2.38E+00	3.50E+00	0.00E+00	2.60E+01	U.S. EPA (1997b); Tbl 13-63
Consumption rate: exposed vegetables (child 1 farmer)	g WW/kg-d	Gamma		9.70E-01	2.62E+00	0.00E+00	2.10E+01	U.S. EPA (1997b); Tbl 13-63
Consumption rate: exposed vegetables (child 2 farmer)	g WW/kg-d	Lognormal		1.64E+00	3.95E+00	0.00E+00	2.70E+01	U.S. EPA (1997b); Tbl 13-63
Consumption rate: exposed vegetables (child 3 farmer)	g WW/kg-d	Gamma		9.10E-01	1.19E+00	0.00E+00	1.10E+01	U.S. EPA (1997b); Tbl 13-63
Consumption rate: exposed vegetables (adult home gardener)	g WW/kg-d	Weibull		8.90E-01	1.48E+00	0.00E+00	2.10E+01	U.S. EPA (1997b); Tbl 13-63
Consumption rate: exposed vegetables (child 1 home gardener)	g WW/kg-d	Gamma		9.70E-01	2.62E+00	0.00E+00	2.10E+01	U.S. EPA (1997b); Tbl 13-63
Consumption rate: exposed vegetables (child 2 home gardener)	g WW/kg-d	Lognormal		1.64E+00	3.95E+00	0.00E+00	2.70E+01	U.S. EPA (1997b); Tbl 13-63
Consumption rate: exposed vegetables (child 3 home gardener)	g WW/kg-d	Gamma		9.10E-01	1.19E+00	0.00E+00	1.10E+01	U.S. EPA (1997b); Tbl 13-63
Consumption rate: fish (adult)	g/d	Lognormal		6.48E+00	1.99E+01	0.00E+00	1.50E+03	U.S. EPA (1997b); Tbl 10-64

(continued)

Table J-1. (continued)

Parameter	Units	Variable Type	Constants	Mean (or shape)	Std Dev (or scale)	Minimum	Maximum	Reference
Consumption rate: milk (adult farmer)	g WW/kg-d	Gamma		1.38E+00	1.19E+01	0.00E+00	1.16E+02	U.S. EPA (1997b); Tbl 13-28; CSFII (1997)
Consumption rate: milk (child 1 farmer)	g WW/kg-d	Gamma		9.61E-01	6.18E+01	0.00E+00	4.82E+02	U.S. EPA (1997b); Tbl 11-2, 13-28; USDA (1997)
Consumption rate: milk (child 2 farmer)	g WW/kg-d	Gamma		9.61E-01	3.14E+01	0.00E+00	2.45E+02	U.S. EPA (1997b); Tbl 11-2, 13-28; USDA (1997)
Consumption rate: milk (child 3 farmer)	g WW/kg-d	Gamma		9.61E-01	1.39E+01	0.00E+00	1.09E+02	U.S. EPA (1997b); Tbl 11-2, 13-28; USDA (1997)
Consumption rate: poultry (adult farmer)	g WW/kg-d	Gamma		1.38E+00	1.16E+00	0.00E+00	1.10E+01	U.S. EPA (1997b); Tbl 11-5, 13-55; USDA (1997)
Consumption rate: poultry (child 1 farmer)	g WW/kg-d	Gamma		1.69E+00	1.92E+00	0.00E+00	2.10E+01	U.S. EPA (1997b); Tbl 11-5, 13-55; USDA (1997)
Consumption rate: poultry (child 2 farmer)	g WW/kg-d	Gamma		1.69E+00	1.21E+00	0.00E+00	1.40E+01	U.S. EPA (1997b); Tbl 11-5, 13-55; USDA (1997)
Consumption rate: poultry (child 3 farmer)	g WW/kg-d	Gamma		1.69E+00	8.70E-01	0.00E+00	1.00E+01	U.S. EPA (1997b); Tbl 11-5, 13-55; USDA (1997)
Consumption rate: root vegetables (adult farmer)	g WW/kg-d	Lognormal		1.45E+00	2.06E+00	0.00E+00	1.50E+01	U.S. EPA (1997b); Tbl 13-65
Consumption rate: root vegetables (child 1 farmer)	g WW/kg-d	Lognormal		2.31E+00	6.05E+00	0.00E+00	4.10E+01	U.S. EPA (1997b); Tbl 13-65
Consumption rate: root vegetables (child 2 farmer)	g WW/kg-d	Weibull		6.80E-01	1.06E+00	0.00E+00	1.50E+01	U.S. EPA (1997b); Tbl 13-65
Consumption rate: root vegetables (child 3 farmer)	g WW/kg-d	Weibull		8.40E-01	9.10E-01	0.00E+00	9.00E+00	U.S. EPA (1997b); Tbl 13-65
Consumption rate: root vegetables (adult home gardener)	g WW/kg-d	Weibull		8.70E-01	1.07E+00	0.00E+00	1.50E+01	U.S. EPA (1997b); Tbl 13-65
Consumption rate: root vegetables (child 1 home gardener)	g WW/kg-d	Lognormal		2.31E+00	6.05E+00	0.00E+00	4.10E+01	U.S. EPA (1997b); Tbl 13-65

(continued)

Table J-1. (continued)

Parameter	Units	Variable Type	Constants	Mean (or shape)	Std Dev (or scale)	Minimum	Maximum	Reference
Consumption rate: root vegetables (child 2 home gardener)	g WW/kg-d	Weibull		6.80E-01	1.06E+00	0.00E+00	1.50E+01	U.S. EPA (1997b); Tbl 13-65
Consumption rate: root vegetables (child 3 home gardener)	g WW/kg-d	Weibull		8.40E-01	9.10E-01	0.00E+00	9.00E+00	U.S. EPA (1997b); Tbl 13-65
Exposure duration (adult resident)	yr	Weibull		1.34E+00	1.74E+01	1.00E+00	1.00E+02	U.S. EPA (1999) (ACS)
Exposure duration (child resident, child farmer)	yr	Weibull		1.32E+00	7.06E+00	1.00E+00	1.00E+02	U.S. EPA (1999) (ACS)
Exposure duration (adult farmer)	yr	Gamma		6.07E-01	2.98E+01	1.00E+00	1.00E+02	U.S. EPA (1997c); Tbl 15-163, 15-164
Exposure frequency	d/y	Constant	3.50E+02					U.S. EPA (1991)
Fraction home caught: fish	Fraction	Constant	1.00E+00					U.S. EPA policy
Fraction home-produced: beef (farmer)	Fraction	Constant	4.85E-01					U.S. EPA (1997b); Tbl 13-71
Fraction home-produced: milk (farmer)	Fraction	Constant	2.54E-01					U.S. EPA (1997b); Tbl 13-71
Fraction home-produced: egg (farmer)	Fraction	Constant	1.46E-01					U.S. EPA (1997b); Tbl 13-71
Fraction home-produced: poultry (farmer)	Fraction	Constant	1.56E-01					U.S. EPA (1997b); Tbl 13-71
Fraction contaminated: soil	Fraction	Constant	1.00E+00					U.S. EPA Policy
Fraction homegrown: exposed fruit (farmer)	Fraction	Constant	3.28E-01					U.S. EPA (1997b); Tbl 13-71
Fraction homegrown: exposed vegetables (farmer)	Fraction	Constant	4.20E-01					U.S. EPA (1997b); Tbl 13-71
Fraction homegrown: root vegetables (farmer)	Fraction	Constant	1.73E-01					U.S. EPA (1997b); Tbl 13-71
Fraction homegrown: exposed fruit (home gardener)	Fraction	Constant	1.16E-01					U.S. EPA (1997b); Tbl 13-71
Fraction homegrown: exposed vegetables (home gardener)	Fraction	Constant	2.33E-01					U.S. EPA (1997b); Tbl 13-71

(continued)

Table J-1. (continued)

Parameter	Units	Variable Type	Constants	Mean (or shape)	Std Dev (or scale)	Minimum	Maximum	Reference
Fraction homegrown: root vegetables (home gardener)	Fraction	Constant	1.06E-01					U.S. EPA (1997b); Tbl 13-71
Fraction food preparation loss: exposed fruit	Fraction	Constant	2.10E-01					U.S. EPA (1997b); Tbl 13-6
Fraction food preparation loss: exposed vegetables	Fraction	Constant	1.61E-01					U.S. EPA (1997b); Tbl 13-7
Fraction food preparation loss: root vegetables	Fraction	Constant	5.30E-02					U.S. EPA (1997b); Tbl 13-7
Percent cooking loss: beef	Fraction	Constant	2.70E-01					U.S. EPA (1997b); Tbl 13-5
Percent postcooking loss: beef	Fraction	Constant	2.40E-01					U.S. EPA (1997b); Tbl 13-5
Percent cooking loss: poultry	Fraction	Constant	3.20E-01					U.S. EPA (1997b); Tbl 13-5
Percent postcooking loss: poultry	Fraction	Constant	2.95E-01					U.S. EPA (1997b); Tbl 13-5
Fraction of fish consumed that is trophic level 3 (T3) fish	Fraction	Constant	3.60E-01					U.S. EPA (1997b); Tbl 10-66
Fraction of fish consumed that is trophic level 4 (T4) fish	Fraction	Constant	6.40E-01					U.S. EPA (1997b); Tbl 10-66
Ingestion rate: soil (adult)	kg/d	Constant	5.00E-05					U.S. EPA (1997a); Tbl 4-23
Ingestion rate: soil (child 1)	kg/d	Constant	1.00E-04					U.S. EPA (1997a); Tbl 4-23
Ingestion rate: soil (child 2)	kg/d	Constant	5.00E-05					U.S. EPA (1997a); Tbl 4-23
Ingestion rate: soil (child 3)	kg/d	Constant	5.00E-05					U.S. EPA (1997a); Tbl 4-23
Inhalation (breathing) rate (adult)	m^3/d	Lognormal		1.33E+01	3.99E+00	1.00E+00	5.00E+01	U.S. EPA (1997a), U.S. EPA (2000a)
Inhalation (breathing) rate (child 1)	m^3/d	Lognormal		7.55E+00	3.78E+00	1.00E+00	4.00E+01	U.S. EPA (1997a), U.S. EPA (2000a)
Inhalation (breathing) rate (child 2)	m^3/d	Lognormal		1.18E+01	3.53E+00	1.00E+00	4.50E+01	U.S. EPA (1997a), U.S. EPA (2000a)
Inhalation (breathing) rate (child 3)	m^3/d	Lognormal		1.40E+01	4.20E+00	1.00E+00	5.50E+01	U.S. EPA (1997a), U.S. EPA (2000a)

inhalation rate), data were not adequate to fit a distribution, and the lognormal model was assumed as the default.

Lognormal, gamma, Weibull, and generalized gamma distributions were fit to each factor data set using maximum likelihood estimation (Burmaster and Thompson, 1998). When sample sizes were available, the goodness of fit was calculated for each of the four models using the chi-square test (Bickel and Doksum, 1977). When percentile data were available but sample sizes were unknown, a regression F-test for the goodness of fit against the generalized gamma model was used. For each of the two-parameter models, parameter uncertainty information (i.e., mean, standard deviation, scale, and shape) was provided as parameter estimates for a bivariate normal distribution that could be used for simulating parameter values (Burmaster and Thompson, 1998). The information necessary for such simulations includes estimates of the two model parameters, their standard errors, and their correlation. To obtain this parameter uncertainty information, the asymptotic normality of the maximum likelihood estimate (Burmaster and Thompson, 1998) was used when sample sizes were available, and a regression approach was used when sample sizes were not available (Jennrich and Moore, 1975; Jennrich and Ralston, 1979). In either case, uncertainty can be expressed as a bivariate normal distribution for the model parameters.

This section describes how stochastic or distributed input data for each exposure factor were collected and processed. Section J.1.3 discusses fixed parameters. Section J.1.4 describes, for each exposure factor, the EFH data used to develop the distributions, along with the final distributional statistics. Section J.1.5 describes minimums and maximums. Summary tables provided at the end of this appendix (Tables J-17, J-18, J-19, and J-20) present the final (raw) EFH data used to develop each exposure factor distribution used and the models selected (i.e., lognormal, Weibull, or gamma) and estimated means and standard deviations for each of the two-parameter models fit to the exposure factors data.

J.1.3 Fixed Parameters

Certain parameters were fixed, based on central tendency values from the best available source (usually *Exposure Factors Handbook* recommendations), either because no variability was expected or because the available data were not adequate to generate distributions. Fixed (constant) parameters are shown in Table J-2 along with the value selected for the risk analysis and data source. These constants include variables for which limited or no percentile data were provided in the EFH: exposure frequency and fraction contaminated for the various media and foodstuffs. Most of these values were extracted directly from the EFH. The fraction contaminated for various foodstuffs was assumed to be equivalent to the fraction of household food intake that is attributed to home-produced forms of the food items evaluated (Table 13-71, U.S. EPA, 1997b). The fraction of consumed trophic level 3 (T3) and trophic level 4 (T4) fish was determined from data in Table 10-66 of the EFH (U.S. EPA, 1997b), which contains the only fish consumption data reported in the handbook with an adequate species breakdown to make this distinction. When evaluating carcinogens, total dose is averaged over the lifetime of the individual, assumed to be 70 years.

Table J-2. Summary of Human Exposure Factor Data Used in Modeling: Constants

Description	Units	Average	Source
Fraction homegrown: exposed fruit (farmer)	Fraction	0.328	EFH, Table 13-71
Fraction homegrown: exposed fruit (home gardener)	Fraction	0.116	EFH, Table 13-71
Fraction homegrown: exposed vegetables (farmer)	Fraction	0.42	EFH, Table 13-71
Fraction homegrown: exposed vegetables (home gardener)	Fraction	0.233	EFH, Table 13-71
Fraction homegrown: root vegetables (farmer)	Fraction	0.173	EFH, Table 13-71
Fraction homegrown: root vegetables (home gardener)	Fraction	0.106	EFH, Table 13-71
Fraction home-raised: beef (farmer)	Fraction	0.485	EFH, Table 13-71
Fraction home-produced: milk (farmer)	Fraction	0.254	EFH, Table 13-71
Fraction home-produced: egg (farmer)	Fraction	0.146	EFH, Table 13-71
Fraction home-produced: poultry (farmer)	Fraction	0.156	EFH, Table 13-71
Fraction food preparation loss: exposed fruit	Fraction	0.21	EFH, Table 13-6
Fraction food preparation loss: exposed vegetables	Fraction	0.161	EFH, Table 13-7
Fraction food preparation loss: root vegetables	Fraction	0.053	EFH, Table 13-7
Percent cooking loss: beef	Fraction	0.27	EFH, Table 13-5
Percent postcooking loss: beef	Fraction	0.24	EFH, Table 13-5
Percent cooking loss: poultry	Fraction	0.32	EFH, Table 13-5
Percent postcooking loss: poultry	Fraction	0.295	EFH, Table 13-5
Fraction home caught: fish (recreational fisher)	Fraction	1	EPA policy
Fraction of trophic level 3 (T3) fish consumed	Fraction	0.36	EFH, Table 10-66
Fraction of trophic level 4 (T4) fish consumed	Fraction	0.64	EFH, Table 10-66
Fraction contaminated: soil	Fraction	1	EPA policy
Exposure frequency (adult home gardener, fisher, farmer; child home gardener, farmer)	d/yr	350	EPA policy
Averaging time for carcinogens (adult home gardener, fisher, farmer; child home gardener, farmer)	yr	70	U.S. EPA, 1989, RAGS
Ingestion rate: soil (adult, 6- to 11-yr-old child, 12- to 19-yr-old child)	kg/d	5.0E-5	EFH, Table 4-23
Ingestion rate: soil (1- to 5-yr-old child)	kg/d	1.0E-4	EFH, Table 4-23
Biological half-life of contaminant in lactating women	d	2555	U.S. EPA, 1998, 2000b
Concentration in aqueous phase of maternal milk	mg/kg	0	U.S. EPA, 1998
Fraction of fat in maternal breast milk	Fraction	0.04	U.S. EPA, 1998, 2000b
Fraction of ingested contaminant absorbed by the infant	Fraction	0.9	U.S. EPA, 1998, 2000c
Fraction of ingested contaminant absorbed by the mother	Fraction	1	U.S. EPA, 1998
Fraction of mother's weight that is fat	Fraction	0.3	U.S. EPA, 1998, 2000b
Proportion of contaminant stored in maternal fat	Fraction	0.9	U.S. EPA, 1998, 2000b

Source: EFH (U.S. EPA, 1997a, 1997b, 1997c)

The fraction contaminated for soil was assumed to be 1 (i.e., all soil available for consumption at a site is potentially contaminated), with actual concentrations depending on fate and transport model results. Exposure frequency was set to 350 days per year in accordance with EPA policy, assuming that residents take an average of 2 weeks' vacation time away from their homes each year.

Mean soil ingestion rates were cited as 100 mg/d for children and 50 mg/d for adults (Table 4-23, U.S. EPA, 1997a). No percentile data were recommended for use in the EFH. Adult data were also used for the 6- to 11- and 12- to 19-yr-olds. The soil ingestion rates were not varied for the probabilistic analysis.

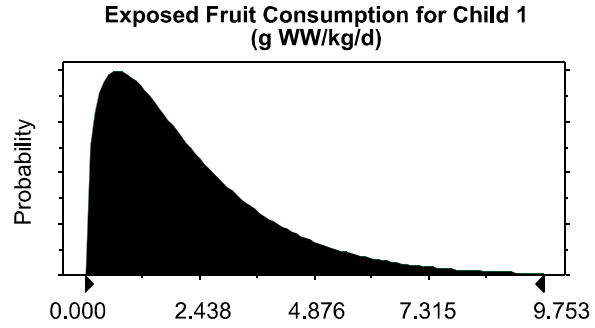
J.1.4 Variable Parameters

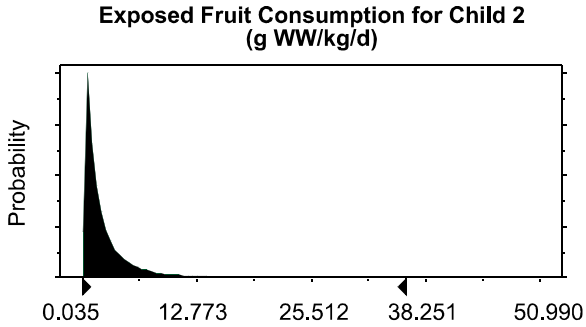
J.1.4.1 <u>Exposed Fruit Consumption</u>. Table J-3 presents exposed fruit consumption data. Data for consumption of homegrown exposed fruit were obtained from Table 13-61 of the EFH (U.S. EPA, 1997b). Data (in g WW/kg-d) were presented by age groups and for farmers and home gardeners (adults). For the 1- to 5-yr old age group, data were only available for those ages 3 to 5 years (not available for 1- to 2-yr-olds); therefore, these data were used for the entire 1- to 5-yr-old age group. Percentile data were used to fit parametric models (gamma, lognormal, and Weibull) using maximum likelihood estimation. Measures of goodness of fit were used to select the most appropriate model. The fraction of exposed fruit intake that is home-produced is 0.328 for households that farm and 0.116 for households that garden (Table 13-71, U.S. EPA, 1997b).

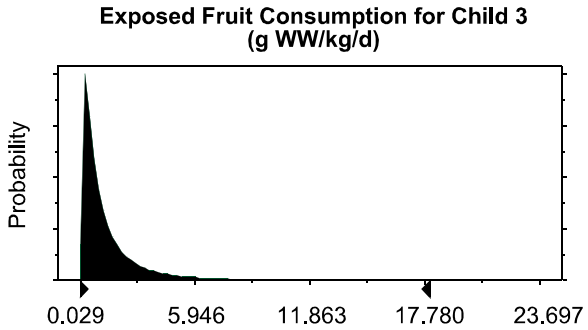
Table J-3. Exposed Fruit Consumption Data and Distributions

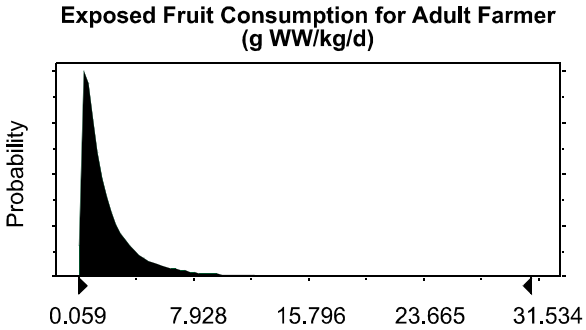
		EFH Data (g WW/kg-d)											Distributions		
Age Cohort	N	Data Mean	Data SDev	P01	P05	P10	P25	P50	P75	P90	P95	P99	Distribution	Pop-Estd Mean	Pop-Estd SDev
1-5	49	2.6	3.947			0.373	1	1.82	2.64	5.41	6.07		Gamma	2.25	1.89
6-11	68	2.52	3.496		0.171	0.373	0.619	1.11	2.91	6.98	11.7		Lognormal	2.78	5.12
12-19	50	1.33	1.457		0.123	0.258	0.404	0.609	2.27	3.41	4.78		Lognormal	1.54	2.44
Adult Farmer	112	2.32	2.646	0.072	0.276	0.371	0.681	1.3	3.14	5	6.12	15.7	Lognormal	2.36	3.33
Home gard.	596	1.55	2.226	0.042	0.158	0.258	0.449	0.878	1.73	3.41	5	12.9	Lognormal	1.57	2.3

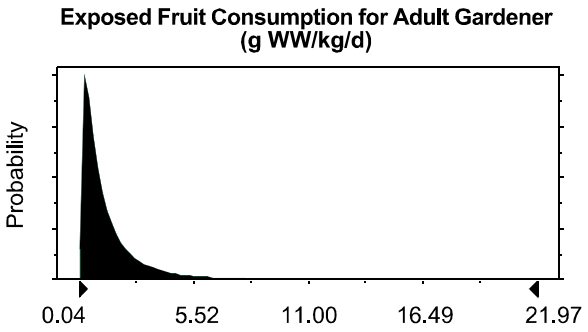
N = Number of samples; P01-P99 = Percentiles; Pop-Estd = Population-estimated; SDev = Standard deviation.


Exposed Fruit Consumption for Child 1
(g WW/kg/d)
Probability
0.000
2.438
4.876
7.315
9.753


Exposed Fruit Consumption for Child 2
(g WW/kg/d)
Probability
0.035
12.773
25.512
38.251
50.990


Exposed Fruit Consumption for Child 3
(g WW/kg/d)
Probability
0.029
5.946
11.863
17.780
23.697


Exposed Fruit Consumption for Adult Farmer
(g WW/kg/d)
Probability
0.059
7.928
15.796
23.665
31.534

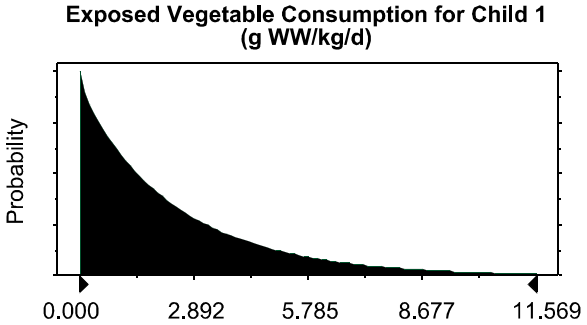

Exposed Fruit Consumption for Adult Gardener
(g WW/kg/d)
Probability
0.04
5.52
11.00
16.49
21.97

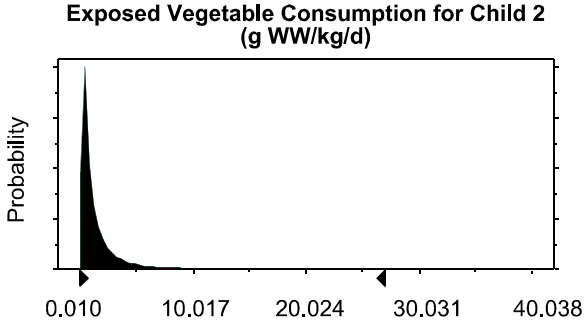
J.1.4.2 Exposed Vegetable Consumption. Table J-4 presents exposed vegetable consumption data and distribution. Data for consumption of homegrown exposed vegetables were obtained from Table 13-63 of the EFH (U.S. EPA, 1997b). Data (in g WW/kg/d) were presented for those ages 1 to 2, 3 to 5, 6 to 11, 12 to 19, 20 to 39, and 40 to 69 years, as well as farmers and home gardeners. Weighted averages of percentiles, means, and standard deviations were calculated for the 1- to 5-yr-old age group (combining groups of those ages 1 to 2 years and 3 to 5 years). Percentile data were used to fit parametric models (gamma, lognormal, and Weibull) using maximum likelihood estimation. Measures of goodness of fit were used to select the most appropriate model. The fraction of exposed vegetable intake that is home-produced is 0.42 for households that farm and 0.233 for households that garden (Table 13-71, U.S. EPA, 1997b).

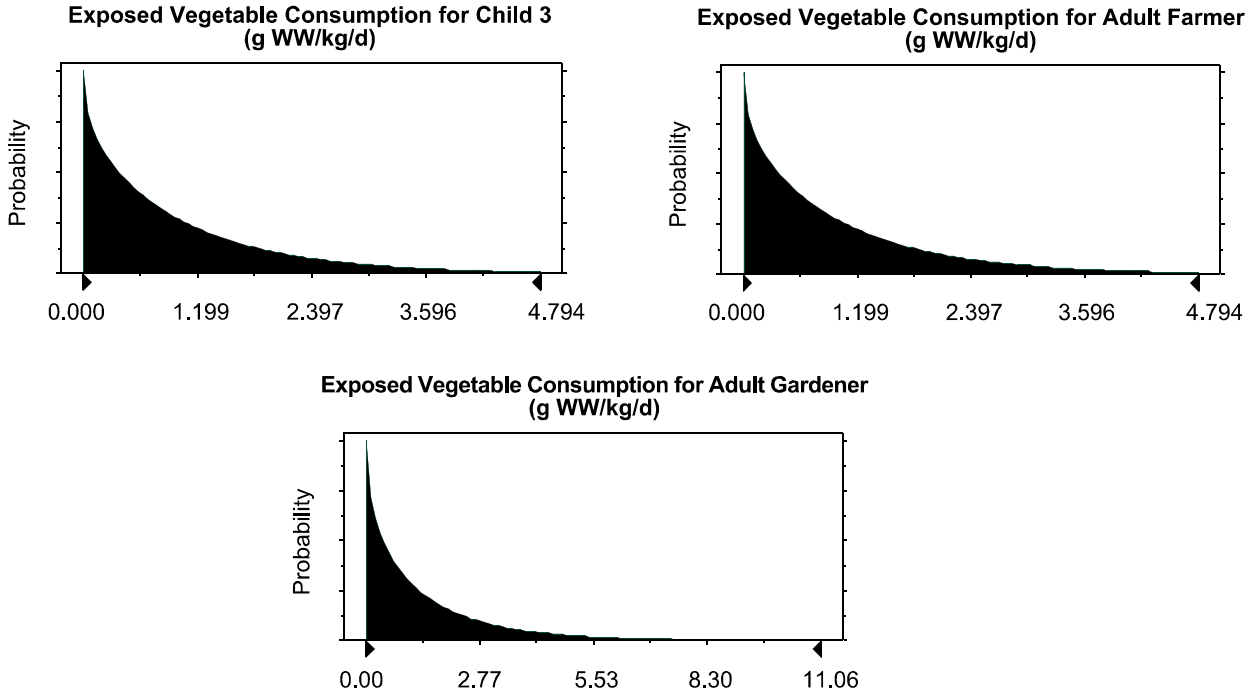
Table J-4. Exposed Vegetable Consumption Data and Distributions

Age Cohort	N	EFH Data (g WW/kg-d)											Distributions		
		Data Mean	Data SDev	P01	P05	P10	P25	P50	P75	P90	P95	P99	Distribution	Pop-Estd Mean	Pop-Estd SDev
1-5	105	2.453	2.675		0.102	0.37	0.833	1.459	3.226	6.431	8.587		Gamma	2.55	2.58
6-11	134	1.39	2.037		0.044	0.094	0.312	0.643	1.6	3.22	5.47	13.3	Lognormal	1.64	3.95
12-19	143	1.07	1.128		0.029	0.142	0.304	0.656	1.46	2.35	3.78	5.67	Gamma	1.08	1.13
Adult farmer	207	2.17	2.316		0.184	0.372	0.647	1.38	2.81	6.01	6.83	10.3	Lognormal	2.38	3.5
Home gard.	1,361	1.57	2.029	0.003	0.089	0.168	0.413	0.889	1.97	3.63	5.45	10.3	Weibull	1.57	1.76

N = Number of samples; P01-P99 = Percentiles; Pop-Estd = Population-estimated; SDev = Standard deviation.



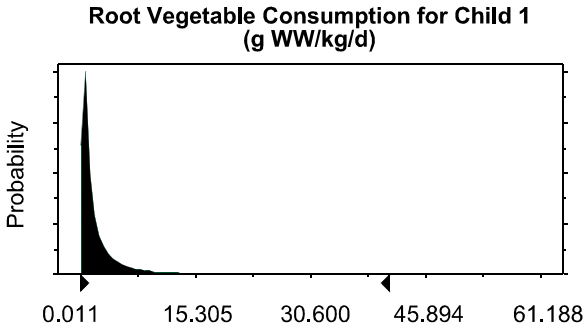


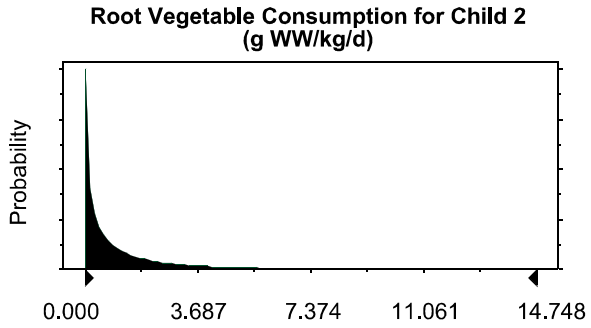


J.1.4.3 <u>Root Vegetable Consumption</u>. Table J-5 presents root vegetable consumption rate and distributions. Homegrown root vegetable consumption data were obtained from Table 13-65 of the EFH (U.S. EPA, 1997b). Data (in g WW/kg/d) were presented for those ages 1 to 2, 3 to 5, 6 to 11, 12 to 19, 20 to 39, 40 to 69 years, and adult farmers and home gardeners. Weighted averages of percentiles, means, and standard deviations were calculated for the child1 age group (combining groups of those ages 1 to 2 and 3 to 5 years). Percentile data were used to fit parametric models (gamma, lognormal, and Weibull) using maximum likelihood estimation. Measures of goodness of fit were used to select the most appropriate model. The fraction of root vegetable intake that is home-produced is 0.173 for households that farm and 0.106 for households that garden (Table 13-71, U.S. EPA, 1997b).

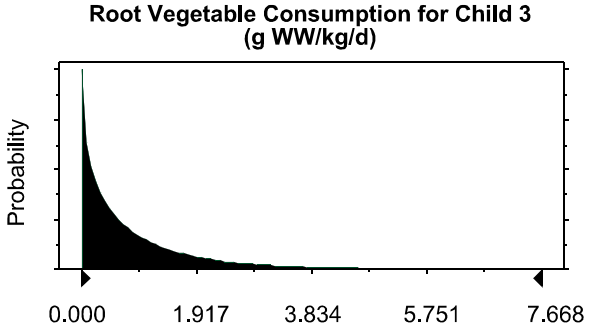
Table J-5. Root Vegetable Consumption Data and Distributions

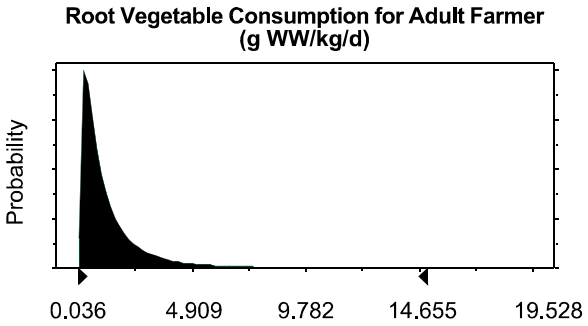
		EFH Data (g WW/kg-d)											Distributions		
Age Cohort	N	Data Mean	Data SDev	P01	P05	P10	P25	P50	P75	P90	P95	P99	Distribution	Pop-Estd Mean	Pop-Estd SDev
1-5	45	1.886	2.371		0.081	0.167	0.291	0.686	2.653	5.722	7.502		Lognormal	2.31	6.05
6-11	67	1.32	1.752		0.014	0.036	0.232	0.523	1.63	3.83	5.59		Weibull	1.38	2.07
12-19	76	0.937	1.037		0.008	0.068	0.269	0.565	1.37	2.26	3.32		Weibull	0.99	1.19
Adult farmer	136	1.39	1.469	0.111	0.158	0.184	0.365	0.883	1.85	3.11	4.58	7.47	Lognormal	1.45	2.06
home gard.	682	1.15	1.494	0.005	0.036	0.117	0.258	0.674	1.5	2.81	3.64	7.47	Weibull	1.15	1.32

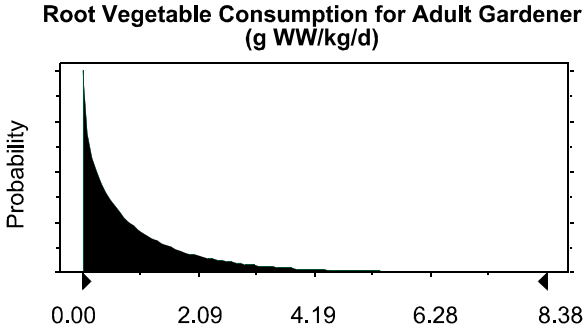




N = Number of samples; P01-P99 = Percentiles; Pop-Estd = Population-estimated; SDev = Standard deviation.







J.1.4.4 <u>Dairy Products (Milk) Consumption</u>. Table J-6 presents summary statistics on consumption of dairy products. Home-produced dairy product consumption rate data were obtained from Table 13-28 of the EFH (U.S. EPA, 1997b) for farmers, all ages combined, and individual age groups. No age-specific data for children were available for home-produced dairy products consumption. Per capita intake data for dairy products (including store-bought products), however, were available for those 1 to 2, 3 to 5, 6 to 11, and 12 to 19 years old from the EFH and from USDA (1997); the data in the EFH was based on the 1989-1991 CSFII and it was decided to use the more recent 1994-96 CSFII raw data. Therefore, data for the general population were used to calculate adjustment factors to develop distributions for the non-adult age groups for consumption of home-produced dairy products.

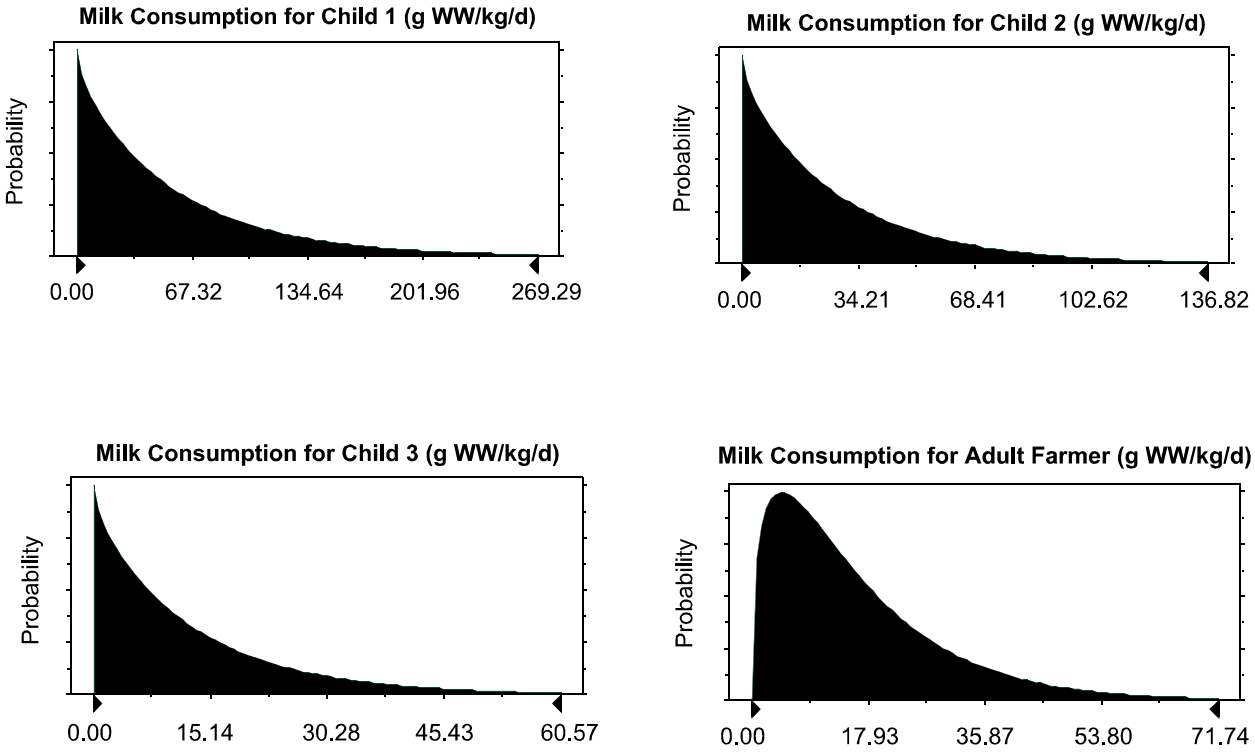
Percentile data (USDA, 1997) were used to fit parametric models (gamma, lognormal, and Weibull) using maximum likelihood estimation. Measures of goodness of fit were used to select gamma as the most appropriate model in all cases. Tables J-19 and J-20 (see end of appendix) provide the data used to develop the distributions and adjustment factors. It was assumed that the relative standard deviations (RSD) for consumption rates were the same for all age groups; the similarity of coefficients of variation (CV) suggest that this is a reasonable approximation for the general population. The other assumption used to develop distributions for the child age groups for the consumption of home-produced dairy products was that the mean intake rates have the same fixed ratio for all the age groups of a given food type. That is, the ratio of the mean amount consumed of home-produced dairy products divided by the mean amount of dairy products consumed in the general population is the same for any two age groups. These two assumptions, of constant RSD and constant mean ratio, were used to infer the parameters of the gamma distributions for the home-produced foods from those of the general population (i.e., mean, standard deviation, shape, and scale).

The fraction of dairy product intake that is home-produced is 0.254 for households that farm (Table 13-71, U.S. EPA, 1997b).

Table J-6. Dairy Products (Milk) Consumption Data and Distributions

		Data (g WW/kg-d)									Distributions		
Source	Age Cohort	Data Mean	Data SDev	P05	P10	P25	P50	P75	P90	P95	Distribution	Pop-Estd Shape	Pop-Estd Scale
CSFII (gen)	All	6.81	10.8	0.199	0.392	1.14	3.25	7.59	16.9	26.1			
CSFII (gen)	1-5	27.4	22.3	1.12	4.39	12.2	22.3	37.1	55.9	70.1			
CSFII (gen)	6-11	14	10	0.826	2.16	6.48	12.3	19.2	27.3	33.5			
CSFII (gen)	12-19	6.2	5.87	0.264	0.484	1.88	4.55	8.88	13.5	17.8			
CSFII (gen)	20-69	3.23	3.3	0.162	0.303	0.854	2.22	4.48	7.45	9.88			
HP	1-5										Gamma	0.961	61.80
HP	6-11										Gamma	0.961	31.40
HP	12-19										Gamma	0.961	13.90
EFH (HP)	20_39	7.41	6.12	0.396	0.446	1.89	6.46	12.1	15.4	19.5	Gamma	0.961	8.01
EFH (HP)	All	14	15.28	0.446	0.508	3.18	10.2	19.5	34.2	44	Gamma	0.78	18.26
EFH (HP)	Adult farmer	17.1	15.8	0.736	3.18	9.06	12.1	20.4	34.9	44	Gamma	1.38	11.85

CSFII = USDA (1997); gen = general population data; EFH = U.S. EPA (1997b); HP = home-produced data; P05-P95 = Percentiles; Sdev = standard deviation; Pop-Estd = population-estimated



J.1.4.5 <u>Beef Consumption</u>. Table J-7 presents beef consumption data and distributions. Home-produced beef consumption data were obtained from Table 13-36 of the EFH (U.S. EPA, 1997b). Data (in g WW/kg-d) were presented for farmers and those 6 to 11, 12 to 19, 20 to 39, and 40 to 69 years old. Percentile data were used to fit parametric models (gamma, lognormal, and Weibull) using maximum likelihood estimation. Measures of goodness of fit were used to select the most appropriate model.

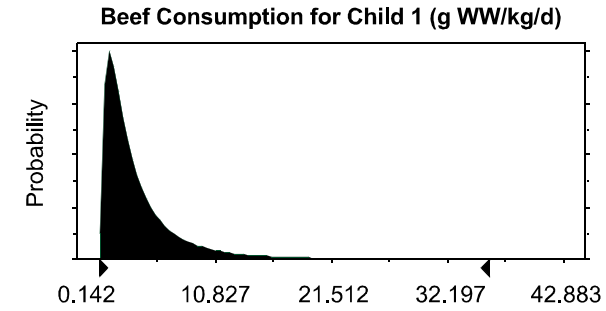
Data were not available for those 1 to 2 and 3 to 5 years old. For beef consumption for 1- to 5-yr-olds, the lognormal model was used because, among the other age groups, it was the best-fitted model in all but one case. The population-estimated mean and standard deviation for 6- to 11-yr-olds were used for 1- to 5-yr-olds for the analysis (normalized for body weight) and are supported by data in Table 11-3 (per capita intake for beef, including store-bought products), which indicate that those 1 to 2, 3 to 5, and 6 to 11 years old have the highest consumption rate of beef on a gram/kilogram/day basis. The fraction of beef intake that is home-produced is 0.485 for households that farm (Table 13-71, U.S. EPA, 1997b).

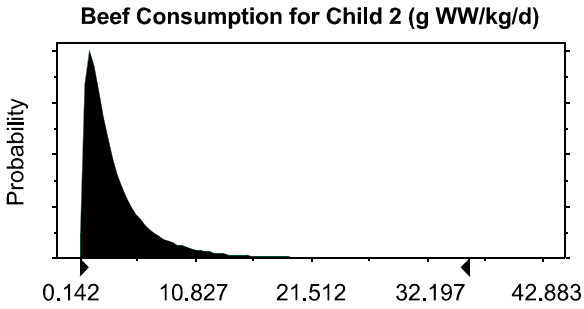
Beef consumption rate data were adjusted to account for food preparation and cooking losses. A mean net cooking loss of 27 percent accounts for dripping and volatile losses during cooking (averaged over various cuts and preparation methods). A mean net postcooking loss of 24 percent accounts for losses from cutting, shrinkage, excess fat, bones, scraps, and juices. These data were obtained from Table 13-5 of the EFH (U.S. EPA, 1997b).

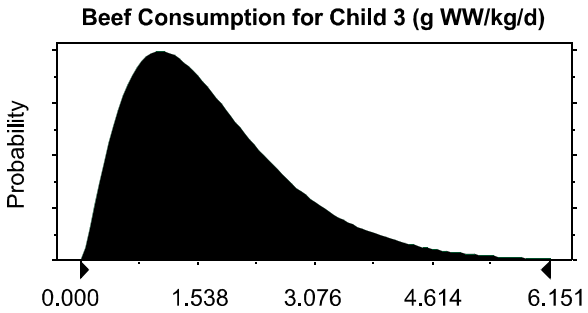
Table J-7. Beef Consumption Data and Distributions

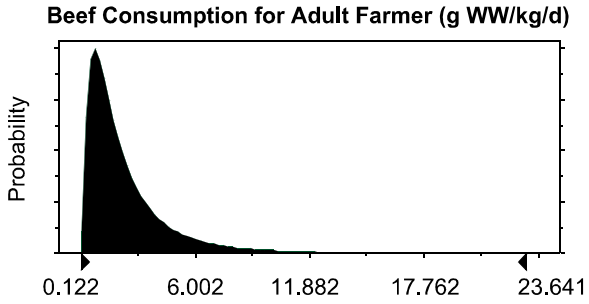
Age Cohort	N	EFH Data (g WW/kg-d)											Distributions		
		Data Mean	Data SDev	P01	P05	P10	P25	P50	P75	P90	P95	P99	Distribution	Pop-Estd Mean	Pop-Estd SDev
1-5		ND	ND										Lognormal	3.88	4.71
6-11	38	3.77	3.662		0.663	0.753	1.32	2.11	4.43	11.4	12.5		Lognormal	3.88	4.71
12-19	41	1.72	1.044		0.478	0.513	0.896	1.51	2.44	3.53	3.57		Gamma	1.77	1.12
Adult farmer	182	2.63	2.644	0.27	0.394	0.585	0.896	1.64	3.25	5.39	7.51	11.3	Lognormal	2.5	2.69

N = Number of samples; P01-P99 = Percentiles; Pop-Estd = Population-estimated; SDev = Standard deviation.









J.1.4.6 <u>Egg Consumption</u>. Table J-8 presents summary statistics on consumption of eggs. Home-produced egg consumption rate data were obtained from Table 13-43 of the EFH (U.S. EPA, 1997b) for farmers, all ages combined, and individual age groups 20-39 and 40-69; statistics for the 20- to 69-yr-old age group were calculated as simple averages of the statistics for the 20- to-39- and 40- to 69-yr-old age groups. No age-specific data for children were available for home-produced egg consumption. Per capita intake data for eggs (including store-bought products), however, were available for those 1 to 2, 3 to 5, 6 to 11, and 12 to 19 years old from the EFH and from USDA (1997); the data in the EFH were based on the 1989-1991 CSFII and it was decided to use the more recent 1994-1996 CSFII raw data. Therefore, data for the

general population were used to calculate adjustment factors to develop distributions for the nonadult age groups for consumption of home-produced eggs.

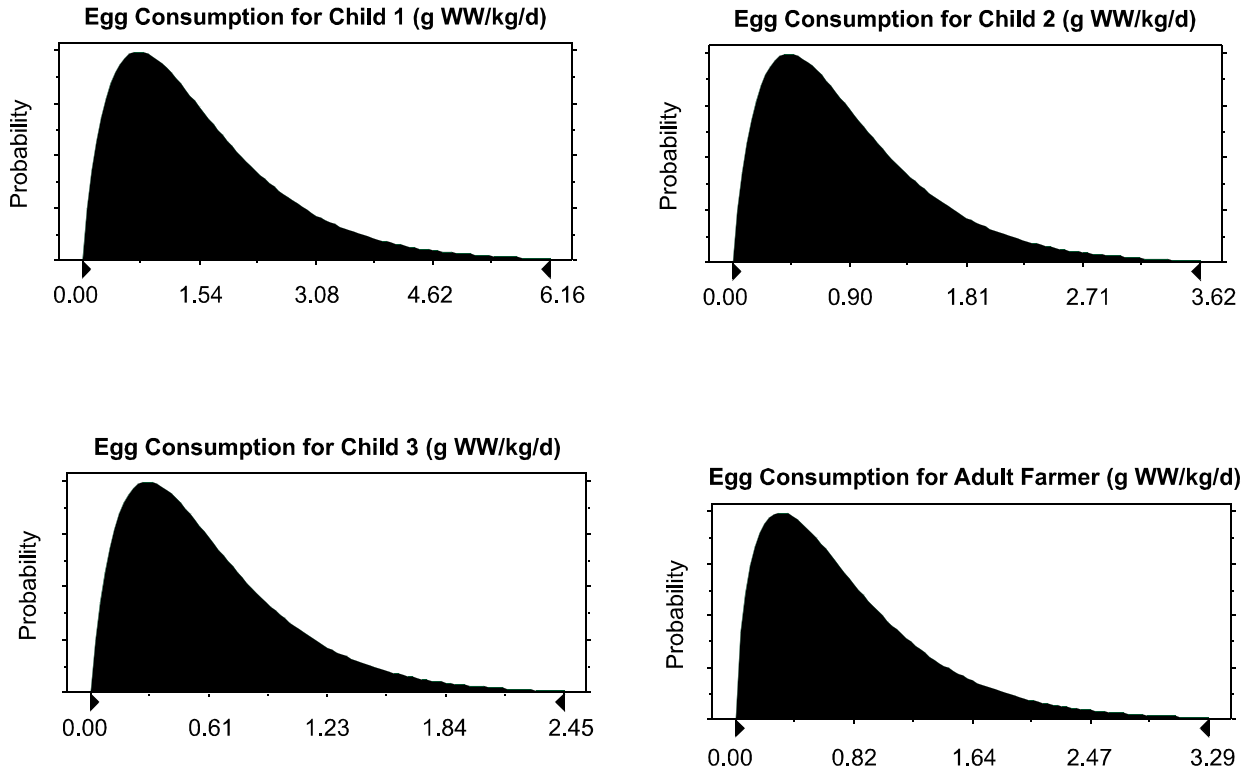
Percentile data (USDA, 1997) were used to fit parametric models (gamma, lognormal, and Weibull) using maximum likelihood estimation. Measures of goodness of fit were used to select gamma as the most appropriate model in all cases. Tables J-19 and J-20 (see end of appendix) provide the data used to develop the distributions and adjustment factors. It was assumed that the relative standard deviations (RSD) for consumption rates were the same for all age groups; the similarity of coefficients of variation (CV) suggest that this is a reasonable approximation for the general population. The other assumption used to develop distributions for the child age groups for the consumption of home-produced eggs was that the mean intake rates have the same fixed ratio for all the age groups of a given food type. That is, the ratio of the mean amount consumed of home-produced eggs divided by the mean amount of eggs consumed in the general population is the same for any two age groups. These two assumptions, of constant RSD and constant mean ratio, were used to infer the parameters of the gamma distributions for the home-produced foods from those of the general population (i.e., mean, standard deviation, shape, and scale).

The fraction of egg intake that is home-produced is 0.146 for households that farm (Table 13-71, U.S. EPA, 1997b).

Table J-8. Egg Consumption Data and Distributions

Source	Age Cohort	Data (g WW/kg-d)									Distributions		
		Data Mean	Data SDev	P05	P10	P25	P50	P75	P90	P95	Distribution	Pop-Estd Shape	Pop-Estd Scale
CSFII (gen)	All	1.01	1.04	0.133	0.253	0.422	0.724	1.22	1.99	2.82			
CSFII (gen)	1-5	2.41	1.94	0.101	0.328	1.16	1.88	3.23	5.03	6.15			
CSFII (gen)	6-11	1.44	1.25	0.125	0.302	0.641	1.08	1.87	2.95	3.45			
CSFII (gen)	12-19	0.962	0.708	0.092	0.328	0.469	0.821	1.22	1.71	2.24			
CSFII (gen)	20-69	0.792	0.663	0.145	0.248	0.389	0.633	1.01	1.52	1.88			
HP	1-5										Gamma	1.88	0.839
HP	6-11										Gamma	1.88	0.493
HP	12-19										Gamma	1.88	0.334
EFH (HP)	20-69	0.611	0.442	0.106	0.183	0.308	0.465	0.829	1.31	1.645	Gamma	1.88	0.336
EFH (HP)	All	0.731	1.114	0.15	0.175	0.268	0.466	0.902	1.36	1.69	Gamma	1.81	0.357
EFH (HP)	Adult farmer	0.898	1.128	0.165	0.177	0.272	0.666	1.19	1.65	1.85	Gamma	1.64	0.488

CSFII = USDA (1997); gen = general population data; EFH = U.S. EPA (1997b); HP = home-produced data; Sdev = standard deviation; Pop-Estd = population-estimated



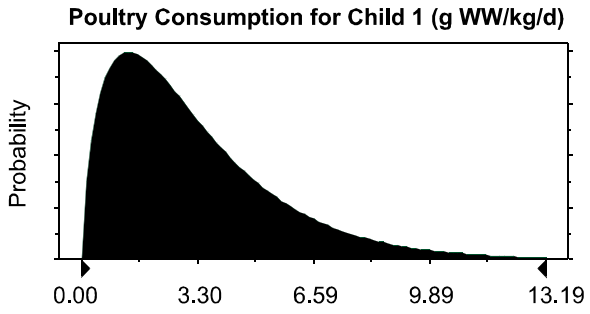
J.1.4.7 <u>Poultry Consumption</u>. Table J-9 presents summary statistics on consumption of poultry. Home-produced poultry consumption rate data were obtained from Table 13-55 of the EFH (U.S. EPA, 1997b) for farmers, all ages combined, and individual age groups 20 to 39 and 40 to 69; statistics for the 20- to 69-yr-old age group were calculated as simple averages of the statistics for the 20- to 39 and 40- to 69-yr-old age groups. No age-specific data for children were available for home-produced poultry consumption. Per capita intake data for poultry (including store-bought products), however, were available for those 1 to 2, 3 to 5, 6 to 11, and 12 to 19 years old from the EFH and from USDA (1997); the data in the EFH were based on the 1989-1991 CSFII and it was decided to use the more recent 1994-1996 CSFII raw data. Therefore, data for the general population were used to calculate adjustment factors to develop distributions for the nonadult age groups for consumption of home-produced poultry.

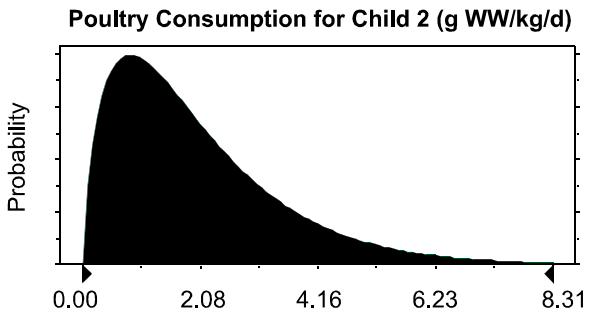
Percentile data (USDA, 1997) were used to fit parametric models (gamma, lognormal, and Weibull) using maximum likelihood estimation. Measures of goodness of fit were used to select gamma as the most appropriate model in all cases. Tables J-19 and J-20 (see end of appendix) provide the data used to develop the distributions and adjustment factors. Constant RSD and constant mean ratio were assumed and these data were used to infer the parameters of the gamma distributions for the home-produced foods from those of the general population (i.e., mean, standard deviation, shape, and scale). The fraction of poultry intake that is home-produced is 0.156 for households that farm (Table 13-71, U.S. EPA, 1997b).

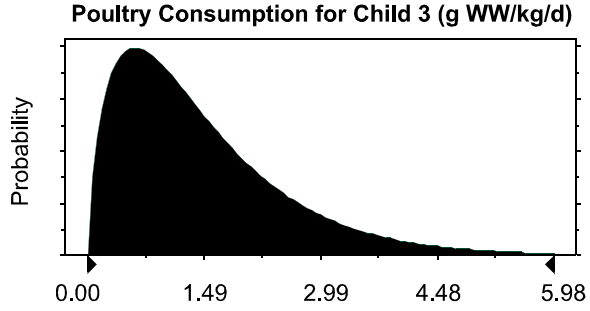
Table J-9. Poultry Consumption Data and Distributions

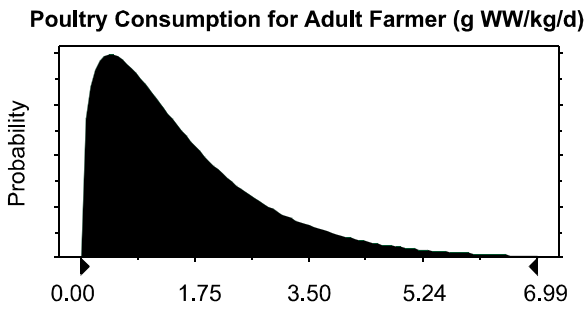
Source	Age Cohort	Data (g WW/kg-d)									Distributions		
		Data Mean	Data SDev	P05	P10	P25	P50	P75	P90	P95	Distribution	Pop-Estd Shape	Pop-Estd Scale
CSFII (gen)	All	0.688	0.942	0.018	0.034	0.111	0.334	0.917	1.76	2.47			
CSFII (gen)	1-5	1.43	1.73	0.025	0.056	0.192	0.736	2.2	3.63	4.66			
CSFII (gen)	6-11	0.884	1.15	0.019	0.036	0.116	0.365	1.29	2.42	3.22			
CSFII (gen)	12-19	0.645	0.795	0.019	0.034	0.103	0.346	0.896	1.71	2.23			
CSFII (gen)	20-69	0.57	0.712	0.017	0.032	0.105	0.303	0.804	1.4	1.92			
HP	1-5										Gamma	1.69	1.92
HP	6-11										Gamma	1.69	1.21
HP	12-19										Gamma	1.69	0.87
EFH (HP)	20-69	1.34	1.088	0.299	0.352	0.524	0.962	2.03	2.545	3.765	Gamma	1.69	0.80
EFH (HP)	All	1.57	1.178	0.303	0.418	0.637	1.23	2.19	3.17	3.83	Gamma	1.83	0.85
EFH (HP)	Adult farmer	1.54	1.375	0.228	0.303	0.595	1.06	2.18	3.47	4.83	Gamma	1.38	1.16

CSFII = USDA (1997); gen = general population data; EFH = U.S. EPA (1997b); HP = home-produced data; P05-P95 = Percentiles; Sdev = standard deviation; Pop-Estd = population-estimated







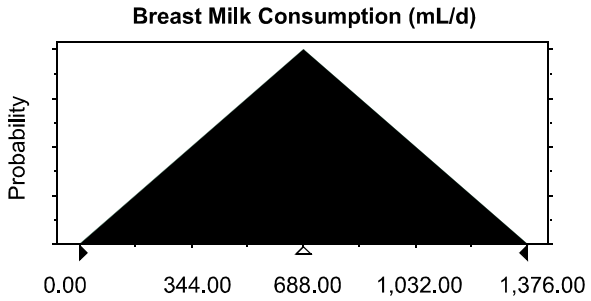


J.1.4.8 Breast Milk Consumption. Table J-10 presents breast milk consumption data for infants. The data mean and upper percentile for breast milk consumption in 1- to 12-month-olds were 688 and 980 mL/d, respectively (Table 14-16, U.S. EPA, 1997b). The triangular model was used for breast milk consumption (12-month-olds) because no percentile or related data were available; other distributions (e.g., lognormal) resulted in overestimation of the upper percentile. The EFH population mean for breast milk consumption was 688 mL/d and was assumed to equal the mode.

Table J-10. Breast Milk Consumption Data and Distribution

Age Cohort	Data Mean (mL/d)	Data SDev	Upper Percentile	Distribution	Pop-Estd Mode (mL/d)	Pop-Estd SDev (mL/d)
<1	688	ND	980	Triangular	688	688

Pop-Estd = population-estimated; SDev = Standard deviation.
ND =



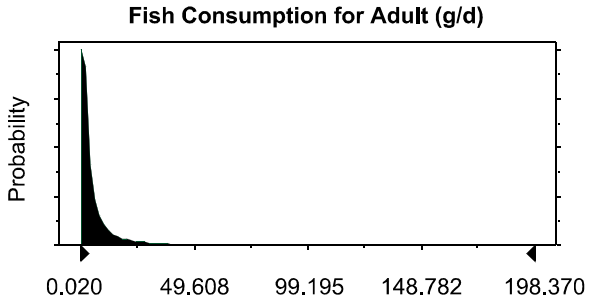
J.1.4.9 Fish Consumption. Table J-11 presents fish consumption data and distribution. Fish consumption data were obtained from Table 10-64 of the EFH (U.S. EPA, 1997b). Data (in g/d) were available for adult freshwater anglers in Maine. The Maine fish consumption study was one of four recommended freshwater angler studies in the EFH (U.S. EPA, 1997b). The other recommended fish consumption studies (i.e., Michigan and New York) had large percentages of anglers who fished from the Great Lakes, which is not consistent with the modeling scenarios used in this risk analysis. The anglers in the Maine study fished from streams, rivers, and ponds; these data are more consistent with modeling scenarios for this risk analysis. Although the Maine data have a lower mean than the Michigan data, the Maine data compared better with a national U.S. Department of Agricultural (USDA) study. Also, the Maine study had percentile data available, which were necessary to develop a distribution.

Percentile data were used to fit parametric models (gamma, lognormal, and Weibull) and measures of goodness of fit were used to select lognormal as the most appropriate model. The fraction of fish intake that is locally caught is 0.325 for adult fishers (Table 13-71, U.S. EPA, 1997b). The fraction of consumed trophic level 3 (T3) and trophic level 4 (T4) fish was 0.36 and 0.64, respectively (Table 10-66, U.S. EPA, 1997b).

Table J-11. Fish Consumption Data and Distributions

Age Cohort	N	EFH Data (g/d)							Distributions		
		Data Mean	Data SDev	P50	P66	P75	P90	P95	Distribution	Pop-Estd Mean	Pop-Estd SDev
Adult	1,053	6.4		2	4	5.8	13	26	Lognormal	6.48	19.9

N = Number of samples; P50-P95 = Percentiles; Pop-Estd = Population-estimated; SDev = Standard deviation.

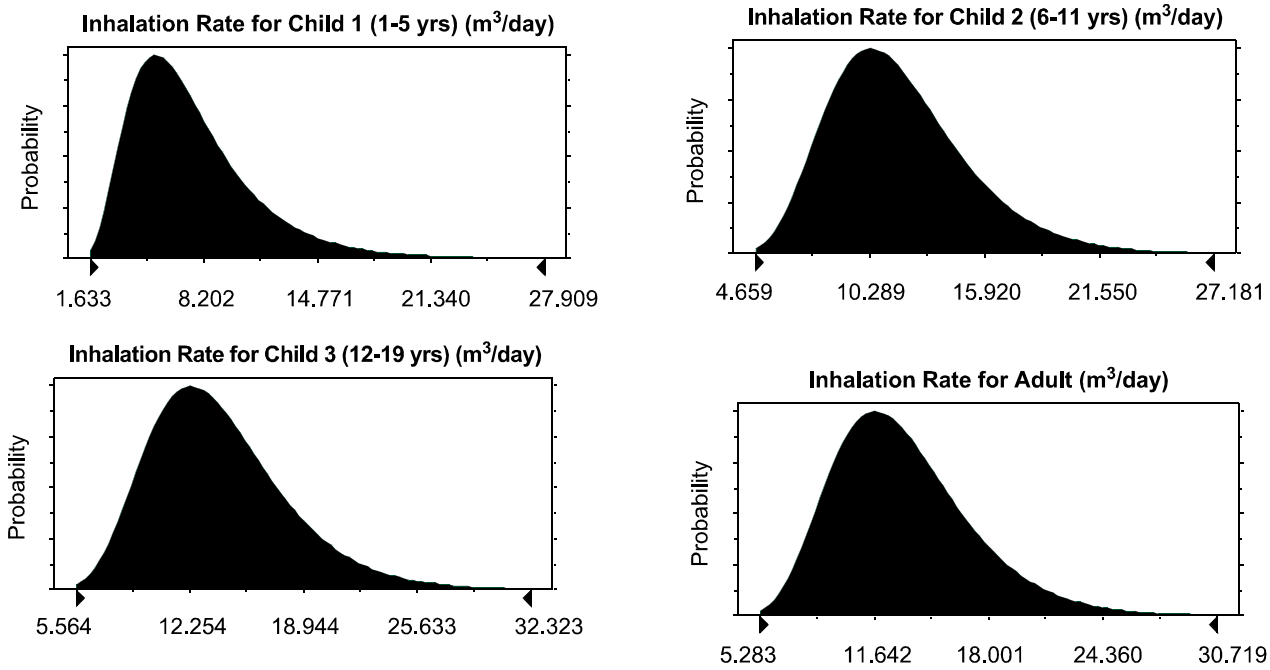


J.1.4.10 <u>Inhalation Rate</u>. Table J-12 presents inhalation rate data and distribution. No percentile data were available for the inhalation rate, and the default lognormal model was assumed. In an analysis of inhalation data, Myers et al. (U.S. EPA, 2000a) found that, for those younger than 3 years, CV was close to 70 percent; for other age groups, it was close to 30 percent. The lognormal distribution was fitted by using CV=50 percent [(30+70)/2] for the 1- to 5-yr-old age group and CV=30 percent for the 6- to 11-yr-olds, 12- to 19-yr-olds, and adult age groups.

Table J-12. Inhalation Rate Data and Distribution

Age Cohort	Distribution	Population-Estimated Mean (m^3/d)	Population-Estimated SDev (m^3/d)
1-5	Lognormal	7.55	3.78
6-11	Lognormal	11.75	3.53
12-19	Lognormal	14.0	4.2
Adult	Lognormal	13.3	3.99

SDev = Standard deviation.

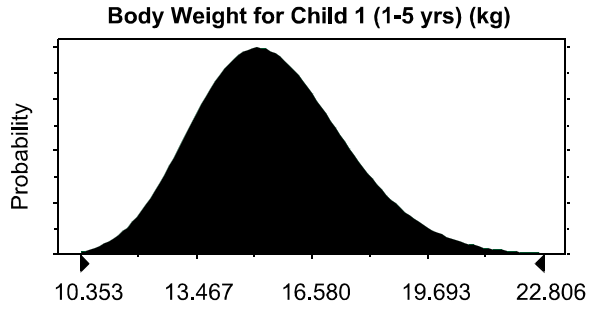


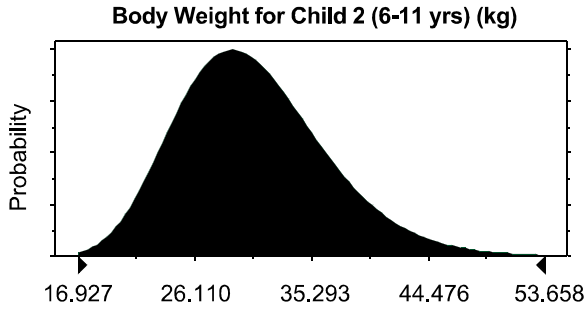
J.1.4.11 <u>Body Weight</u>. Table J-13 presents body weight data and distribution. Body weight data were obtained from Tables 7-2 through 7-7 of the EFH (U.S. EPA, 1997a). Data (in kg) were presented by age and gender. Weighted averages of percentiles, means, and standard deviations were calculated for infants (<1 year old), 1- to 5-yr-olds, 6- to 11-yr-olds, 12- to 19-year olds, and adult age groups; male and female data were weighted and combined for each age group. These percentile data were used as the basis for fitting distributions. These data were analyzed to fit parametric models (gamma, lognormal, and Weibull) using maximum likelihood estimation. Measures of goodness of fit were used to select the most appropriate model.

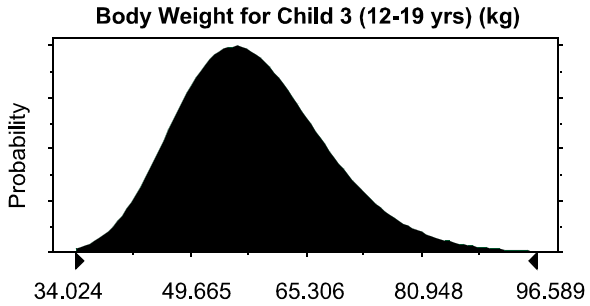
Table J-13. Body Weight Data and Distributions

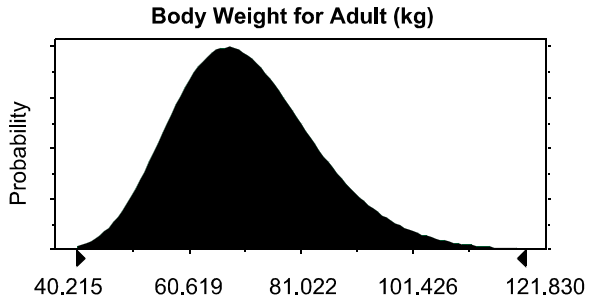
		EFH Data (kg)											Distributions		
Age Cohort	N	Data Mean	Data SDev	P05	P10	P15	P25	P50	P75	P85	P90	P95	Distribution	Pop-Estd Mean	Pop-Estd SDev
<1	356	9.102	1.287	7.053	7.451	7.852	8.252	9.151	9.752	10.4	10.65	11.15	Gamma	9.09	1.23
1-5	3,762	15.52	3.719	12.5	13.1	13.45	14.03	15.26	16.67	17.58	18.32	19.45	Lognormal	15.5	2.05
6-11	1,725	30.84	9.561	22.79	24.05	25.07	26.44	29.58	33.44	36.82	39.66	43.5	Lognormal	30.7	5.96
12-19	2,615	58.45	13.64	43.84	46.52	48.31	50.94	56.77	63.57	68.09	71.98	79.52	Lognormal	58.2	10.2
20+	12,504	71.41	15.45	52.86	55.98	58.21	61.69	69.26	78.49	84.92	89.75	97.64	Lognormal	71.2	13.3

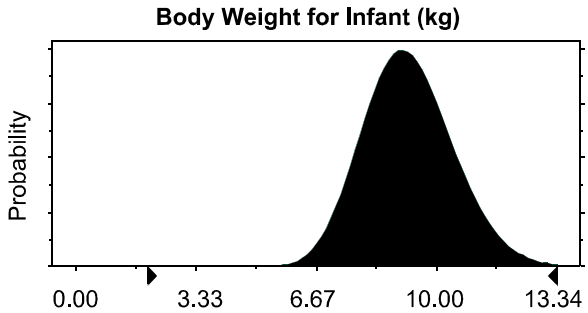
N = Number of samples; P05-P95 = Percentiles; Pop-Estd = Population-estimated; SDev = Standard deviation.











J.1.4.12 <u>Exposure Duration</u>. Table J-14 presents exposure duration data and distributions. Exposure duration was assumed to be equivalent to the average residence time for each receptor. Exposure durations for adult residents and children (resident and farmer) were determined using data on residential occupancy from the EFH, Table 15-168 (U.S. EPA, 1997c). The data represent the total time a person is expected to live at a single location, based on age. The table presented male and female data combined. For adult residents, age groups from 21 to 90 were pooled. For children, the 3-yr-old age group was used for the 1- to 5-yr-olds.

In an analysis of residential occupancy data, Myers et al. (U.S. EPA, 2000a) found that the data, for most ages, were best fit by a Weibull distribution. The Weibull distribution as implemented in Crystal Ball® is characterized by three parameters: location, shape, and scale. Location is the minimum value and, in this case, was presumed to be 0. Shape and scale were determined by fitting a Weibull distribution to the pooled data, as follows. To pool residential occupancy data for the age cohorts, an arithmetic mean of data means was calculated for each age group. Then, assuming a Weibull distribution, the variance within each age group (e.g., 6-

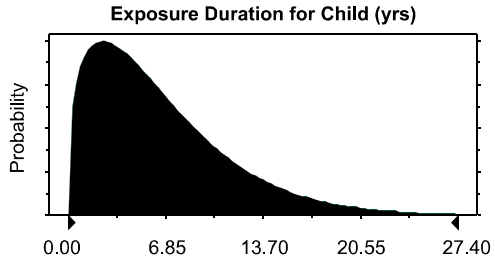
yr-olds) was calculated in the age cohort. These variances in turn were pooled over the age cohort using equal weights. This is not the usual type of pooled variance, which would exclude the variation in the group means. However, this way the overall variance reflected the variance of means within the age groups (e.g., within the 6-yr-old age group). The standard deviation was estimated as the square root of the variance. The coefficient of variation was calculated as the ratio of the standard deviation divided by the Weibull mean. For each cohort, the population-estimated parameter uncertainty information (e.g., shape and scale) was calculated based on a Weibull distribution, the calculated data mean for the age cohort, and the CV.

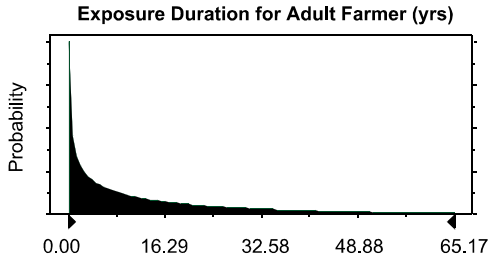
Exposure duration for adult farmers was determined using data on residential occupancy from the EFH, Tables 15-163 and 15-164 (U.S. EPA, 1997c). The data represent the total time a person is expected to live at a single location, based on household type. Age-specific data were not provided. For residence duration of farmers (U.S. EPA 1997c, Tables 15-163 and 15-164), the gamma model was used because it was the best-fitted model in five age groups and was the second-best-fitted model in two cases (based on data in U.S. EPA 1997c, Tables 15-167 and 15-168). A population mean of 18.07 years and a population standard deviation of 23.19 years were calculated for adult farmers.

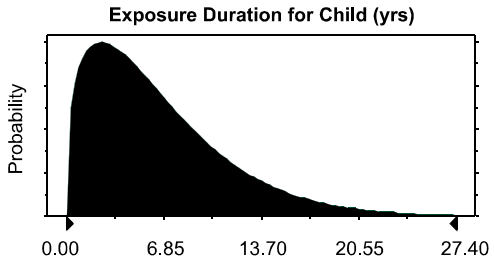
Table J-14. Exposure Duration Data and Distributions

EFH Data		Distributions		
Age Cohort	**Data Mean (yr)**	**Distribution**	**Pop-Estd Shape (yr)[a]**	**Pop-Estd Scale (yr)**
Child (1- to 5-yr-olds)	6.5	Weibull	1.32	7.059
Adult resident	16.0	Weibull	1.34	17.38
Adult farmer	18.75	Gamma	0.607	29.76

Pop-Estd = Population-estimated.
[a] Distributions used in risk assessment.







J.2 Minimums/Maximums

Probabilistic risk analyses involve "sampling" values from probability distribution functions (PDFs) and using the values to estimate risk. In some cases, distributions are infinite, and there is a probability, although very small, that very large or very small values might be selected from the distributions. Because selecting extremely large or extremely small values is unrealistic (e.g., the range of adult body weights is not infinite), maximum and minimum values were imposed on the distributions. The minimum and maximum values are summarized in Table J-15. For the probabilistic analyses, the maximum intake rates for most food items were defined as 2 × (mean + 3 SD). For adult farmer beef, adult farmer eggs, adult farmer exposed fruit, adult home gardener exposed fruit, child3 exposed vegetable, and adult home gardener root vegetable, 2 × 99th percentile value was used as the maximum intake rates. For fish, adult subsistence fisher ingestion rates were used as the maximum. Minimum intake values for all food items were zero.

Table J-15. Minimum and Maximum Values

Receptor	Parameter Name	Minimum	Source	Maximum	Source
General	Averaging time for carcinogens				
Adult resident	Body weight (adult)	15	0.5*(mean-3SD)	300	Prof. judgment
Child resident	Body weight (child 1)	4	0.5*(mean-3SD)	50	Prof. judgment
Child resident	Body weight (child 2)	6	0.5*(mean-3SD)	200	Prof. judgment
Child resident	Body weight (child 3)	13	0.5*(mean-3SD)	300	Prof. judgment
Infant resident	Body weight (infant)	2	0.5*(mean-3SD)	26	2*(mean+3SD)
Adult farmer	Consumption rate: beef (adult farmer)	0		23	2*(P99)
Child farmer	Consumption rate: beef (child 1 farmer)	0		36	2*(mean+3SD)
Child farmer	Consumption rate: beef (child 2 farmer)	0		36	2*(mean+3SD)
Child farmer	Consumption rate: beef (child 3 farmer)	0		10	2*(mean+3SD)
Infant resident	Consumption rate: breast milk (infant)	0		1376	2*mean
Adult farmer	Consumption rate: eggs (adult farmer)	0		13	2*(P99)
Child farmer	Consumption rate: eggs (child 1 farmer)	0		10	2*(mean+3SD)
Child farmer	Consumption rate: eggs (child 2 farmer)	0		6	2*(mean+3SD)
Child farmer	Consumption rate: eggs (child 3 farmer)	0		4	2*(mean+3SD)
Adult farmer	Consumption rate: exposed fruit (adult farmer)	0		31	2*(P99)
Adult home gardener	Consumption rate: exposed fruit (adult home gardener)	0		26	2*(P99)

(continued)

Table J-15. (continued)

Receptor	Parameter Name	Minimum	Source	Maximum	Source
Child farmer, home gardener	Consumption rate: exposed fruit (child 1 farmer, home gardener)	0		16	2*(mean+3SD)
Child farmer, home gardener	Consumption rate: exposed fruit (child 2 farmer, home gardener)	0		36	2*(mean+3SD)
Child farmer, home gardener	Consumption rate: exposed fruit (child 3 farmer, home gardener)	0		18	2*(mean+3SD)
Adult farmer	Consumption rate: exposed vegetables (adult farmer)	0		26	2*(mean+3SD)
Adult home gardener	Consumption rate: exposed vegetables (adult home gardener)	0		21	2*(mean+3SD)
Child farmer, home gardener	Consumption rate: exposed vegetables (child 1 farmer, home gardener)	0		21	2*(mean+3SD)
Child farmer, home gardener	Consumption rate: exposed vegetables (child 2 farmer, home gardener)	0		27	2*(mean+3SD)
Child farmer, home gardener	Consumption rate: exposed vegetables (child 3 farmer, home gardener)	0		11	2*(P99)
Adult fisher	Consumption rate: fish (adult fisher)	0		1500	EFH-subsist
Adult farmer	Consumption rate: milk (adult farmer)	0		117	2*(mean+3SD)
Child farmer	Consumption rate: milk (child 1 farmer)	0		482	2*(mean+3SD)
Child farmer	Consumption rate: milk (child 2 farmer)	0		245	2*(mean+3SD)
Child farmer	Consumption rate: milk (child 3 farmer)	0		109	2*(mean+3SD)
Adult farmer	Consumption rate: poultry (adult farmer)	0		11	2*(mean+3SD)
Child farmer	Consumption rate: poultry (child 1 farmer)	0		21	2*(mean+3SD)
Child farmer	Consumption rate: poultry (child 2 farmer)	0		14	2*(mean+3SD)
Child farmer	Consumption rate: poultry (child 3 farmer)	0		10	2*(mean+3SD)
Adult farmer	Consumption rate: root vegetables (adult farmer)	0		15	2*(mean+3SD)
Adult home gardener	Consumption rate: root vegetables (adult home gardener)	0		15	2*(P99)
Child farmer, home gardener	Consumption rate: root vegetables (child 1 farmer, home gardener)	0		41	2*(mean+3SD)

(continued)

Table J-15. (continued)

Receptor	Parameter Name	Minimum	Source	Maximum	Source
Child farmer, home gardener	Consumption rate: root vegetables (child 2 farmer, home gardener)	0		15	2*(mean+3SD)
Child farmer, home gardener	Consumption rate: root vegetables (child 3 farmer, home gardener)	0		9	2*(mean+3SD)
Adult resident	Exposure duration (adult resident)	1		100	
Child resident	Exposure duration (child)	1		100	
Adult farmer	Exposure duration (adult farmer)	1		100	
Adult resident	Inhalation (breathing) rate (adult resident)	1	0.5*(mean-3SD)	50	2*(mean+3SD)
Child resident	Inhalation (breathing) rate (child 1 resident)	1	0.5*(mean-3SD)	40	2*(mean+3SD)
Child resident	Inhalation (breathing) rate (child 2 resident)	1	0.5*(mean-3SD)	45	2*(mean+3SD)
Child resident	Inhalation (breathing) rate (child 3 resident)	1	0.5*(mean-3SD)	55	2*(mean+3SD)

J.3 Exposure Parameters Used in Deterministic Analysis

For most exposure factor parameters, data used in the deterministic analyses were based on distributions developed from data and recommendations in the EFH (U.S. EPA, 1997a, 1997b, 1997c). Central tendency values were represented by the 50th percentile (median) values. High-end values were represented by the 90th percentile values. The exposure factors parameters used in the biosolids deterministic analyses are summarized in Table J-16.

Three deterministic analyses were performed for the farmer scenario:

Scenario 1: Central tendency values were used for all exposure parameters.

Scenario 2: High-end values were used for exposure duration and consumption rates for produce and animal products (i.e., exposed fruit, exposed vegetables, root vegetables, beef, dairy, poultry, and eggs) while central tendency values were used for all other exposure parameters (i.e., body weight, inhalation rate, soil consumption rate, and breast milk consumption rate).

Scenario 3: Central tendency values were used for all exposure parameters except exposure duration, for which the high-end value was used.

Table J-16. Summary of Exposure Parameters Used in Deterministic Analyses

Scenario	**1**	**1**	**1**	**2**	**2**	**2**	**3**	**3**	**3**	
Receptor	**Adult Farmer**	**Child Farmer**	**Infant Farmer**	**Adult Farmer**	**Child Farmer**	**Infant Farmer**	**Adult Farmer**	**Child Farmer**	**Infant Farmer**	**Units**
Waste management unit	LAU	LAU	LAU	LAU	LAU	LAU	LAU	LAU	LAU	
Averaging time	70	70		70	70		70	70		yr
Inhalation rate	1.27E+01	9.73E+00		1.27E+01	9.73E+00		1.27E+01	9.73E+00		m^3/d
Body weight	7.00E+01	2.41E+01	9.16E+00	7.00E+01	2.41E+01	9.16E+00	7.00E+01	2.41E+01	9.16E+00	kg
Consumption rate: exposed fruit	1.36E+00	1.69E+00		5.16E+00	4.91E+00		1.36E+00	1.69E+00		g WW/kg-d
Consumption rate: exposed vegetable	1.38E+00	1.29E+00		5.21E+00	4.44E+00		1.38E+00	1.29E+00		g WW/kg-d
Consumption rate: root vegetable	8.20E-01	9.09E-01		3.14E+00	3.72E+00		8.20E-01	9.09E-01		g WW/kg-d
Consumption rate: egg	6.47E-01	1.02E+00		1.63E+00	2.26E+00		6.47E-01	1.02E+00		g WW/kg-d
Consumption rate: poultry	1.26E+00	2.14E+00		3.44E+00	4.76E+00		1.26E+00	2.14E+00		g WW/kg-d
Consumption rate: beef	1.73E+00	2.60E+00		5.17E+00	7.24E+00		1.73E+00	2.60E+00		g WW/kg-d
Consumption rate: fish	1.99E+00			1.40E+01			1.99E+00			g/d
Consumption rate: milk	1.26E+01	2.98E+01		3.55E+01	9.02E+01		1.26E+01	2.98E+01		g WW/kg-d
Consumption rate: soil	5.00E-05	7.00E-05		5.00E-05	7.00E-05		5.00E-05	7.00E-05		kg/d
Consumption rate: breast milk			6.87E+02			6.87E+02			6.87E+02	mL/d
Exposure duration	10	5		47	13		47	13		yr

Table J-17. Exposure Factor Raw Data: Descriptive Statistics by Standardized Age Groups

Parameter	Age Cohort	N	Avg	SDev	Units	P01	P02	P05	P10	P15	P25	P50	P75	P85	P90	P95	P98	P99
beef	6-11	38	3.77	3.662	g WW/kg-d			0.663	0.753		1.32	2.11	4.43		11.4	12.5		
beef	12-19	41	1.72	1.044	g WW/kg-d			0.478	0.513		0.896	1.51	2.44		3.53	3.57		
beef	Farmer	182	2.63	2.644	g WW/kg-d	0.27		0.394	0.585		0.896	1.64	3.25		5.39	7.51		11.3
bodywt	1-5	3,762	15.52	3.719	kg			12.5	13.1	13.45	14.03	15.26	16.67	17.58	18.32	19.45		
bodywt	6-11	1,725	30.84	9.561	kg			22.79	24.05	25.07	26.44	29.58	33.44	36.82	39.66	43.5		
bodywt	12-19	2,615	58.45	13.64	kg			43.84	46.52	48.31	50.94	56.77	63.57	68.09	71.98	79.52		
bodywt	20+	12,504	71.41	15.45	kg			52.86	55.98	58.21	61.69	69.26	78.49	84.92	89.75	97.64		
expfruit	1-5	49	2.6	3.947	g WW/kg-d				0.373		1	1.82	2.64		5.41	6.07		
expfruit	6-11	68	2.52	3.496	g WW/kg-d			0.171	0.373		0.619	1.11	2.91		6.98	11.7		
expfruit	12-19	50	1.33	1.457	g WW/kg-d			0.123	0.258		0.404	0.609	2.27		3.41	4.78		
expfruit	Farmer	112	2.32	2.646	g WW/kg-d	0.072		0.276	0.371		0.681	1.3	3.14		5	6.12		15.7
expveg	1-5	105	2.453	2.675	g WW/kg-d			0.102	0.37		0.833	1.459	3.226		6.431	8.587		
expveg	6-11	134	1.39	2.037	g WW/kg-d			0.044	0.094		0.312	0.643	1.6		3.22	5.47		13.3
expveg	12-19	143	1.07	1.128	g WW/kg-d			0.029	0.142		0.304	0.656	1.46		2.35	3.78		5.67
expveg	Farmer	207	2.17	2.316	g WW/kg-d			0.184	0.372		0.647	1.38	2.81		6.01	6.83		10.3
rootveg	1-5	45	1.886	2.371	g WW/kg-d			0.081	0.167		0.291	0.686	2.653		5.722	7.502		
rootveg	6-11	67	1.32	1.752	g WW/kg-d			0.014	0.036		0.232	0.523	1.63		3.83	5.59		
rootveg	12-19	76	0.937	1.037	g WW/kg-d			0.008	0.068		0.269	0.565	1.37		2.26	3.32		
rootveg	Farmer	136	1.39	1.469	g WW/kg-d	0.111		0.158	0.184		0.365	0.883	1.85		3.11	4.58		7.47

Avg = average; N = number of samples; P01-P99 = percentiles; SDev = standard deviation.
Source: *Exposure Factors Handbook* (U.S. EPA, 1997a, 1997b, 1997c).

Table J-18. Population-Estimated Averages, Standard Deviations, and Coefficients of Variation

Parameter	Age Cohort	N	First	Data Mean	Gam Mean	Log Mean	WEI Mean	Data SDev	Gam SDev	Log SDev	WEI CV	Data CV	Gam CV	Log CV	WEI CV
beef	6-11	38	Lognormal	3.77	3.83	3.88	3.86	3.66	3.48	4.71	3.67	0.97	0.91	1.22	0.95
beef	12-19	41	Gamma	1.72	1.77	1.82	1.76	1.04	1.12	1.41	1.07	0.61	0.64	0.78	0.61
beef	Farmer	182	Lognormal	2.63	2.47	2.5	2.49	2.64	2.02	2.69	2.09	1.01	0.82	1.07	0.84
bodywt	1-5	3,762	Lognormal	15.5	15.5	15.5	15.4	3.72	2.05	2.05	2.35	0.24	0.13	0.13	0.15
bodywt	6-11	1,725	Lognormal	30.8	30.7	30.7	30.4	9.56	5.94	5.96	6.87	0.31	0.19	0.19	0.23
bodywt	12-19	2,615	Lognormal	58.5	58.1	58.2	57.7	13.6	10.2	10.2	11.6	0.23	0.17	0.18	0.2
bodywt	20+	12,504	Lognormal	71.4	71.2	71.2	70.7	15.5	13.2	13.3	14.8	0.22	0.18	0.19	0.21
expfruit	1-5	49	Gamma	2.6	2.25	2.46	2.25	3.95	1.89	2.91	1.84	1.52	0.84	1.18	0.82
expfruit	6-11	68	Lognormal	2.52	2.63	2.78	2.63	3.5	2.9	5.12	3.16	1.39	1.1	1.84	1.2
expfruit	12-19	50	Lognormal	1.33	1.43	1.54	1.44	1.46	1.44	2.44	1.51	1.1	1.01	1.59	1.05
expfruit	Farmer	112	Lognormal	2.32	2.24	2.36	2.24	2.65	2.1	3.33	2.18	1.14	0.94	1.41	0.97
expveg	1-5	105	Gamma	2.45	2.55	3.06	2.56	2.68	2.58	5.61	2.65	1.09	1.01	1.83	1.04
expveg	6-11	134	Lognormal	1.39	1.4	1.64	1.39	2.04	1.66	3.95	1.81	1.47	1.19	2.41	1.3
Expveg	12-19	143	Gamma	1.07	1.08	1.32	1.08	1.13	1.13	2.69	1.15	1.05	1.05	2.03	1.07
Expveg	Farmer	207	Lognormal	2.17	2.22	2.38	2.22	2.32	2.13	3.5	2.18	1.07	0.96	1.47	0.98
Fish	Adult	1,053	Lognormal	6.4	5.24	6.48	5.45		8.3	19.9	9.79		1.58	3.07	1.8
Rootveg	1-5	45	Lognormal	1.89	1.95	2.31	1.95	2.37	2.37	6.05	2.63	1.26	1.22	2.62	1.35
Rootveg	6-11	67	Weibull	1.32	1.35	2.3	1.38	1.75	1.78	10.6	2.07	1.33	1.32	4.62	1.5
Rootveg	12-19	76	Weibull	0.94		1.7	0.99	1.04		5.97	1.19	1.11		3.51	1.2
Rootveg	Farmer	136	Lognormal	1.39	1.39	1.45	1.39	1.47	1.31	2.06	1.36	1.06	0.95	1.42	0.98

CV = Coefficient of variation; CV = SDev/avg. GAM = Gamma; LOG = Lognormal; N = Number of samples; SDev = Standard deviation; WEI = Weibull.

Table J-19. Exposure Factor Raw Data for Egg, Dairy, and Poultry Consumption Rates: Descriptive Statistics by Standardized Age Groups

Paramter	Age Cohort	Data Mean	Data SDev	Data CV	P05	P10	P25	P50	P75	P90	P95
eggs_gen	All	1.01	1.04	1.03	0.133	0.253	0.422	0.724	1.22	1.99	2.82
eggs_gen	1-5	2.41	1.94	0.807	0.101	0.328	1.16	1.88	3.23	5.03	6.15
eggs_gen	6-11	1.44	1.25	0.872	0.125	0.302	0.641	1.08	1.87	2.95	3.45
eggs_gen	12-19	0.962	0.708	0.736	0.092	0.328	0.469	0.821	1.22	1.71	2.24
eggs_gen	20-69	0.792	0.663	0.836	0.145	0.248	0.389	0.633	1.01	1.52	1.88
eggs_hp	20-69	0.611	0.442	0.72	0.106	0.183	0.308	0.465	0.829	1.31	1.645
eggs_hp	All	0.731	1.114	1.523	0.15	0.175	0.268	0.466	0.902	1.36	1.69
eggs_hp	Adult farmer	0.898	1.128	1.256	0.165	0.177	0.272	0.666	1.19	1.65	1.85
milk_gen	All	6.81	10.8	1.59	0.199	0.392	1.14	3.25	7.59	16.9	26.1
milk_gen	1-5	27.4	22.3	0.817	1.12	4.39	12.2	22.3	37.1	55.9	70.1
milk_gen	6-11	14	10	0.717	0.826	2.16	6.48	12.3	19.2	27.3	33.5
milk_gen	12-19	6.2	5.87	0.946	0.264	0.484	1.88	4.55	8.88	13.5	17.8
milk_gen	20-69	3.23	3.3	1.02	0.162	0.303	0.854	2.22	4.48	7.45	9.88
milk_hp	20_39	7.41	6.12	0.826	0.396	0.446	1.89	6.46	12.1	15.4	19.5
milk_hp	All	14	15.28	1.092	0.446	0.508	3.18	10.2	19.5	34.2	44
milk_hp	Adult farmer	17.1	15.8	0.924	0.736	3.18	9.06	12.1	20.4	34.9	44
poul_gen	All	0.688	0.942	1.37	0.018	0.034	0.111	0.334	0.917	1.76	2.47
poul_gen	1-5	1.43	1.73	1.21	0.025	0.056	0.192	0.736	2.2	3.63	4.66
poul_gen	6-11	0.884	1.15	1.3	0.019	0.036	0.116	0.365	1.29	2.42	3.22
poul_gen	12-19	0.645	0.795	1.23	0.019	0.034	0.103	0.346	0.896	1.71	2.23
poul_gen	20-69	0.57	0.712	1.25	0.017	0.032	0.105	0.303	0.804	1.4	1.92
poul_hp	20-69	1.34	1.088	0.802	0.299	0.352	0.524	0.962	2.03	2.545	3.765
poul_hp	All	1.57	1.178	0.751	0.303	0.418	0.637	1.23	2.19	3.17	3.83
poul_hp	Adult farmer	1.54	1.375	0.893	0.228	0.303	0.595	1.06	2.18	3.47	4.83

Sdev = standard deviation; CV = coefficient of variation; HP = home produced; gen = general population; poul = poultry

Table J-20. Population-Estimated Means, Standard Deviations, Coefficients of Variation, and Crystal Ball Parameters for Egg, Dairy, and Poultry Consumption Rates

Parameter	Group	N	Distribution Type	Data Mean	Gam Mean	Data SDev	Gam SDev	Data CV	Gam CV	Shape	Scale	Minimum	Maximum
eggs_hp	1-5		gamma		1.58		1.15		0.73	1.88	0.839	0	10
eggs_hp	6-11		gamma		0.92		0.67		0.73	1.88	0.493	0	6
eggs_hp	12-19		gamma		0.63		0.46		0.73	1.88	0.334	0	4
eggs_hp	20-69	73	gamma	0.611	0.63	0.442	0.46	0.72	0.73	1.88	0.336	0	4
eggs_hp	All	124	gamma	0.731	0.647	1.11	0.481	1.52	0.74	1.81	0.357	0	4
eggs_hp	Adult farmer	44	gamma	0.898	0.803	1.13	0.621	1.26	0.77	1.64	0.488	0	13
milk_hp	1-5		gamma		59.40		60.59		1.02	0.961	61.80	0	482
milk_hp	6-11		gamma		30.24		30.78		1.02	0.961	31.40	0	245
milk_hp	12-19		gamma		13.41		13.63		1.02	0.961	13.90	0	109
milk_hp	20-69	36	gamma	7.41	7.7	6.12	7.87	0.826	1.02	0.961	8.01	0	63
milk_hp	All	89	gamma	14	14.3	15.3	16.1	1.09	1.13	0.78	18.26	0	126
milk_hp	Adult farmer	63	gamma	17.1	16.4	15.8	13.9	0.924	0.85	1.38	11.85	0	117
poul_hp	1-5		gamma		3.26		2.50		0.77	1.69	1.92	0	21
poul_hp	6-11		gamma		2.04		1.57		0.77	1.69	1.21	0	14
poul_hp	12-19		gamma		1.47		1.13		0.77	1.69	0.87	0	10
poul_hp	20-69	63	gamma	1.34	1.36	1.09	1.04	0.802	0.77	1.69	0.80	0	9

(continued)

Table J-20. (continued)

Parameter	Group	N	Distribution Type	Data Mean	Gam Mean	Data SDev	Gam SDev	Data CV	Gam CV	Shape	Scale	Minimum	Maximum
poul_hp	All	105	gamma	1.57	1.56	1.18	1.15	0.751	0.74	1.83	0.85	0	10
poul_hp	Adult farmer	59	gamma	1.54	1.6	1.37	1.36	0.893	0.86	1.38	1.16	0	11
eggs_gen	All	2728	gamma	1.01	0.99	1.04	0.79	1.03	0.8				
eggs_gen	1-5	585	gamma	2.41	2.41	1.94	2	0.81	0.83				
eggs_gen	6-11	219	gamma	1.44	1.41	1.25	1.11	0.87	0.78				
eggs_gen	12-19	223	gamma	0.96	0.96	0.71	0.62	0.74	0.65				
eggs_gen	20-69	1700	gamma	0.79	0.78	0.66	0.53	0.84	0.68				
milk_gen	All	8284	gamma	6.81	6.62	10.8	8.15	1.59	1.23				
milk_gen	1-5	1736	gamma	27.4	27.5	22.3	22.7	0.82	0.82				
milk_gen	6-11	892	gamma	14	14	10	11.1	0.72	0.79				
milk_gen	12-19	860	gamma	6.2	6.21	5.87	6.34	0.95	1.02				
milk_gen	20-69	4797	gamma	3.23	3.22	3.3	3.31	1.02	1.03				
poul_gen	All	7718	gamma	0.69	0.68	0.94	0.85	1.37	1.24				
poul_gen	1-5	1632	gamma	1.43	1.42	1.73	1.81	1.21	1.27				
poul_gen	6-11	836	gamma	0.88	0.89	1.15	1.16	1.3	1.3				
poul_gen	12-19	829	gamma	0.64	0.64	0.8	0.79	1.23	1.22				
poul_gen	20-69	4420	gamma	0.57	0.57	0.71	0.67	1.25	1.19				

N= number; GAM = gamma; SDEV = standard deviation; CV = coefficient of variation; hp = home produced; gen = general population; poul = poultry

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Appendix K

Sensitivity Analysis Results

Sensitivity Analysis Results

K.1 Introduction

The probabilistic risk analysis conducted in support of the agricultural application of biosolids considered the variability in the following types of parameters:

- Agricultural field size and biosolids characteristics
- Agricultural practices
- Regional-specific environmental conditions
- Exposure factors for each receptor.

Taken together, these variables provide nationally applicable distribution of risk for dioxins, furans, and PCBs in biosolids.

K.2 Sensitivity Analysis Methods

A statistically based sensitivity analysis was performed to rank the variables in the analysis according to their contribution to the variability of the risk for each pathway and for the total exposure of a receptor (i.e., adult farmer, child of farmer, etc). The method used for this risk assessment is referred to as a response surface regression approach. Response surface methodology is frequently used as a statistical approach to designing experiments and an associated model estimation methodology. The terminology "response surface" derives from the fact that a regression model involving a number of continuous independent variables can be viewed as providing an estimated surface of the results in space. Often a goal of response surface experimentation is to ascertain the combination(s) of input variable values that will yield a minimum or a maximum response. The complexity of the model (e.g., whether it contains only first- and second-order terms or terms of higher degree) determines the general shape of the contours and the degree to which the "true" surface can be approximated.

In this analysis, a regression analysis was applied to a linear equation to estimate the relative change in the output (risk results) of a probabilistic simulation relative to the changes in the input variable values (e.g., exposure factors). This methodology is one of the recommended methods for conducting a sensitivity analysis based on the results of a Monte Carlo analysis described in *Appendix B of RAGS 3A - Process For Conducting Probabilistic Risk Assessment - Draft (1999)* (U.S. EPA, 1999).

Historically sensitivity analyses for risk assessments were conducted by evaluating how much change in risk occurred in risk as a result of varying an individual input variable from a median or mean value to a 90^{th} percentile or high-end value. However, when the risk depends on the aggregate impact of a number of input variables, such an approach may not necessarily identify the most important one. This may occur for several reasons:

- The ranges chosen for the various input variables may not be defined consistently.

- Various input variables may interact with one another (i.e., the effect of one input on risk may depend on the level of other inputs, so that the observed effect of the first input also depends on the values chosen for the other variables as well).

- Nonlinear effects may obscure the effect of the input variable (e.g., if only low and high values of an input variable are examined, but the relationship between the risk and the input variable is of a quadratic nature, then the importance of the input variable may be overlooked).

To address such issues, statistical regression methods were used to perform the sensitivity analyses. Although regression methods have distinct advantages over previous approaches, certain limitations remain. Regression methods are not capable of determining the sensitivity of model results to input variables that are not varied in the analysis (e.g., assumptions) or are not otherwise included within the scope of the analysis (e.g., model-derived variables). If, for some reason, the most important variables are not varied or their variability is improperly characterized, the sensitivity analysis may not identify them as being important.

The sensitivity analysis was conducted on a data set generated during modeling of risk for each pathway. For example, a set of input variables was used in the modeling simulation were associated with the risk results for that patheway..

The individual risk calculated for each pathway as a result of exposure to all dioxin-like congeners as expressed as a TEQ was the outcome of concern in this sensitivity analysis. In this case, the input parameters are associated with agricultural practices, site, environmental conditions, and exposure parameters.

The regression approach uses the various combinations of input values that were used during the simulation and the resulting risk values as input data to a regression model. Functions of the results variables (denoted as Ys) were treated as dependent variables; for example, Y denoted the logarithm of the risk. Functions of the input variables were treated as independent variables. The goals of the approach were

1. To determine a fairly simple polynomial approximation to the simulation results that expressed the risks (Ys) as functions of the inputs (Xs)

2. To optimize this "response surface" and assess the importance of the various inputs by performing statistical tests on the model parameters

3. To rank the inputs based on their relative contribution (in terms of risk) to the final response surface regression model.

These goals were realized using a second-order regression model. Such a model takes the following form:

$$\hat{Y} = \hat{\beta}_0 + \sum_{k=1}^{p} \hat{\beta}_k x_k + \sum_{k=1}^{p} \hat{\beta}_{kk} x_k^2 + \sum_{k=1}^{p-1} \sum_{j=k+1}^{p} \hat{\beta}_{kj} x_k x_j \qquad \text{(K-1)}$$

where the βs are the least squares regression estimates of the model parameters.

The statistical significance of the parameters associated with the first-order, squared, and cross product terms were tested and all nonsignificant terms were removed from the model. The parameters in this reduced model were then reestimated and the process of testing was repeated. This was done to capture the most important independent variables inputs (Xs) that influence the dependent variables risk results (Ys).

Once the final regression model was developed, the input parameters (Xs) were ranked based on percentage of risk accounted for by that parameter. The percent of the risk accounted for by each important variable was calculated using the following equation:

$$Percent\ Risk = \frac{[FMSS - RMSS]}{[FMSS + ERSS]} \quad \text{(K-2)}$$

where

FMSS = model sum of squares for the final model

RMSS = model sum of squares for a model in which all terms involving x_u are removed (i.e., a reduced model)

ERSS = model error sum of squares.

The major steps in the analysis once the initial data set of corresponding input and output values have been assembled are identified below, along with details on the reasons for these steps.

- **Perform any necessary manipulations to the data set.** To perform the sensitivity analysis, the data set must contain only one record for each Monte Carlo iteration, and all variables in the data set must be numeric.

- **Remove any variables that are constants.** Any variable that was constant across all the probabilistic iterations does not have any effect on the resulting risk and was removed from the data set prior to the start of the regression analysis.

- **Perform transformations (log, square root, etc.) to the continuous input variables, if necessary, so that all input variables will have approximately symmetric distributions.** Transforming the input variables so that each one has an approximately symmetric distribution is necessary to make the standardization of the variables meaningful (i.e., so the mean is near the midpoint of the extremes, and the mean and standard deviation are not highly related).

- **Check the correlations of the transformed input variables. Remove any input variables that are highly correlated with other input variables in the data set.** Regression analysis measures the linear relationship between the terms in the model and the response variable. If two or more input variables are highly correlated with one another, then there is a strong linear relationship between those input variables. Keeping all highly correlated variables in the model will reduce the significance of each of the correlated input variables since each one is essentially explaining the same linear relationship with the response variable (i.e., the effect of one such variable may mask the effect of another). One must keep in mind that the effect of the variable remaining in the analysis also applies the correlated variable removed from the analysis. For example, frequently many soil parameters are correlated and all but one of them, therefore, are removed from the analysis. When the sensitivity analysis results are presented it is important to present the results for the retained variable as the results for the group of correlated soil variables not just the single variable retained in the analysis.

- **Standardize the transformed variables.** Standardizing the input variables (i.e., subtracting the mean and dividing by the standard deviation) allows the regression results to be independent of the magnitude of the value of the input variables. The larger value input variables could cause the regression results to seriously underestimate the effects of the smaller value input variables on the changes in environmental concentration and risk. The combination of transforming and standardizing the input variables creates more optimal conditions for regression analysis.

- **Use response surface regression methods to test for the main effects, squared terms and cross products that have the greatest effect on the log(risk). Develop a model for risk based on the results of the regression analysis.** After the response surface regression results are obtained, the significance of each term on risk is evaluated. First, any second-order terms that are determined to not have a significant effect on the risk are dropped from the model. Any first-order term that is part of a significant second-order term will remain in the model, regardless of the level of significance of that first-order term. For example, if the second- order term X1*X2 has a significant effect on the risk and remains in the model, then both of the first-order terms, X1 and X2, will also remain in the model. Any first-order terms that are determined not to be significant and not to have any significant second-order terms are dropped from the model. The regression analysis is then conducted on the reduced model. This process is repeated until all of the second-order terms in the model have significant effects on the environmental concentration and no more terms can be removed. The iterative process of dropping insignificant terms and reevaluating the model allows only the input variables with the most effect on the risk to remain in the model.

- **Test for the effect of each variable on log(risk) and use the p-values to rank the variables by the amount of effect each variable has on log(risk).** Because the final model will most likely contain first- and second-order terms involving

the same input variables, F-tests need to be performed to evaluate the effect of each input variable in the final model on the log(risk). The F-tests of each variable will be of the form

$$F = \frac{[FMSS - RMSS] \ / \ [FMDF - RMDF]}{FRSS \ / \ FRDF} \qquad \text{(K-3)}$$

where

FMSS = model sum of squares for full model containing all significant terms

RMSS and RMDF = model sum of squares and degrees of freedom for reduced model

FMDF = model degrees of freedom for full model

FRSS and FRDF = residual sum of squares and degrees of freedom, respectively, for full model.

The full model refers to the model containing all significant terms in the final log(risk) model. The reduced model refers to the full model minus all terms containing the input variable X whose significance is being tested. The F-tests evaluate the effect of variable X on the risk by evaluating the differences when variable X is in the regression model (full model) and when all model terms containing variable X are removed (reduced model). If a substantial increase in the residuals results from ignoring terms involving the variable X, then F will be "large," implying that these factors can be considered important, in the sense that they require different regression coefficients for the Xs. The ordering of the p-values from such tests can then be used to rank the importance of the various factors on the risk. The results of the sensitivity analysis is presented in Tables K-1 through K-10.

Table K-1. Sensitivity Analysis Results - Inhalation of Ambient Air

Variable Name	Reduced ModelSS	Reduced ModelDF	Full ModelSS	Full ModelDF	VariableSS	Variable DF	FullErrorSS	Full ErrorDF	Variable MS	FullErrorMS	Percent Variation	F test Statistic	F test P Value
ED	2620.713453	65	7607.497505	66	4986.784052	1	132.2476372	2933	4986.784052	0.045089546	65.60%	110597.3455	0.00E+00
BRi	7328.56038	65	7607.497505	66	278.9371249	1	132.2476372	2933	278.9371249	0.045089546	3.70%	6186.292659	0.00E+00
b	7467.670372	52	7607.497505	66	139.8271327	14	132.2476372	2933	9.987652334	0.045089546	1.80%	221.5070524	0.00E+00
RapplP	7486.122527	64	7607.497505	66	121.3749784	2	132.2476372	2933	60.68748918	0.045089546	1.60%	1345.932597	0.00E+00
BW	7506.657846	65	7607.497505	66	100.8396594	1	132.2476372	2933	100.8396594	0.045089546	1.30%	2236.431041	0.00E+00
CutOffYrC	7508.654601	63	7607.497505	66	98.84290393	3	132.2476372	2933	32.94763464	0.045089546	1.30%	730.7156065	0.00E+00
AvgPeriodStartYrP	7514.936434	60	7607.497505	66	92.56107088	6	132.2476372	2933	15.42684515	0.045089546	1.20%	342.1379601	0.00E+00
AreaCrCr	7533.129076	62	7607.497505	66	74.36842877	4	132.2476372	2933	18.59210719	0.045089546	1.00%	412.3374266	0.00E+00
MetID	7552.120719	62	7607.497505	66	55.37678625	4	132.2476372	2933	13.84419656	0.045089546	0.70%	307.0378373	0.00E+00
CYVPaCr	7553.173882	64	7607.497505	66	54.32362323	2	132.2476372	2933	27.16181161	0.045089546	0.70%	602.3971026	0.00E+00
uw	7554.753302	63	7607.497505	66	52.7442036	3	132.2476372	2933	17.5814012	0.045089546	0.70%	389.9218982	0.00E+00
Runoff_LWS	7571.316609	61	7607.497505	66	36.18089664	5	132.2476372	2933	7.236179327	0.045089546	0.50%	160.4846364	0.00E+00
foc_soil	7574.315839	57	7607.497505	66	33.18166614	9	132.2476372	2933	3.686851793	0.045089546	0.40%	81.76733088	0.00E+00
CYVCrPa	7575.398787	64	7607.497505	66	32.09871803	2	132.2476372	2933	16.04935901	0.045089546	0.40%	355.9441286	0.00E+00
DYWVPaWa	7582.785725	64	7607.497505	66	24.71178021	2	132.2476372	2933	12.35589011	0.045089546	0.30%	274.0300428	0.00E+00
DYDPPaPa	7585.503501	63	7607.497505	66	21.99400433	3	132.2476372	2933	7.331334776	0.045089546	0.30%	162.5950025	0.00E+00
SsC	7590.321603	61	7607.497505	66	17.17590196	5	132.2476372	2933	3.435180391	0.045089546	0.20%	76.18573989	0.00E+00
AirTempP	7593.044049	63	7607.497505	66	14.45345566	3	132.2476372	2933	4.817818554	0.045089546	0.20%	106.8500135	0.00E+00
CYPPaPa	7596.407513	63	7607.497505	66	11.08999204	3	132.2476372	2933	3.696664014	0.045089546	0.10%	81.98494721	0.00E+00
CYPCrSt	7596.568503	63	7607.497505	66	10.92900214	3	132.2476372	2933	3.643000715	0.045089546	0.10%	80.79479773	0.00E+00
AreaCrWa	7599.48725	64	7607.497505	66	8.010255537	2	132.2476372	2933	4.005127769	0.045089546	0.10%	88.82608411	0.00E+00
BD	7600.673439	62	7607.497505	66	6.824065808	4	132.2476372	2933	1.706016452	0.045089546	0.10%	37.83618642	0.00E+00
CnwmuP	7600.762842	63	7607.497505	66	6.734663227	3	132.2476372	2933	2.244887742	0.045089546	0.10%	49.78732239	0.00E+00
DYDPPaRe	7602.983544	63	7607.497505	66	4.513960732	3	132.2476372	2933	1.504653577	0.045089546	0.10%	33.37034246	0.00E+00
T	7603.227361	64	7607.497505	66	4.270143907	2	132.2476372	2933	2.135071954	0.045089546	0.10%	47.35181795	0.00E+00
DYWPPaPa	7604.565438	63	7607.497505	66	2.932066911	3	132.2476372	2933	0.977355637	0.045089546	0.00%	21.67588128	6.98E-14
Huc_Region	7604.728964	62	7607.497505	66	2.768541083	4	132.2476372	2933	0.692135271	0.045089546	0.00%	15.35023833	1.98E-12
Td	7607.080223	64	7607.497505	66	0.41728249	2	132.2476372	2933	0.208641245	0.045089546	0.00%	4.627264305	9.85E-03

Table K-2. Sensitivity Analysis Results - Ingestion of Beef

VariableName	Reduced ModelSS	Reduced ModelDF	Full ModelSS	FullModelDF	VariableSS	VariableDF	FullErrorSS	FullErrorDF	VariableMS	FullErrorMS	Percent Variation	FTestStatistic	FTestPValue
ED	3337.456434	57	8352.08	58	5014.621413	1	64.3679406	2941	5014.621413	0.021886413	60.00%	229120.2956	0.00E+00
Crb	6148.995979	57	8352.08	58	2203.081868	1	64.3679406	2941	2203.081868	0.021886413	26.40%	100659.7961	0.00E+00
RapplP	8237.512756	56	8352.08	58	114.565091	2	64.3679406	2941	57.28254549	0.021886413	1.40%	2617.265128	0.00E+00
AvgPeriodStartYrP	8254.746331	51	8352.08	58	97.33151559	7	64.3679406	2941	13.90450223	0.021886413	1.20%	635.3029267	0.00E+00
CutOffYrC	8281.122348	54	8352.08	58	70.9554992	4	64.3679406	2941	17.7388748	0.021886413	0.80%	810.4971248	0.00E+00
b	8312.893697	47	8352.08	58	39.18414959	11	64.3679406	2941	3.562195418	0.021886413	0.50%	162.7583021	0.00E+00
AreaCrCr	8338.834047	55	8352.08	58	13.24380013	3	64.3679406	2941	4.414600042	0.021886413	0.20%	201.7050507	0.00E+00
AirTempP	8342.071905	56	8352.08	58	10.00594172	2	64.3679406	2941	5.002970859	0.021886413	0.10%	228.5879766	0.00E+00
foc_soil	8343.937202	53	8352.08	58	8.14064527	5	64.3679406	2941	1.628129054	0.021886413	0.10%	74.3899448	0.00E+00
CYVPaRe	8344.759165	57	8352.08	58	7.318681576	1	64.3679406	2941	7.318681576	0.021886413	0.10%	334.3938351	0.00E+00
DYWPPaPa	8345.778292	56	8352.08	58	6.29955492	2	64.3679406	2941	3.14977746	0.021886413	0.10%	143.9147412	0.00E+00
Huc_Region	8345.871885	53	8352.08	58	6.205961578	5	64.3679406	2941	1.241192316	0.021886413	0.10%	56.71063213	0.00E+00
MetID	8348.106143	54	8352.08	58	3.971704206	4	64.3679406	2941	0.992926051	0.021886413	0.00%	45.36723546	0.00E+00
Runoff_LWS	8348.476291	51	8352.08	58	3.601556404	7	64.3679406	2941	0.514508058	0.021886413	0.00%	23.50810332	0.00E+00
uw	8349.169422	54	8352.08	58	2.908424971	4	64.3679406	2941	0.727106243	0.021886413	0.00%	33.22180949	0.00E+00
SsC	8349.273034	54	8352.08	58	2.804813291	4	64.3679406	2941	0.701203323	0.021886413	0.00%	32.03829349	0.00E+00
BD	8349.451315	55	8352.08	58	2.626532462	3	64.3679406	2941	0.875510821	0.021886413	0.00%	40.00248105	0.00E+00
CnwmuP	8349.794431	51	8352.08	58	2.283415681	7	64.3679406	2941	0.32620224	0.021886413	0.00%	14.90432627	0.00E+00
CYVPaCr	8350.284739	57	8352.08	58	1.793107678	1	64.3679406	2941	1.793107678	0.021886413	0.00%	81.92789193	0.00E+00
CYPPaPa	8350.603134	57	8352.08	58	1.474713213	1	64.3679406	2941	1.474713213	0.021886413	0.00%	67.3803064	3.33E-16
CYPCrSt	8350.834037	55	8352.08	58	1.243810165	3	64.3679406	2941	0.414603388	0.021886413	0.00%	18.94341429	3.63E-12
DYDPPaRe	8351.089134	57	8352.08	58	0.988713539	1	64.3679406	2941	0.988713539	0.021886413	0.00%	45.17476386	2.16E-11
T	8351.103141	57	8352.08	58	0.974706318	1	64.3679406	2941	0.974706318	0.021886413	0.00%	44.53476767	2.97E-11
CYVCrPa	8351.532642	56	8352.08	58	0.545205465	2	64.3679406	2941	0.272602733	0.021886413	0.00%	12.4553408	4.11E-06
DYDPCrPa	8351.583507	55	8352.08	58	0.494339661	3	64.3679406	2941	0.164779887	0.021886413	0.00%	7.528866749	5.12E-05
BW	8352.077761	57	8352.08	58	8.57417E-05	1	64.3679406	2941	8.57417E-05	0.021886413	0.00%	0.003917578	9.50E-01
Chem3268879	8389.020624	49	8389.15	51	0.12771062	2	59.64467238	2948	0.06385531	0.02023225	1.52233E-05	3.156115139	4.27E-02
BW	8389.138359	50	8389.15	51	0.009975025	1	59.64467238	2948	0.009975025	0.02023225	1.18904E-06	0.493025987	4.83E-01

Table K-3. Sensitivity Analysis Results - Ingestion of Eggs

VariableName	Reduced ModelSS	Reduced ModelDF	FullModelSS	Full ModelDF	VariableSS	VariableDF	FullErrorSS	FullErrorDF	VariableMS	FullErrorMS	Percent Variation	FTestStatistic	FTestPValue
ED	3387.13499	75	8402.22	76	5015.089043	1	95.38972003	2923	5015.089043	0.032634184	59.70%	153675.944	0.00E+00
CR_egg	6036.879632	75	8402.22	76	2365.3444	1	95.38972003	2923	2365.3444	0.032634184	28.20%	72480.57422	0.00E+00
AvgPeriodStartYrP	8202.934582	67	8402.22	76	199.2894511	9	95.38972003	2923	22.14327234	0.032634184	2.40%	678.5299824	0.00E+00
RapplP	8286.605569	74	8402.22	76	115.6184638	2	95.38972003	2923	57.8092319	0.032634184	1.40%	1771.431815	0.00E+00
CutOffYrC	8356.18199	68	8402.22	76	46.04204311	8	95.38972003	2923	5.755255388	0.032634184	0.50%	176.3566503	0.00E+00
foc_soil	8357.66654	62	8402.22	76	44.5574926	14	95.38972003	2923	3.182678043	0.032634184	0.50%	97.52589604	0.00E+00
AirTempP	8376.138898	72	8402.22	76	26.08513447	4	95.38972003	2923	6.521283617	0.032634184	0.30%	199.829835	0.00E+00
AreaCrCr	8387.161443	71	8402.22	76	15.06258948	5	95.38972003	2923	3.012517896	0.032634184	0.20%	92.31172717	0.00E+00
Runoff_LWS	8387.576398	69	8402.22	76	14.64763449	7	95.38972003	2923	2.092519212	0.032634184	0.20%	64.12046975	0.00E+00
b	8387.86771	68	8402.22	76	14.35632272	8	95.38972003	2923	1.79454034	0.032634184	0.20%	54.98958809	0.00E+00
uw	8393.899577	71	8402.22	76	8.3244553	5	95.38972003	2923	1.66489106	0.032634184	0.10%	51.01678217	0.00E+00
T1	8395.703646	68	8402.22	76	6.520386997	8	95.38972003	2923	0.815048375	0.032634184	0.10%	24.97529501	0.00E+00
T	8397.361067	72	8402.22	76	4.862965382	4	95.38972003	2923	1.215741346	0.032634184	0.10%	37.2536155	0.00E+00
CnwmuP	8398.299104	73	8402.22	76	3.92492836	3	95.38972003	2923	1.308309453	0.032634184	0.00%	40.09015365	0.00E+00
DYWVPaWa	8398.54711	73	8402.22	76	3.676923124	3	95.38972003	2923	1.225641041	0.032634184	0.00%	37.55696906	0.00E+00
Huc_Region	8398.718821	72	8402.22	76	3.505211425	4	95.38972003	2923	0.876302856	0.032634184	0.00%	26.85229864	0.00E+00
SsC	8398.752529	72	8402.22	76	3.471504013	4	95.38972003	2923	0.867876003	0.032634184	0.00%	26.59407698	0.00E+00
CYVPaRe	8399.091757	73	8402.22	76	3.132275876	3	95.38972003	2923	1.044091959	0.032634184	0.00%	31.99381227	0.00E+00
CYPPaPa	8399.590297	72	8402.22	76	2.633735371	4	95.38972003	2923	0.658433843	0.032634184	0.00%	20.17620056	2.22E-16
ConVsP	8399.898346	73	8402.22	76	2.32568706	3	95.38972003	2923	0.77522902	0.032634184	0.00%	23.75512188	3.44E-15
CYVPaCr	8400.168208	74	8402.22	76	2.055825203	2	95.38972003	2923	1.027912602	0.032634184	0.00%	31.49803284	2.92E-14
DYDPPaRe	8400.197175	72	8402.22	76	2.026858282	4	95.38972003	2923	0.506714571	0.032634184	0.00%	15.52711015	1.42E-12
BD	8400.674306	72	8402.22	76	1.549727098	4	95.38972003	2923	0.387431775	0.032634184	0.00%	11.87196143	1.44E-09
AreaCrWa	8401.007051	74	8402.22	76	1.216981627	2	95.38972003	2923	0.608490814	0.032634184	0.00%	18.64581055	8.98E-09
DYDPPaPa	8401.334425	74	8402.22	76	0.889607828	2	95.38972003	2923	0.444803914	0.032634184	0.00%	13.62999955	1.28E-06
Td	8401.796197	74	8402.22	76	0.427835534	2	95.38972003	2923	0.213917767	0.032634184	0.00%	6.555021154	1.44E-03
CYVCrPa	8401.956682	74	8402.22	76	0.267350482	2	95.38972003	2923	0.133675241	0.032634184	0.00%	4.096172311	1.67E-02
BW	8402.207629	75	8402.22	76	0.016403316	1	95.38972003	2923	0.016403316	0.032634184	0.00%	0.502642147	4.78E-01

Table K-4. Sensitivity Analysis Results - Ingestion of Fish

VariableName	Reduced ModelSS	Reduced ModelDF	Full ModelSS	Full ModelDF	VariableSS	VariableDF	FullErrorSS	FullErrorDF	VariableMS	FullErrorMS	Percent Variation	FTestStatistic	FTestPValue
CRf	7933.15	77	14870.22	78	6937.07099	1	166.4878162	2921	6937.07099	0.056996856	46.70%	121709.7132	0.00E+00
ED	9863.72	77	14870.22	78	5006.497445	1	166.4878162	2921	5006.497445	0.056996856	33.70%	87838.13355	0.00E+00
AvgPeriodStartYrP	14741.71	68	14870.22	78	128.5037167	10	166.4878162	2921	12.85037167	0.056996856	0.90%	225.4575529	0.00E+00
RapplP	14750.21	77	14870.22	78	120.0081235	1	166.4878162	2921	120.0081235	0.056996856	0.80%	2105.521813	0.00E+00
foc_soil	14762.18	67	14870.22	78	108.0424016	11	166.4878162	2921	9.822036509	0.056996856	0.70%	172.3259353	0.00E+00
BW	14771.65	77	14870.22	78	98.57022414	1	166.4878162	2921	98.57022414	0.056996856	0.70%	1729.397569	0.00E+00
CutOffYrC	14805.54	71	14870.22	78	64.68190439	7	166.4878162	2921	9.240272056	0.056996856	0.40%	162.1189784	0.00E+00
b	14823.49	69	14870.22	78	46.72695589	9	166.4878162	2921	5.191883988	0.056996856	0.30%	91.09070844	0.00E+00
Runoff_LWS	14827.09	70	14870.22	78	43.13190001	8	166.4878162	2921	5.391487502	0.056996856	0.30%	94.59271764	0.00E+00
BD	14842.77	70	14870.22	78	27.44348098	8	166.4878162	2921	3.430435123	0.056996856	0.20%	60.18639213	0.00E+00
CYVPaRe	14844.39	74	14870.22	78	25.82359275	4	166.4878162	2921	6.455898188	0.056996856	0.20%	113.2676194	0.00E+00
AreaCrWa	14846.17	75	14870.22	78	24.04679403	3	166.4878162	2921	8.015598011	0.056996856	0.20%	140.6322836	0.00E+00
DYWVPaWa	14846.99	76	14870.22	78	23.22625032	2	166.4878162	2921	11.61312516	0.056996856	0.20%	203.7502765	0.00E+00
AirTempP	14847.65	75	14870.22	78	22.56788179	3	166.4878162	2921	7.522627264	0.056996856	0.20%	131.9831969	0.00E+00
DYDPCrPa	14851.50	73	14870.22	78	18.717369	5	166.4878162	2921	3.7434738	0.056996856	0.10%	65.6786017	0.00E+00
SsC	14852.20	75	14870.22	78	18.01531116	3	166.4878162	2921	6.005103721	0.056996856	0.10%	105.3585083	0.00E+00
CYVCrPa	14852.74	75	14870.22	78	17.48137523	3	166.4878162	2921	5.827125076	0.056996856	0.10%	102.2359037	0.00E+00
Huc_Region	14854.15	75	14870.22	78	16.07205158	3	166.4878162	2921	5.357350525	0.056996856	0.10%	93.99379028	0.00E+00
T1	14857.23	73	14870.22	78	12.9886068	5	166.4878162	2921	2.59772136	0.056996856	0.10%	45.57657289	0.00E+00
uw	14863.00	75	14870.22	78	7.213705683	3	166.4878162	2921	2.404568561	0.056996856	0.00%	42.18774037	0.00E+00
DYDPPaRe	14863.67	74	14870.22	78	6.550315753	4	166.4878162	2921	1.637578938	0.056996856	0.00%	28.73103983	0.00E+00
DYWPPaPa	14863.82	76	14870.22	78	6.3975787	2	166.4878162	2921	3.19878935	0.056996856	0.00%	56.12220703	0.00E+00
MetID	14863.85	76	14870.22	78	6.369316802	2	166.4878162	2921	3.184658401	0.056996856	0.00%	55.87428197	0.00E+00
T	14863.96	74	14870.22	78	6.25814691	4	166.4878162	2921	1.564536728	0.056996856	0.00%	27.44952685	0.00E+00
CYVPaCr	14864.24	77	14870.22	78	5.975909524	1	166.4878162	2921	5.975909524	0.056996856	0.00%	104.8463012	0.00E+00
CnwmuP	14864.89	75	14870.22	78	5.324894891	3	166.4878162	2921	1.774964964	0.056996856	0.00%	31.14145393	0.00E+00
DYDPPaPa	14864.93	77	14870.22	78	5.284500244	1	166.4878162	2921	5.284500244	0.056996856	0.00%	92.71564468	0.00E+00
PICrWa	14865.96	75	14870.22	78	4.261201193	3	166.4878162	2921	1.420400398	0.056996856	0.00%	24.92067981	6.66E-16
AreaCrCr	14866.37	75	14870.22	78	3.849895658	3	166.4878162	2921	1.283298553	0.056996856	0.00%	22.51525161	2.08E-14
CYPPaPa	14867.78	76	14870.22	78	2.43975138	2	166.4878162	2921	1.21987569	0.056996856	0.00%	21.40250843	5.92E-10
ConVsP	14869.34	76	14870.22	78	0.880077742	2	166.4878162	2921	0.440038871	0.056996856	0.00%	7.720406038	4.53E-04

Table K-5. Sensitivity Analysis Results - Ingestion of Fruit

VariableName	Reduced ModelSS	Reduced ModelDF	Full ModelSS	Full ModelDF	VariableSS	VariableDF	FullErrorSS	FullErrorDF	VariableMS	FullErrorMS	Percent Variation	F test Statistic	F test P Value
ED	3975.822986	59	9073.53	60	5097.705376	1	928.3449001	2939	5097.705376	0.315871011	56.20%	16138.56671	0.00E+00
CR_exfruit	8118.356119	59	9073.53	60	955.1722421	1	928.3449001	2939	955.1722421	0.315871011	10.50%	3023.93132	0.00E+00
AvgPeriodStartYrP	8858.43654	54	9073.53	60	215.0918209	6	928.3449001	2939	35.84863682	0.315871011	2.40%	113.4913798	0.00E+00
b	8876.308533	47	9073.53	60	197.2198279	13	928.3449001	2939	15.17075599	0.315871011	2.20%	48.02832638	0.00E+00
RapplP	8960.231777	58	9073.53	60	113.2965839	2	928.3449001	2939	56.64829195	0.315871011	1.20%	179.3399522	0.00E+00
CutOffYrC	8995.560762	57	9073.53	60	77.96759882	3	928.3449001	2939	25.98919961	0.315871011	0.90%	82.27788793	0.00E+00
CYVPaCr	9011.953941	55	9073.53	60	61.5744199	5	928.3449001	2939	12.31488398	0.315871011	0.70%	38.98706614	0.00E+00
AirTempP	9025.211189	58	9073.53	60	48.31717202	2	928.3449001	2939	24.15858601	0.315871011	0.50%	76.48244125	0.00E+00
foc_soil	9031.313835	56	9073.53	60	42.21452624	4	928.3449001	2939	10.55363156	0.315871011	0.50%	33.41120649	0.00E+00
uw	9035.870536	56	9073.53	60	37.65782531	4	928.3449001	2939	9.414456326	0.315871011	0.40%	29.80474944	0.00E+00
SsC	9053.512237	55	9073.53	60	20.0161243	5	928.3449001	2939	4.00322486	0.315871011	0.20%	12.6736064	3.32E-12
Runoff_LWS	9054.122539	56	9073.53	60	19.40582266	4	928.3449001	2939	4.851455664	0.315871011	0.20%	15.35897725	1.95E-12
AreaCrCr	9055.859079	57	9073.53	60	17.66928241	3	928.3449001	2939	5.889760802	0.315871011	0.20%	18.64609478	5.58E-12
MetID	9058.754906	55	9073.53	60	14.77345543	5	928.3449001	2939	2.954691086	0.315871011	0.20%	9.35410654	7.44E-09
BD	9059.635562	54	9073.53	60	13.89279913	6	928.3449001	2939	2.315466521	0.315871011	0.20%	7.330417934	8.53E-08
CYPPaPa	9063.692365	58	9073.53	60	9.83599604	2	928.3449001	2939	4.91799802	0.315871011	0.10%	15.56964031	1.88E-07
CYVPaRe	9068.110121	59	9073.53	60	5.418240449	1	928.3449001	2939	5.418240449	0.315871011	0.10%	17.15333243	3.55E-05
DYDPPaRe	9068.197276	58	9073.53	60	5.331085152	2	928.3449001	2939	2.665542576	0.315871011	0.10%	8.438705949	2.22E-04
CnwmuP	9069.443591	56	9073.53	60	4.084769965	4	928.3449001	2939	1.021192491	0.315871011	0.00%	3.232941476	1.17E-02
DYDPPaPa	9069.807265	58	9073.53	60	3.72109585	2	928.3449001	2939	1.860547925	0.315871011	0.00%	5.890214241	2.80E-03
DYWVPaWa	9070.553653	56	9073.53	60	2.974708471	4	928.3449001	2939	0.743677118	0.315871011	0.00%	2.354369641	5.17E-02
DYWPPaPa	9071.182587	59	9073.53	60	2.345774281	1	928.3449001	2939	2.345774281	0.315871011	0.00%	7.426367732	6.47E-03
AreaCrWa	9071.451019	58	9073.53	60	2.077341873	2	928.3449001	2939	1.038670937	0.315871011	0.00%	3.288275599	3.75E-02
Huc_Region	9071.555569	59	9073.53	60	1.972792099	1	928.3449001	2939	1.972792099	0.315871011	0.00%	6.245562374	1.25E-02
zrufP	9073.386809	58	9073.53	60	0.14155266	2	928.3449001	2939	0.07077633	0.315871011	0.00%	0.22406719	7.99E-01
CYPCrSt	9073.488876	58	9073.53	60	0.039484882	2	928.3449001	2939	0.019742441	0.315871011	0.00%	0.062501592	9.39E-01
BW	9073.511579	59	9073.53	60	0.0167824	1	928.3449001	2939	0.0167824	0.315871011	0.00%	0.053130549	8.18E-01

Table K-6. Sensitivity Analysis Results - Ingestion of Milk

VariableName	Reduced ModelSS	Reduced ModelDF	FullModel SS	Full ModelDF	VariableSS	VariableDF	FullErrorSS	FullErrorDF	VariableMS	FullErrorMS	Percent Variation	Ftest Statistic	FTestPValue
ED	4273.625337	58	9278.96	59	5005.332249	1	69.02088415	2940	5005.332249	0.023476491	53.90%	213206.1476	0.00E+00
CRm	6300.509583	58	9278.96	59	2978.448003	1	69.02088415	2940	2978.448003	0.023476491	32.10%	126869.3851	0.00E+00
AvgPeriodStartYrP	9149.041971	51	9278.96	59	129.9156156	8	69.02088415	2940	16.23945195	0.023476491	1.40%	691.7324997	0.00E+00
RapplP	9164.601915	57	9278.96	59	114.3556716	2	69.02088415	2940	57.17783578	0.023476491	1.20%	2435.535842	0.00E+00
CutOffYrC	9203.317994	54	9278.96	59	75.6395926	5	69.02088415	2940	15.12791852	0.023476491	0.80%	644.3858405	0.00E+00
b	9240.253565	46	9278.96	59	38.70402164	13	69.02088415	2940	2.977232434	0.023476491	0.40%	126.8176069	0.00E+00
AreaCrCr	9264.269333	57	9278.96	59	14.68825337	2	69.02088415	2940	7.344126684	0.023476491	0.20%	312.8289751	0.00E+00
AirTempP	9266.177512	56	9278.96	59	12.78007462	3	69.02088415	2940	4.260024875	0.023476491	0.10%	181.4591813	0.00E+00
CYVPaCr	9269.719456	57	9278.96	59	9.238130645	2	69.02088415	2940	4.619065322	0.023476491	0.10%	196.7527976	0.00E+00
CYVCrPa	9273.503456	57	9278.96	59	5.45412996	2	69.02088415	2940	2.72706498	0.023476491	0.10%	116.1615233	0.00E+00
foc_soil	9273.512328	54	9278.96	59	5.44525817	5	69.02088415	2940	1.089051634	0.023476491	0.10%	46.38902911	0.00E+00
Huc_Region	9274.128569	54	9278.96	59	4.8290171	5	69.02088415	2940	0.96580342	0.023476491	0.10%	41.13917244	0.00E+00
MetID	9274.456722	56	9278.96	59	4.500864508	3	69.02088415	2940	1.500288169	0.023476491	0.00%	63.90597965	0.00E+00
CnwmuP	9274.719558	54	9278.96	59	4.238028412	5	69.02088415	2940	0.847605683	0.023476491	0.00%	36.10444487	0.00E+00
SsC	9275.276592	56	9278.96	59	3.680994038	3	69.02088415	2940	1.226998013	0.023476491	0.00%	52.26496591	0.00E+00
Runoff_LWS	9275.40949	53	9278.96	59	3.548096374	6	69.02088415	2940	0.591349396	0.023476491	0.00%	25.1890025	0.00E+00
DYWPPaPa	9275.982086	57	9278.96	59	2.975500473	2	69.02088415	2940	1.487750236	0.023476491	0.00%	63.37191632	0.00E+00
CYPPaPa	9276.271258	56	9278.96	59	2.686328566	3	69.02088415	2940	0.895442855	0.023476491	0.00%	38.14210767	0.00E+00
DYDPCrPa	9276.370547	56	9278.96	59	2.587039029	3	69.02088415	2940	0.862346343	0.023476491	0.00%	36.73233514	0.00E+00
BD	9276.762571	55	9278.96	59	2.195015606	4	69.02088415	2940	0.548753901	0.023476491	0.00%	23.37461321	0.00E+00
uw	9277.169082	57	9278.96	59	1.7885045	2	69.02088415	2940	0.89425225	0.023476491	0.00%	38.09139289	0.00E+00
CYPCrSt	9277.782899	56	9278.96	59	1.174687219	3	69.02088415	2940	0.391562406	0.023476491	0.00%	16.67891521	9.61E-11
DYWVPaWa	9278.240809	58	9278.96	59	0.716777384	1	69.02088415	2940	0.716777384	0.023476491	0.00%	30.53170841	3.57E-08
AreaCrWa	9278.655899	58	9278.96	59	0.301687424	1	69.02088415	2940	0.301687424	0.023476491	0.00%	12.85061816	3.43E-04
fdP	9278.706911	56	9278.96	59	0.250675575	3	69.02088415	2940	0.083558525	0.023476491	0.00%	3.559242488	1.37E-02
BW	9278.957578	58	9278.96	59	8.67E-06	1	69.02088415	2940	8.67E-06	0.023476491	0.00%	0.000369178	9.85E-01

Table K-7. Sensitivity Analysis Results - Ingestion of Poultry

VariableName	Reduced ModelSS	Reduced ModelDF	FullModelSS	Full ModelDF	VariableSS	VariableDF	FullErrorSS	FullErrorDF	VariableMS	FullErrorMS	Percent Variation	FTestStatistic	FTestPValue
ED	4147.00571	79	9163.65	80	5016.640701	1	99.20504331	2919	5016.640701	0.033985969	54.70%	147609.1711	0.00E+00
CR_poultry	6167.929355	79	9163.65	80	2995.717056	1	99.20504331	2919	2995.717056	0.033985969	32.70%	88145.70101	0.00E+00
AvgPeriodStartYrP	8976.676266	71	9163.65	80	186.9701446	9	99.20504331	2919	20.77446051	0.033985969	2.00%	611.2658006	0.00E+00
RapplP	9046.702808	78	9163.65	80	116.9436031	2	99.20504331	2919	58.47180156	0.033985969	1.30%	1720.46887	0.00E+00
CutOffYrC	9115.244857	73	9163.65	80	48.40155409	7	99.20504331	2919	6.914507727	0.033985969	0.50%	203.4518345	0.00E+00
foc_soil	9117.113329	66	9163.65	80	46.5330817	14	99.20504331	2919	3.32379155	0.033985969	0.50%	97.79893452	0.00E+00
AirTempP	9135.675075	75	9163.65	80	27.97133577	5	99.20504331	2919	5.594267155	0.033985969	0.30%	164.6051983	0.00E+00
b	9147.397568	71	9163.65	80	16.24884253	9	99.20504331	2919	1.805426948	0.033985969	0.20%	53.12271519	0.00E+00
AreaCrCr	9148.324529	75	9163.65	80	15.32188218	5	99.20504331	2919	3.064376436	0.033985969	0.20%	90.16592825	0.00E+00
Runoff_LWS	9151.28198	73	9163.65	80	12.3644309	7	99.20504331	2919	1.766347272	0.033985969	0.10%	51.97283843	0.00E+00
uw	9153.876436	75	9163.65	80	9.769975225	5	99.20504331	2919	1.953995045	0.033985969	0.10%	57.49416911	0.00E+00
T1	9155.18715	72	9163.65	80	8.459261304	8	99.20504331	2919	1.057407663	0.033985969	0.10%	31.11306508	0.00E+00
T	9158.482263	76	9163.65	80	5.164148212	4	99.20504331	2919	1.291037053	0.033985969	0.10%	37.98735459	0.00E+00
SsC	9158.831027	75	9163.65	80	4.815383605	5	99.20504331	2919	0.963076721	0.033985969	0.10%	28.33748018	0.00E+00
DYWVPaWa	9159.915672	76	9163.65	80	3.730738622	4	99.20504331	2919	0.932684655	0.033985969	0.00%	27.44322686	0.00E+00
CYVPaRe	9160.069309	77	9163.65	80	3.577101808	3	99.20504331	2919	1.19236727	0.033985969	0.00%	35.08410403	0.00E+00
CnwmuP	9160.476646	77	9163.65	80	3.169764999	3	99.20504331	2919	1.056588333	0.033985969	0.00%	31.08895718	0.00E+00
Huc_Region	9160.606851	76	9163.65	80	3.039560016	4	99.20504331	2919	0.759890004	0.033985969	0.00%	22.35893305	0.00E+00
CYPPaPa	9160.61957	76	9163.65	80	3.026841219	4	99.20504331	2919	0.756710305	0.033985969	0.00%	22.26537388	0.00E+00
CYVPaCr	9160.778728	78	9163.65	80	2.867683004	2	99.20504331	2919	1.433841502	0.033985969	0.00%	42.18921946	0.00E+00
ConVsP	9161.112732	76	9163.65	80	2.533678764	4	99.20504331	2919	0.633419691	0.033985969	0.00%	18.63768228	3.89E-15
BD	9161.219234	75	9163.65	80	2.427177391	5	99.20504331	2919	0.485435478	0.033985969	0.00%	14.28340852	7.72E-14
DYDPPaPa	9162.80523	78	9163.65	80	0.841181025	2	99.20504331	2919	0.420590513	0.033985969	0.00%	12.37541626	4.45E-06
AreaCrWa	9162.515562	78	9163.65	80	1.130848792	2	99.20504331	2919	0.565424396	0.033985969	0.00%	16.63699502	6.54E-08
DYDPPaPa	9162.80523	78	9163.65	80	0.841181025	2	99.20504331	2919	0.420590513	0.033985969	0.00%	12.37541626	4.45E-06
DYDPCrPa	9163.090214	77	9163.65	80	0.556197238	3	99.20504331	2919	0.185399079	0.033985969	0.00%	5.455165326	9.74E-04
CYVCrPa	9163.172116	78	9163.65	80	0.47429495	2	99.20504331	2919	0.237147475	0.033985969	0.00%	6.977805327	9.48E-04
Td	9163.280144	78	9163.65	80	0.366267363	2	99.20504331	2919	0.183133682	0.033985969	0.00%	5.388508471	4.61E-03
BW	9163.615701	79	9163.65	80	0.030710215	1	99.20504331	2919	0.030710215	0.033985969	0.00%	0.903614515	3.42E-01

Table K-8. Sensitivity Analysis Results - Ingestion of Root Vegetables

VariableName	Reduced ModelSS	Reduced ModelDF	Full ModelSS	FullModel DF	VariableSS	VariableDF	FullErrorSS	FullError DF	VariableMS	FullErrorMS	Percent Variation	FTestStatistic	FTestPValue
ED	5357.374507	26	10421.72	27	5064.341778	1	33.48439082	2972	5064.341778	0.011266619	48.60%	449499.7041	0.00E+00
CR_root	7252.443885	26	10421.72	27	3169.272401	1	33.48439082	2972	3169.272401	0.011266619	30.40%	281297.5642	0.00E+00
foc_soil	9380.070341	22	10421.72	27	1041.645945	5	33.48439082	2972	208.3291889	0.011266619	10.00%	18490.83511	0.00E+00
AvgPeriodStartYrP	10029.08867	23	10421.72	27	392.6276119	4	33.48439082	2972	98.15690296	0.011266619	3.80%	8712.188231	0.00E+00
RapplP	10303.54152	25	10421.72	27	118.1747634	2	33.48439082	2972	59.08738169	0.011266619	1.10%	5244.464483	0.00E+00
CutOffYrC	10392.1281	22	10421.72	27	29.58818894	5	33.48439082	2972	5.917637788	0.011266619	0.30%	525.2363587	0.00E+00
BD	10420.70186	26	10421.72	27	1.014423501	1	33.48439082	2972	1.014423501	0.011266619	0.00%	90.03797204	0.00E+00
b	10420.94787	25	10421.72	27	0.768414846	2	33.48439082	2972	0.384207423	0.011266619	0.00%	34.10139571	2.33E-15
DYDPPaRe	10421.12941	25	10421.72	27	0.586877782	2	33.48439082	2972	0.293438891	0.011266619	0.00%	26.04498285	6.12E-12
CYVPaCr	10421.5943	25	10421.72	27	0.121987736	2	33.48439082	2972	0.060993868	0.011266619	0.00%	5.413679978	4.50E-03
SsC	10421.6097	26	10421.72	27	0.106590141	1	33.48439082	2972	0.106590141	0.011266619	0.00%	9.460703655	2.12E-03
DYDPCrPa	10421.6401	25	10421.72	27	0.076181833	2	33.48439082	2972	0.038090917	0.011266619	0.00%	3.380864978	3.41E-02
CYPCrSt	10421.65383	25	10421.72	27	0.062456156	2	33.48439082	2972	0.031228078	0.011266619	0.00%	2.771734677	6.27E-02
Td	10421.66583	25	10421.72	27	0.050458407	2	33.48439082	2972	0.025229204	0.011266619	0.00%	2.239287961	1.07E-01
fdP	10421.68099	25	10421.72	27	0.035295621	2	33.48439082	2972	0.01764781	0.011266619	0.00%	1.566380374	2.09E-01
BW	10421.70642	26	10421.72	27	0.009870501	1	33.48439082	2972	0.009870501	0.011266619	0.00%	0.87608368	3.49E-01

Table K-9. Sensitivity Analysis Results - Ingestion of Soil

VariableName	Reduced ModelSS	Reduced ModelDF	Full ModelSS	FullModelDF	VariableSS	VariableDF	FullErrorSS	FullErrorDF	VariableMS	FullErrorMS	Percent Variation	FTestStatistic	FTestPValue
ED	1401.452624	82	6441.45	83	5039.99811	1	112.8976598	2916	5039.99811	0.038716619	78.20%	130176.6087	0.00E+00
AvgPeriodStartYrP	6230.139895	72	6441.45	83	211.3108386	11	112.8976598	2916	19.21007624	0.038716619	3.30%	496.1713324	0.00E+00
RapplP	6327.240995	81	6441.45	83	114.2097382	2	112.8976598	2916	57.10486911	0.038716619	1.80%	1474.944641	0.00E+00
BW	6344.808583	82	6441.45	83	96.64215015	1	112.8976598	2916	96.64215015	0.038716619	1.50%	2496.141286	0.00E+00
foc_soil	6394.040772	71	6441.45	83	47.4099616	12	112.8976598	2916	3.950830133	0.038716619	0.70%	102.0448137	0.00E+00
CutOffYrC	6398.35841	75	6441.45	83	43.09232322	8	112.8976598	2916	5.386540403	0.038716619	0.70%	139.1273463	0.00E+00
AirTempP	6405.039287	78	6441.45	83	36.41144655	5	112.8976598	2916	7.28228931	0.038716619	0.60%	188.0920797	0.00E+00
Runoff_LWS	6416.771554	76	6441.45	83	24.67917918	7	112.8976598	2916	3.525597026	0.038716619	0.40%	91.06159457	0.00E+00
AreaCrCr	6418.753436	78	6441.45	83	22.6972974	5	112.8976598	2916	4.539459481	0.038716619	0.40%	117.2483457	0.00E+00
T1	6424.49572	71	6441.45	83	16.95501357	12	112.8976598	2916	1.412917798	0.038716619	0.30%	36.49383259	0.00E+00
b	6428.681309	80	6441.45	83	12.76942452	3	112.8976598	2916	4.25647484	0.038716619	0.20%	109.9392197	0.00E+00
CnwmuP	6429.949132	77	6441.45	83	11.50160112	6	112.8976598	2916	1.91693352	0.038716619	0.20%	49.51190443	0.00E+00
T	6433.582111	77	6441.45	83	7.868622024	6	112.8976598	2916	1.311437004	0.038716619	0.10%	33.87271543	0.00E+00
uw	6437.329871	78	6441.45	83	4.120861828	5	112.8976598	2916	0.824172366	0.038716619	0.10%	21.28730234	0.00E+00
SsC	6437.853285	76	6441.45	83	3.597448447	7	112.8976598	2916	0.513921207	0.038716619	0.10%	13.27391764	1.11E-16
CYVPaRe	6438.169114	80	6441.45	83	3.281619067	3	112.8976598	2916	1.093873022	0.038716619	0.10%	28.2533202	0.00E+00
CYPPaPa	6438.20393	81	6441.45	83	3.246802788	2	112.8976598	2916	1.623401394	0.038716619	0.10%	41.93035065	0.00E+00
ConVsP	6438.379239	79	6441.45	83	3.071494601	4	112.8976598	2916	0.76787365	0.038716619	0.00%	19.83317961	4.44E-16
BD	6438.496501	80	6441.45	83	2.954232108	3	112.8976598	2916	0.984744036	0.038716619	0.00%	25.43466015	3.33E-16
CYVPaCr	6438.777548	81	6441.45	83	2.673185387	2	112.8976598	2916	1.336592694	0.038716619	0.00%	34.52245423	1.55E-15
DYDPPaRe	6438.87013	78	6441.45	83	2.58060335	5	112.8976598	2916	0.51612067	0.038716619	0.00%	13.33072692	7.16E-13
Huc_Region	6438.924174	80	6441.45	83	2.526558761	3	112.8976598	2916	0.842186254	0.038716619	0.00%	21.75257768	6.26E-14
CYVCrPa	6439.080105	78	6441.45	83	2.370628538	5	112.8976598	2916	0.474125708	0.038716619	0.00%	12.24605156	9.02E-12
DYWPPaPa	6439.541852	82	6441.45	83	1.908881325	1	112.8976598	2916	1.908881325	0.038716619	0.00%	49.30392668	2.72E-12
DYDPCrPa	6440.254072	81	6441.45	83	1.196660939	2	112.8976598	2916	0.59833047	0.038716619	0.00%	15.45409933	2.11E-07
DYWVPaWa	6440.291159	81	6441.45	83	1.159574282	2	112.8976598	2916	0.579787141	0.038716619	0.00%	14.97514923	3.38E-07
Td	6440.667465	80	6441.45	83	0.783268014	3	112.8976598	2916	0.261089338	0.038716619	0.00%	6.743598679	1.57E-04
DYDPPaPa	6440.93677	81	6441.45	83	0.513963071	2	112.8976598	2916	0.256981536	0.038716619	0.00%	6.637499477	1.33E-03
zrufP	6440.975209	80	6441.45	83	0.47552372	3	112.8976598	2916	0.158507907	0.038716619	0.00%	4.094053467	6.55E-03

Table K-10. Sensitivity Analysis Results - Ingestion of Exposed Vegetables

VariableName	Reduced ModelSS	Reduced ModelDF	FullModelSS	Full ModelDF	VariableSS	VariableDF	FullErrorSS	FullErrorDF	VariableMS	FullErrorMS	Percent Variation	FTestStatistic	FTestPValue
ED	3521.661562	59	8673.73	60	5152.069762	1	1328.141937	2939	5152.069762	0.451902667	59.40%	11400.83948	0.00E+00
CR_exveg	8118.356119	59	8673.73	60	555.375205	1	1328.141937	2939	555.375205	0.451902667	6.40%	1228.970852	0.00E+00
AvgPeriodStartYrP	8460.593064	54	8673.73	60	213.1382605	6	1328.141937	2939	35.52304342	0.451902667	2.50%	78.60773136	0.00E+00
b	8484.162602	47	8673.73	60	189.5687224	13	1328.141937	2939	14.58220941	0.451902667	2.20%	32.26847392	0.00E+00
RapplP	8557.124651	58	8673.73	60	116.6066736	2	1328.141937	2939	58.30333681	0.451902667	1.30%	129.0174657	0.00E+00
CutOffYrC	8601.903567	57	8673.73	60	71.82775756	3	1328.141937	2939	23.94258585	0.451902667	0.80%	52.98173174	0.00E+00
CYVPaCr	8607.684061	55	8673.73	60	66.04726352	5	1328.141937	2939	13.2094527	0.451902667	0.80%	29.23074741	0.00E+00
foc_soil	8622.735216	56	8673.73	60	50.9961079	4	1328.141937	2939	12.74902697	0.451902667	0.60%	28.21188702	0.00E+00
AirTempP	8626.387122	58	8673.73	60	47.34420252	2	1328.141937	2939	23.67210126	0.451902667	0.50%	52.3831856	0.00E+00
uw	8640.614631	56	8673.73	60	33.11669362	4	1328.141937	2939	8.279173405	0.451902667	0.40%	18.32070049	6.99E-15
MetID	8651.687508	55	8673.73	60	22.04381668	5	1328.141937	2939	4.408763335	0.451902667	0.30%	9.756002035	2.94E-09
SsC	8654.485671	55	8673.73	60	19.2456537	5	1328.141937	2939	3.84913074	0.451902667	0.20%	8.51761015	5.11E-08
Runoff_LWS	8657.321824	56	8673.73	60	16.40950047	4	1328.141937	2939	4.102375118	0.451902667	0.20%	9.078005997	2.76E-07
BD	8659.891861	54	8673.73	60	13.83946305	6	1328.141937	2939	2.306577176	0.451902667	0.20%	5.104145972	3.18E-05
AreaCrCr	8660.37038	57	8673.73	60	13.36094375	3	1328.141937	2939	4.453647917	0.451902667	0.20%	9.855325596	1.82E-06
CYVPaRe	8663.192844	59	8673.73	60	10.53848066	1	1328.141937	2939	10.53848066	0.451902667	0.10%	23.32024447	1.44E-06
CYPPaPa	8666.994532	58	8673.73	60	6.736792284	2	1328.141937	2939	3.368396142	0.451902667	0.10%	7.453808952	5.90E-04
DYDPPaRe	8667.798196	58	8673.73	60	5.933128144	2	1328.141937	2939	2.966564072	0.451902667	0.10%	6.564608468	1.43E-03
CnwmuP	8668.661463	56	8673.73	60	5.069861186	4	1328.141937	2939	1.267465297	0.451902667	0.10%	2.804730731	2.44E-02
DYDPPaPa	8669.371374	58	8673.73	60	4.359949751	2	1328.141937	2939	2.179974875	0.451902667	0.10%	4.823992059	8.10E-03
DYWPPaPa	8669.826492	59	8673.73	60	3.90483185	1	1328.141937	2939	3.90483185	0.451902667	0.00%	8.640869237	3.31E-03
AreaCrWa	8670.655917	58	8673.73	60	3.075407303	2	1328.141937	2939	1.537703652	0.451902667	0.00%	3.402731971	3.34E-02
DYWVPaWa	8670.919898	56	8673.73	60	2.811426312	4	1328.141937	2939	0.702856578	0.451902667	0.00%	1.555327352	1.84E-01
Huc_Region	8672.742755	59	8673.73	60	0.98856895	1	1328.141937	2939	0.98856895	0.451902667	0.00%	2.187570518	1.39E-01
CYPCrSt	8673.244684	58	8673.73	60	0.486640128	2	1328.141937	2939	0.243320064	0.451902667	0.00%	0.538434672	5.84E-01
zrufP	8673.49621	58	8673.73	60	0.235113957	2	1328.141937	2939	0.117556978	0.451902667	0.00%	0.260137829	7.71E-01
BW	8673.720186	59	8673.73	60	0.011138345	1	1328.141937	2939	0.011138345	0.451902667	0.00%	0.024647664	8.75E-01

Parameter Codes for Variables in Sensitivity Analysis

Parameter code	Units	Description
AirTemp	°C	Long-Term Average Air Temperature
b	unitless	Soil moisture coefficient b
BD	g/cm3	Bulk soil density
BRi	m3/day	Breathing rate
BW	kg	average body weight
CN	unitless	SCS curve number
CR_exfruit	g WW/kg BW/day	consumption rate of exposed fruits
CR_exveg	g WW/kg BW/day	consumption rate of exposed vegetables
CR_root	g WW/kg BW/day	consumption rate of root vegetables
CRb	g WW/kg BW/day	consumption rate of beef
CRe	g/day	consumption rate of eggs
CRf	g WW/day	consumption rate of fish
CRl	g/day	consumption rate of above ground vegetables
CRm	g WW/kg BW/day	consumption rate of milk
CRp	g/day	consumption rate of poultry
CRw	L/day	consumption of drinking water
CutOffYr	year	Number of years over which biosolids are applied
Cwmu	unitless	USLE cover factor for the pasture
Cyp	ug-s/g-m3	particulate concentration all correlated
Cyv	ug-s/g-m3	vapor concentration - all correlated
Dydp	ug-s/g-m3	dry particulate deposition all locations correlated
Dywp	s/m2-yr	wet particulate concentration deposition all correlated
Dywv	s/m2-yr	wet vapor concentration due to deposition all correlated
ED	year	Exposure duration
foc_soil	mass fraction	Fraction organic carbon for soil
K	kg/m2	USLE soil erodibility factor
Ksat	cm/h	Saturated hydraulic conductivity
Lc	unitless	Roughness ratio
LS	unitless	USLE length-slope factor
MetID	unitless	Climate region designation
n	ml/cm3	Saturated volumetric water content, porosity for soil
P	unitless	USLE erosion control factor of rural agricultural land
Precip	cm/yr	meteorological parameter - average annual precipitation
Psoil	g/cm3	particle density of soil
R	1/yr	USLE rainfall/erosivity factor
Rappl	Mg/m2-year	Waste application rate

(continued)

Parameter Codes for Variables in Sensitivity Analysis (continued)

Parameter code	Units	Description
Rf	cm/yr	Average annual runoff
Rh	cm	roughness height
SiteLatitude	degrees	Latitude
SMFC	volume %	Soil moisture field capacity
SMWP	volume %	Soil moisture wilting point
SrcArea	m^2	Area of the agricultural field
SrcLWSBufferArea	m2	Area of buffer (Residence)
SrcLWSNumSubArea	unitless	Number of local watershed subareas
Ss	mass percent	Silt content for surface soil
Sw	mass percent	Silt content (waste solids)
SY	year	Start time exposure begins
T	degrees K	Waterbody temperature
Td	year	Time period of deposition
Theta	degrees	Slope of local watershed
Tss	mg/l	Total suspended solids in water column
TSSb	mg/l	total suspended solids in bed sediments
Tvol	sec	time over which volatilization occurs
uw	m/sec	Mean annual wind speed
V	m3	flow independent mixing volume
veg	fraction	Fraction vegetative cover
Vf	m/s	threshold friction velocity
Vfx	m3/yr	Waterbody flow mixing volume
Wai_LWS	m2	Impervious watershed area for local watershed
Wai_percent_LWS	percent	percent of impervious watershed area for local watershed
Wai_percent_RWS	percent	percent of impervious watershed area for regional watershed
Wai_RWS	m2	Impervious watershed area for regional watershed
Wat	m2	Total area of watershed
Waw	m2	Area of waterbody
WCS	volume fraction	Saturated volumetric water content, porosity for soil
zav	m	Averaging depth for soil concentration

Appendix L

Screening Ecological Risk Assessment Data

Table L-1. Bioaccumulation Factors (BAFs) for TCDD

Receptor Type	BAF (Wet weight basis)	Data Source
Worms	1.9	Dry weight basis BAF taken from Sample et al. (1998a); wet weight basis value was derived assuming a moisture content of 83.3% (U.S. EPA 1997a)
Other Invertebrates	0.15	Dry weight basis BAF taken from Meyn et al (1997); wet weight basis value was derived assuming a moisture content of 65% (Sample et al., 1997).
Small Mammals	0.35	Dry weight basis BAF for terrestrial vertebrates taken from Sample et al. (1998b); wet weight value was derived assuming a moisture content of 68% (Sample et al., 1997).
Herbivorous Vertebrates	0.35	Dry weight basis BAF for terrestrial vertebrates taken from Sample et al. (1998b); wet weight value was derived assuming a moisture content of 68% (Sample et al., 1997).
Omnivorous Vertebrates	0.35	Dry weight basis BAF for terrestrial vertebrates taken from Sample et al. (1998b); wet weight value was derived assuming a moisture content of 68% (Sample et al., 1997).
Small Birds	0.35	Dry weight basis BAF for terrestrial vertebrates taken from Sample et al. (1998b); wet weight value was derived assuming a moisture content of 68% (Sample et al., 1997).
Small Herpetofauna	0.35	Dry weight basis BAF for terrestrial vertebrates taken from Sample et al. (1998b); wet weight value was derived assuming a moisture content of 68% (Sample et al., 1997).

The terrestrial BAFs for TCDD identified in the literature were calculated on a dry weight basis. Wet weight BAFs were derived by multiplying the dry weight BAF by a moisture adjustment factor (MAF). MAFs were calculated based on the moisture contents shown in Table L-1 above. BAFs were not identified for terrestrtial vertebrates other than small mammals; therefore, the small mammal BAF was used for all terrestrial vertebrates.

Table L-2. Biota-to-Sediment Bioaccumulation Factors (BSAFs)

CAS	Constituent_short	Benthic Flter Feeders *	T3 fish	T4 fish	Aquatic Plants*
1746016	TCDD, 2,3,7,8-	1	0.09	0.09	1
3268879	OCDD, 1,2,3,4,6,7,8,9-	1	0.001	0.001	1
19408743	HxCDD, 1,2,3,7,8,9-	1	0.013	0.013	1
31508006	PeCB, 2,3',4,4',5-	1	3.59	3.59	1
32598133	TeCB, 3,3',4,4'-	1	2.205	2.205	1
32598144	PeCB, 2,3,3',4,4'-	1	4.18	4.18	1
32774166	HxCB, 3,3',4,4',5,5'-	1	11.85	11.85	1
35822469	HpCDD, 1,2,3,4,6,7,8-	1	0.003	0.003	1
38380084	HxCB, 2,3,3',4,4',5-	1	3.97	3.97	1
39001020	OCDF	1	0.001	0.001	1
39227286	HxCDD, 1,2,3,4,7,8-	1	0.028	0.028	1
39635319	HpCB, 2,3,3',4,4',5,5'-	1	2.08	2.08	1
40321764	PeCDD, 1,2,3,7,8-	1	0.083	0.083	1
51207319	TCDF, 2,3,7,8-	1	0.072	0.072	1
52663726	HxCB, 2,3',4,4',5,5'-	1	8.35	8.35	1
55673897	HpCDF, 1,2,3,4,7,8,9-	1	0.035	0.035	1
57117314	PeCDF, 2,3,4,7,8-	1	0.144	0.144	1
57117416	PeCDF, 1,2,3,7,8-	1	0.02	0.02	1
57117449	HxCDF, 1,2,3,6,7,8-	1	0.017	0.017	1
57465288	PeCB, 3,3',4,4',5-	1	3.21	3.21	1
57653857	HxCDD, 1,2,3,6,7,8-	1	0.011	0.011	1
60851345	HxCDF, 2,3,4,6,7,8-	1	0.057	0.057	1
65510443	PeCB, 2',3,4,4',5-	1	6.4	6.4	1
67562394	HpCDF, 1,2,3,4,6,7,8-	1	0.001	0.001	1
70362504	TeCB, 3,4,4',5-	1	1.005	1.005	1
70648269	HxCDF, 1,2,3,4,7,8-	1	0.007	0.007	1
72918219	HxCDF, 1,2,3,7,8,9-	1	0.06	0.06	1
74472370	PeCB, 2,3,4,4',5-	1	6.4	6.4	1

* Because of a lack of data, a default BSAF of 1 was used for fish and aquatic plants.

Appendix L

Benchmark Development

For the biosolids SERA, exposure for all 29 congeners in the assessment was expressed in terms of 2,3,7,8-TCDD toxicity equivalence. Benchmark doses for TCDD for mammals and birds were identified in the literature (from Murray et al. (1979) and Nosek et al. (1992), respectively), and species-specific scaled benchmarks were calculated for each mammal and bird receptor. These benchmarks are based on measures of effect (e.g., reproductive studies; survival) that are considered appropriate to infer risks to ecological receptors at various levels of biological organization, including individual organisms and wildlife populations. In identifying appropriate studies to develop benchmarks, study selection criteria were developed to ensure consistency in the interpretation of ecotoxicological data and to satisfy relevant data quality objectives. The study selection criteria address the appropriateness of the study data and the quality of the study with respect to endpoint selection, dose-response information, and appropriate use of extrapolation techniques (e.g., tools for statistical inference).

The benchmarks represent de minimis levels of effect and were developed to infer risks to species populations of mammals and birds exposed through the ingestion of contaminated media and prey. In order of importance, the study selection criteria included the following: (1) relevance of study endpoints to population-level effects, (2) adequate data to demonstrate the dose-response relationship, (3) appropriateness of study design with respect to the exposure route (e.g., gavage versus dietary exposure) and exposure duration, and (4) quality of the study as determined by the use of appropriate dosing regimes, statistical tools, etc.

Methodology for Deriving Benchmarks

- <u>*Assessment Endpoint*</u>*: maintain viable mammalian and avian wildlife populations*. The attribute to be protected was the reproductive and developmental success of representative species.

- <u>*Measure of Effect*</u>*: a de minimis threshold for developmental and reproductive toxicity in mammalian and avian wildlife species*. The threshold was calculated as the geometric mean of the NOAEL and LOAEL, frequently referred to as the MATL. Implicit in this calculation is the assumption that the toxicological sensitivity is lognormal.

For mammals and birds, ecotoxicological data were evaluated to determine the most appropriate study with which to develop ecological benchmarks (in units of dose) to infer risk to the population level. Once the benchmark study was identified, a scaled benchmark was calculated for each receptor species. This method used an allometric scaling equation based on body weight to extrapolate test species doses to estimate wildlife species doses. For mammals, a scaling factor of 1/4 was used (Equation L-1). This is the default methodology EPA proposes for carcinogenicity assessments and reportable quantity documents for adjusting animal data to an equivalent human dose (U.S. EPA, 1992).

For birds, research suggests that the cross-species scaling equation used for mammals is not appropriate for avian species (Mineau et al., 1996). Using a database that characterized acute toxicity of pesticides to avian receptors of various body weights, Mineau et al. (1996) concluded that applying mammalian scaling equations may not sufficiently predict protective doses for avian species. Mineau et al. further suggested that a scaling factor of 1 provided a better dose estimate for birds. Therefore, a scaling factor of 1 was applied for avian receptors (Equation 2).

$$EB_w = MATL_t \times \left(\frac{bw_t}{bw_w} \right)^{1/4} \quad \text{(L-1)}$$

$$EB_w = MATL_t \times \left(\frac{bw_t}{bw_w} \right)^{1} \quad \text{(L-2)}$$

where

EB_w	=	scaled ecological benchmark for species *w* (mg/kg-d)
$MATL_t$	=	maximum acceptable toxicant concentration (mg/kg-d)
bw_t	=	body weight of the surrogate test species (kg)
bw_w	=	body weight of the representative wildlife species (kg).

Table L-3. Ecological Benchmarks

Receptor Name	Class	NOAEL (mg/kg-day)	MATL (mg/kg-day)	LOAEL (mg/kg-day)
American kestrel	B	1.40E-05	1.40E-04	4.40E-05
American robin	B	1.40E-05	1.40E-04	4.40E-05
American woodcock	B	1.40E-05	1.40E-04	4.40E-05
Bald eagle	B	1.40E-05	1.40E-04	4.40E-05
Beaver	M	3.96E-07	3.96E-06	1.25E-06
Belted kingfisher	B	1.40E-05	1.40E-04	4.40E-05
Black bear	M	2.46E-07	2.46E-06	7.79E-07
Canada goose	B	1.40E-05	1.40E-04	4.40E-05
Cooper's hawk	B	1.40E-05	1.40E-04	4.40E-05
Coyote	M	4.36E-07	4.36E-06	1.38E-06
Deer mouse	M	2.22E-06	2.22E-05	7.02E-06
Eastern cottontail rabbit	M	7.89E-07	7.89E-06	2.49E-06
Great blue heron	B	1.40E-05	1.40E-04	4.40E-05
Green heron	B	1.40E-05	1.40E-04	4.40E-05
Herring gull	B	1.40E-05	1.40E-04	4.40E-05
Least weasel	M	1.85E-06	1.85E-05	5.84E-06
Lesser scaup	B	1.40E-05	1.40E-04	4.40E-05
Little brown bat	M	2.71E-06	2.71E-05	8.57E-06
Long-tailed weasel	M	1.26E-06	1.26E-05	3.98E-06
Mallard duck	B	1.40E-05	1.40E-04	4.40E-05
Meadow vole	M	2.19E-06	2.19E-05	6.91E-06
Mink	M	8.32E-07	8.32E-06	2.63E-06
Muskrat	M	8.59E-07	8.59E-06	2.72E-06
Northern bobwhite	B	1.40E-05	1.40E-04	4.40E-05
Osprey	B	1.40E-05	1.40E-04	4.40E-05
Prairie vole	M	1.84E-06	1.84E-05	5.81E-06
Raccoon	M	5.37E-07	5.37E-06	1.70E-06
Red fox	M	5.69E-07	5.69E-06	1.80E-06
Red-tailed hawk	B	1.40E-05	1.40E-04	4.40E-05
River otter	M	4.84E-07	4.84E-06	1.53E-06
Short-tailed shrew	M	2.37E-06	2.37E-05	7.50E-06
Short-tailed weasel	M	1.24E-06	1.24E-05	3.92E-06
Tree swallow	B	1.40E-05	1.40E-04	4.40E-05
Western meadowlark	B	1.40E-05	1.40E-04	4.40E-05
White-tailed deer	M	2.88E-07	2.88E-06	9.10E-07

Table L-4. Ecological Exposure Factors

Receptor Name	Body weight (kg)	Consumption rate of food items (kg/day)	Water consumption rate (L/day)	Sediment fraction of total diet (unitless)	Soil fraction of total diet (unitless)
American kestrel	0.118915339	0.095734522	0.014166462	-999	0.01
American robin	0.0773	0.072325853	0.0106153	-999	0.01
American woodcock	0.17747325	0.124243659	0.018525548	-999	0.104
Bald eagle	3.75	0.905280301	0.143038505	0.059	-999
Beaver	19.30859066	5.111207944	1.421709	0.033	-999
Belted kingfisher	0.147057068	0.109931471	0.01633306	0.059	-999
Black bear	128.874222	24.3328554	7.848463546	-999	0.028
Canada goose	2.996629957	0.782306383	0.123082469	-999	0.082
Cooper's hawk	0.404864593	0.212543287	0.03219212	-999	0.01
Coyote	13.12889529	3.722375189	1.00470962	-999	0.028
Deer mouse	0.0196	0.017695835	0.002875184	-999	0.02
Eastern cottontail rabbit	1.226135331	0.530169998	0.118937762	-999	0.063
Great blue heron	2.229	0.645220815	0.10094522	0.094	-999
Green heron	0.226035395	0.145431199	0.021784632	0.094	-999
Herring gull	1.091233068	0.405296655	0.06255424	0.059	-999
Least weasel	0.040830303	0.032349254	0.005565697	-999	0.01
Lesser scaup	0.792389627	0.329077252	0.050482516	0.033	-999
Little brown bat	0.008789198	0.009152987	0.001396978	-999	0
Long-tailed weasel	0.188646952	0.113820557	0.022065817	-999	0.028
Mallard duck	1.170158282	0.424146567	0.065550484	0.033	-999
Meadow vole	0.020821722	0.018597615	0.003035989	-999	0.024
Mink	0.992422597	0.445575413	0.098324597	0.094	-999
Muskrat	0.873	0.401005459	0.087608857	0.033	-999
Northern bobwhite	0.19125764	0.130443532	0.019477652	-999	0.093
Osprey	1.601382632	0.520253528	0.080884208	0.059	-999
Prairie vole	0.041567017	0.032828281	0.005655997	-999	0.024
Raccoon	5.691468746	1.872539541	0.473518678	0.094	-999
Red fox	4.532144522	1.552809787	0.385752341	-999	0.028
Red-tailed hawk	1.130926184	0.41483407	0.064069741	-999	0.01
River otter	8.660254038	2.644154065	0.690896135	0.094	-999
Short-tailed shrew	0.015	0.014203115	0.003538614	-999	0.01
Short-tailed weasel	0.201530285	0.120172285	0.023417551	-999	0.028
Tree swallow	0.02095	0.030915731	0.004426346	-999	0.01
Western meadowlark	0.106442473	0.089071866	0.013152825	-999	0
White-tailed deer	69.41716207	14.63262799	4.497336296	-999	0.068

Table L-5. Exposure Factor Data Sources

Species	Scientific Name	References
American kestrel	*Falco sparverius*	Terres, 1980; U.S. EPA, 1993; Lane and Fischer, 1997; Stokes and Stokes, 1996
American robin	*Turdus migratorius*	Terres, 1980; U.S. EPA, 1993; Stokes and Stokes, 1996
American woodcock	*Scolopax minor*	Terres, 1980; U.S. EPA, 1993; Stokes and Stokes, 1996
Bald eagle	*Haliaeetus leucocephalus*	Terres, 1980; U.S. EPA, 1993; Stokes and Stokes, 1996
Beaver	*Castor canadensis*	Stokes and Stokes, 1986; Whitaker, 1997; Jenkins and Busher, 1979
Belted kingfisher	*Ceryle alcyon*	Terres, 1980; U.S. EPA, 1993; Stokes and Stokes, 1996
Black bear	*Ursus americanus*	Schaefer and Sargent, 1990; Stokes and Stokes, 1986; Whitaker, 1997
Canada goose	*Branta canadensis*	Terres, 1980; U.S. EPA, 1993; Niering, 1985; Stokes and Stokes, 1996
Cooper's hawk	*Accipiter cooperi*	Terres, 1980; Sample et al., 1997; Stokes and Stokes, 1996
Coyote	*Canis latrans*	Bekoff, 1977; Sample et al, 1997; Whitaker, 1997; Stokes and Stokes, 1986
Deer mouse	*Peromyscus maniculatus*	Whitaker, 1997; U.S. EPA, 1993; Stokes and Stokes, 1986
Eastern cottontail rabbit	*Sylvilagus floridanus*	Stokes and Stokes, 1986; Chapman et al., 1980; Whitaker, 1997; U.S. EPA, 1993
Great blue heron	*Ardea herodias*	Terres, 1980; U.S. EPA, 1993; Stokes and Stokes, 1996; Niering, 1985
Green heron	*Butorides virescens*	Terres, 1980; Sample et al., 1997; Stokes and Stokes, 1996; Niering, 1985
Herring gull	*Larus argentatus*	Terres, 1980; U.S. EPA, 1993; Stokes and Stokes, 1996
Least weasel	*Mustela nivalis*	Whitaker, 1997; Stokes and Stokes, 1986; Sample et al., 1997
Lesser scaup	*Aythya affinis*	Terres, 1980; U.S. EPA, 1993; Stokes and Stokes, 1996

(continued)

Table L-5. (continued)

Species	Scientific Name	References
Little brown bat	*Myotis lucifugus*	Whitaker, 1997; Sample et al., 1997.
Long-tailed weasel	*Mustela frenata*	Sutton and Sutton, 1985; Sample et al., 1997; Stokes and Stokes, 1996
Mallard	*Anas platyrhynchos*	Terres, 1980; U.S. EPA, 1993; Stokes and Stokes, 1996; Niering, 1985
Marsh wren	*Cistothorus palustris*	Terres, 1980; U.S. EPA, 1993; Stokes and Stokes, 1996; Niering, 1985
Meadow vole	*Microtus pennsylvanicus*	Whitaker, 1997; U.S. EPA, 1993; Stokes and Stokes, 1986
Mink	*Mustela vison*	Niering, 1985; U.S. EPA, 1993; Whitaker, 1997; Stokes and Stokes,1986
Muskrat	*Ondatra zibethicus*	Niering, 1985; U.S. EPA, 1993; Stokes and Stokes, 1986; Willner et al., 1980; Whitaker, 1997
Northern bobwhite	*Colinus virginianus*	Terres, 1980; U.S. EPA, 1993; Stokes and Stokes, 1996
Osprey	*Pandion haliaetus*	Terres, 1980; U.S. EPA, 1993; Stokes and Stokes, 1996
Prairie vole	*Microtus ochrogaster*	Whitaker, 1997; U.S. EPA, 1993
Raccoon	*Procyon lotor*	Lotze and Andersen, 1979; U.S. EPA, 1993; Whitaker, 1997; Stokes and Stokes, 1986
Red fox	*Vulpes vulpes*	Whitaker, 1997; U.S. EPA, 1993; Stokes and Stokes, 1986
Red-tailed hawk	*Buteo jamaicensis*	Terres, 1980; U.S. EPA, 1993; Stokes and Stokes, 1996
River otter	*Lutra canadensis*	Whitaker, 1997; U.S. EPA, 1993; Niering, 1985; Stokes and Stokes, 1986
Short-tailed shrew	*Blarina brevicauda*	Whitaker, 1997; U.S. EPA, 1993; Stokes and Stokes, 1986
Short-tailed weasel	*Mustela erminea*	King, 1983; Sample et al., 1997; Whitaker, 1997
Tree swallow	*Tachycineta bicolor*	Terres, 1980; Sample et al., 1997; Stokes and Stokes, 1996
Western meadowlark	*Sturnella neglecta*	Terres, 1980; Sample et al., 1997; Stokes and Stokes, 1996
White-tailed deer	*Odocoileus virginianus*	Whitaker, 1997; Stokes and Stokes, 1986; Smith, 1991

Table L-6. Phase 2: Dietary Composition for Agricultural Field Habitat

Receptor Name	Worms	Other inverte-brates	Small mammals	Herbivorous verte-brates	Omnivorous verte-brates	Small birds	Exposed fruits	Exposed vegetables	Forage	Grains	Roots	Silage	Small herpetofauna
American kestrel	0	0.38	0.255	0	0	0.11	0	0	0	0	0	0	0.255
American robin	0	0.505	0	0	0	0	0.495	0	0	0	0	0	0
American woodcock	0.86	0.085	0	0	0	0	0	0	0.055	0	0	0	0
Black bear	0	0.4	0.025	0	0	0	0.4	0	0.175	0	0	0	0
Canada goose	0	0	0	0	0	0	0	0	0.6	0.4	0	0	0
Cooper's hawk	0	0	0.43	0	0	0.57	0	0	0	0	0	0	0
Coyote	0	0.055	0.415	0.1	0.1	0.155	0.125	0	0	0	0	0	0.05
Deer mouse	0	0.325	0	0	0	0	0.235	0	0.055	0.385	0	0	0
Eastern cottontail rabbit	0	0	0	0	0	0	0	0	0.875	0	0	0.125	0
Least weasel	0	0.05	0.9	0	0	0.05	0	0	0	0	0	0	0
Little brown bat	0	1	0	0	0	0	0	0	0	0	0	0	0
Long-tailed weasel	0.05	0.05	0.525	0.125	0.125	0.125	0	0	0	0	0	0	0
Meadow vole	0	0	0	0	0	0	0	0	0.75	0.075	0.175	0	0
Northern bobwhite	0	0.18	0	0	0	0	0.125	0	0.125	0.57	0	0	0
Prairie vole	0	0.075	0	0	0	0	0	0	0.75	0	0.175	0	0
Raccoon	0	0.445	0	0	0	0	0.555	0	0	0	0	0	0
Red fox	0	0	0.51	0	0	0.19	0.3	0	0	0	0	0	0
Red-tailed hawk	0	0.125	0.5	0.125	0.125	0.125	0	0	0	0	0	0	0
Short-tailed shrew	0.425	0.3	0.05	0	0	0	0.05	0.175	0	0	0	0	0
Short-tailed weasel	0	0.125	0.65	0	0	0.125	0	0	0	0	0	0	0.1
Tree swallow	0	0.75	0	0	0	0	0.125	0	0.125	0	0	0	0
Western meadowlark	0	0.875	0	0	0	0	0	0	0	0.125	0	0	0
White-tailed deer	0	0	0	0	0	0	0	0	0.75	0.25	0	0	0

Table L-7. Phase 2: Dietary Composition for Stream and Pond/Lake Habitat

Receptor Name	Benthic filter feeders	T3 fish	T4 fish	Aquatic plants
Bald eagle	0	0.505	0.495	0
Beaver	0	0	0	1
Belted kingfisher	0.05	0.95	0	0
Great blue heron	0	0.515	0.485	0
Green heron	0	0.985	0	0.015
Herring gull	0.22	0.39	0.39	0
Lesser scaup	0.75	0	0	0.25
Mallard duck	0.35	0.35	0	0.3
Mink	0	0.55	0.45	0
Muskrat	0.25	0.05	0	0.7
Osprey	0	0.625	0.375	0
Raccoon	0.375	0.345	0.28	0
River otter	0	0.595	0.405	0

Table L-8. Toxicity Equivalence Factors (TEFs)

CAS	Constituent_short	MammalTEF	BirdTEF
1746016	TCDD, 2,3,7,8-	1	1
40321764	PeCDD, 1,2,3,7,8-	1	1
39227286	HxCDD, 1,2,3,4,7,8-	0.1	0.05
57653857	HxCDD, 1,2,3,6,7,8-	0.1	0.01
19408743	HxCDD, 1,2,3,7,8,9-	0.1	0.1
35822469	HpCDD, 1,2,3,4,6,7,8-	0.01	0.001
3268879	OCDD, 1,2,3,4,6,7,8,9-	0.0001	0.00001*
51207319	TCDF, 2,3,7,8-	0.1	1
57117416	PeCDF, 1,2,3,7,8-	0.05	0.1
57117314	PeCDF, 2,3,4,7,8-	0.5	1
70648269	HxCDF, 1,2,3,4,7,8-	0.1	0.1
57117449	HxCDF, 1,2,3,6,7,8-	0.1	0.1
72918219	HxCDF, 1,2,3,7,8,9-	0.1	0.1
60851345	HxCDF, 2,3,4,6,7,8-	0.1	0.1
67562394	HpCDF, 1,2,3,4,6,7,8-	0.01	0.01
55673897	HpCDF, 1,2,3,4,7,8,9-	0.01	0.01
39001020	OCDF	0.0001	0.0001
32598133	TeCB, 3,3',4,4'-	0.0001	0.05
32598144	PeCB, 2,3,3',4,4'-	0.0001	0.0001
74472370	PeCB, 2,3,4,4',5-	0.0005	0.0001
31508006	PeCB, 2,3',4,4',5-	0.0001	0.00001
65510443	PeCB, 2',3,4,4',5-	0.0001	0.00001
57465288	PeCB, 3,3',4,4',5-	0.1	0.1
38380084	HxCB, 2,3,3',4,4',5-	0.0005	0.0001
52663726	HxCB, 2,3',4,4',5,5'-	0.00001	0.00001
32774166	HxCB, 3,3',4,4',5,5'-	0.01	0.001
39635319	HpCB, 2,3,3',4,4',5,5'-	0.0001	0.00001
70362504	TeCB, 3,4,4',5-	0.0001	0.1

Reference: WHO Consensus 1998

No TEF was recommended by the WHO Consensus for birds for OCDD. For modeling purposes, the lowest TEF for birds was used as a surrogate for OCDD.

Table L-9. Aquatic Diet Item Lipid Fractions

PreyType	Lipid raction (whole body)	Reference
Benthic filter feeders	0.05	Gobas, F.A.P.C. and H.A. Morrison. 2000. Bioconcentration and Biomagnification in the Aquatic Environment. In Handbook of Property Estimation Methods for Chemicals: Environmental and Health Sciences. Eds. R. Boethling and D. Mackay. Lewis Publishers: Boca Raton, FL. pp189-231.
T3 Fish	0.0646	Great Lakes Water Quality Initiative Technical Support Document for the Procedure to Determine Bioaccumulation Factors, USEPA 1995
T4 Fish	0.1031	Great Lakes Water Quality Initiative Technical Support Document for the Procedure to Determine Bioaccumulation Factors, USEPA 1995
Aquatic plants	0.01	Gobas, F.A.P.C. and H.A. Morrison. 2000. Bioconcentration and Biomagnification in the Aquatic Environment. In Handbook of Property Estimation Methods for Chemicals: Environmental and Health Sciences. Eds. R. Boethling and D. Mackay. Lewis Publishers: Boca Raton, FL. pp189-231.

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Appendix M

Climate Region Selection

Appendix M
Climate Region Selection

Background

Dispersion and deposition of volatile and particulate contaminants and air concentrations of contaminants at specified receptor locations are estimated with EPA's Industrial Source Complex, Short-Term Model, version 3 (ISCST3). ISCST3 calculates dispersion, deposition and air concentrations. Running ISCST3 is time consuming and requires extensive technical expertise. Therefore, dispersion and deposition were modeled using ISCST3 for selected scenarios designed to cover a broad range of characteristics. For the dioxins, furans and PCBs in biosolids, these scenarios include

- 41 meteorological stations, chosen to represent the nine general climate regions of the continental United States
- 41 farm sizes representing the median farm size for each climate region

The remainder of this section details how the country was divided into areas that could be adequately represented by one meteorological station.

Approach

Bailey's ecoregions and subregions of the United States (Bailey et al., 1994) are used to associate coverage areas with meteorological stations. This hierarchical classification scheme is based primarily on rainfall regimes; subregions are delineated by elevation and other factors affecting ecology.

The approach used involved two main steps:

1. Identify contiguous areas that are sufficiently similar with regard to the parameters that affect dispersion that they can be reasonably represented by one meteorological station. The parameters used are
    - Surface level meteorological data (e.g., wind patterns and atmospheric stability)
    - Physiographic features (e.g., mountains, plains)
    - Bailey’s ecoregions and subregions

- Land cover (e.g., forest, urban areas).

2. For each contiguous area, select one meteorological station to represent the area. The station selection step considered the following parameters:

   - Location within the area
   - Years of meteorological data available
   - Average windspeed.

These steps are described in the following subsections.

Identify Contiguous Areas

A hierarchical procedure based on features affecting wind flow was used to divide the country. The primary delineation of areas was based on geographic features affecting synoptic (broad area) winds, including mountain ranges and plains. These features are also known as physiography. Data were obtained from Fenneman and Johnson (1946). The secondary delineation was based on features affecting mesoscale (10- to 1,000-km) winds, including coastal regions and basic land cover classifications of forest, agriculture, and barren lands. These land cover features were obtained from U.S. Geological Survey (1999).

The methodology for identifying contiguous areas uses wind data and atmospheric stability data derived from surface-level meteorological data as the primary consideration, modified by physiography, Bailey's ecoregions and subregions, and land cover. The approach focuses on how well the windspeed and direction and atmospheric stability patterns measured at a surface-level meteorological station represent the surrounding area. The limit of appropriate representation varies by area of the country and is substantially determined by terrain and topography. For example, a station in the Midwest, where topography and vegetation are uniform, may adequately represent a very large area, while a mountainous station, where ridges and valleys affect the winds, may represent a much smaller area.

Primary Grouping on Wind Rose and Atmospheric Stability Data. The surface-level meteorological data were downloaded from EPA's SCRAM Web site (www.epa.gov/scram001). SCRAM has these data from 1984 to 1991. A 5-year period is commonly used to obtain an averaged depiction of the winds for each station; 5 years covers most of the usual variation in meteorological conditions. Not all stations had 5 years of data in this time period. Three years of data was considered a desirable minimum for stations, therefore, stations that had less than 3 years of data during this time period were not considered for selection.

Two types of wind data were considered: wind directionality and windspeed. Wind directionality describes the tendency of winds to blow from many different directions (weakly directional) or primarily from one direction (strongly directional). Strongly directional winds will tend to disperse air pollutants in a consistent direction, resulting in higher air concentrations in that direction and higher overall maximum air concentrations. Weakly directional winds will

tend to disperse pollutants in multiple directions, resulting in lower air concentrations in any one direction and lower overall maximum air concentration.

Windspeed also affects dispersion. A greater average windspeed tends to disperse pollutants more quickly, resulting in lower air concentrations than lower average windspeeds would produce. Windspeed was used in the station selection process, but not to identify contiguous areas of the country.

A wind rose is a graphical depiction of the frequency of windspeeds by wind direction (see Figure 2-1). Wind roses were produced from the surface-level meteorological data for each station using WRPLOT (available from www.epa.gov/scram001/models/relat/wrplot.zip). Winds are plotted in 16 individual directions; thus, if every direction has the same frequency, the wind would blow from each direction 6.25 percent of the time. Based on the wind roses, each station was assigned to one of four bins based on the frequency of wind in the predominant direction (the direction from which the wind blows the greatest percentage of the time). These bins were as follows:

- W, weakly directional: blowing from predominant direction less than 10 percent of the time
- Mildly directional: blowing from predominant direction 10 to 14 percent of the time
- Moderately directional: blowing from predominant direction 15 to 20 percent of the time
- Strongly directional: blowing from predominant direction over 20 percent of the time.

Atmospheric stability class frequency distributions were also used for some stations. Atmospheric stability is a measure of vertical movement of air and can be classified as stable, unstable, or neutral. For sources at ground level sources such as are modeled in the agricultural use scenarion, pollutants tend to stay close to the ground in a stable atmosphere, thereby increasing the air concentration of the pollutant. In an unstable atmosphere, the pollutants will tend to disperse more in the vertical direction, thereby decreasing the air concentration of the pollutant. Atmospheric stability varies throughout the day and year, as well as by location, because atmospheric stability is determined from variable factors such as windspeed, strength of solar radiation, and the vertical temperature profile above the ground. In addition, the presence of large bodies of water, hills, large urban areas, and types and height of vegetation all affect atmospheric stability. If all other factors are the same at two stations, the one with stable air a larger percentage of the time will have higher air concentrations than the station with stable air a smaller percentage of the time.

Secondary Grouping Considerations. After spatially grouping the wind roses in similar bins, the next step was to delineate geographic areas around these groups of meteorological stations using maps of physiography, Bailey's ecoregions, and land cover. Physiography includes major topographic features such as mountains or plains. Land cover

classifications include urban, cropland, grassland, forest, large waterbody, wetland, barren, and snow or ice. Regional boundaries were chosen to coincide with physiographic, Bailey's ecoregion, and land cover boundaries to the extent possible.

Station Selection

The above approach used to delineate contiguous areas ensures that the stations grouped together are fairly similar in most cases. Therefore, the selection of an appropriate station to represent each area was based on other considerations, including

- **Number of years of surface-level meteorological data available.** More years of data provide a more realistic long-term estimate of air concentration.

- **Central location within the area.** All other factors being equal, central locations are more likely to be representative of the entire contiguous geographic area, because they have the smallest average distance from all points in the region.

- **Windspeed**. Lower windspeeds lead to less dispersion and higher air concentrations.

Windspeed was summarized as average speed in the prevailing wind direction. This value is not readily extractable from the wind roses; therefore, it was obtained from the *International Station Meteorological Climate Summary* CD (NOAA, 1992) of meteorological data. For a few stations, this value was unrealistically low; in those cases, an average windspeed in the prevailing wind direction was estimated from the wind rose data.

EPA used a hierarchical procedure to select a representative station, as follows:

- Stations with less than 5 years of data in SCRAM were eliminated, unless no station had 5 years of data.

- Stations centrally located in the area were preferred if the above factors did not identify a clear choice.

- If all other factors were equal, stations with lower average windspeeds were selected to ensure that air concentration was not underestimated. Variations in windspeed within regions were minor.

Table M-1. Surface-Level Meteorology Stations in Dioxins, Furans, and PCBs in Biosolids

Station Number	Station Name	State
13963	Little Rock/Adams Field	AR
23183	Phoenix/Sky Harbor International Airport	AZ
93193	Fresno/Air Terminal	CA
23174	Los Angeles/International Airport	CA
23234	San Francisco/International Airport	CA
23062	Denver/Stapleton International Airport	CO
14740	Hartford/Bradley International Airport	CT
12839	Miami/International Airport	FL
12842	Tampa/International Airport	FL
13874	Atlanta/Atlanta-Hartsfield International	GA
24131	Boise/Air Terminal	ID
94846	Chicago/O'Hare International Airport	IL
03937	Lake Charles/Municipal Airport	LA
12916	New Orleans/International Airport	LA
13957	Shreveport/Regional Airport	LA
14764	Portland/International Jetport	ME
94847	Detroit/Metropolitan Airport	MI
14840	Muskegon/County Airport	MI
14922	Minneapolis-St Paul/International Airport	MN
13865	Meridian/Key Field	MS
24033	Billings/Logan International Airport	MT
03812	Asheville/Regional Airport	NC
13722	Raleigh/Raleigh-Durham Airport	NC
24011	Bismarck/Municipal Airport	ND
14935	Grand Island/Airport	NE
23050	Albuquerque/International Airport	NM
23169	Las Vegas/McCarran International Airport	NV
24128	Winnemucca/WSO Airport	NV
14820	Cleveland/Hopkins International Airport	OH

(continued)

Table M-1. (continued)

Station Number	Station Name	State
13968	Tulsa/International Airport	OK
94224	Astoria/Clatsop County Airport	OR
24232	Salem/McNary Field	OR
14751	Harrisburg/Capital City Airport	PA
13739	Philadelphia/International Airport	PA
14778	Williamsport-Lycoming/County	PA
13880	Charleston/International Airport	SC
13877	Bristol/Tri City Airport	TN
13897	Nashville/Metro Airport	TN
12960	Houston/Intercontinental Airport	TX
24127	Salt Lake City/International Airport	UT
13737	Norfolk/International Airport	VA
14742	Burlington/International Airport	VT
24233	Seattle/Seattle-Tacoma International	WA
03860	Huntington/Tri-State Airport	WV
24089	Casper/Natrona Co International Airport	WY

For purposes of that discussion, we have divided the United States into the following sections: West Coast, Desert Southwest, Western Mountains, Gulf Coast, Southeast, Middle Atlantic, Northeast, Great Lakes, Central States, Alaska, and Hawaii. The process of selecting stations and delineating the region assigned to each station is discussed by these sections.

Table M-1 shows the selected stations for the continental United States.

Figure M-1 shows these stations and their boundaries.

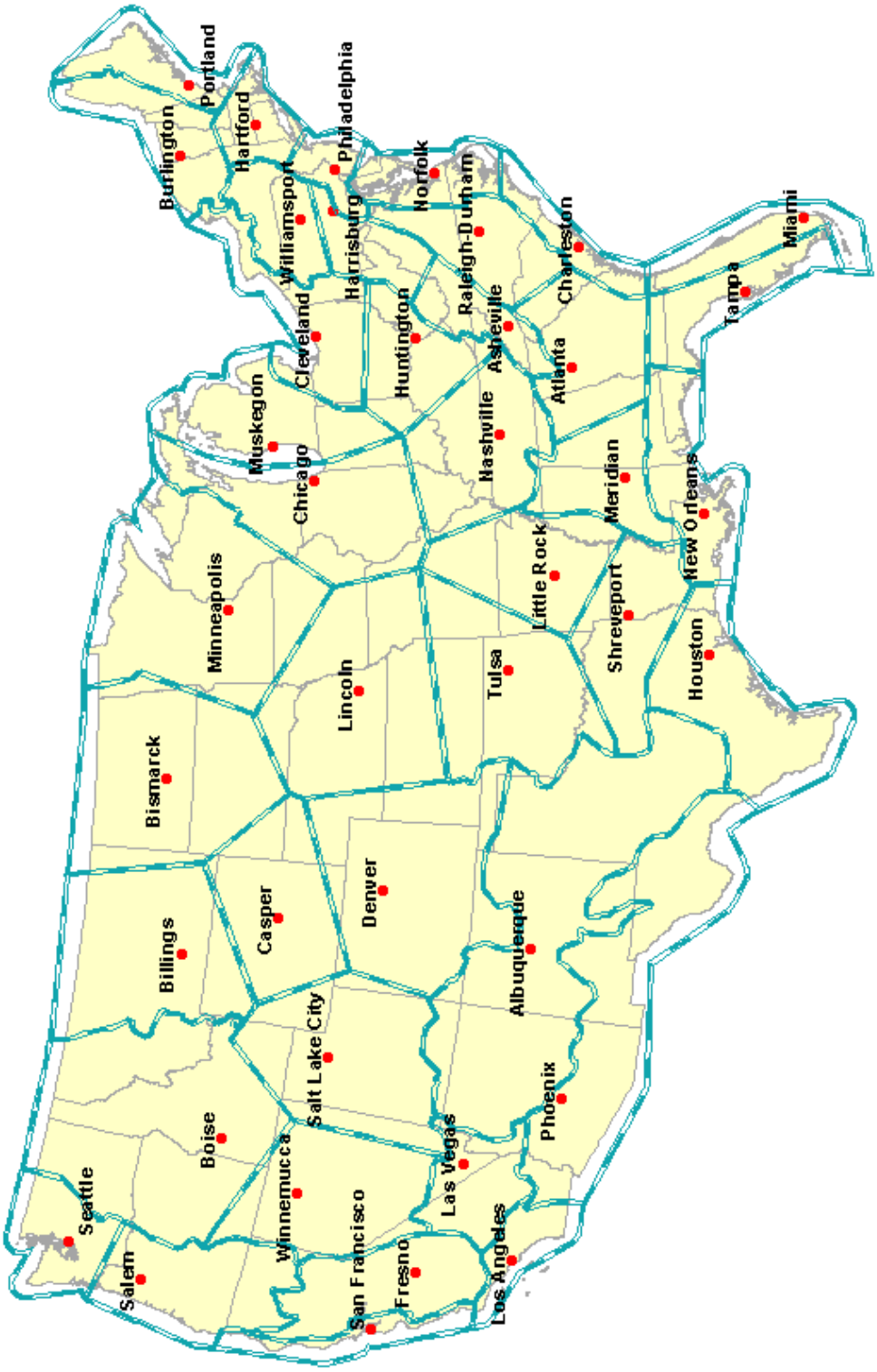

Figure M-1. Climate regions.

West Coast

The West Coast is defined by a narrow coastal plain and mountain chains running parallel to the coast of the Pacific Ocean. In many areas the mountainous region is broken by a large central valley, such as in California. The northwestern Pacific coast contains a narrow plain between the Pacific Ocean and the Coast Ranges.

The California coast is divided just north of Point Conception above Los Angeles. This northern section is represented by the **San Francisco** International Airport (23234). The wind rose shows strong directionality with an average windspeed of 12 knots.

The southern California coast contains the Los Angeles basin south to the California/Mexico border. This region is represented by the **Los Angeles** International Airport (23174). The wind rose shows strong directionality and an average windspeed of 8 knots.

The California central valley region, which encompasses the Sacramento Valley to the north and the San Joaquin Valley to the south, is defined by the Coast Range and Diablo Range on the west and the Sierra Nevada mountains on the east. The valley extends south to the northern rim of the Los Angeles basin.. The region represented by **Fresno** Air Terminal (93193),

The inland portion of Washington is bounded by the Coast Ranges on the west, the edge of the Humid Temperate Domain to the east, the Washington/Canada border to the north and the Columbia River to the south. This region is represented by the **Seattle**-Tacoma International Airport (24233). Its wind rose shows moderate directionality and an average windspeed of 10 knots.

Desert Southwest

The Desert Southwest is defined by various deserts and mountain ranges. One distinguishing feature is the transition between low desert in southern Arizona and high desert in northern Arizona. The southern boundary of this section is the U.S./Mexico border.

Southern Arizona contains the Sonoran Desert. This region of low desert is represented by the station at **Phoenix**/Sky Harbor International Airport (23183). The region is bounded to the north between Phoenix and Prescott, Arizona, along the southern edge of the Columbia Plateau, which represents the transition from low to high desert. The wind rose for Phoenix shows moderate directionality and an average windspeed of 6 knots.

The northern portion of Arizona, southeastern California, southern Nevada, and southern Utah are represented by the station at **Las Vegas**/McCarran International Airport (23169). This is one of the original 29 stations. This region is characterized by high desert, including the Columbia Plateau. Relatively few facilities and people are located here. The wind rose is mildly directional with an average windspeed of 10 knots.

The station at **Albuquerque** International Airport (23050), which is one of the original 29 stations, represents the mountainous region of western New Mexico and far west Texas. This region is bounded on the east by the Sacramento Mountains east of El Paso, Texas, and by the

Sangre de Cristo Mountains east of Albuquerque, New Mexico. The wind rose is weakly directional and the average windspeed is 8 knots.

Western Mountains

The Western Mountains include numerous mountain ranges, plateaus, and valleys that affect wind flows. Boundaries between these regions follow major terrain features.

The inland region of Oregon includes both the central valley area and the Great Sandy Desert, east to the Columbia Plateau. The western boundary is the Coast Ranges. The Black Rock Desert forms the southern boundary. This region is represented by the station at McNary Field in **Salem, Oregon** (24232). The wind rose shows moderate directionality and an average windspeed of 9 knots.

The Snake River Plain of southern Idaho forms the region represented by **Boise** Air Terminal (24131) in Idaho. This region is bounded by the Salmon River Mountains on the north and the Columbia Plateau to the west and south. The wind rose shows moderate directionality and average windspeed of 9 knots.

Northern Nevada and northeastern California are represented by the station at **Winnemucca** WSO Airport (24128) in Nevada. This is the Great Basin area. The wind rose shows mild directionality and an average windspeed of 8 knots.

The Salt Lake Basin and the Great Divide Desert in Utah and Colorado are represented by the station at **Salt Lake City** International Airport (24127) in Utah. The eastern boundary of this region is formed by the Wind River Range and the Front Range. The wind rose shows moderate directionality and an average windspeed of 9 knots.

Gulf Coast

The wind regime along the Gulf of Mexico is strongly influenced by that body of water. However, its effects do not reach very far inland. A series of regions have been designated to represent the coastal section.

The middle Texas Gulf Coast is represented by the station at **Houston** Intercontinental Airport (12960). Although Houston itself is somewhat inland, it is expected to have a more coastal environment due to Galveston Bay. This region extends south past Victoria to the vegetative boundary marking Southern Texas. The wind rose in this region is only mildly directional with an average windspeed of 8 knots.

The Central Gulf Coast extends from eastern Louisiana through the Florida panhandle. This entire region is part of the Outer Coastal Plain Mixed Forest Province and is characterized by weakly directional winds. The station at **New Orleans** International Airport (12916) in Louisiana was chosen to represent this region. Its wind rose is weakly directional with an average windspeed of 8 knots.

The West Coast of the Florida Peninsula is heavily influenced by the Gulf of Mexico, which has warmer water than the Atlantic Ocean off the East Coast of the Florida Peninsula. This region extends from the Florida Panhandle to the north to Cape Romano, which is just north of the Everglades in South Florida. The station at **Tampa** International Airport (12842) was chosen to represent this region. The wind rose displays very mild directionality and average windspeed of 7 knots.

Southeast

The Southeast section extends from the Atlantic coastal region of Florida and the Florida keys northward through Georgia and South Carolina. This region has an extremely broad coastal plain, requiring it to be divided between coastal region and more inland regions for Georgia and South Carolina. This section also includes the inland areas of Louisiana, Mississippi, and Alabama.

The southern tip of Florida includes the Everglades, which have been drained along the Atlantic coast to provide land for Miami, Ft. Lauderdale, West Palm Beach, and other coastal cities. This region is represented by the original station at **Miami** International Airport (12839). Its wind rose is mildly directional with an average windspeed of 9 knots. Miami was chosen to represent the keys because its directionality and average windspeed are similar to that of Key West.

A long stretch of the Southeastern Atlantic Coast extends from north of Vero Beach, Florida (i.e., just south of Cape Canaveral), through Georgia and South Carolina. The Atlantic Ocean forms the eastern boundary, and the land cover boundary between the more forested coast and more agricultural inland area forms the western boundary. Wind rose analysis reveals a different wind pattern for this region than for the southern tip of Florida. For example, the wind rose for Vero Beach Municipal Airport, which is assigned to the station at Miami, shows mild directionality, with the wind from the predominant direction 10 percent of the time. Just to the north at Daytona Beach, the wind shows weak directionality, with the predominant direction at 8 percent of the time and an average windspeed of 9 knots. Considering the length of this region, a centrally located station would have been desirable, such as the one at Jacksonville International Airport (predominant wind direction 6 percent of the time, average windspeed 8 knots). The station at **Charleston** International Airport (13880), represents this region. Its wind rose shows weak directionality and an average windspeed of 8 knots.

Further inland in Georgia and South Carolina lies the Blue Ridge region. This region is delineated by physiographic boundaries—the transition to the Coastal Plain on the coastal side and to the Appalachian Plateaus on the inland side. The station at **Atlanta** Hartsfield International Airport (13874) represents this region. The wind rose reveals mild directionality and an average windspeed of 9 knots.

The inland areas of Alabama and Mississippi are represented by the station at **Meridian** Key Field (13865), which is located in Mississippi close to the Alabama border. This region extends from the Central Gulf Coast region northward into southern Tennessee (including Memphis) and westward into the Coastal Plain region of eastern Arkansas. The wind rose for this region is mildly directional with an average windspeed of 7 knots.

The inland portion of Louisiana and eastern Texas is part of the Coastal Plain. This region extends northward to the Ouachita Mountains, which are just south of the Ozark Plateau in Arkansas. The western boundary is the vegetative transition from the forests in this region to the prairies in Texas. This region is represented by the station at **Shreveport** Regional Airport (13957) in Louisiana. The wind rose is mildly directional with an average windspeed of 9 knots.

Middle Atlantic

The Middle Atlantic section includes coastal areas with bays, sounds, inlets, and barrier islands; a broad coastal plain; and the southern Appalachian Mountains. The physiographic features generally extend from northeast to southwest, parallel to the coast of the Atlantic Ocean.

The coastal region of North Carolina and Virginia is represented by the station at **Norfolk** International Airport (13737) in Virginia. This region is bounded by the Atlantic Ocean on the east, the physiographic boundary to the Piedmont section to the west, the political border between North Carolina and South Carolina to the south, and a line bisecting the Chesapeake Bay to the north. The wind rose is mildly directional with an average windspeed of 10 knots.

The Piedmont region of North Carolina and Virginia is just inland from the coastal region. This region is delineated on the east by the physiographic boundary with the coastal plain, and on the west with the physiographic boundary with the Appalachian Mountains. This region is also part of the Southeastern Mixed Forest Province of Bailey's ecoregions. The station at **Raleigh-Durham** Airport (13722) in North Carolina represents this region, with a weakly directional wind rose and average windspeed of 8 knots.

The eastern portion of the southern Appalachian Mountains lies to the west of the Piedmont region of North Carolina and Virginia. This region extends to the southwest to include a portion of western South Carolina and northeastern Georgia. The station at **Asheville** Regional Airport (03812) in North Carolina was chosen to represent this region. Its wind rose shows moderate directionality and an average windspeed of 10 knots.

The Appalachian Mountains of West Virginia and eastern Kentucky are characterized by mountainous ridges and valleys extending from northeast to southwest. This region is represented by the station at **Huntington** Tri-State Airport (03860) in West Virginia. The wind rose is mildly directional with an average windspeed of 7 knots.

The inland region encompassing northern Virginia, part of Maryland, and eastern Pennsylvania is composed of another section of the Appalachian Mountains. Boundaries are approximated by the Bailey's Central Appalachian Forest province. The original station at **Harrisburg**/Capital City Airport (14751) in Pennsylvania represents this region. The wind rose is mildly directional with average windspeed at 9 knots.

The northern portion of the Chesapeake Bay northward through New Jersey, eastern Pennsylvania, and New York City is characterized by the Eastern Broadleaf Forest (Oceanic) Province in the coastal plain. The original station at **Philadelphia** International Airport (13739) in Pennsylvania represents this region. The wind rose is mildly directional with an average windspeed of 9 knots.

Northeast

The Northeast section includes Maine and New England. This region is characterized by forests to the north, large urban areas along the southern coastal plain, and the mountain ridges and valleys of the northern Appalachian Mountains. This section is bounded by the Atlantic Ocean on the east, the U.S. Canada border on the north, and the coastal plain of the eastern Great Lakes to the west.

The station at Bradley International Airport (14740) in **Hartford**, Connecticut, represents the New England region, which encompasses Connecticut, Massachusetts, Rhode Island and a small portion of Vermont, New Hampshire, and eastern New York. The wind rose shows mild directionality with an average windspeed of 8 knots.

Northern New England and Maine are represented by the station located at the International Jetport (14764) in **Portland**, Maine. This region includes Maine and most of New Hampshire and Vermont. The northwest portion of Vermont is in a unique location and represented separately. The wind rose for this region has mild directionality and an average windspeed of 9 knots.

The station at the International Airport (14742) in **Burlington**, Vermont, represents a very small region. Burlington is located in a valley between mountainous areas of the northern Appalachian Mountains. This location is reflected in its wind rose, which blows from its predominant direction 20 percent of the time, and average windspeed of 10 knots.

The remainder of the northern Appalachian Mountains in New York and Pennsylvania is represented by the station at **Williamsport**-Lycoming (14778) in Pennsylvania. This region is bounded on the west by the Adirondack Mountains, just to the east of the coastal plain of Lake Ontario. The wind rose for this region is mildly directional with an average windspeed of 9 knots.

Great Lakes

The Great Lakes are bodies of water large enough to affect weather patterns in that portion of the country. Land and sea breezes affect wind patterns along the coasts, especially along Lake Michigan in the summer. The moisture of the lakes also affects winter precipitation patterns (i.e., lake effect snow storms). This version of IWAIR, therefore, has refined the description of the coastal regions bordering the Great Lakes.

The Eastern Great Lakes divide the United States and Canada. On the U.S. side, the western portion of New York, a small portion of Pennsylvania, and northeastern Ohio border the eastern shores of Lake Ontario and Lake Erie. Mountains form the eastern boundary. The southwestern border is drawn southward from the southern shore of Lake Erie. The original station at Hopkins International Airport (14820) in **Cleveland**, Ohio, represents this region. The wind rose is moderately directional with average windspeed of 10 knots.

The Lower Peninsula of Michigan is bordered by the Great Lakes on three sides. Although this region has relatively few topographic features, the presence of the lakes may result

in different dispersion analyses for the eastern and western portions of the state. Therefore, the Lower Peninsula has been divided into two regions—East and West.

The Western region of the Lower Peninsula of Michigan is bordered by Lake Michigan on the west and the Straits of Mackinac on the north. The eastern portion of the Upper Peninsula of Michigan is also included in this region. The station at **Muskegon** County Airport (14840) represents this region, although it has only 2 years of data for this time period. Its wind rose is weakly directional and its average windspeed is 11 knots.

The western shore of Lake Michigan, which includes Green Bay, is formed by the northeastern portion of Illinois, eastern Wisconsin, and part of the Upper Peninsula of Michigan. Lake Superior forms the northern boundary of this region, and the western boundary is formed by the hills to the east of the Wisconsin River and the Upper Mississippi River. This region is represented by the station at O'Hare International Airport (94846) in **Chicago**, Illinois. The wind rose for this region is mildly directional with an average windspeed of 9 knots.

Central States

This section includes the Central Lowlands (south of the Great Lakes), the Midwest, and the Great Plains. The elevation for this section is generally lowest in the Mississippi Valley, which extends through the Midwest and drains a large portion of the center of the continental United States. This section also includes other major river valleys, including the Ohio, Tennessee, and Missouri. This section is bordered on the east by the Appalachian Mountains, on the west by the Rocky Mountains, on the north by the border with Canada, and on the south by the Southeast, Texas, and the Desert Southwest.

Although definitive boundaries are rare within this section the wind roses for stations that were not selected represent additional data useful for drawing boundaries.

The region includes western Kentucky, central and western Tennessee north of Memphis, and southeastern Missouri east of the Ozark Plateau. This region is represented by the station at **Nashville** Metropolitan Airport (13897) in Tennessee. The wind rose is moderately directional with an average windspeed of 8 knots.

A large region is assigned to the station at Adams Field (13963) in **Little Rock**, Arkansas. Little Rock, however, is situated in an area heavily influenced by the Ozark Plateau and its accompanying mountains.. The wind rose for this station is weakly directional with an average windspeed of 7 knots.

The northern portion of the Midwest includes the portion of Wisconsin west of the Lake Michigan coastal plain, Minnesota, and the eastern portion of North and South Dakota. The western boundary through the Dakotas is the physiographic boundary between the Central Lowland and the Great Plains. This region is represented by the station at **Minneapolis-St. Paul** International Airport (14922) in Minnesota. The wind rose is mildly directional with an average windspeed of 11 knots.

The Great Plains lie between the Central Lowlands to the east and the Rocky Mountains to the west. The headwaters of the Mississippi and the Missouri rivers are located in the Great Plains. Lands at higher elevations are more grassland and shrub land used for cattle ranges, while the lower elevations are used more frequently for crops. The region that includes the western portion of North and South Dakota and eastern Montana is represented by the original station at **Bismarck** Municipal Airport (24011) in North Dakota. The wind rose is weakly directional with an average windspeed of 12 knots.

The central portion of Montana is more rugged, but still part of the Great Plains. The Rocky Mountains form the western and southwestern boundaries of this region, which is represented by the station at **Billings** Logan International Airport (24033) in Montana. The wind rose is strongly directional with an average windspeed of 10 knots.

The station at **Casper**/Natrona County International Airport (24089) in Wyoming represents Wyoming east of the Front Range of the Rocky Mountains, southwestern South Dakota, and western Nebraska. The wind rose is strongly directional with an average windspeed of 14 knots. In this region, most cities are located in valleys or near the base of a mountain ridge. The wind regime at Casper, therefore, may not adequately represent other locations in this region.

This region is represented by the station at Stapleton International Airport (23062) in **Denver**, Colorado The southern boundary is formed by the southern edge of the Great Plains. The wind rose for this region is mildly directional with an average windspeed of 8 knots.

The north central portion of the Great Plains includes most of Nebraska, northern Kansas, western Iowa, southwestern South Dakota, and northwestern Missouri. This region is represented by the station at **Grand Island** Airport (14935) in Nebraska (this station is labeled as Lincoln). The wind rose is moderately directional with an average windspeed of 12 knots.

The southern portion of the Great Plains includes most of Kansas, and eastern Oklahoma. This region also includes the lower area of the western Ozark Plateau in southwestern Missouri and northwestern Arkansas. This region is represented by the station at **Tulsa** International Airport (13968). The wind rose is moderately directional with an average windspeed of 11 knots.