1. GUIDANCE FOR CONDUCTING MIXING ZONE ANALYSES

The key products from a mixing zone analysis are the dilution factors. They are used in conjunction with the water quality criteria for calculating reasonable potentials and effluent limits. There are aquatic life-based water quality criteria and human health-based water quality criteria. The former are applied at both the acute and chronic boundaries; the latter are (presently) applied at the chronic boundary. The processes for conducting aquatic life-based analyses and human health-based analyses parallel each other. The differences are in the choice of mixing zone boundaries, and the selection of reasonable worst-case versus average values for the various parameters used in the analyses - as explained in the next section. The permit manager should be consulted about the need for a human health-based analysis.

Steady-state models are the most frequently used tools for conducting mixing zone analyses. However, in some circumstances the primary tool may be a dye study - with a model filling a secondary role. One such circumstance would be when it's apparent that an effluent plume doesn't develop normally (for any number of reasons): The dilution factors must then be measured directly in the field. But, they're the dilution factors for one set of effluent and receiving water conditions only, and a model may still be necessary for analyzing other sets of conditions that are quite different from those present during the dye study. The most appropriate model to use will be the one that validates best against the dye results.

This Guidance provides the specific, detailed information that is needed to select the correct values for the effluent and receiving water parameters, select the appropriate model, and determine when a dye study should be used. It is not a stand alone user's manual or a "cookbook". It's essential to have a working knowledge of how water quality-based effluent limits are developed in Washington state. This knowledge can be gained through reading and understanding the *Water Quality Standards for Surface Waters of the State of Washington* (in particular the subparts on **Toxic Substances** and **Mixing Zones**) and the Department of Ecology's *Permit Writer's Manual* (in particular Chapters VI and VII) - and through experience. That's why this guidance is an appendix to Chapter VI.

This Guidance fills in most of the knowledge gaps so that consultants and permit managers will be able to operate and communicate from the same, uniformly high, level of understanding and expertise needed to produce quality products. Placing this guidance in the *Permit Writer's Manual* and on the Internet (http://www.ecy.wa.gov/programs/eap/mixzone/mixzone.html) ensures that it's a living document that is continually updated as more experience and feedback occurs. As with the *Permit Writer's Manual*, it's expected that ample justification will be provided whenever the guidance is not followed.

1.1 Selecting Aquatic Life-Based And Human Health-Based Values for Parameters

Aquatic life-based analyses involve the concept of determining reasonable worst-case values for various parameters because the durations established for these water quality criteria are one-hour (acute) and four-day (chronic). There are two types of human health-based water quality criteria: Those based on non-cancer effects and those based on cancer effects. The same concept of reasonable worst-case applies in non-cancer analyses as applies in aquatic life-based analyses. The concept of average values applies to carcinogenic human health-based analyses because the duration established for these criteria is the average life span of a person.

The term reasonable worst-case refers to a selected value for a specific effluent or receiving water parameter, (*e.g.*, reasonable worst-case current). Critical condition refers to a scenario involving reasonable worst-case parameters, which has been set up to run in a mixing zone model; (*e.g.*, critical condition scenario to determine mixing at the chronic boundary). Steady-state mixing zone models are usually applied using a combination of parameters (*e.g.*, effluent flow, current speed, depth, density, etc.) packaged to simulate either a critical or an average condition. It's understood that each critical condition (by itself) has a low probability of occurrence. Discharges to tidally-influenced rivers where a saltwater wedge is present may warrant special consideration of critical conditions which are known to occur simultaneously (*e.g.*, during low tides, the predominance of freshwater may always create a well-mixed profile; while during high tides a stratified profile may always exist).

A mixing zone analysis should include a sensitivity analysis. A sensitivity analysis is a series of scenarios organized such that only one reasonable worst-case parameter in each scenario is changed while all others are held constant in a logical progression. Figure 1 is an example of a sensitivity analysis.

Those reasonable worst-case and average parameters that are required input to a model are discussed in subsections 1.1-1.7. Subsections 1.8 and 1.9 discuss other parameters which aren't essential to using the models, but are essential ingredients in a complete mixing zone analysis. Subsection 1.10 addresses two other factors which must be considered before arriving at the correct dilution factors for the acute and chronic boundaries: The Standards require that mixing zones not occupy more than a certain percentage of the channel width and that the effluent flowrate not utilize more than a certain percentage of the available receiving water flowrate in the process of dilution. So actually, the dilution factor to use when determining whether the effluent contributes to acute or chronic toxicity must be the lowest one of three that can be generated for both the acute and chronic boundaries.

1.2 Municipal Effluent Flowrate

For analyses at the acute boundary, the flow-rate to use depends on how close to design capacity the plant is presently operating. If the plant is operating at less than 85% of the dry weather design flow during the critical season, then the flow-rate to use is the highest daily maximum plant effluent flow for the past three years during the season in which the critical flow or condition is likely to occur. If the facility is operating between 85 and 100% of dry weather design flow during the critical season, then use a peaking factor applied to dry weather design to determine acute design flow. The peaking factor is a ratio of daily maximum to monthly average flows derived from actual plant data during the critical season. A peaking factor may also be available in the engineering report for the facility.

For critical condition analyses at the chronic boundary, the flow-rate to use depends on how close to design capacity the plant is presently operating. If the plant is operating at less than 85% of dry weather design flow during the critical season, then the flowrate to use is the highest monthly average plant effluent flow for the past three years during the season in which the critical flow or condition is likely to occur. If the facility is operating between 85 and 100% of dry weather design flow during the critical season, then use the dry weather design flow. For average condition (human health-based) analyses, the flow-rate to use is the annual average design flow as specified in the engineering report, permit application, or projection of annual average flow over the life of the permit by analyzing Discharge Monitoring Report (DMR) data.

1.3 Industrial Effluent Flowrate

For analyses at the acute boundary, the flowrate to use is the highest daily maximum flow for the past three years during the season in which the critical flow or condition is likely to occur. If plant effluent flows are expected to increase during the life of the permit, the highest daily maximum flow must be estimated.

For critical condition analyses at the chronic boundary, the flowrate to use is the highest monthly average flow for the past three years during the season in which the critical flow or condition is likely to occur. If plant effluent flows are expected to increase during the life of the permit, the highest average monthly flow must be estimated. For average condition (human health-based) analyses, the flow-rate to use is the annual average design flow based on permit application or DMR analysis.

1.4 Intermittent Effluent Flowrate

For analyses at both the acute and chronic boundaries, it is necessary to use an instantaneous flow when the effluent flowrate is intermittent. (Steady-state (averaged) effluent flowrates are a

commonly accepted approximation of inherent variability - but only for continuous discharges). The reasonable worst-case flowrate to use is the maximum that can occur - whether through pumps or gravity flow. The resultant model generated dilution factor for the acute boundary must then be adjusted upward by a ratio of maximum flowrate to one-hour, time-averaged flowrate (if the maximum flowrate occurs for less than one hour); and the resultant dilution factor for the chronic boundary must then be adjusted upward by a ratio of maximum flowrate to four-day, time-averaged flowrate.

1.5 Stormwater Flowrate

For analyses at the acute boundary, the flowrate to use in western Washington is the average of the peak one-hour flowrate generated by the two-year, six-hour storm event. For analyses at the chronic boundary, the flowrate to use in western Washington is an estimate of the average run-off generated by the two-year, 72-hour storm event (Ecology, 1993) (Ecology, 1995). Guidance for other areas of the state is evolving.

1.6 Current

For aquatic life-based analyses at both the acute and chronic boundaries in unidirectional waters, both low flow and high flow condition currents should be used. The low flow velocity to use is that which occurs with the 7-day low flow period with a recurrence interval of 10 years (7Q10 by the appropriate statistical method). The high flow velocity to use is that which occurs with the 7Q10 high flow. For non-carcinogenic human health-based analyses, the current velocity associated with a 30Q5 flow should be used if available - or a 7Q10. For carcinogenic human health-based analyses, the velocity associated with the harmonic mean flow for the representative period of record should be used. These can usually be calculated if a cross-sectional profile of the channel bottom has been measured.

Determining the reasonable worst-case current in tidally-influenced water is deceptively difficult. It is true that dilution factors at the hydrodynamic mixing zone boundary (also referred to as the end of initial dilution or near-field) are increased by increased current velocities (assuming other variables are held constant). Conversely, the lower the current velocity, the lower the dilution factor at the end of initial dilution. Early EPA guidance (*e.g.*, that guidance written for the 301(h) waiver application process) suggested that currents approaching zero contributed to critical condition scenarios. However, what is true at the hydrodynamic mixing zone boundary is not necessarily true at a regulatory mixing zone boundary - because the two are not synonymous. (Refer to Figure 5 in the 3PLUMES User's Manual (EPA, 1994) for confirmation of this statement).

Roberts' Froude number (F) is a dimensionless number which characterizes the importance of current velocity relative to the buoyancy flux. It evolved from research into plume behavior and mixing in marine waters. As a dependent variable, it is calculated automatically whenever a case is set up in the 3PLUMES model and appears in the [**Roberts' F**] cell on the 3PLUMES interface. Small values of the Roberts' Froude number signify little effect of current on mixing. According to Roberts (1991) the current exerts no effect on dilution if Roberts' $F < 0.1$. (Refer

to section **3.2 Range of the Experiments** for additional information).

For analyses at the acute boundary in tidally-influenced water, the velocity to use is the critical 10th percentile velocity. This is defined as both the 10th and the 90th percentile velocities derived from a cumulative frequency distribution analysis. The distribution analysis should be produced from a data set consisting of periodic readings taken by an instrument deployed over a neap and spring tide cycle. In the absence of a comprehensive field data set, a sensitivity analysis should be run using a wide range of possible velocities which could reasonably occur for any 1-hour duration. The velocity which produces the lowest dilution should be considered the critical velocity.

For analyses at the chronic boundary in tidally-influenced water, the critical velocity is defined as the 50th percentile current velocity derived from a cumulative frequency distribution analysis. In the absence of a comprehensive field data set, a sensitivity analysis should be run using a wide range of velocities, any of which could reasonably occur as the average velocity for any 4-day duration. The velocity which produces the lowest dilution should be considered the critical velocity.

1.7 Depth

For aquatic life-based analyses at both the acute and chronic boundaries in unidirectional water, use the depth of the port(s) at the 7Q10 low flow period. For non-carcinogenic human health-based analyses, use the depth at 30Q5 or 7Q10. For carcinogenic human health-based analyses, use the depth at the harmonic mean flow. These can usually be calculated if a cross-sectional profile of the channel bottom has been measured.

For analyses at both the acute and chronic boundaries in marine water (sea level), use the depth of the port(s) at Mean Lower Low Water (MLLW) - the depth given on most nautical charts.

For analyses at both the acute and chronic boundaries in upstream tidally-influenced riverine waters, use the depth of the port(s) at MLLW during a 7Q10 low flow period.

[Note: EPA mixing zone models should be used advisedly when the depth is less than 5 times the plume diameter. Refer to **3.5 Boundary Conditions**.]

1.8 Stratification

The density profile to use in aquatic life-based analyses is the one that results in the least mixing. Generally, this is either the minimum or maximum stratification, defined as follows: "Minimums" are characterized by profiles that extend to the same depth as the outfall with (1) the smallest differential between sigma-t values at the bottom and top of the profile; and (2) collectively, the highest sigma-t values. "Maximums" are characterized by profiles that extend to the same depth as the outfall with (1) the largest differential between sigma-t values at the bottom and the plume trapping depth; and (2) collectively, the lowest sigma-t values. Some profiles which are profoundly nonlinear warrant more thoughtful consideration.

The density profile to use in human health-based analyses is the one that results in average mixing. This is determined as follows: (1) Generate the dilution factors for the two profiles (minimum and maximum), (2) calculate the reciprocal of the dilution factors to convert them to effluent concentrations, (3) calculate the average of the reciprocal dilution factors (average effluent concentration), and (4) calculate the reciprocal of the average effluent concentration and use that as the harmonic mean dilution factor.

In Puget Sound, changes in density correlate most closely to changes in season (Glenn and Giglio, 1997). Minimum stratifications frequently occur in October, while maximum stratifications frequently occur from May 1-July 15. There is little or no correlation between changes in stages of tide and changes in profiles. The natural tendency, when selecting best-available regional data sets, is to pick the one which is in close proximity to the discharger location. However, "similarity in physical characteristics of the two areas" should receive equal weight with "proximity to the discharger location" as a criterion. This is true with current as well as stratification profiles.

[Note: The manufacturer of SEABIRD field monitoring equipment has proprietary software for downloading, analyzing, and presenting salinity-temperature-depth (STD) data from Ecology's Ambient Monitoring Program. SEAPLOT is a module of this software which may prove useful for quickly reviewing the graphs of stratification profiles from a large STD data set.]

1.9 Pollutants of Concern

All toxic effects testing has some degree of uncertainty associated with it. The more limited the amount of test data available, the larger the uncertainty. A statistical approach has been developed to better characterize the effects of receiving water and effluent variability and reduce uncertainty in the process of deciding whether to require an effluent limit.

The statistical approach to use when determining the background concentration in the receiving water for aquatic life-based analyses depends on the number of data points. For 20 or fewer samples, the geometric mean of the receiving water values should be multiplied by a factor of 2 to estimate the 90th percentile. This estimated background value should then be used in conjunction with the plant effluent data to evaluate reasonable potential to cause an exceedance of the criteria for aquatic life protection and to derive effluent limits.

For 21 or more samples, the reasonable worst-case value is the 90th percentile value derived from a cumulative frequency distribution analysis. This derived background value should be used in conjunction with the plant effluent data to evaluate reasonable potential to cause a violation of the criteria for aquatic life protection and to derive effluent limits.

The statistical approach to use when determining the background concentration for human health-based analyses when there are multiple data points is the geometric mean. Use 0 for value(s) below the MDL and use the MDL for values between the MDL and the QL.

The statistical approach to use when determining the concentration in the plant effluent for aquatic life-based analyses also depends on the number of data points. For 10 or fewer samples, assume a coefficient of variation (CV) of 0.6 and use the reasonable potential multiplying factors to calculate the highest effluent value. These factors can be found in Table 3-2 of the TSD (EPA, 1991) or calculated using the algorithm in Ecology's Excel spreadsheet called TSDCAL6.XLW (Internet address - http://www.ecy.wa.gov/programs/eap/pwspread/pwspread.html). This estimated value should then be used in conjunction with the background receiving water data to evaluate a reasonable potential to cause a violation of the criteria for aquatic life/human health protection and to derive effluent limits.

For 11 or more samples, calculate the CV and use the reasonable potential multiplying factors to calculate the highest effluent value. These factors can be found in Table 3-2 of the TSD or calculated using the algorithm in Ecology's Excel spreadsheet called TSDCAL7.XLW (Internet address http://www.ecy.wa.gov/programs/eap/pwspread/pwspread.html). This estimated effluent value should then be used in conjunction with the background receiving water data to evaluate a reasonable potential to cause a violation of the criteria for aquatic life/human health protection and to derive effluent limits.

The statistical approach to use when determining the concentration in the plant effluent for human health-based analyses is to use the 50th percentile concentration. If there are less than 10 data points use a multiplier on the highest concentration to estimate the 50th percentile concentration. (The multipliers can be found in Table VII-2 of the *Permit Writer's Manual*). If there are more than 10 values use the cumulative percentile calculation at a 95% confidence to derive the 50th percentile (Excel).

1.10 Other Parameters

Temperature, pH, and hardness are the most noteworthy examples of other parameters, which are necessary ingredients in toxic effects testing; and are not considered pollutants of concern for purposes of this guidance. When selecting a reasonable worst-case value for temperature and pH, use the 90th percentile value derived from a cumulative frequency distribution analysis of a complete data set. For hardness, use the lowest value. A complete data set should include at least three years of DMR or ambient data corresponding to the "critical design period" (*i.e.*, the period of time within the year or season which corresponds to the most likely occurrence of the design flow). If annual data (from all months) are used to select the value, then the 95th or 5th

percentile value from the frequency distribution should be used. For limited data sets (n<20) the upper or lower percentile values can be estimated by methods in Gilbert (1987).

Dissolved oxygen concentration is another parameter which may need to be analyzed at the chronic boundary. A critical condition may occur when effluent becomes a relatively high percentage of the receiving water flowrate. The 10th percentile value for effluent D.O. concentration should be input to a mass-balance equation. Such an equation is available from Ecology in the Excel workbook called PWSPREAD (the particular spreadsheet is IDOD2).

1.11 Other Factors

The subpart pertaining to mixing zones in the Water Quality Standards restricts the width of a water body that can be "occupied" by both the acute and chronic mixing zones to twenty-five percent. Implementation of this restriction involves generating a dilution factor (DF) at a lateral boundary, which is located such that the width of the specified mixing zone does not occupy more than 25% of the channel width. The Channel width must be determined during a 7Q10 (in freshwater), MLLW (in sea level marine water), or combination thereof (in upstream tidally-influenced riverine waters). The dilution factor can be generated in one of two ways: (1) Use a model and note the DF associated with the plume diameter at the point where the plume has spread to one of the lateral boundaries; or (2) use dye and measure the DF at the lateral boundary(ies).

This same subpart of the Standards restricts the flowrate in rivers and streams that can be "utilized" by a chronic mixing zone to 25% and by an acute mixing zone to 2.5%. Formulation of this dilution factor for an entire receiving water involves solving the volume fraction equation:

$$DF = \frac{\left(Q_{amb} + Q_e\right)}{Q_e} \qquad (1)$$

where

Q_{amb} is the flowrate of a receiving (ambient) water; and

Q_e is the flowrate of effluent.

The ambient portion must be reduced by the appropriate percentage to give the amount available for dilution before the equation is solved for DF.

2.0 UNDERSTANDING INITIAL DILUTION THEORY

2.1 General

The general theory behind wastefield formation is easily understood. Visualize wastewater discharged horizontally as a jet from a single round port or a series of jets from ports spaced at equal distances along a diffuser. If the wastewater has a lower density than the surrounding water, then the resulting buoyancy force deflects the jet(s) upward forming plumes which are swept downstream by the current. The plume(s) entrain ambient water as they rise, causing them

to be diluted and decreasing the density difference between them and the ambient. If the ambient is stratified, then its density at the depth of the ports is greater than near the surface. The greater density ambient water is entrained initially, and the rising, expanding plumes can reach a level where their density is the same as the surrounding water (*i.e.*, neutral buoyancy). This is the trapping depth.

If the receiving water is unstratified, then its density is the same throughout the water column. In marine water the plume will always surface - if it remains intact. In freshwater the plume will nearly always surface. (Ambient temperatures equal to or less than 4 degrees Centigrade may generate exceptions. Refer to section **3.8 Nascent Density and Buoyancy**).

The more specific theory behind initial dilution is less easily understood. It applies downstream from the port(s) until the turbulent kinetic energy generated by the buoyancy and momentum of the discharge dissipates. This is commonly referred to as the hydrodynamic mixing zone, initial dilution, or the near-field. (The term initial dilution will be used because near-field is defined and used differently in section **6.0 Conducting a Dye Study**). Generally, initial dilution ceases because a layer boundary (water surface or trapping depth) is encountered. At the end of initial dilution, the wastefield is said to be established. The established wastefield then passes into "far-field". Designers of the outfall can usually affect what occurs in the hydrodynamic mixing zone, but have little or no control over what occurs in the far-field.

All initial dilution models are based on the conservation principles of mass, momenta, and energy. The most important principle is that of conservation of mass - the equation of continuity. In mixing zone modeling it's better understood as the entrainment equation. Different models use different conceptual "building blocks" for constructing their plumes along the trajectory. But regardless, the initial mass of the plume building block plus that added, or entrained, over some discrete period of time has to be conserved (*i.e.*, there has to be a mass balance).

Another important aspect of a mass balance involves knowing the effect of water movement, which is determined with the conservation of momentum principle. Like the mass balance approach, accounting is undertaken for fluid momentum in a defined building block. Horizontal momentum is conserved. It is the product of building block mass and horizontal velocity and is increased by the horizontal momentum of the fluid that is entrained in the same period of time. Vertical momentum is not conserved but is altered by buoyancy, which arises from the density difference between the building block and the ambient water. Kinetic and thermal energy are conserved.

2.2 The Conceptual Dilution Factor

The volume fraction equation (Refer to section **1.10 Other Factors,** equation (1)) is the simplest formulation of the dilution factor. Q_{amb} was defined somewhat differently in equation (1) than it will be defined here; it is replaced by Q_a in the following equation:

$$DF = \frac{\left(Q_a + Q_e\right)}{Q_e} \tag{1a}$$

where,

Q_a is the volume flux of receiving (ambient) water entrained in the plume from an outfall at some sampling point in the plume; and
Q_e is the volume flux of effluent in the plume.

The Q_a value is easier to visualize than to obtain directly, *i.e.*, it is extremely difficult to measure at any sampling point that might be chosen in the plume. What can be measured directly in the plume is the concentration of a pollutant of concern (or a dye tracer) at any sampling point whose location is a known measured distance from the outfall. Call this concentration (C_p). The background concentration in the ambient water (C_a) and the concentration being discharged in effluent (C_e) can also be measured.

To understand initial dilution theory it is necessary to formulate the dilution factor using the basic mass balance equation:

$$\left(Q_a * C_a\right) + \left(Q_e * C_e\right) = \left(Q_a + Q_e\right)C_p \tag{2}$$

The volume fluxes (including the Q_a that's so difficult to measure) can be factored out of the equation by algebraic manipulation:

If the % effluent is represented by the term X; then the % ambient water which has been entrained in the plume of effluent that emerged from the outfall must be (1-X), because the sum of the two is 100% of the water in the plume. Substituting (1-X) for Q_a and X for Q_e (and understanding from equation (1) that 1 / X = DF) gives

$$DF = \frac{\left(C_e - C_a\right)}{\left(C_p - C_a\right)} \tag{3}$$

A DF calculated using equation (3) is an empirical result for the particular sampling point where the C_p value is measured.

An initial dilution model generates dilution factors using outfall, effluent, and receiving water characteristics supplied to it. Each DF that prints out is for a particular calculated distance as the model iterates along the plume trajectory away from the outfall. Depending on the model used, the DF (and C_p) may be calculated simply using the volume fraction equation, or the C_p may be calculated as an actual, effective diluted concentration (depending on whether the model accepts C_e and C_a as inputs).

Rearranging equation (3) gives

$$C_p = C_e\left(\frac{1}{DF}\right) + C_a\left(1 - \left(\frac{1}{DF}\right)\right) \tag{4}$$

Again depending on the model used, the printout may occur repeatedly reflecting the model's iterative process along the plume trajectory or it may occur only upon completion of initial dilution. Whatever the capability of the model, it is imperative that its generated C_ps can be validated, *i.e.*, compared to measured C_ps at the same distance from the outfall to establish how well the model is simulating the plume. A dye tracer is generally better for this task because dye can be measured *in situ* with a fluorometer.

2.3 Theoretical Models

The two theoretical models discussed in detail in this Guidance are UM and UDKHDEN. They both solve the equations of fluid motion and mass transport using an integration scheme in which they march forward in discrete increments along the trajectory of the buoyant jet (prompting the phrase "jet-integral models", which often appears in the literature). UM is a Lagrangian model and uses a time increment; UDKHDEN is an Eulerian model and uses a distance increment.

The basic model building block in UM is the wafer-shaped plume element; in UDKHDEN it's the control volume. In theoretical modeling terms the building block mass is incremented by the amount of fluid that flows over the outside boundary of the building block during each time or distance increment. The theoretical models, using these analytical tools, are capable of yielding fair approximations for the turbulent-flow problems encountered in mixing zone analyses. But, this particular field (*i. e.*, the field of fluid mechanics) is more heavily involved with empirical work than are other fields because these analytical tools are not capable of yielding exact solutions to many of the problems.

2.4 Empirical Models

A considerable amount of experimental evaluation has been done using dynamic similitude (models and towing tanks in the laboratory) and dimensional analysis. This led to the development of empirically-derived curve fit equations to make dilution predictions and verify accuracy of the theoretical models. Eventually, the graphs and equations in the original papers were codified and became useful models in their own right.

The empirical models, like RSB and CORMIX, predict initial dilution by stringing together a series of building blocks called length scales. Each length scale evolves from an empirically-derived curve-fit equation and is, literally, a distance along the trajectory where one parameter predominates (*i.e.*, controls the flow). Once strung together by this analysis, the length scales should describe the relative importance of all parameters - discharge volume flux, momentum flux, buoyancy flux, ambient crossflow, and density stratification - throughout the trajectory. For example, the solution for a pure jet can be applied as an approximate solution to that portion of a buoyant jet in a crossflow where jet momentum dominates the flow. Likewise, the results for a pure plume can be applied to the buoyancy-dominated regions for the buoyant jet. The length scales are linked by "appropriate transition conditions" to create a path for the trajectory through completion of initial dilution. These transition conditions are relative unknowns and a cause for concern.

2.5 Average Versus Centerline

When conducting mixing zone analyses it is necessary to have an elementary understanding of the difference between average and centerline plume concentrations (and dilutions) and the role of each in modeling. In theoretical models average concentrations are integral to the integration scheme, center-of-mass of the building block, and total mass flux. Centerline concentrations become important when determining the potential for acute toxicity to organisms.

Plume velocities in a cross section of each building block (perpendicular to the path of the trajectory) resemble a bell-shaped curve. Concentrations, on the other hand, do not resemble a bell-shaped curve (*i.e.*, peak concentrations do not occur at the same location as the center-of-mass). Therefore, an average concentration involves weighting the concentration distribution by the velocity distribution. This average may be referred to as either a "top hat" or "flux-average", depending upon how it is formulated in a particular model. It is the value to be multiplied by the total plume volume flux to get total mass flux, which is passed on to the farfield algorithm.

In theoretical models, the ratio between centerline and average concentration varies between $\sqrt{2}$ (1.44) (for a fully-merged line plume) and 1.94 (for round plumes). It depends on a number of factors: The type of bell-shaped curve employed by a particular model (two examples are 3/2 power profile and Gaussian), the plume geometry, where the building block is on the trajectory relative to the point of discharge, and whether the individual plumes have merged. Models employing the 3/2 power profile may deliver more accurate ratios because that curve better "feathers" the cross-section into complete ambient.

It is difficult to quantify the relationship between average and centerline values based on empirical measurements. Average dilution is difficult to measure in the laboratory, and virtually impossible to measure in the field since it is necessary to define the plume boundary and know the velocity distribution over the plume cross-section. Some direct measurements of average dilutions by Roberts (1991) indicate that the average may differ by only 10 to 20% from the centerline in stagnant currents and is 0% when Roberts' $F < 0.1$. When initial dilution ends due to contact with a layer boundary the distinction between average and centerline ends soon afterward. There is no longer an elliptical plume - it becomes more rectangular.

For aquatic life-based analyses at both the acute and chronic boundaries in unidirectional water, centerline values should be used. For all other analyses flux-average values should be used. All comparisons of outputs between models must use centerline values.

3.0 CHOOSING AN INITIAL DILUTION MODEL

3.1 Descriptions

Five models are described: Three are theoretical (UM, UDKHDEN, and VSW), and two are

empirical (RSB and CORMIX). UM is the current version of the earlier models UOUTPLM (vintage 1979) and UMERGE (vintage 1985). It acts as a two-dimensional model for single ports, though a pseudo-three-dimensional version is employed when there is a multiport diffuser with potential merging. It uses the 3/2 power profile to calculate the ratio and determine the centerline concentration as a function of the top hat concentration that it predicts. The ratio changes continuously with each integration step along the trajectory (EPA, 1994). Merging is simulated with the reflection technique (Turner, 1970). (Refer also to section **3.5 Boundary Condition(s)**).

It is showcased when there are multiple (1) densities/currents/pollutant concentrations with depth (up to 11), (2) cases that must be run, and/or (3) ports that are co-flowing (*i.e.*, discharging in the direction of the current). It terminates automatically (ending initial dilution) when the surface is reached, but will also terminate at the command of the modeler when: (1) the vertical velocity of the plume becomes negative (trapping), (2) an "overlap" message appears, or (3) it's asked to "pause" upon reaching one of any number of other predetermined conditions. It can then transition smoothly to a farfield algorithm (Refer to section **5.1 FARFIELD**).

Two shortcomings of UM are its (1) inability to recognize and address lateral boundary constraints (Refer to section **3.5 Boundary Condition(s)**), and (2) inadequacy in simulating three-dimensional plume trajectories. (Refer to section **3.6 Extreme Horizontal Angle**). It is set up and run through the 3PLUMES interface, available from EPA's Center for Environmental Assessment Modeling (CEAM) in Athens GA.

UDKHDEN should generate similar predictions to UM in those situations where the discharge port(s) are oriented horizontal and parallel to the current (Refer to section **3.6 Extreme Horizontal Angle**). However, it is a three-dimensional model, and if the plume bends in a three-dimensional trajectory, then predictions will be less conservative but more accurate than UM. It considers either single or multiport discharges at an arbitrary horizontal angle into a stratified, flowing current. The current speed and density can vary with depth. It terminates when the surface is reached, the plume reaches its maximum rise height, or when errors are encountered. It does not transition to a farfield algorithm, but this is not a problem (Refer to section **5.0 CHOOSING A FARFIELD MODEL**). Presently, it must be obtained through one of its developers - Professor Lorin Davis at Oregon State University.

VSW stands for Very Shallow Water. It is the only initial dilution model that will provide reliable results when the depth approaches three pipe diameters - or less. It is one of three models that operates out of the 3PLUMES interface. VSW employs the reflection technique (Turner, 1970), which is the same algorithm employed by UM to simulate merging of multiple plumes. A user's manual for VSW can be found at Appendix 6.2 of the Permit Writer's Manual.

RSB is an updated version of ULINE which is based on experimental studies of multiport diffusers in marine water as described in Roberts (1991). Its strengths are: (1) It is set up and run through the 3PLUMES interface, so that many cases can be run quickly and compared to UM results; (2) it simulates opposing-port diffusers; and (3) the user is advised whenever the model is operating outside the range of the experiments. (Refer to section **3.2 Range of the Experiments**). One present shortcoming of RSB is that it does not provide dilution factors for

distances prior to the end of initial dilution, although it does transition smoothly to the same farfield algorithm employed by UM. It uses a constant centerline-to-flux-average ratio of 1.15. RSB is also available from CEAM.

CORMIX stands for CORnell MIXing zone models. The package consists of CORMIX1, CORMIX2, and CORMIX3 for the analysis of submerged single port discharges, submerged diffusers, and surface discharges, respectively. EPA's decision to proceed with the development of CORMIX was an attempt to exploit accumulated laboratory and field experience to compile a set of methods and empirical models to bridge the gaps that were evident in theoretical modeling at that time. The system was designed for the non-specialist model user, so that plume predictions could be made without having prior knowledge about dilution modeling.

Representing a stratification profile is limited to two layers (*i.e.*, inputting densities at bottom, one intermediate depth, and top). A discontinuity in a profile (*e.g.*, a thermocline) can be represented by inputting two densities at this intermediate depth. Nevertheless, this limits its effectiveness in marine waters where maximum stratifications are usually nonlinear. The top density does not have to be at the water surface if it's known that the plume is trapping. Another concern is its infrequent, but unpredictable, creation of plume trajectories with discontinuities. These may be due to the transition conditions. (Refer to section **2.4 Empirical Models**). "CORMIX1 & CORMIX2 near-field simulations now use the jet integral model CORJET for simulations. A few simulation modules still do use 'empirical' approach, but these cases are now in the minority " (Doneker, 1997).

The strengths of this model are its ability to acknowledge the effects of boundary constraints and gravitational collapse. The initial dilution modules in CORMIX generate only centerline values. It is available through EPA's CEAM in Athens GA.

UM should perform well for a majority of the critical condition scenarios encountered - particularly in tidally-influenced waters. It can also be used frequently for the purpose of comparing dilutions with the other models. Appendix 1 of the 3PLUMES User's Manual (EPA, 1994) and part III MATHEMATICAL MODELS OF INITIAL DILUTION, subpart B. EPA Models, found in Roberts (1991) are excellent general references to consult. The following sections (3.2 - 3.8) discuss specific circumstances and outfall configurations which might influence which model is selected or how a particular mixing zone analysis is conducted.

3.2 Range of the Experiments

"Empirical models are most effective when prototype and model variables and conditions match closely. When they do not, the predictions can degrade substantially. In other words, it is often difficult to extrapolate to conditions which were not included in the experimental design [range of experiments] on which the models are based. Since it is often not clear to the user when extrapolation occurs, this can be a real problem" (EPA, 1994). Inaccurate extrapolations are manifested in the form of discontinuities in the plume trajectory.

The authors of RSB went through a careful consideration of the possible critical condition scenarios which their model might be expected to analyze before choosing the range of

experiments (Roberts *et al*, 1989). The studies were conducted with the following experimental configuration: (1) A straight diffuser consisting of horizontally discharging round ports which were uniformly spaced; (2) ports discharging from both sides of the diffuser through T-shaped risers; (3) marine water - both density-stratified and well-mixed; (4) current at an arbitrary angle relative to the diffuser axis; and (5) individual plumes merging rapidly. As a result, there is a straightforward approach to determining whether the model will be operating within this range:

The two length scale ratios $\frac{l_m}{l_b}$ and $\frac{s}{l_b}$ are diffuser parameters which characterize the significance of source momentum flux and port spacing, respectively. (Refer to section **2.0 UNDERSTANDING INITIAL DILUTION THEORY** for an explanation of length scales and fluxes). Note that these length scale ratios encompass all of the "diffuser" parameters: jet exit velocity, port diameter, port spacing, effluent density, and ambient stratification. The model is operating within its range of "diffuser" parameters when:

$$0.31 < \frac{s}{l_b} < 1.92 \text{ , and}$$

$$0.078 < \frac{l_m}{l_b} < 0.5$$

Roberts' Froude number (F) is a more important parameter. The tests were run at differing current speeds to obtain F in the range 0 (zero current speed) to 100. As was stated in section **1.5 Current**, values of F < 0.1 signify no effect of current on dilution.

The effect of current also depends on its direction relative to the diffuser axis (Θ is the horizontal angle). Tests were run with $\Theta = 90^o$, 45° and 0° (parallel to the current).

The length scale ratios, F, and Θ for each scenario are included in the output for each RSB model run. It then becomes a simple matter to determine whether the model is operating within its capability. Consideration should be given to using Figure 13 in Roberts (1991) (included as Figure 2) if the length scale ratios $\frac{l_m}{l_b}$ and $\frac{s}{l_b}$ are less than 0.2 and 0.3, respectively. The normalized equation on the x-axis of the graph must be solved for S_m - the minimum initial dilution.

[Note: The volume flux per unit length of diffuser (q) is easily calculated. The Roberts Froude number (F)[Roberts F], buoyancy flux per unit length of diffuser (b)[buoy flux], and Brunt-Vaisalla frequency (N)[N (freq)] needed to solve for S_m are included on the interface among the "red" cells. The “red” cells can also be used to calculate other fluxes, length scales, and length scale ratios].

The authors of the CORMIX family of plume models have recently released a technical report

which may contain information on the tow-tank arrangement and procedures used during their experiments (Jirka *et al*, 1996a). Information from this report will be provided in a future update to this Guidance. Presently there is no straightforward approach to determining whether the model will be operating within its range of experiments on any particular analysis.

CORMIX2 uses the “equivalent slot diffuser” concept and thus neglects the details of the individual jets issuing from each diffuser port and their merging process. It assumes that the flow emerges from a long slot discharge with equivalent dynamic characteristics (Jirka *et al*, 1996b). Thus, mixing is based on the plume characteristics after the individual ports have merged.

3.3 Densimetric Froude Number Less Than 1 or Negative

The densimetric Froude number is the ratio of the momentum to the buoyancy of the plume. If the Froude number is less than 1, then the plume separates from the bottom of the port orifices allowing ambient water to flow into the diffuser. This may also occur in marine waters if the total area of the port orifices exceeds 70% of the diffuser cross-sectional area. Either of these two conditions will result in unbalanced flows, and the diffuser section must be evaluated hydraulically as a manifold prior to completing the mixing zone analysis (Ecology, 1997).

The 3PLUMES interface signals this condition in several ways: (1) The input cell [Froude #] contains the number; and (2) the output from the run may contain the message "absolute value Froude # < 1, potential diffuser intrusion", or the message "begin overlap". UM should generate accurate results with either a marine or freshwater ambient as the Froude Number approaches zero - provided the correct conditions are described to it. RIVPLUM5 or FARFIELD may be a better choice in some unidirectional receiving waters. (Refer to section **5.0 CHOOSING A FARFIELD MODEL**).

[Note: UDKHDEN has a built-in safeguard which causes it to terminate and display an “IHLF-11” error message when the Froude number is less than 2.5 and it cannot provide an accurate answer.]

If the Froude Number is negative, then the effluent is more dense than the ambient water. The plume may hit bottom (Refer to section **3.5 Boundary Condition(s)**); or perform even more atypical (Refer to section **3.8 Nascent Density and Buoyancy**).

3.4 Overlap Condition

This condition is associated with highly buoyant plumes (*i.e.*, when the upward curvature of the plume is great). As UM iterates through the curvature the bottom portions of consecutive plume building blocks (elements) actually overlap, resulting in physically unreal negative volume and negative mass. The radius of each element, and entrainment, are overestimated. Plumes that perform in this manner and surface will usually protrude upstream from the outfall. Output from a UM run which is performing through this condition will contain the error message "begin

overlap". The results from UM should not be used unless the following information appears in the output after the message: (1) An "end overlap" message indicating the cessation of the condition causing the error, and (2) relatively little change in the dilution between the "begin overlap" and "end overlap" messages.

[Note: It may be necessary to invoke the ^R command in order to force the model to simulate through the "end overlap" message to maximum rise. This will allow the comparison to be made between dilutions at the beginning and end of overlap.]

Refer to section **3.2 Range of the Experiments** to determine whether RSB can be used under those conditions when UM should not be used.

3.5 Boundary Condition(s)

Boundary conditions are side, surface, and/or bottom constraints which interfere with entrainment of receiving water into the plume. Banks, levees, docks, shallow water, port(s) discharging directly on the bottom, and confined embayments are all examples. The concern is whether the model will reflect these interferences accurately by limiting the entrainment. An additional consideration is whether the constraints are more likely to affect initial dilution or farfield entrainment.

If side boundaries are in close proximity such that initial dilution entrainment is likely to be affected, then CORMIX should be used exclusively - provided there do not appear to be discontinuities. CORMIX simply gives a cautionary message acknowledging attachment to the side boundary, but does not proceed to calculate adjusted dilutions. Side boundaries may become interferences in the farfield phase of the plume, such as when the plume attaches to the bank downstream in a unidirectional river or stream. Then it may be appropriate to use RIVPLUM5, if the attachment (or close proximity) affects horizontally transverse spreading of the mixed effluent. Otherwise, the Constant Eddy algorithm may be appropriate. (Refer to section **5.0 CHOOSING A FARFIELD MODEL).**

It is suggested that all of the models except VSW be used with caution in shallow waters (*i.e,*, less than five pipe diameters deep) and not be used at all if it is very shallow water (*i.e.*, less than three plume diameters deep). VSW is the best choice. If UM is used, consideration should be given to using the “Pause” command to force the model to terminate initial dilution when the plume width is the same as the depth of water (The plume is no longer entraining properly). RIVPLUM5 is a very good alternative in unidirectional waters. (Refer to section **5.0 CHOOSING A FARFIELD MODEL**). If the discharge is actually to the surface of the receiving water (*e.g.*, during mean lower low water (MLLW)), then either VSW or CORMIX3 should be used. Justifying the model chosen is advised.

Plumes that surface inside one or both of the two regulatory boundaries are a common occurrence in estuarine receiving waters because of the additional buoyancy. The surface is the one boundary condition that all five models signal decisively. However, simulations from that point to either or both of the regulatory boundaries may be suspect. (Refer to section **4.0 UNDERSTANDING FARFIELD THEORY**).

UM will issue a "-> bottom hit" message when the extremities of the plume element intersect the bottom. The bottom is assumed to be either (1) at a distance below the port equal to the port elevation [port elev], or (2) at the deepest ambient depth (in the column headed [depth] on the interface) - whichever is greater. Often times this constraint can be ignored or eliminated. Frequently it is the downstream portion of the plume which hits the bottom. Since this is not the primary entraining surface of the plume, the condition can be ignored, as long as it isn't violated excessively. The condition can be eliminated by increasing the deepest ambient depth (in the [depth] column), as long as it is reasonable to do so, *e.g.*, anytime there is a positive gradient to the bottom in the direction of the plume trajectory.

3.6 Extreme Horizontal Angle

The horizontal angle is defined as the angle between the axis of the diffuser and the current (*i.e.*, an angle of 90 degrees simulates a situation where the effluent plume(s) and current are co-flowing). The dialogue box on the 3PLUMES interface indicates that UM is valid over angles ranging from 45 to 135 degrees; it can also be used advisedly for angles between 20 and 45 degrees, and 135 and 160 degrees. It's most accurate at 90 degrees because UM is a two-dimensional model. The effect of changing the direction of the current simply reduces the spacing between ports, invoking a pseudo-three-dimensional version. UDKHDEN may be a better choice the further away from 90 degrees the horizontal angle is because it's a true three-dimensional model.

It is recommended that RSB be used for multi-port diffusers in marine water - particularly if the diffuser is an opposing-port configuration. (Refer to section **3.7 Opposing-port Diffuser Configuration)**. It evolved from an EPA model (ULINE), which was designed to simulate multi-port configurations where upstream plumes are bent over by the current to interact with downstream plumes. (These zero and 180 degree horizontal angle situations are termed line plumes). It may also be the model of choice for many other horizontal angles, including negative (*i.e.*, a counter-flowing situation). . However, it must perform within its range of experiments. (Refer to section **3.2 Range of the Experiments**).

UM can be adapted to simulate line plumes in freshwater - and in marine water when RSB is not appropriate. The procedure to follow is relatively straightforward: Run UM to simulate one plume (using the actual flowrate from only one of the ports in the diffuser). Assume that it is the most upstream plume. The output from this case will provide enough information about the plume trajectory so that an estimate can be made of the horizontal distance this plume will travel before merging with the plume from the next downstream port. The output will also provide the average concentration within the plume at this point of merging. This concentration is then input as the ambient pollutant concentration [amb conc] to the UM case for the next downstream port. The procedure is completed for this particular critical condition scenario when the last downstream port in the sequence is simulated.

In order for this procedure to accurately simulate line plumes, the interaction among upstream and downstream plumes must be quite thorough. This can be determined by examining the output from the first UM run to see whether the plume is sufficiently strongly bent over to

envelop most of the downstream plume's trajectory. This procedure is explained in a citation by Frick (1996). It may sometimes be advisable to compare dilutions from several models and provide justification for the one chosen.

[Note: Horizontal angle is defined differently in UDKHDEN.]

3.7 Opposing-port Diffuser Configuration

Opposing-port diffuser configurations have ports discharging in opposite directions. The configuration may consist of paired ports which are directly opposite each other or staggered ports, which are all equal distance apart but alternate from one side to the other. In a current, the upstream plumes create a counter-flowing situation wherein they frequently bend over and merge with downstream plumes. UM assumes that the diffuser is configured with all ports on one side, the downstream side, creating a co-flowing situation. The counter-flowing situation resulting in cross-diffuser merging is not simulated explicitly.

The preferred approach to modeling these configurations in freshwater is to simply divide the diffuser length by the total number of segments (*i.e.*, total number of ports minus one). The quotient is the appropriate spacing; this number should be entered in the cell [spacing] on the 3PLUMES interface. The number of ports is entered in the cell [# ports]. The simulation offered by UM will be quite good if the Roberts' Froude number (F) is > 0.1 because at this current speed the plumes from opposite sides of the diffuser merge rapidly.

The preferred approach in marine water is to use RSB - if it will be operating within its range of experiments. (Refer to section **3.2 Range of the Experiments**). It is based on experiments conducted in the lab using opposing-port diffusers. However, RSB does require a minimum of 3 ports in the diffuser; and it presently does not provide dilution factors for intermediate points prior to the end of initial dilution. The latter will not be a problem when initial dilution ends inside the acute boundary.

Another acceptable approach for either fresh or marine water involves simulating only downstream ports. However, it is best used with paired port configurations. This necessitates doubling the flow per port (assuming there is an even number of ports in the diffuser) and increasing the diameter of the ports to maintain approximately the same densimetric Froude number. With this approach only the downstream ports would be used when determining spacing and number of ports. This method may give better simulations than the preferred freshwater approach if the Roberts' Froude number (F) is < 0.1. However, a cautionary message will sometimes appear stating that far-field results are unreliable because the plumes did not merge prior to the end of initial dilution.

3.8 Nascent Density and Buoyancy

It is well understood that the density of water is not a linear function of temperature or salinity, *e.g.*, water expands below about four degrees Celsius. However, it is not well understood that the non-linear response of water density to changes in temperature and salinity can cause surprising and unanticipated changes in plume behavior. A thermally buoyant freshwater plume discharged to unstratified freezing freshwater will initially rise, as expected, before unexpectedly sinking to the bottom. The plume will rise only briefly before becoming denser than the ambient and beginning to sink because, as the plume entrains ambient water and cools, it eventually acquires a temperature at which fresh water is at or near maximum density. In another situation, a highly buoyant plume may rise less than a less buoyant plume. These phenomena are known

as the nascent density effect.

Nascent buoyancy effects also occur under many combinations of ambient and effluent salinities and temperatures. A high salinity plume, *e.g.*, a blended effluent such as desalination brine and sewage, may sink briefly before becoming less dense than the ambient and beginning to rise - reversing buoyancy. The citation mentioned below contains several additional examples involving freshwater discharges to the Columbia River.

The linear density assumption is a popular theoretical and empirical simplification in most models. The latest version of UM (8/7/95) is a non-linear model which will simulate nascent conditions. A draft citation by Frick *et al* (1995) is an excellent reference on this subject.

4.0 UNDERSTANDING FARFIELD THEORY

It is reasonable to always assume that the plume's motion in the ambient receiving water is turbulent. Spreading takes place much faster in turbulent flow than in laminar flow. Farfield begins with gravitational collapse (also referred to as buoyant spreading or density current). This is characterized by lateral spreading of the plume along the layer boundary while it is being advected by the ambient current. Plume thickness probably decreases during this phase; the mixing rate is relatively small.

Following gravitational collapse, the remainder of farfield mixing is best explained by either the theory of turbulent diffusion or shear flow dispersion. Turbulent diffusion employs the turbulent mixing equation of Brooks (1960), wherein the coefficient describing the rate of spread of the plume increases with the size of the plume. The best known facet of this theory is the celebrated "4/3 Power Law" - which says that the diffusion coefficient is proportional to the 4/3 power of the size of the plume. In reality, the Law only applies in homogeneous turbulence far from any boundaries.

Shear flow dispersion employs the longitudinal dispersion equation of Taylor (1954) by the method of Fischer *et al* (1979). The theory common to all shear flow is that spreading in the direction of flow is caused primarily by the velocity profile in the cross section. The mechanism Taylor analyzed is often referred to as the "shear effect". It gives a reasonably accurate estimate of the rate of longitudinal dispersion in rivers, and a partial estimate of longitudinal disperison in estuaries.

5.0 CHOOSING A FARFIELD MODEL

The two empirical, initial dilution models discussed earlier do account for gravitational collapse. This phenomenon was observed during the tow-tank experiments, and plume performance during this phase was measured and factored into the empirical equations. Gravitational collapse is not accounted for in the three theoretical , initial dilution models or the two farfield models discussed in this section. It may be included in a later version of the forthcoming Windows Interface for

Simulating Plumes (WISP) - the next generation of UM and its farfield component. The 3PLUMES interface presently allows the modeler to choose the diffusivity coefficient (the [far dif] cell). (Refer to section **5.1 FARFIELD**).

There are two farfield models which are presently recommended for use. They are code named FARFIELD and RIVPLUM5. Each can serve as a stand-alone mixing zone model when warranted by the situation and has been set up in spreadsheet format to accommodate this (Internet at http://www.ecy.wa.gov/programs/eap/pwspread/pwspread.html).

FARFIELD also serves as the farfield algorithm in the 3PLUMES interface, so that it operates in conjunction with UM and RSB by taking the plume diameter delivered to it at the cessation of initial dilution. This may change in the future, since RSB presently accounts for gravitational collapse and the UM/FARFIELD interface does not.

The appropriate farfield model to use in a particular mixing zone analysis depends on the combination of conditions involved:

1. The receiving water is sufficiently deep such that a plume will form and pass through the initial dilution phase without "Froude number less than 1", "overlap", or "boundary constraint" problems. Use FARFIELD as the algorithm (*i.e.*, the version in 3PLUMES interface). (Refer to **5.1 FARFIELD**.)

2. The receiving water is shallow and unidirectional; the effluent is thoroughly mixed surface to depth (*i.e.*, no defined plume); and the discharge is a single port or short diffuser. Use RIVPLUM5. (Refer to **5.2 RIVPLUM5**.)

3. There is/are bank constraint(s). Use RIVPLUM5, provided the conditions in 2. above are also met. (Refer to **5.2 RIVPLUM5**.)

4. Other shallow receiving waters (with no bank constraints) which occur with all other combinations of effluent plumes and discharger configurations. Use FARFIELD as a stand-alone model. (Refer to **5.1 FARFIELD**). A three-dimensional advective dispersion equation may also be appropriate.

5.1 FARFIELD

FARFIELD calculates dilution using the method of N.H. Brooks (1960). Four variations have been set up as spreadsheets in an EXCEL workbook - FARFIELD.XLS. The spreadsheets are:

- 3PLUMES algorithms;
- Brook's exponential diffusivity (4/3 power law);
- Brook's linear diffusivity; and
- Brook's constant (eddy) diffusivity.

The "3PLUMES algorithms" spreadsheet calculates dilutions by assuming either an exponential increase, a linear increase, or a constant diffusivity - just as the other three spreadsheets do.

Linear diffusivity was added to the two algorithms already incorporated in the 3PLUMES interface in order to make it the same package that is offered by the other three spreadsheets. Its utility is in allowing direct comparisons to be made between dilutions at the regulatory boundaries as generated by one or the other of the models in 3PLUMES and dilutions generated by other initial dilution models which have no far-field algorithm, *e.g.*, UDKHDEN.

The default value for the dispersion coefficient in the 3PLUMES interface, the [far dif] cell, is 0.0003 $m^{2/3}$/sec. For areas of high energy dissipation and where there are no constraints, *e.g.*, a large, relatively deep embayment, then the value 0.000453 $m^{2/3}$/sec can be used. In less turbulent situations, it may be as low as 0.0001 $m^{2/3}$/sec.

The exponential increase is referred to as the 4/3 Power Law in the output from 3PLUMES. It is Richardson's Law, which is basically only applicable in situations where there is unobstructed spread of the plume. It is reasonable to assume that the spread is unobstructed if the plume diameter at all locations on its trajectory is less than 1/10 the distance to the nearest side boundary. It is unreasonable to assume that diffusivity will increase exponentially when the plume can only spread along a nearby side boundary. Provided this boundary does not act as a constraint (as discussed in section **3.4 Boundary Condition(s**)), it is reasonable to assume that it will increase as the first power of the plume width (*i.e.*, linearly). Dilutions generated by the Constant Eddy Diffusion algorithm should be used in all other situations.

To understand why "3PLUMES algorithms" differs from the other spreadsheets, it is necessary to understand the motivation of the authors of the interface. They felt it was important that users of the interface should have to input only one dispersion coefficient in the [far dif] cell; but still be able to receive the output from two far-field algorithms - the 4/3 Power Law and the Constant Eddy. This resulted in some coding changes in the initial steps of the algorithms (including linear diffusivity), where the dispersion coefficient in the [far dif] cell is converted for the first and only time to the diffusivity coefficient used in the Brook's equation. The dispersion coefficient is multiplied by (the width of the plume field at the end of initial dilution)$^{4/3}$. The 4/3 Power Law is described by R.A. Grace (1978).

Following these initial steps, the diffusivity coefficient is either (1) continuously increased according to the 4/3 power of the width of the plume field at the end of the previous iteration, (2) continuously increased according to the first power of the width of the plume field at the end of the previous iteration, or (3) held constant according to the zero power of the width of the plume field at the end of the previous iteration. Each algorithm then inserts its coefficient into a modified Brooks' Equation, as described in the text associated with equations 66-73 of the User's Manual (EPA, 1994).

Each of the other three spreadsheets contains one of the algorithms; they are also based on Brook's Equation. Their utility is that they're purer forms, unencumbered by the slight inaccuracies associated with the need to input a single dispersion coefficient to an interface. All of these far-field algorithms are much simpler and rudimentary than the initial dilution models. The quality of the estimates should not, in general, be expected to be as high as the initial dilution models. Consequently, if better methods for estimating the far-field dilutions are available they should be used.

User instructions for the input section of FARFIELD.XLS are available in another appendix to this chapter and on the Internet at the address given earlier. The user does not need to enter or change any values or formulas in the Output Section. The spreadsheets calculate dilution along the trajectory of the plume and at the specified mixing zone boundary. Optional calculation of pollutant concentrations assuming first-order decay rates is also provided.

5.2 RIVPLUM5

The spreadsheet RIVPLUM5.XLS calculates dilution using the theory of Taylor (1954) by the method described in Fischer *et al*, (1979) and referred to in EPA's Technical Support Document (1991). It is a one-dimensional model that calculates dilution at a specified point of interest downstream in a river. The calculation for dilution factors incorporates the boundary effect of shore lines using the method of superposition. This model is based on the assumption that the discharge is: (1) a single point source, which is most appropriate for single port or short diffusers, or side-bank discharges; and (2) completely and rapidly mixed vertically, which usually only occurs in shallow rivers. If the diffuser length occupies a substantial portion of the stream width, or the discharge is not vertically mixed over the entire water column within the acute mixing zone, an alternative model should be used. The spreadsheet also includes optional calculation of the effective origin of a wastewater source. User instructions for the input section are available in another appendix to this chapter and on the Internet at the address mentioned earlier in this text.

6.0 CONDUCTING A DYE STUDY

There are four primary objectives that justify conducting a dye study:

1. Confirm the presence of an eddy.

2. Quantify dilution.

3. Quantify far-field accumulation (reflux).

4. Develop a far-field diffusivity coefficient.

It is advisable to conduct a reconnaissance survey before the main field work. If the receiving water is tidally-influenced, then the survey should be conducted at the same time in the neap or spring tide cycle and covering the same stages of tide as will be covered during the dye injection. Consideration should be given to deploying a meter to record time, current speed and direction, and depth of water during the survey in order to develop a thorough understanding of anomalies that may be occurring between published tide data and actual field data. Consider taking a cross-section of the channel bottom, if appropriate. These data will allow accurate times to be established for dye injection and measurement. It will also afford an opportunity to set up and run some preliminary cases; which, in turn, will provide some early estimates of plume

performance, *e.g.*, trapping depth and horizontal distance to the end of initial dilution.

Concentration of dye in effluent, total loading, and duration of injection deserve careful consideration. Each varies in importance depending upon the objectives of the study, and is discussed below for each objective. A draft plan of study explaining the methods and QA/QC to be employed should be submitted to the Department for review and approval following the reconnaissance survey and prior to initiation of the study.

6.1 Confirm the Presence of an Eddy

If the objective of the study is to simply confirm the presence of an eddy, then concentration, loading, and duration of injection are all relatively unimportant. It's only necessary that the path of the plume can be traced. If, on the other hand, it is necessary to know the mixing ratio in the eddy in order to determine it's contribution, then concentration, loading and duration may all be important.

6.2 Quantify Dilution

It may be important to validate a model using a dye study and one set of conditions. This may be the only feasible alternative if critical condition scenarios that need to be examined are quite different from the set of conditions present during the dye study (*e.g.*, future growth). Calibration may also be the only feasible alternative (*e.g.*, tide-flex diffuser). Validation and calibration, while admittedly unpredictable exercises, may serve to increase confidence in model performance.

A constant dye concentration in effluent is important. Total loading is not important *per* se; however, it is important that effluent flowrate be at or near its reasonable worst-case. Duration is relatively unimportant. In tidally-influenced waters, injection and measurements should begin after the start of an ebb tide stage. By using this timing it may be possible to capture one critical condition scenario.

The most appropriate location to take the measurements for comparing dilutions from the dye study and a model is at the end of the hydrodynamic mixing zone, particularly if the end follows rapid surfacing of the plume in shallow water. (Refer to section **3.5 Boundary Condition(s)**). The best way of determining the location is via a reconnaissance survey in conjunction with preliminary model runs, using the set of conditions that will be encountered during the field work.

A dye study may be the only reliable way to quantify dilutions if boundary constraints are such that all model results will be suspect. A critical condition scenario may include a rapidly surfacing plume with upstream protrusion and/or side boundaries that are affecting entrainment and dilution. (Refer to **3.5 Boundary Condition(s)**). Measurements would be taken at both the acute and chronic boundaries.

A dye study may also be the most reliable way to quantify dilutions at a lateral boundary when

the width of a mixing zone is restricted to 25% of the channel width. (Refer to section **1.10 Other Factors**). The field work should be conducted when conditions are as close as possible to critical.

In this situation, a constant concentration in effluent and duration of injection are important. Total loading is relatively unimportant, *per se*; however, it is important that effluent flowrate be at or near its reasonable worst-case. In tidally-influenced waters, injection and measurements should begin soon after the start of a Lower Low Water slack at sea level during a neap tide or soon after a small flood if it's riverine. This affords the best opportunity to capture a critical condition scenario.

[Note: It can be assumed that upstream protrusion does not occur whenever the Roberts' F is > 0.1.]

6.3 Quantify Far-field Accumulation (Reflux)

This objective warrants considerable discussion because it's difficult to accomplish. Tidal currents may cause effluent to accumulate in the receiving water surrounding an outfall in a tidal river or estuary. The receiving water may also contain background concentrations of pollutants from sources other than effluent. Various methods are available to account for the accumulation of effluent and ambient background sources when determining potential to exceed water quality criteria or estimating waste load allocations.

There are three methods which are acceptable to Ecology. Two of the methods involve a dye study. Total loading and duration are important factors in both methods; concentration in the effluent can vary during application. The third method involves simply accepting a default value for reflux in lieu of conducting a dye study. Detailed guidance for conducting the methods and mass-balance equations follow.

Far-field accumulation of effluent may be estimated based on either of two methods:

- Method 1: the USGS superposition method (Hubbard and Stamper, 1972) may be used by injecting the tracer during one tidal day and measuring continuously at a fixed monitoring station to determine maximum concentrations during succeeding days until the tracer is undetectable; or

- Method 2: the Jirka method (EPA, 1992) may be used by injecting the tracer over several tidal cycles (usually five or more) until a quasi-maximum steady state is reached. Concentrations of the tracer are usually monitored continuously at a fixed monitoring station.

In addition to two methods of tracer injection, two alternative schemes for locating monitoring stations are acceptable:

- Alternative 1: tracer concentrations are measured in the near-field at the mixing zone boundary in the approximate centerline of the effluent plume; or

- Alternative 2: tracer concentrations are measured in the far-field at some considerable distance from the effluent plume at a position that is representative of the source of dilution water for the plume.

Either the superposition or Jirka methods may be used to conduct the tracer studies for both Alternatives 1 and 2. A third method is also proposed if a tracer study is not conducted:

- Method 3: A default correction which can be used as an approximation of far-field accumulation will be based on recommendations by EPA (1992).

A number of terms which will be used during this discussion need to be defined.

near-field: at the chronic mixing zone boundary in the approximate center-line of the effluent plume.

far-field: at some considerable distance from the effluent plume at a position that is representative of the source of dilution water for the plume.

V: initial maximum effluent concentration (volume fraction of effluent*; e.g.* 5 percent effluent corresponds to V of 0.05) during first tidal cycle prior to influence of far-field accumulation from previous tidal cycles.

$\overline{V}$: quasi-steady-state maximum effluent concentration (volume fraction of effluent*; e.g.* 5 percent effluent corresponds to $\overline{V}$ of 0.05) after several tidal cycles result in equilibrium with far-field accumulation.

r_d: return rate of dye or effluent mass discharged in the previous tidal cycle as defined in EPA (1992).

DF: initial effluent dilution factor (reciprocal of volume fraction of effluent*; e.g.* 5 percent effluent corresponds to DF of 20) during first tidal cycle prior to influence of far-field accumulation from previous tidal cycles. DF may be estimated using a model (e.g. PLUMES) or by near-field tracer measurement. DF is usually determined at critical conditions.

$\overline{DF}$: quasi-steady-state effluent dilution factor (reciprocal of volume fraction of effluent*; e.g.* 5 percent effluent corresponds to $\overline{DF}$ of 20) after several tidal cycles (usually 5 or more cycles) result in equilibrium with far-field accumulation. $\overline{DF}$ is usually determined at critical conditions.

C_p: pollutant concentration measured as a flux-average value in the plume at the mixing zone boundary. (Refer to section **2.5 Average versus Centerline**).

C_e pollutant concentration in effluent discharged from the outfall pipe.

C_a: pollutant concentration in upstream ambient receiving water (*i.e.*, away from the influence of far-field accumulation).

WLA: effluent concentration to use for Waste Load Allocation (acute or chronic) for derivation of water quality-based permit limits.

WQC: pollutant concentration for water quality criteria (acute or chronic).

Mass Balance Equations for Alternative 1

If the tracer monitoring station is located in the near-field, then the following mass-balance equations are appropriate:

- calculate Jirka's r_d from near-field $\overline{V}$ and V (based on equation 22 in (EPA, 1992)):

$$r_d = \frac{\left(\overline{V} - V\right)}{\overline{V}} \tag{5}$$

- calculate the near-field $\overline{DF}$ (acute or chronic boundary), including the effect of far-field accumulation of effluent, from model or tracer estimates of DF and estimated r_d in the previous step (based on equation 22 in (EPA, 1992)):

$$\overline{DF} = DF\left(1 - r_d\right) \tag{6}$$

- The following equation is appropriate to calculate pollutant concentrations (C_p) at the mixing zone boundaries for comparisons with water quality criteria. Near-field dilution is corrected for far-field accumulation of effluent in the previous step. The following equation incorporates the effect of ambient background (C_a) from sources of pollutants other than effluent. Estimates of C_e may also include a reasonable potential multiplier using methods in chapter VI of this Manual. Pollutant concentrations (C_p) are estimated as follows (based on equation 9 in (EPA, 1994):

$$C_p = C_e\left(\frac{1}{\overline{DF}}\right) + C_a\left(1 - \left(\frac{1}{\overline{DF}}\right)\right) \tag{4a}$$

- calculate acute and chronic WLAs:

$$WLA = WQC * \overline{DF} - C_a\left(\overline{DF} - 1\right) \tag{7}$$

Example**:**

Given: near-field V = .02 (2 percent effluent); near-field $\overline{V}$ = .07 (7 percent effluent).

Calculation of near-field $\overline{DF}$ including far-field accumulation of effluent:

$$r_d = \frac{(.07-.02)}{.07} = .7143; \quad DF = \frac{1}{.02} = 50; \text{ therefore, near-field } \overline{DF} = 50(1-.7143) = 14.3$$

Mass Balance Equations for Alternative 2

If the tracer monitoring station is located in the far-field, then the following mass-balance equations are applicable:

- calculate near-field DF, excluding the far-field accumulation of effluent, from a mixing zone model or from an additional near-field tracer monitoring station (*e.g*. near-field DF = reciprocal of near-field V)

- calculate the near-field $\overline{DF}$ (acute or chronic boundary), including the effect of far-field accumulation of effluent, by mass balance with near-field DF from the previous step and far-field $\overline{V}$ (based on equation 8 in (EPA, 1994)):

$$\overline{DF} = \frac{DF}{\left(1+\overline{V}(DF-1)\right)} \tag{8}$$

- The following equation is appropriate to calculate pollutant concentrations (C_p) at the mixing zone boundaries for comparisons with water quality criteria. Near-field dilution is corrected for far-field accumulation of effluent in the previous step. The following equation incorporates the effect of ambient background (C_a) from sources of pollutants other than effluent. Estimates of C_e may also include a reasonable potential multiplier using methods in chapter VI of this Manual. Pollutant concentrations (C_p) are estimated as follows (based on equation 9 in (EPA, 1994)):

$$C_p = C_e\left(\frac{1}{\overline{DF}}\right) + C_a\left(1-\left(\frac{1}{\overline{DF}}\right)\right) \tag{4a}$$

- calculate acute and chronic WLAs:

$$WLA = WQC * \overline{DF} - C_a\left(\overline{DF} - 1\right) \tag{7}$$

Example:

Given**:** near-field DF=50 from PLUMES model excluding far-field accumulation of

effluent; far-field $\overline{V}$ =.051 (5.1 percent effluent) from tracer study using super-position method.

Calculation of near-field $\overline{DF}$ including far-field accumulation of effluent**:**

near-field $\overline{DF} = \dfrac{50}{\left(1+.051\left(50-1\right)\right)} = 14.3$

Mass Balance Equations for Method 3

If it is decided to use a default correction for far-field accumulation, then the following mass balance equations are applicable:

- estimate default for Jirka's r_d = 0.5 from EPA (1992).

- calculate the near-field $\overline{DF}$ (acute or chronic boundary), including the effect of far-field accumulation of effluent, from model or tracer estimates of DF and estimated r_d in the previous step (based on equation 22 in (EPA, 1992)):

$$\overline{DF} = DF\left(1 - r_d\right) \tag{6}$$

- The following equation is appropriate to calculate pollutant concentrations (C_p) at the mixing zone boundaries for comparisons with water quality criteria. Near-field dilution is corrected for far-field accumulation of effluent in the previous step. The following equation incorporates the effect of ambient background (C_a) from sources of pollutants other than effluent. Estimates of C_e may also include a reasonable potential multiplier using methods in chapter VI of this Manual. Pollutant concentrations (C_p) are estimated as follows (based on equation 9 in (EPA, 1994):

$$C_p = C_e\left(\frac{1}{\overline{DF}}\right) + C_a\left(1 - \left(\frac{1}{\overline{DF}}\right)\right) \tag{4a}$$

- calculate acute and chronic WLAs:

$$WLA = WQC * \overline{DF} - C_a\left(\overline{DF} - 1\right) \tag{7}$$

Example:

Given**:** r_d=0.5; DF=50

Calculation of $\overline{DF}$**:** $\overline{DF} = 50\left(1 - 0.5\right) = 25.$

6.4 Develop a Farfield Diffusion Coefficient

[RESERVED].

7.0 REFERENCES

Brooks, N. H., 1960. *Diffusion of Sewage Effluent in an Ocean Current,* Proceedings of the First Conference on Waste Disposal in the Marine Environment, pages 246-267, edited by E.A. Pearson, Pergamon Press, New York, NY.

Davis, L. R., 1996. Personal communication, Oregon State University, Department of Mechanical Engineering, Corvalis OR 97331-6001, July.

Doneker, R. L., 1997. Personal communication, Oregon Graduate Institute, Department of Environmental Science and Engineering, Portland OR 97291-1000, July.

Ecology, 1993. *Dam Safety Guidelines, Technical Note 3:* Design Storm Construction, Publication # 92-55G, April.

Ecology, 1995. *An Analysis of Regulatory Issues Raised by Application of the NPDES Permit Program to Municipal and Industrial Stormwater Discharges* (draft issue paper), Washington State Department of Ecology, Water Quality Program, Olympia WA, December.

Ecology, 1996. *An Analysis of the Effect of Discharged Wastewater on the Stillaguamish River at Stanwood*, Washington state Department of Ecology, Environmental Investigations and Laboratory Services Program, Olympia WA 98504-7710, July.

Ecology, 1997. Criteria for Sewage Works Design (the "Orange Book"), as revised, Washington state Department of Ecology, Water Quality Program, Olympia WA, chapter E2.

EPA, 1991. *Technical Support Document for Water Quality-based Toxics Control*, U.S. Environmental Protection Agency, EPA/505/2-90-001, pages 77-78.

EPA, 1992. *Technical Guidance Manual for Performing Waste Load Allocations Book III: Estuaries Part 3: Use of Mixing Zone Models in Estuarine Waste Load Allocations*, U.S. Environmental Protection Agency, EPA/823/R-92/004, section 2.6.

EPA, 1994. Dilution Models for Effluent Discharges, U.S. Environmental Protection Agency, EPA/600/R-94/086, Washington, D.C.

Fischer, H.B., E.F. List, R.C.Y. Koh, J. Imberger, and N.H. Brooks, 1979. Mixing in Inland and Coastal Waters, Academic Press, Inc., Harcourt Brace Jovanovich Publishers, New York NY, pp. 126-127.

Frick, W.E., *et al*, 1995. *Nascent Buoyancy Effects on Blended and Exotic Effluents*, Draft, U.S. Environmental Protection Agency, Center for Environmental Assessment Modeling, Athens GA, April 16.

Frick, W. E., 1996. *Estimating Parallel Diffuser Dilutions Using PLUMES UM*, U.S. Environmental Protection Agency, Center for Environmental Assessment Modeling, Athens GA, July 11.

Gilbert, R.O., 1987. Statistical Methods for Environmental Pollution Monitoring, Van Nostrand Reinhold, New York.

Glenn, N. L. and D. Giglio, 1997. K*itsap County Mixing Zone Study*, Washington state Department of Ecology, Environmental Investigations and Laboratory Services Program, Olympia WA 98504-7710, July.

Grace, R.A., 1978. Marine Outfall Systems: Planning, Design, and Construction, Prentice-Hall, Englewood Cliffs NJ, Chapter 7.

Hubbard, E.F. and W.G. Stamper, 1972. *Movement and Dispersion of Soluble Pollutants in the Northeast Cape Fear Estuary, North Carolina*, Water-supply paper 1873-E, U.S. Geological Survey, United States Department of the Interior.

Jirka, G.H., P.K. Akar and J.D. Nash, 1996a. *Enhancements to the CORMIX Mixing Zone Expert System: Technical Background*, Technical report, DeFrees Hydraulics Laboratory, School of Civil and Environmental Engineering, Cornell University, Ithaca NY 14853-3501.

Jirka, G.H., R.L. Doneker and S.W. Hinton, 1996b. *User's Manual for CORMIX: A Mixing Zone Expert System for Pollutant Discharges into Surface Waters*, draft, DeFrees Hydraulics Laboratory, School of Civil and Environmental Engineering, Cornell University, Ithaca NY 14853-3501, page 16.

Roberts, P.J.W., 1991. *Ocean Outfalls*, Critical Reviews in Environmental Control, Volume 20, Issues 5 & 6, pages 311-339.

Roberts, P.J.W., W.H. Snyder, and D.J. Baumgartner, 1989. *Ocean Outfalls. I: Submerged Wastefield Formation*, Journal of Hydraulic Engineering, Volume 115, No. 1, January.

Taylor, G.I., 1954. *The* d*ispersion of matter in turbulent flow through a pipe*, Proceedings of R. Soc. London Ser., A223, 446-468, Sci. Pap. 2, 466-488.

Turner, D.B., 1970. *Workbook of atmospheric dispersion estimates*. Office of Air Programs, Publication No. AP-26, USEPA, Research Triangle Park, North Carolina.

Figure 1.

A SENSITIVITY ANALYSIS FOR THE PORT ANGELES WWTP
showing Critical Condition Scenarios

Case	Design considerations at WWTP		MZ	Reasonable worst-case variables			
number	flowrate	diffuser	boundary	flowrate	current	strat/depth	effl. temp.
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
1	3.3 MGD	13 @ 4 inch	acute	13.4 MGD	10th percentile	10% (well-mixed)	high
2	"	"	"	"	"	"	low
3	"	"	"	"	"	90% (max-strat)	high
4	"	"	"	"	"	"	low
5	"	"	"	"	90th percentile	10% (well-mixed)	low
6	"	"	"	"	"	90% (max-strat)	low
7	"	"	chronic	5.3 MGD	50th percentile	10% (well-mixed)	high
8	"	"	"	"	"	"	low
9	"	"	"	"	"	90% (max-strat)	high
10	"	"	"	"	"	"	low
11	"	13 @ 6 inch	acute	13.4 MGD	10th percentile	10% (well-mixed)	high
12-20	"	"					
21	"	tide flex valves	acute	13.4 MGD	10th percentile	10% (well-mixed)	high
22-30	"	"					
31	? MGD	13 @ 6 inch	acute	21 MGD	10th percentile	10% (well-mixed)	high
32-40	"	"					

Figure 2.

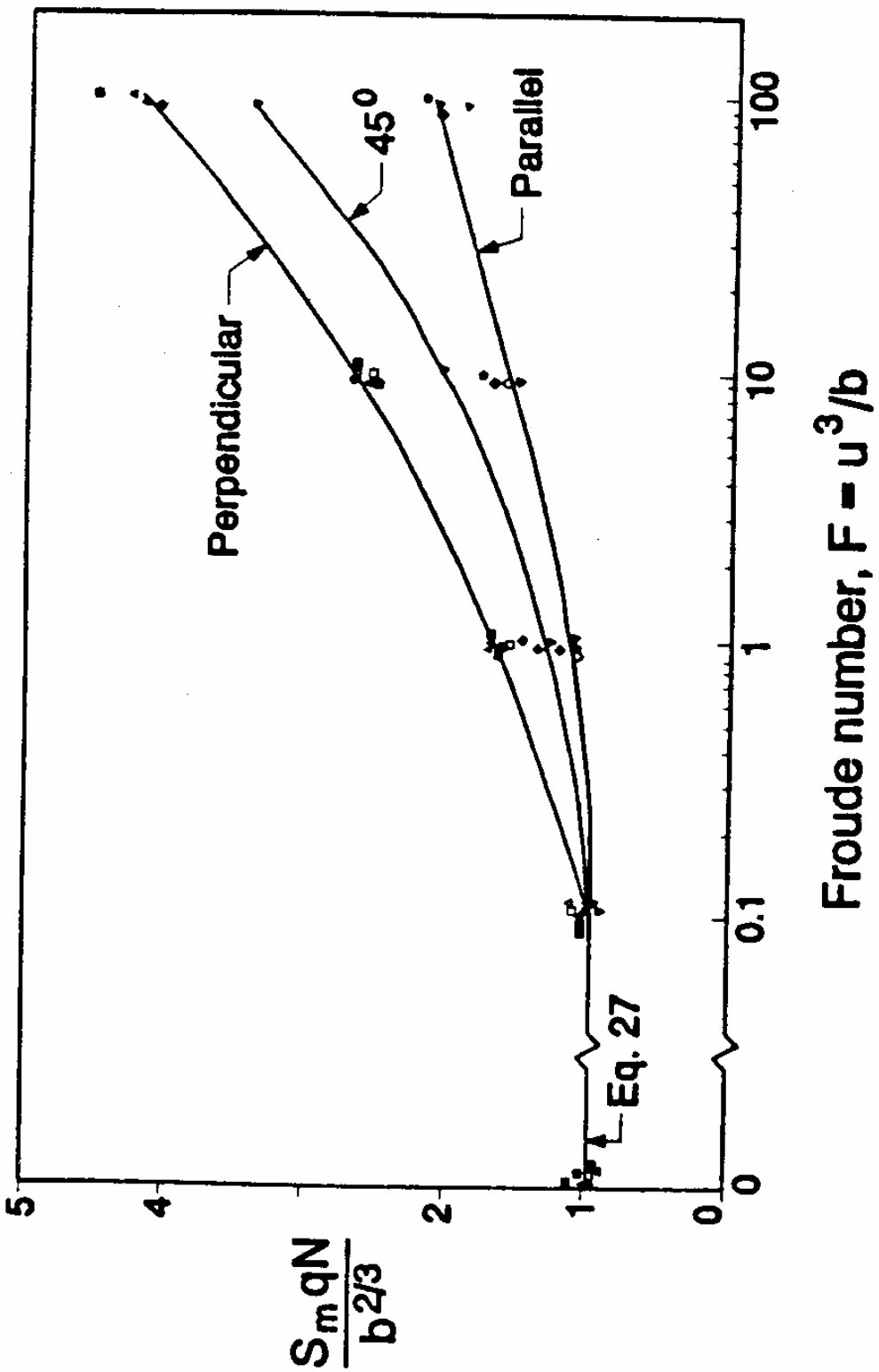

FIGURE 13. Minimum initial dilution for discharges from line diffusers into a stratified current. (From Roberts, P. J. W., Snyder, W. H., and Baumgartner, D. J., *J. Hydraul. Eng. ASCE.*, 115(1), 1, 1989. With permission.)

2. USER'S MANUAL FOR THE VERY SHALLOW

WATER (VSW) MIXING ZONE MODEL

2.1 INTRODUCTION

Single port discharges in shallow water or at the surface are frequently encountered in Washington state. There are numerous examples of wastewater treatment plant discharges through outfalls to shallow streams, and irrigation return water is an example of the latter. In the User's Manual for 3PLUMES (EPA, 1994), it states that "....plume models were developed for deep water discharges and modelers are not confident in extrapolating verification data from deep water situations to shallow water applications" - defined on page 150 of the Manual as, "less than three plume diameters deep. Under some circumstances where the standard plume models seem inappropriate, the UM model (one of two models in the 3PLUMES interface) may be specially configured and run to provide dilution estimates. This special configuration of UM is referred to as the Very Shallow Water (VSW) algorithm.
This User's Manual first presents the theory behind VSW and then steps through the actual process which was followed in analyzing the mixing and dilution available to the city of Sumner, Washington. The following discussion of the theory was excerpted from materials provided by Walt Frick of EPA's Center for Environmental Assessment Modeling (CEAM) in Athens GA. The VSW algorithm is contained in present versions of the 3PLUMES software, but all discussion pertaining to theory and use was omitted from the User's Manual because the algorithm is not yet officially supported by EPA.

8.2 SHALLOW WATER, SURFACE DISCHARGE PLUME THEORY

The reflection technique (Turner, 1970) is built into the UM model merging algorithm. By making the appropriate adjustments to the input data, the algorithm can be applied to shallow water, surface discharge problems. When this is done, the ability to predict the trajectory is lost. However, often this is not a problem because the possibilities for trajectory development are limited by the shallow water, surface discharge and the resulting geometric constraints.

First, it should be understood that for diffusers the merging algorithm works on the basis of symmetry; *i.e.*, a series of identical sources is assumed to exist such that a vertical plane of symmetry may be established between any two ports near the center of the diffuser. Relative to this plane, each side of the diffuser appears identical and the plane may be regarded as a reflecting mirror. When two such planes are established, one on each side of a chosen port, the plume problem may be isolated from the rest of the diffuser. The central idea is that whatever a plume loses to the other side of such a "reflection" plane it gains back from its identical neighbor, for no net loss or gain. To complete the technique, all that is needed are the equations to limit the mass between the two planes and to adjust the entrainment surfaces to account for the loss of entrainment surface where the plume contacts a plane.

To make the connection to shallow water, surface discharge problems, it is only necessary to appreciate the exact parallelism between the vertical reflecting planes and the surface and bottom (or a horizontal plane elevated above the surface a distance equal to the depth of the water) of the

shallow water, submerged discharge problem. Thus, the merging problem, when it is laid on its side, is largely equivalent to the shallow water, surface discharge problem, at least with respect to the entrainment (dilution) process.

However, the rotation from vertical to horizontal is not appropriate for the plume trajectory problem. Consequently, the analogy is strictly valid only when the discharge is a horizontal jet, *i.e.*, a "plume" which has no buoyancy (densimetric Froude number > 9). Furthermore, because UM is a two-dimensional model, is strictly valid only for co-flowing jets. In order to maintain consistency with these assumptions, the ambient should be weakly stratified or unstratified. Nevertheless, useful results can be obtained when these conditions are not fully met; but, the quality degrades as the departure from these ideal conditions increases.

The geometry of a mid-depth discharge to shallow water is shown in Figure 1a. The geometry of a surface discharge is given in Figure 1b.

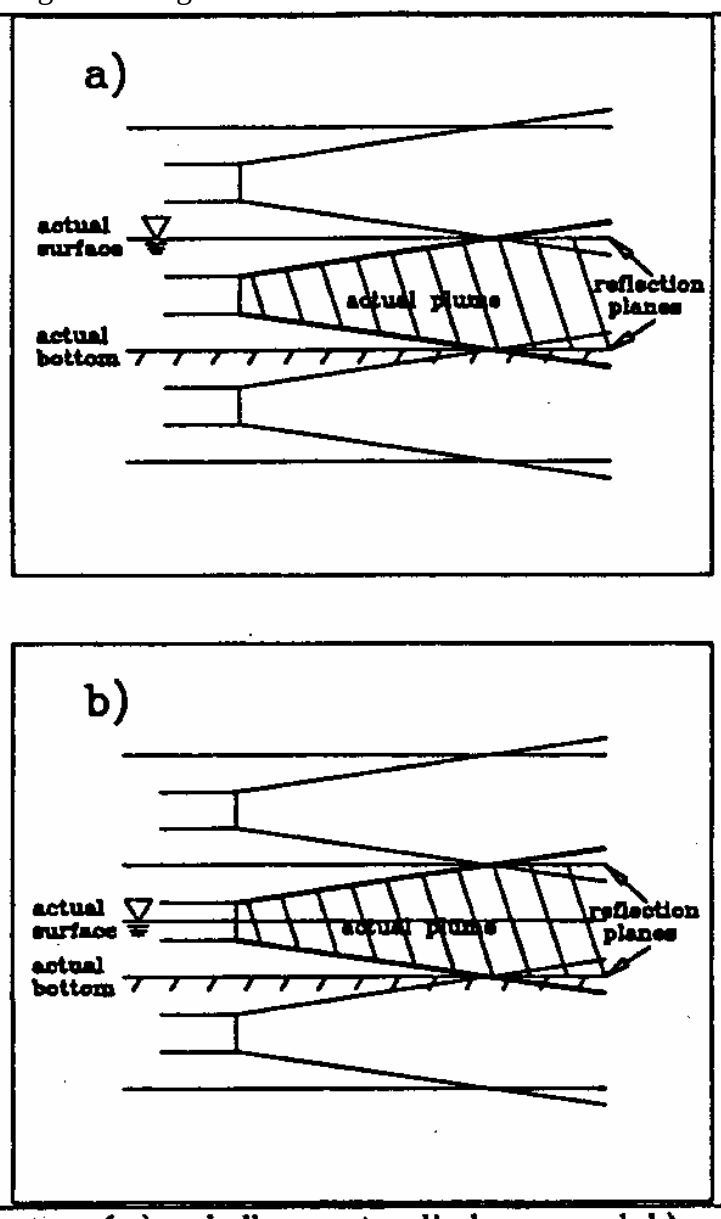

Figure 1. Geometry of a) a shallow water discharge, and, b) a surface discharge.

2.3 THE CITY OF SUMNER EXAMPLE

A Total Maximum Daily Load (TMDL) study has been completed for the Puyallup River system, indicating that Waste Load Allocations (WLAs) will be necessary in portions of the system for some pollutants. Ammonia among others, is a pollutant of concern. Given the large number of existing NPDES permits (20), a basin-wide evaluation of the need for water quality-based permits has begun.

The City of Sumner discharges into the White River, 140 feet upstream from the confluence with the Puyallup River. Their permit must be modified to include water quality-based effluent limits. The City wants to ensure that ample credit is given for mixing provided at the confluence. However, this may be irrelevant if toxicity at the acute boundary governs.

The wastewater treatment plant discharges through a 24 inch outfall anchored at mid-channel in 1.37 m of water. Reasonable worst-case parameters for the effluent are: a flow of 3.42 MGD, temperature of 19.9^{o}C., and ammonia concentration of 25 mg/L. The 7Q10 flowrate in the White River is 437 cfs, which gives a width and average depth of 41.5 m and 0.70 m, respectively; velocity is 0.40 m/sec. At this low flow, the temperature of the River is 17.4^{o}C., pH is 9.1 mg/L (apparently due to attached algae), and the background concentration of ammonia is 0.07 mg/L.

Sumner makes a good example for demonstrating the reflection technique and the Very Shallow Water (VSW) algorithm. Call up the 3PLUMES interface screen. The default filename (found on the help line) is **plmstuff.var**. The filename can be readily changed by invoking <get **W**ork file>, [CTRL **W**] from the main menu and creating a filename for this project. Do that now; use the filename **sumner.var**. **Plmstuff.var** will simply be saved by 3PLUMES and remain unused. Before inputting the data, invoke the <configu**Re** models>, [CTRL **R]** command and set up the configuration string NTNO0. (The first letter of the 5 letter configuration code should always be toggled to "N" to signify ambient "off", because this technique requires two (and only two) lines of ambient data.)

Enter the input data as shown in Figure 2. Reasons for some of the data, which don't seem logical now, should be clear as the example progresses. Remember to simplify the conversion from one unit to another by using <units **K**onversion>, [CTRL **K**] in order to input [**tot flow**] and [**plume dia**] without having to convert the units

```
Sept 8, 1993,  9:00:00      ERL-N      PROGRAM PLUMES,  April 26, 1993          Case:  1 of  1
Title Sumner WWTP: Ammonia/Chronic/3.42 MGD/7Q10
    tot flow      # ports     port flow     spacing      effl sal     effl temp     far inc      far dis
     0.1498           1                      1000           0           19.9        9.144        92.8
    port dep      port dia    plume dia    total vel    horiz vel     vertl vel    asp coefff    print frq
      1.067        0.6096                                                            0.1          500
    port elev     ver angle   cont coef     effl den     poll conc      decay      Froude #     Roberts F
     0.3048           0          1                        25        5.21e-6
   hor angle     red space   p amb den      current      far dif      far vel     K:vel/cur     Stratif #
      90                                     0.43      0.000453        0.4
      depth        current     density     salinity      temp      amb conc      N (freq)     red grav.
        0           0.43                      0          17.4        0.07
       1.38         0.43                      0          17.3        0.07       buoy flux      puff-ther

                                                                               jet-plume      jet-cross

                                                                               plu-cross      jet-strat

                                                                                plu-strat

                                                                                 hor dis  >=

CORMIX1 flow category algorithm is turned          Off

Help: F1.  Quit: <esc>.  Configuration:          NTNO0          File:     sumner.var
```

Figure 2. Independent variables (data input through keyboard).

Data is input in the usual way <u>except</u> that changes may have to be made to the stratification and buoyancy parameters in order to better conform to the reflection theory assumptions. The ambient should be minimum stratification, *i.e.*, the bottom and surface temperatures (and salinities) should be basically identical. The bottom layer is made slightly colder (denser) to avoid undefined cells from appearing elsewhere; and the temperature and salinity of the effluent flow produce a largely non-buoyant plume. In summary, the [**effl den**] cell and ambient [**density**] cells should contain values that are very nearly equal.

Ordinarily it is a good idea to sketch out the tentative sensitivity analysis (*i.e.* the list of cases to be run) ahead of time when using the VSW algorithm . This helps to ensure that cases to be run later, which may involve changing only one or two independent variables, are created before VSW is implemented. As you will see, implementing VSW introduces artificial numbers into many of the cells, and the original data is lost to that case.

At this point it's appropriate to interpret some language from the Washington State water quality standards pertaining to mixing zones. The dilution factor to use when determining whether Sumner's effluent causes chronic toxicity must be the lowest one of three generated as follows:

- at the longitudinal boundary, which is located downstream from the discharge 300 feet plus the depth of the port(s)[**port dep**];

- at a lateral boundary, which is located such that the width of the mixing zone does not occupy more than 25% of the channel width;

- such that the effluent flowrate is no more than 25% of the flowrate available for dilution.

The dilution factor to use when determining whether Sumner's effluent causes acute toxicity must be the lower one of two generated as follows:

- at the longitudinal boundary, which is located downstream from the discharge at a distance equal to 10% of the length of the chronic mixing zone;

- such that the effluent flowrate is no more than 2.5% of the flowrate available for dilution.

After examining the data in Figure 2, a question may arise about the [**far dis**] of 92.8 m. This is 304.5 feet, which is the maximum length of the chronic mixing zone for Sumner and, therefore, the farthest distance to which the analysis needs to extend. Note that this extends beyond the confluence of the two rivers and all model results will have to be reassessed if a chronic criterion is determined to be limiting. Use 0.40 m/sec for the far-field velocity [**far vel**]. This also must be considered a temporary assumption because it extends beyond the confluence. The [**depth**] for the last line of ambient data (1.38 m in this example) should be greater than the sum of [**port dep**] + [**port elev**]. The densimetric Froude number [**Froude #**] (a dependent variable calculated by the model) is greater than 1 - which is important.

Assume that the list of cases to be run has already been sketched out, and that two cases will be needed to examine ammonia chronic toxicity and two for ammonia acute toxicity. Make one extra case for each as a backup. Use <go to **C**ase>, [CTRL **C**] (or [**Page Up**]) to create 3 more copies of Case 1. Now make several of the necessary changes in Case 4 ([**title**], [**current**]) in order to produce an acute case; then create two copies of Case 4 in Cases 5 and 6. After you are done, use the [CTRL **C**] command again to return to Case 1.

Use<shallow/surface **Z**>, [CTRL **Z**] from 3PLUMES' drop down main menu to implement the VSW algorithm. When the input screen (window) appears, answer the question by pressing [**S**] to choose the surface/bottom option. After the choice is made, an additional cell appears for inputting the width of the stream: **Input effective channel width (m): _____.**
Input 30 meters. Comparing width and average depth of the White River, and depth of outfall suggests that the effective channel width is ~ 30 m, much less than the channel width of the wetted perimeter (41.5 m).

The input screen is now updated as shown in Figure 3. Notice that the title has been changed by the addition of the letters ^ZS to the beginning of the title string (CTRL(^)Z for the command and 'S' for surface/bottom discharge). This is a reminder that 3PLUMES has changed some of the cells in order to prepare the data for running in the reflection mode. The affected cells are the [**tot flow**], [**port flow**], [**spacing**], [**port dep**], [**port dia**], [**plume dia**], [**red space**], and (bottom) [**depth.**

```
Sept 8, 1993,  9:00:00     ERL-N      PROGRAM PLUMES,  April 26, 1993          Case:  1 of   6
Title ^ZSSumner WWTP: Ammonia/Chronic/3.42 MGD/7Q10
    tot flow     # ports    port flow    spacing     effl sal    effl temp     far inc      far dis
     0.2996                  0.2996      2.744
    port dep     port dia   plume dia   total vel   horiz vel    vertl vel    asp coefff    print frq
     15.00       0.8621      0.8621
    port elev    ver angle  cont coef   effl den    poll conc     decay       Froude #     Roberts F

   hor angle     red space  p amb den   current     far dif      far vel      K:vel/cur     Stratif #
                  2.744
      depth      current    density     salinity     temp       amb conc      N (freq)     red grav.

      30.00                                                                   buoy flux     puff-ther

                                                                              jet-plume     jet-cross

                                                                              plu-cross     jet-strat

                                                                               plu-strat

                                                                                hor dis  >=

CORMIX1 flow category algorithm is turned                    Off

Help: F1.  Quit: <esc>.  Configuration:          NTNO0          File:   sumner.var
```

Figure 3. Variables that are altered by reflection technique algorithm.

Notice that [**port dep**] (15.00 m) is now half the width of the stream, and the bottom [**depth**] is equal to the width of the stream (30 m). The bottom and surface substitute for the vertical planes of the merging plume problem. Obviously, plume buoyancy and stratification would be not only meaningless because the dimensions have been changed, but would introduce trajectory motion which would interfere with the proper execution of the plume model.

The spacing distance is now 2.744 m, or twice the total depth of the stream. This must be true because otherwise the plume, which is at the surface (or bottom), would be on the reflection plane and symmetry would be broken. This problem is overcome by doubling the total flow with half of the flow discharging into the imaginary layer above the surface of the water. The port diameter is adjusted accordingly so that the basic momentum properties of the plume (for example, the total velocity) are not changed. This assures that the dynamics of the problem are treated consistently. Note that the diameter is multiplied by the square root of 2 so that the area of the port is doubled.

Next, run VSW by using the [CTRL **U**] command. A prompt on the dialogue line will ask for the desired form of output: printer, console or disk file. Output to the printer. Results of the simulation are shown in Figure 4. Some interpretation of the results is in order. Note, first of all, that the total stream flow is 32.9 m^3/sec (30x2.74x0.40); therefore, since the effluent flow is 0.2996 m^3/sec, the maximum dilution that can be achieved is 111:1. Thus, any predictions beyond the point of a dilution equal to 111:1 should be ignored.

```
Sep  8, 1993,   9:30:23  ERL-N PROGRAM PLUMES, Apr 26, 1993   Case:   1 of   6
Title   ^ZSSumner WWTP:  Ammonia/Chronic/3.42 MGD/7Q10                non-linear
 tot flow   # ports port flow   spacing  effl sal effl temp   far inc   far dis
   0.2996         1    0.2996     2.744       0.0      19.9     9.144      92.8
 port dep  port dia plume dia total vel horiz vel vertl vel asp coeff print frq
    15.00    0.8621    0.8621    0.5133    0.5133     0.000      0.10       500
port elev ver angle cont coef  effl den poll conc     decay  Froude # Roberts F
   0.3048       0.0       1.0    -1.712        25   5.21e-6     7.974     47.61
hor angle rad space p amb den p current   far dif   far vel K:vel/cur Stratif #
       90     2.744    -1.223      0.43  0.000453       0.4     1.194  0.001045
    depth   current   density  salinity      temp  amb conc  N (freq) red grav.
      0.0      0.43    -1.232       0.0      17.4      0.07  0.002413  0.004806
       30    0.4300    -1.214       0.0      17.3      0.07 buoy flux puff-ther
                                                              0.001440     3.368
                                                             jet-plume jet-cross
                                                                 6.472    0.9119
                                                             plu-cross jet-strat
                                                               0.01811     12.75
                                                             plu-strat
                                                                 17.89
                                                              hor dis>=

CORMIX1 flow category algorithm is turned off.
 0.2996 m3/s, 6.838 MGD, 10.58 cfs.                      >0.0 to 100 m3/s range
Help: F1.  Quit: <esc>.  Configuration:NTNOO.  FILE: sumner.var;
UM INITIAL DILUTION CALCULATION (non-linear mode)
 plume dep plume dia poll conc  dilution   CL conc   hor dis
        m         m                                       m
    15.00    0.8621     25.00     1.000     25.00     0.000
    15.00    0.8651     24.83     1.007     25.00   0.09226 -> bottom hit
    13.74     2.763     2.898     8.811     9.243     22.82
 -> surface reflection begins
    10.83     8.165    0.8491     31.98     1.758     75.48
    7.370     14.96    0.4904     59.27    0.9328     141.1 -> bank(s) reach
FARFIELD CALCULATION (based on Brooks, 1960, see guide)
Farfield dispersion based on wastefield width of      14.96m
   --4/3 Power Law--   -Const Eddy Diff-
      conc  dilution      conc  dilution  distance        Time
                                               m        sec   hrs
    0.4893      59.4    0.4893      59.4     146.3      12.98   0.0
```

Figure 4. Model run at [print frq] of 500.

The theoretical model, UM, conserves momentum - in this case the combined momentum of both the entrained fluid and the effluent fluid. This assumption appears to work well in deep, unconfined water; but here, frictional and other open channel flow effects, which are ignored in the theoretical model, play a role in subtracting momentum from the stream. Hence, these predictions should be used with caution. Nevertheless, the user has some idea when the plume

spreads vertically throughout the water column and the surface is hit. This is the point at which the plume reflects off the two planes. The output refers to it as -> surface reflection begins (at 22.82 m downstream).

More interpretation of the data is needed in order to help in developing an effluent limit and a mixing zone for Sumner. Remember that the length of the chronic mixing zone cannot exceed 92.8 m; AND, therefore, length of the acute zone cannot exceed 9.28 m. However, the model didn't provide a fine enough resolution in the output data to clearly interpret the data at a horizontal distance of either 92.8 or 9.28 m. But, the capability is there!

Move to Case 2 by using [CTRL **C**]. Changing the [**print frq**] number from 500 to 25 will provide the needed resolution. Lines of output will occur more frequently, i.e., less meters of [**hor dis**] will be traveled by the plume for each calculated [**dilution**] and [**poll conc**]. Rerun UM just as was done for Case 1, and the results for Case 2 should look like those in Figure 5.

```
Sep  8, 1993,  10:11:53  ERL-N PROGRAM PLUMES, Apr 26, 1993   Case:   2 of   6
Title   ^ZSSumner WWTP:  Ammonia/Chronic/3.42 MGD/7Q10                non-linear
 tot flow   # ports port flow   spacing  effl sal effl temp   far inc   far dis
   0.2996         1    0.2996     2.744       0.0      19.9     9.144      92.8
 port dep  port dia plume dia total vel horiz vel vertl vel asp coeff print frq
    15.00    0.8621    0.8621    0.5133    0.5133     0.000      0.10        25
port elev ver angle cont coef  effl den poll conc     decay  Froude # Roberts F
   0.3048       0.0       1.0    -1.712        25   5.21e-6     7.974     47.61
hor angle red space p amb den p current   far dif   far vel K:vel/cur Stratif #
       90     2.744    -1.223      0.43  0.000453       0.4     1.194  0.001045
    depth   current   density  salinity      temp  amb conc  N (freq) red grav.
      0.0      0.43    -1.232       0.0      17.4      0.07  0.002413  0.004806
       30    0.4300    -1.214       0.0      17.3      0.07 buoy flux puff-ther
                                                              0.001440     3.368
                                                            jet-plume jet-cross
                                                                6.472    0.9119
                                                            plu-cross jet-strat
                                                              0.01811     12.75
                                                            plu-strat
                                                                17.89
                                                              hor dis>=

CORMIX1 flow category algorithm is turned off.
     47.61                                                   0 to 1000  range
Help: F1.  Quit: <esc>.  Configuration:NTNOO.  FILE: sumner.var;
UM INITIAL DILUTION CALCULATION (non-linear mode)
 plume dep plume dia poll conc  dilution   CL conc   hor dis
         m         m                                      m
     15.00    0.8621     25.00     1.000     25.00     0.000
     15.00    0.8651     24.83     1.007     25.00   0.09226 -> bottom hit
     14.98    0.9519     21.03     1.189     25.00     1.399 -> bottom hit
     14.94     1.050     17.70     1.414     25.00     2.803 -> bottom hit
     14.88     1.155     14.89     1.681     25.00     4.146 -> bottom hit
     14.81     1.270     12.54     1.999     25.00     5.493 -> bottom hit
     14.73     1.395     10.55     2.378     25.00     6.894 -> bottom hit
     14.63     1.530     8.884     2.827     25.00     8.386 -> bottom hit
     14.53     1.677     7.482     3.362     22.62     10.00 -> bottom hit
     14.42     1.837     6.303     3.998     19.51     11.78 -> bottom hit
     14.29     2.011     5.311     4.755     16.80     13.74
     14.16     2.200     4.477     5.654     14.44     15.92
     14.00     2.405     3.776     6.724     12.38     18.37
     13.84     2.629     3.186     7.996     10.59     21.12
     13.74     2.763     2.898     8.811     9.243     22.82
 -> surface reflection begins
     13.65     2.890     2.690     9.509     7.921     24.30
     13.43     3.253     2.274     11.31     6.059     28.19
     13.16     3.719     1.923     13.45     4.783     32.91
     12.84     4.299     1.628     15.99     3.840     38.61
     12.46     5.010     1.380     19.02     3.122     45.48
     12.01     5.873     1.172     22.62     2.562     53.73
     11.47     6.914    0.9965     26.90     2.117     63.62
     10.83     8.165    0.8491     31.98     1.758     75.48
     10.06     9.663    0.7251     38.04     1.466     89.72
     9.149     11.45    0.6209     45.23     1.227     106.9
     8.065     13.59    0.5332     53.79     1.029     127.6
     7.370     14.96    0.4904     59.27    0.9328     141.1 -> bank(s) reach
FARFIELD CALCULATION (based on Brooks, 1960, see guide)
Farfield dispersion based on wastefield width of      14.96m
   --4/3 Power Law--    -Const Eddy Diff-
      conc  dilution      conc  dilution  distance         Time
                                                 m        sec   hrs
    0.4893      59.4    0.4893      59.4     146.3      12.98   0.0
```

Figure 5. Model run at [print frq] of 25.

It is now possible to tell with more certainty that the dilution factor (DF) is about 40 and the number in the column [**poll conc**] is about 0.7 at the longitudinal dimension of the chronic mixing zone. The DF at 9.28 m is about 3 and the [**poll conc**] is about 8; obtained by interpolating between rows of data on the output. (Incidentally, interpolate with reservation because it's not a linear relationship.) If more accurate numbers are needed, it is better to lower the [**print frq**] number even further.

The chronic criterion for ammonia (using reasonable worst-case values for pH and temp) is 0.87 mg/L and the acute criterion is 4.5 mg/L. Comparison to the [**poll conc**] numbers generated in Case 2 shows that the chronic criterion won't be violated, but the acute will be. So, it's obvious that the City can't continue to discharge ammonia at a concentration of 25 mg/L. BUT, since a TMDL has been completed, comparison to water quality criteria won't suffice.

However, more modeling could still be needed: If the chronic criterion for another pollutant of concern is the most limiting and it becomes necessary to reevaluate dilution due to the confluence of the rivers. That will be revisited later.

Earlier, some specific language from the Washington State standards was mentioned because it included other factors which must be considered when conducting mixing zone analyses. Examining the two other chronic factors:

(1) Twenty-five percent of channel width: The width of the mixing zone is about 10 m (0.25x41.5m). Scanning down the values in the output column headed **[plume dia]** in Figure 5 to a width (diameter) of about 10 meters gives the DF of about 40;

(2) Twenty-five percent of flowrate available for dilution: The formula for calculating the volumetric dilution factor is

$$DF = (Q_{amb} + Q_{eff}) / Q_{eff} ,$$

where Q represents flowrate (in cfs) available for dilution: ambient (109) and effluent (5.29),

giving an allowable dilution of 21.6 - less than the dilution calculated by the model.

Examining the one other acute factor:

(1) Two-point-five percent of flowrate available for dilution:

$DF = (Q_{amb} + Q_{eff})/ Q_{eff}$,

where Q represents flowrate (in cfs) available for dilution: ambient (10.9) and effluent (5.29).

This provides a dilution of only 3.06 - which becomes the limiting dilution for use in calculating WLAs and effluent limitations.

Effluent and ambient concentrations of ammonia were included in the input to the model, but in the final analysis plume concentrations weren't the overriding consideration.

The extra cases created in **sumner.var** weren't needed because acute was limiting and it wasn't necessary to analyze the plume at and beyond the confluence. We could use <make **N**ew file>, [CTRL **N**] to move just the useful cases into another file for better file management.

2.4 REFERENCES

Ecology, 1994. *Permit Writer's Manual*, Department of Ecology, Water Quality Program, Olympia WA 98504, as later amended.

EPA, 1994. *Dilution Models for Effluent Discharges*, U.S. Environmental Protection Agency, EPA/600/R-94/086, Washington, D.C.

Turner, D.B., 1970. *Workbook of atmospheric dispersion estimates*. Office of Air Programs, Publication No. AP-26, USEPA, Research Triangle Park, North Carolina.