Modeling the Tongue River Watershed with LSPC and CE-QUAL-W2

June 25, 2007

FINAL DRAFT

Prepared by:
U.S. Environmental Protection Agency
Montana Operations Office and Tetra Tech, Inc.

Project Manager: Ron Steg

Modeling the Tongue River Watershed with LSPC and CE-QUAL-W2

FINAL DRAFT

June 25, 2007

Prepared by:
U.S. Environmental Protection Agency
Montana Operations Office
and Tetra Tech, Inc.

Project Manager: Ron Steg

Cover photo by USGS

Acronyms

AMPP	Agronomic Monitoring and Protection Program
ARM	Administrative Rules of Montana
BLM	Bureau of Land Management
CBM	Coal bed methane
CFS	Cubic feet per second
DNRC	Montana Department of Natural Resources and Conservation
DO	Dissolved oxygen
EC	Electrical conductivity
GIS	Geographic information system
HSPF	Hydrological Simulation Program--Fortran
HUC	Hydrologic Unit Code
IEMB	Industrial Energy and Minerals Bureau, Montana DEQ
LSPC	Loading Simulation Program C++
MBOG	Montana Board of Oil and Gas
MDEQ	Montana Department of Environmental Quality
MFWP	Montana Fish, Wildlife, and Parks
mg/L	Milligrams per liter
MRLC	Multi-Resolution Land Characterization
MUID	Map Unit Identifier
NCDC	National Climatic Data Center
NCEPD	Northern Cheyenne Environmental Protection Department
NLCD	National Land Cover Data
NOAA	National Oceanic and Atmospheric Administration
NO_x	Nitrate + Nitrite
NRCS	Natural Resources Conservation Service
NTU	Nephelometric turbidity units
NWIS	National Water Information System
PCS	Permit Compliance System
SAR	Sodium adsorption ratio
SC	Specific conductance
SNOTEL	SNOwpack TELemetry
STATSGO	State Soil Geographic Database
TDS	Total dissolved solids
TKN	Total Kjeldahl Nitrogen
TMDL	Total maximum daily load
TN	Total nitrogen
TP	Total phosphorus
TPA	TMDL planning area
TR	Total Recoverable
TRR	Tongue River Reservoir
TRWU	Tongue River Water Users
TSS	Total suspended solids
T&Y	Tongue and Yellowstone Irrigation District
µS/cm	Micro siemens per centimeter
USDI	United States Department of Interior
USEPA	United State Environmental Protection Agency
USFS	United States Forest Service
USGS	United States Geological Survey
WDEQ	Wyoming Department of Environmental Quality
WRCC	Western Regional Climate Center
WWDC	Wyoming Water Development Commission
WTP	Water Treatment Plant
WWTP	Wastewater Treatment Plan

Table of Contents

EXECUTIVE SUMMARY ..... **IX**
1.0 INTRODUCTION **1**
2.0 MODEL SELECTION **3**
2.1 Technical Criteria 3
2.2 Regulatory Criteria 4
2.3 User Criteria 5
2.4 Loading Simulation Program C++ (LSPC) Overview 5
2.5 CE-QUAL-W2 Overview 6
2.6 Model Linkage 7
3.0 LSPC MODEL SETUP **9**
3.1 Modeled Parameters 9
3.2 Watershed Segmentation 12
3.3 Waterbody Representation 15
3.3.1 Streams 15
3.3.2 Tongue River Reservoir 16
3.4 Weather Data 19
3.4.1 Patching and Disaggregating Rainfall Data 22
3.4.2 Potential Evapotranspiration 23
3.5 Land Cover Representation 24
3.5.1 Impervious Lands 26
3.5.2 Irrigated Lands 26
3.5.3 Final Modeled Land Uses 32
3.6 Watershed Grouping 33
3.7 Point Sources 35
3.7.1 Wastewater Treatment Facilities 37
3.7.2 Coalbed Methane 39
3.7.2.1 CBM Outfalls 39
3.7.2.2 CBM Ponds 43
3.7.2.3 Modeling CBM Outfalls and Ponds 45
3.7.3 Coal Mines 50
3.8 Stock Ponds 51
3.9 High-Altitude Reservoirs and Diversions 54
3.10 Other Diversions 56
3.10.1 Mead-Coffeen, Piney-Cruse, and Prairie Dog Diversions 56
3.10.2 Tongue and Yellowstone Diversion 58
3.10.3 Sheridan Water Treatment Plant 58
3.11 Irrigation 59
3.12 Surface and Subsurface Water Chemistry Concentrations 61
3.12.1 Surface Runoff Concentrations 61
3.12.2 Subsurface Concentrations 61
3.12.2.1 Literature Review 61
3.12.2.2 Modeled Subsurface Concentrations 64
4.0 LSPC CALIBRATION **67**
4.1 Hydrologic Calibration Methodology 68
4.1.1 High-Altitude Hydrologic Calibration Methodology 70
4.1.2 Prairie Hydrologic Calibration Methodology 73
4.2 Water Chemistry Calibration Methodology 74
4.2.1 Salinity and SAR 74
4.2.2 Nutrients 75
4.2.3 Water Temperature 77
5.0 PERFORMANCE AND EVALUATION OF THE CALIBRATED MODEL **79**
5.1 Flow 80

5.2 Specific Conductance 82
5.3 SAR 83
5.4 Total Nitrogen 84
5.5 Total Phosphorus 84
5.6 Salinity and SAR Calibration in the Tongue River Reservoir 85
5.7 Model Limitations 85
5.7.1 Weather Data 86
5.7.2 Flow Alterations 86
5.7.3 Point Sources Discharges 86
5.7.4 Physiographic Characteristics 86
5.7.5 Observation Data 86
5.7.6 Hydrology Calibration Data 87
5.7.7 Water Chemistry Calibration Data 87
6.0 CE-QUAL-W2 MODEL SETUP AND CALIBRATION 89
6.1 CE-QUAL-W2 Model Configuration 89
6.1.1 CE-QUAL-W2 Segmentation/Computational Grid Setup 91
6.1.2 Initial Conditions 94
6.1.3 Boundary Conditions 94
6.1.4 Reservoir Outflow 94
6.1.5 Point Sources 94
6.1.6 Meteorological Data 96
6.1.7 CE-QUAL-W2 Calibration Time Period 96
6.2 Upstream Conditions 97
6.2.1 Flow 97
6.2.2 Water Chemistry 97
6.2.3 Temperature 98
6.3 CE-QUAL-W2 Model Calibration and Validation 99
6.4 CE-QUAL-W2 Modeling Coefficients 107
6.5 CE-QUAL-W2 Data Limitations 109
6.5.1 Point Sources Discharges 109
6.5.2 Observation Data 109
6.5.3 Water Chemistry Calibration Data 109
7.0 UNCERTAINTY 111
7.1 Model Use 111
7.2 Conclusions 115
8.0 STEPS TO IMPROVE MODEL PERFORMANCE 117
9.0 REFERENCES 119

APPENDIX A – Point Sources A-1
APPENDIX B – LSPC Model Evaluation Results B-1

Tables

Table 2-1. Montana's numeric criteria for salinity (measured as electrical conductivity) applicable to the Tongue River watershed. 4
Table 2-2. Montana's numeric SAR criteria for the Tongue River watershed. 4

Table 3-1. Relationships between observed EC and the sum of cations (Ca, Mg, and Na in milliequivalents) at selected USGS gages in the Tongue River watershed. 11
Table 3-2. Weather stations used in the Tongue River watershed modeling. 21
Table 3-3. NLCD land cover in the Tongue River watershed. 24
Table 3-4. Percentage of impervious cover for developed land use classes. 26
Table 3-5. Total acres of irrigated land in the Tongue River watershed in Montana 28
Table 3-6. LSPC land use groupings and their associated NLCD land use classes. 32
Table 3-7. Modeled land uses in the Tongue River watershed. 32
Table 3-8. Watershed groups for the Tongue River LSPC model. 33
Table 3-9. Summary of permitted wastewater discharge data in the Tongue River watershed (average values for the available period of record are reported). 37
Table 3-10. Summary of modeled CBM flow and concentrations. 45
Table 3-11. Summary of modeled CBM outfalls per LSPC subbasin. 48
Table 3-12. Summary of modeled coal mine outfalls and data. 50
Table 3-13. Total volume of stock ponds per modeling subbasin 52
Table 3-14. Summary of modeled high-altitude reservoirs and their associated input parameters. 55
Table 3-15. Average monthly flow (cfs) for the three diversions from the Powder River watershed. 57
Table 3-16. Crop irrigation requirements for irrigated land in the Tongue River watershed. 60
Table 3-17. Summary of Discharge Concentrations (mg/L) from Base of C Horizon, AMPP Alluvial Soils (calculated from data in Schafer et al., 2006) 63
Table 3-18. Calculated discharge concentrations from alluvial soils. 63

Table 4-1. Recommended criteria for the Tongue River watershed hydrology calibration. 67
Table 4-2. Recommended criteria for the Tongue River watershed chemistry calibration. 68
Table 4-3. USGS monitoring sites used for the Tongue River LSPC model hydrology calibration. 68
Table 4-4. USGS monitoring sites used for the Tongue River LSPC model water chemistry calibration. 74

Table 5-1. Model performance criteria (Adapted from Donigian, 2000). 79
Table 5-2. Model performance – average flow at various timescales. 81
Table 5-3. Model performance – average SC at various time scales. 82
Table 5-4. Model performance – average SAR at various timescales. 83

Table 6-1. Annual average water chemistry concentrations (mg/L) at the USGS gage along the Tongue River at Decker, Montana (gage ID 06306300). 98
Table 6-2. Kinetic Coefficients used in the calibration of Tongue River Reservoir. 108

Table 7-1. Qualitative comparison of predicted and observed minimum and maximum SC values (Symbols indicate under or over prediction) 113
Table 7-2. Qualitative comparison of predicted and observed minimum and maximum SAR values (Symbols indicate under or over prediction) 114

Figures

Figure 1-1. Location of the Tongue River watershed. 2

Figure 3-1. Observed cations in the Tongue River at the State Line (USGS Gage 06306300). All data through September 30, 2006 are shown. 10
Figure 3-2. Linear regression of observed cations to observed EC at USGS gage 06306300 (Tongue River at the State Line). 10
Figure 3-3. Modeling subwatersheds for the Upper Tongue River watershed and Tongue River Reservoir. 13
Figure 3-4. Modeling subwatersheds for the lower Tongue River watershed. 14
Figure 3-5. Stream channel representation in the LSPC model. 16
Figure 3-6. Stage-volume-area relationships for the Tongue River Reservoir. 17
Figure 3-7. Sensitivity analysis of five model runs for water released from the Tongue River Reservoir. 18
Figure 3-8. Weather station mapping for the Tongue River watershed. 20
Figure 3-9. Twenty-three years of annual rainfall for weather station 242266 (Decker, Montana). 22
Figure 3-10. NLCD land cover in the Tongue River watershed. 25
Figure 3-11. Example area where irrigated land is classified as “hay/pasture” or “cropland” by the NLCD data. Tongue River near Ashland is shown. 28
Figure 3-12. Example area where irrigated land is classified as “emergent herbaceous wetlands.” Otter Creek near Ashland is shown. 29
Figure 3-13. Location of irrigated land in the Tongue River watershed. 30
Figure 3-14. Watershed groups for the Tongue River LSPC model. 34
Figure 3-15. Location of the permitted surface water discharges in the Tongue River watershed (as of September 30, 2006). 36
Figure 3-16. Location of known CBM outfalls in the Tongue River watershed as of September 30, 2006. 41
Figure 3-17. Summary of total monthly CBM discharge from Montana and Wyoming facilities (all available data from 1997-2006) 42
Figure 3-18. Location of CBM ponds and pond groups. 47
Figure 3-19. CBM pond processes modeled in LSPC. 49
Figure 3-20. Relationship between watershed area and stock pond volume. 51
Figure 3-21. Location of stock ponds in the Tongue River watershed. 53
Figure 3-22. Simplified schematic of high-altitude reservoirs and diversions in the Goose Creek watershed (not to scale). 54
Figure 3-23. Transbasin diversions from the Powder River watershed to the Tongue River watershed. 57
Figure 3-24. Histogram of Discharge Concentrations from Base of C Horizon, AMPP Alluvial Soils (calculated from data in Schafer et al., 2006) 62

Figure 4-1. LSPC calibration sites for the Tongue River watershed. 69
Figure 4-2. Snow budget for the Dome Lake SNOTEL gage. 71
Figure 4-3. Snow budget for the Sucker Creek SNOTEL gage. 72
Figure 4-4. Water versus air temperature regression at State Line (06306300) 77

Figure 5-1. Time series of daily mean predicted and observed flow for the Tongue River at State Line near Decker, Montana (USGS gage 06306300). 80
Figure 5-2. Time series of TN data for the Tongue River at State Line near Decker, Montana (USGS gage 06306300). 84
Figure 5-3. Time series of TP data for the Tongue River at State Line near Decker, Montana (USGS gage 06306300). 85

Figure 6-1. Tongue River Reservoir bathymetry. 90
Figure 6-2. Tongue River Reservoir segmentation. 92

Figure 6-3. Longitudinal profile of the Tongue River Reservoir 93
Figure 6-4. Point source locations in Tongue River Reservoir model. 95
Figure 6-5. Location of weather station used for Tongue River Reservoir modeling. 96
Figure 6-6. Polynomial fit used to derive temperature time series from observed historical data 98
Figure 6-7. Water Surface Elevation Calibration. 99
Figure 6-8. Monitoring station locations. 100
Figure 6-9. Temperature (deg C) calibration (2001) 102
Figure 6-10. Temperature (deg C) validation (2003). 103
Figure 6-11. Dissolved oxygen calibration (2001). 104
Figure 6-12. Dissolved Oxygen validation (2003). 105
Figure 6-13. Chlorophyll-*a* calibration/validation at Station 1. 106
Figure 6-14. PO_4 calibration/validation at Station 1. 106

EXECUTIVE SUMMARY

This document is a companion to the document titled, "Water Quality Assessment for the Tongue River Planning Area, Montana" (EPA, 2007 – hereafter referred to as the "Assessment Report"). Its purpose is to explain the process for and report the results of selecting, setting up, and calibrating the computer models that were created to support development of the Assessment Report. This report is not intended to be a user's manual. A user's manual may be prepared at a future date if and when it is decided how the modeling tools described in this document will be used by others.

Two models were developed to simulate the Tongue River Watershed:

1. *A Loading Simulation Program C++ (LSPC) model to simulate watershed processes in the Tongue River watershed, and fate and transport of selected chemical constituents (i.e., salinity, SAR, total nitrogen, and total phosphorus) in the Tongue River, Tongue River tributaries, and the Tongue River Reservoir.*
2. *A CE-QUAL-W2 model to simulate hydrology and nutrients, dissolved oxygen, and temperature in the Tongue River Reservoir.*

USGS data were used to calibrate both models at various locations in the Tongue River and tributaries to the Tongue River (e.g., Hanging Woman, Otter, and Pumpkin Creeks). The calibration encompassed the time period between 1991 and 2006 and varied for the various chemical constituents and hydrology based on the availability of data at a given USGS gage station. Because of limited weather data, calibration was not performed prior to 1991. A formal model validation was not performed due to limited data.

In general, for the Tongue River, model performance is good to very good for the prediction of average flow, specific conductance, and SAR at time scales of one month or greater and model performance is better during the growing season months than the non-growing season months. Model performance for the prediction of average specific conductance and SAR was good to very good for the growing season and longer time periods in all tributaries (where sufficient data were available to evaluate model performance). With the exception of Hanging Woman Creek where flow prediction was fair to good for the growing season and longer time periods, model performance for the prediction of flow in the tributaries was poor.

The primary use of the model to date relates to the prediction of what water quality might have been like in the absence of anthropogenic influence (i.e., predicting the "natural" condition). The model has also been used to evaluate the potential magnitude of water quality effects associated with historical and future discharges from individual sources or categories of sources (e.g., CBM discharge, irrigation, etc.).

Without other assessment methods and/or data to define the "natural" condition, and/or monitoring data to spatially or temporally isolate individual sources, model simulation is the only option for prediction of the water quality condition. So long as the model results are used with caution and uncertainty is acknowledged, the model is well suited for this purpose.

1.0 INTRODUCTION

In 2003, Montana DEQ published a report titled, *Total Maximum Daily Load (TMDL) Status Report – Tongue River TMDL Planning Area* (referred to herein as the *Status Report*) (MDEQ, 2003). The purpose of that document was to provide a summary of TMDL-related work that had been performed through March 2003, and to facilitate further watershed study and TMDL development in the Tongue River watershed. Two phases of the TMDL process were documented in the Status Report. First, a watershed characterization was completed to obtain a better understanding of the Tongue River watershed and its environmental/socioeconomic setting. Second, preliminary water quality impairment assessments were completed using data available at the time of the report. However, in some streams, the water quality impairment status could not be determined due to lack of data or pending changes to Montana's water quality standards.

After completion of the Status Report, it was determined that a computer model of the Tongue River watershed could help to refine and complete the water quality impairment assessments. The model could be used to fill data gaps, and could be used to compare natural versus existing conditions within the 303(d) listed streams. Also, the model could then be used for other TMDL related activities, such as calculating pollutant loads, allocating loads, calculating load reductions, and predicting future loads under various management scenarios. Model selection and initialization began in May of 2003.

As part of the modeling process, the *Tongue/Powder/Rosebud TMDL Modeling Committee* was formed to provide input and recommendations for the model selection, setup and calibration. The Committee met seven times between July 2003 and August 2004, and was composed of individuals representing a variety of interests including agriculture, Northern Cheyenne Tribe, Crow Tribe, Montana Department of Environmental Quality (MDEQ), Wyoming Department of Environmental Quality (WDEQ), U.S. Environmental Protection Agency (USEPA), Bureau of Land Management (BLM), Natural Resources Conservation Service (NRCS), the Department of Natural Resources and Conservation (DNRC), and industry. Members of the Committee were briefed on the status of the modeling effort, and members provided insight and recommendations related to key water quality issues, characteristics of the watershed, and sources of data. Meeting minutes are available online at: http://deq.mt.gov/wqinfo/TMDL/TonguePowderRosebudTMDL.asp

This document is a companion to the document titled, "Water Quality Assessment for the Tongue River Watershed, Montana" (hereafter referred to as the "Assessment Report") (USEPA, 2007) and its purpose is to explain the process for selecting, setting up, and calibrating the computer models that were created to support TMDL related activities for the Tongue River watershed (Figure 1-1). The model selection process is described in Section 2.0. Model set-up, calibration, and performance for the Tongue River watershed are described in Sections 3.0, 4.0, and 5.0, respectively. Setup and calibration of the Tongue River Reservoir model are discussed in Section 6.0. Section 7.0 discusses model uncertainty.

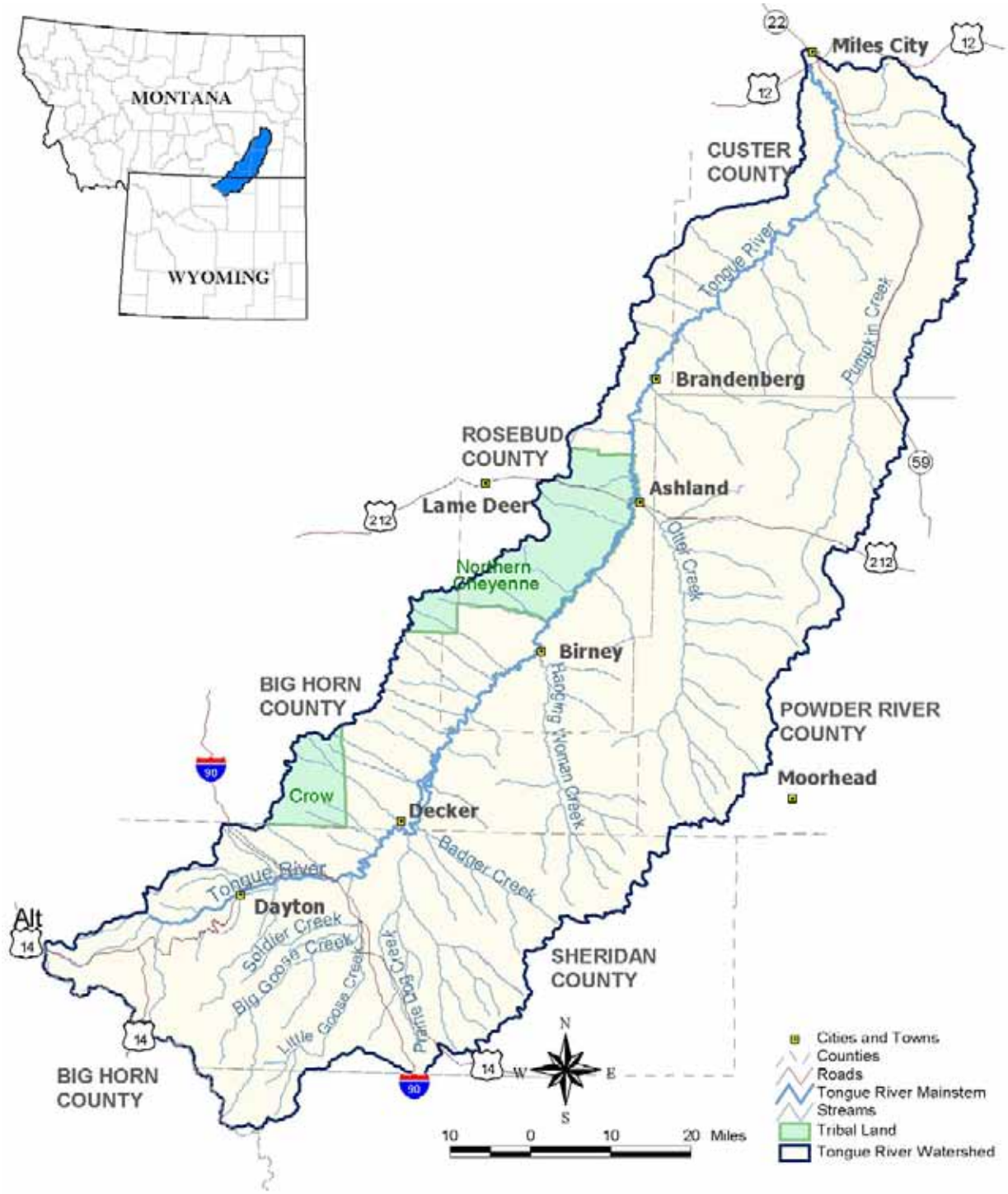


Figure 1-1. Location of the Tongue River watershed.

2.0 MODEL SELECTION

The following criteria were considered and addressed in selecting the appropriate watershed and receiving water models for the Tongue River TMDL Planning Areas (expanding on classification of Mao, 1992):

- Technical Criteria
- Regulatory Criteria
- User Criteria

2.1 Technical Criteria

The pollutants of concern for the current modeling application are salinity (measured as specific conductance, SC), sodium adsorption ratio (SAR), and nutrients. Salinity and SAR are composite measures respectively representing the sum of cations and the ratio of major cations (sodium, calcium, and magnesium), so one approach to simulating salinity and SAR is to simulate individual cations. Land use in the Tongue River watershed includes extensive areas of grasslands, rangelands, shrublands, and forest, with limited urban land uses. Most agricultural and urban land uses are concentrated along the valley floors of perennial streams where much of the agriculture relies on irrigation due to the arid nature of each watershed. Different potential sources of pollutants are associated with each of the various land uses and each land use affects the hydrology of the watershed differently. Some sources contribute relatively constant discharges of pollutants while others are heavily influenced by snowmelt and rain events. The Tongue River Reservoir is also a significant factor in the Tongue River watershed because it alters the timing and magnitude of flows from the upstream portion of the watershed.

Based on these considerations, the following technical factors were critical to selecting an appropriate watershed model:

- The model should be able to address the pollutants of concern (e.g., salinity, SAR [or major cations], and nutrients).
- The model should be able to address a watershed with primarily rural land uses.
- The model should be appropriate for simulating large watersheds.
- The model should provide adequate time-step estimation of flow and not over-simplify storm events to provide accurate representation of rainfall events/snowmelt and resulting peak runoff.
- The model should be capable of simulating various pollutant transport mechanisms (e.g., groundwater contributions, sheet flow, etc.).
- The model should include an acceptable snowmelt routine.
- The model should be flexible enough to accommodate issues such as the arid nature of the watershed and the extensive amount of irrigation activities.
- The model should be able to be linked to an appropriate reservoir model.

Other technical factors were important to consider in selecting an appropriate receiving water model for the Tongue River Reservoir. The reservoir was built for irrigation, recreational, and flood control purposes in 1940 and was re-habilitated from 1996 to 1999. It now has an active storage capacity of approximately 79,000 acre-feet of water (Personal Communications, Kevin Smith, Montana DNRC, June 14, 2004). The reservoir is long and narrow with an average depth of 6.1 meters (20 feet). The reservoir is listed as being impaired due to nutrients, organic enrichment, and total suspended solids, although limited historic water chemistry data are available (MDEQ, 1996, 2006a). The reservoir is also a significant factor in controlling flow and water chemistry in the Tongue River below the dam. Technical criteria associated with modeling the Tongue River Reservoir model therefore included the following:

- The model should be able to address the pollutants of concern (e.g., salinity, SAR, and nutrients).
- The model should be appropriate for a long and narrow reservoir with spatially varying depths.
- The model should provide output from upstream to downstream in the reservoir and at depth.
- The model should be able to be linked to the Tongue River watershed model.

2.2 Regulatory Criteria

Regulatory criteria were also a key consideration in selecting appropriate watershed and reservoir models. A stream or reservoir's assimilative capacity is determined through adherence to numeric water chemistry standards. Table 2-1 and Table 2-2 summarize the water quality standards applicable to the Tongue River and Tongue River Reservoir (MDEQ, 2006b). These tables indicate that the salinity, measured as electrical conductivity (EC), and SAR standards are applied as both monthly average values and maximum "not-to-exceed" values. The selected model therefore needed to be able to provide output that can be directly compared to these standards. For example, some models only provide annual or monthly output and would therefore be inadequate for assessing compliance with the component of Montana's standard that is expressed as an instantaneous maximum. Consistency with water quality standards was the primary regulatory criterion that affected model selection.

Table 2-1. Montana's numeric criteria for salinity (measured as electrical conductivity) applicable to the Tongue River watershed.

Waterbody	Season	Monthly Average EC (µS/cm)	Maximum EC (µS/cm)
Tongue River	Nov 1 – Mar 1	1,000	1,500
	Mar 2 – Oct 31	1,500	2,500
Tongue River Tributaries	Nov 1 – Mar 1	500	500
	Mar 2 – Oct 31	500	500
Tongue River Reservoir	Nov 1 – Mar 1	1,000	1,500
	Mar 2 – Oct 31	1,000	1,500

MDEQ, 2006b

Table 2-2. Montana's numeric SAR criteria for the Tongue River watershed.

Waterbody	Season	Monthly Average SAR	Maximum SAR
Tongue River	Nov 1 – Mar 1	3.0	4.5
	Mar 2 – Oct 31	5.0	7.5
Tongue River Tributaries	Nov 1 – Mar 1	5.0	7.5
	Mar 2 – Oct 31	3.0	4.5
Tongue River Reservoir	Nov 1 – Mar 1	3.0	4.5
	Mar 2 – Oct 31	3.0	4.5

MDEQ, 2006b

2.3 User Criteria

User criteria are associated with the needs, expectations, and resources of the stakeholders involved in the modeling project. Stakeholders expressed a strong desire (via the Modeling Committee) to base management decisions on the best available data and science. Furthermore, the stakeholders indicated that the modeling software should be non-proprietary, tested, and accepted. A further consideration was that the two state agencies (Montana DEQ and Wyoming DEQ) indicated that they would be interested in using the models for future applications (such as supporting NPDES permitting decisions). Each of these criteria was considered during the model selection process.

2.4 Loading Simulation Program C++ (LSPC) Overview

Based on the considerations described above and previous modeling experience, the Loading Simulation Program C++ (LSPC) was selected to address all of the modeling needs except nutrient response in the Tongue River Reservoir (see Section 2.3 for a discussion of the model selected to address nutrients in the Tongue River Reservoir). LSPC is a version of the Hydrologic Simulation Program FORTRAN (HSPF) model that has been ported to the C++ programming language to improve efficiency and flexibility. LSPC integrates a geographical information system (GIS), comprehensive data storage and management capabilities, the original HSPF algorithms, and a data analysis/post-processing system into a convenient PC-based windows interface. LSPC's algorithms are identical to a subset of those in the HSPF model. LSPC is currently maintained by the EPA Office of Research and Development in Athens, Georgia. A brief overview of the HSPF model is provided below and a detailed discussion of HSPF simulated processes and model parameters are available in the HSPF User's Manual (Bicknell et al. 1996).

HSPF is a comprehensive, public domain, watershed and receiving water quality modeling framework that was originally developed in the mid-1970's and is supported by USEPA and USGS. During the past several years it has been used to develop hundreds of USEPA-approved TMDLs and it is generally considered the most advanced hydrologic and watershed loading model available. The hydrologic portion of HSPF is based on the Stanford Watershed Model (Crawford and Linsley, 1966), which was one of the pioneering watershed models developed in the 1960's. The HSPF framework is developed in a modular fashion with many different components that can be assembled in different ways, depending on the objectives of the individual project. The model includes three major modules:

- PERLND for simulating watershed processes on pervious land areas
- IMPLND for simulating processes on impervious land areas
- RCHRES for simulating processes in streams and vertically mixed lakes

All three of these modules include many submodules that calculate the various hydrologic and water chemistry processes in the watershed. Many options are available for both simplified and complex process formulations. Spatially, the watershed is divided into a series of subbasins representing the drainage areas that contribute to each of the stream reaches. These subbasins are then further subdivided into segments representing different land uses. For the developed areas, the land use segments are further divided into the pervious (PERLND) and impervious (IMPLND) fractions. The stream network (RCHRES) links the surface runoff and groundwater flow contributions from each of the land segments and subbasins and routes them through the waterbodies using storage routing techniques. The stream model includes precipitation and evaporation from the water surfaces, as well as flow contributions from the watershed, tributaries, and upstream stream reaches. Flow withdrawals can also be accommodated. The stream network is constructed to represent all of the major tributary streams, as well as different portions of stream reaches where significant changes in water chemistry occur.

Advantages to choosing LSPC for this application include:

- Simulates all of the necessary constituents and applies to rural watersheds.
- Capable of simulating both stream and reservoir processes.
- A comprehensive modeling framework using the proposed LSPC approach facilitates development of TMDLs not only for this project, but also for potential future projects to address other impairments throughout the basin.
- The time-variable nature of the modeling enables a straightforward evaluation of the cause-effect relationship between source contributions and waterbody response and direct comparison to relevant water quality criteria.
- The proposed modeling tools are free and publicly available. This is advantageous for distributing the model to interested stakeholders and amongst government agencies.
- The model simulates both surface and subsurface impacts to flow and water quality.
- LSPC provides storage of all geographic, modeling, and point source permit data in a Microsoft Access database and text file formats to provide for efficient manipulation of data.
- LSPC presents no inherent limitations regarding the size and number of watersheds and streams that can be modeled.
- LSPC provides post-processing and analytical tools designed specifically to support TMDL development and reporting requirements.
- LSPC can be linked to the Tongue River Reservoir CE-QUAL-W2 model (see Section 2.5).

2.5 CE-QUAL-W2 Overview

LSPC simulates lakes and reservoirs, but only as 1-dimensional, completely mixed systems. This is sufficient for the simulation of major cations, as geochemical analysis with MINTEQ suggests that losses to mineralization and settling of cations in the reservoir are not significant. However, a more complex reservoir model was needed to simulate nutrients, eutrophication processes, and reservoir stratification. The U.S. Army Corps of Engineers CE-QUAL-W2 (W2) model was selected as the receiving water model for simulating nutrients in the Tongue River Reservoir. W2 is a two-dimensional, longitudinal/vertical (laterally averaged), hydrodynamic water quality model (Cole and Wells, 2003). The model is applicable to lakes, rivers, and estuaries that do not exhibit significant lateral variability in water quality conditions. It allows application to multiple branches for geometrically complex waterbodies with variable grid spacing, time variable boundary conditions, and multiple inflows and outflows from point/nonpoint sources and precipitation.

Advantages to choosing W2 for the Tongue River Reservoir modeling application include the following:

- W2 is able to address the pollutants of concern in the reservoir (e.g., phosphorus, nitrogen, dissolved oxygen, and chlorophyll *a*).
- W2 is appropriate for a long and narrow reservoir with spatially varying depths.
- W2 is able to provide output from upstream to downstream in the reservoir and at depth.
- W2 has been successfully linked in previous applications to LSPC.
- Simpler receiving water models would be limited in their ability to address the characteristics of the reservoir (long, narrow, and deep).
- Simpler receiving water models would also prove inadequate to support a more detailed analysis should additional data become available.
- W2 is capable of simulating cause-and-effect relationship between loading and reservoir response.

The two major components of the W2 model include hydrodynamics and water quality kinetics. Both of these components are coupled (i.e. the hydrodynamic output is used to drive the water quality at every time step). This makes it very efficient to execute model runs. The hydrodynamic portion of the model predicts water surface elevations, velocities, and temperature. The W2 model uses the ULTIMATE - QUICKEST numerical scheme for advection – dispersion computation. The ULTIMATE – QUICKEST numerical scheme is a third order finite difference scheme. This method reduces the numerical diffusion in the vertical direction to a minimum. In areas of high gradients this scheme reduces undershoots and overshoots which may produce small negative concentrations. The water quality portion of W2 can simulate the constituents required for the Tongue River Reservoir, including dissolved oxygen (DO), nutrients, and phytoplankton interactions.

2.6 Model Linkage

As described in Section 2.4, the LSPC model was adequate for simulating watershed and in-stream processes for all of the pollutants of concern in the Tongue River watershed. LSPC's lake modeling features (i.e., simple, 1-dimensional vertically mixed reservoir model) were also adequate for modeling salinity and SAR. Therefore, LSPC was used to model salinity and SAR for the entire Tongue River watershed, including the Tongue River Reservoir.

The LSPC lake modeling processes were not adequate for modeling the complex interactions of nutrients in the Tongue River Reservoir. Therefore, the CE-QUAL-W2 model was employed to provide a more robust analysis. LSPC was still used to model total nitrogen and total phosphorus loads coming into the Tongue River Reservoir from the upstream watershed (referred to as the "Upper" Tongue River watershed). Loads generated by LSPC were simply input to the W2 model as the upstream boundary condition. Nutrients were not assessed downstream of the Tongue River Reservoir (herein referred to as the "Lower" Tongue River watershed).

3.0 LSPC MODEL SETUP

As described previously, two models have been setup to simulate the Tongue River watershed (i.e., LSPC and CE-QUAL-W2). This section describes the setup and calibration for the LSPC model. Setup and calibration for the Tongue River Reservoir model is described in Section 6.0.

3.1 Modeled Parameters

As describe in Section 2.0, the pollutants of concern in the Tongue River watershed are salinity, sodium adsorption ratio (SAR), and nutrients. SAR is the ratio of sodium (Na) to calcium (Ca) and magnesium (Mg) in a waterbody, and therefore LSPC was setup to model calcium, magnesium, and sodium concentrations.

Salinity (measured as specific conductance [SC] or electrical conductivity [EC]) is an indirect measure of the total dissolved solids in a waterbody. EC is typically expressed in microsiemens per cm (µS/cm) at standard temperature and is approximately equivalent to the sum of *either* anions or cations in solution (expressed as milliequivalents or meq) times 100 (APHA, 1992). Assuming that Na, Mg, and Ca are the dominant cations in the waterbody (ignoring K), then EC ÷ 100 is approximately equal to the sum of {Na + Ca + Mg} in milliequivalents. More generally,

$$EC\,(\mu S/cm) \approx \left(Na + Ca + Mg + Z\right)\cdot 100\,,$$

Where *Z* is the sum of other cations (predominantly K), and all cation concentrations are expressed on a meq basis.

Because of the "Z" component, EC cannot be approximated from only the sum of individual Ca, Mg, and Na cations (as milliequivalents). Also, the activity of individual cations varies with temperature. Therefore, an alternative method was developed to calculate EC using regression equations based on the observed relationship between EC and the sum of the Na, Ca, and Mg concentrations in milliequivalents. To evaluate this approach, cation concentrations and electrical conductivity was evaluated at USGS station 06306300 (Tongue River at the State Line).

Figure 3-1 presents the cation observations in the Tongue River at the State Line (November 1985 to September 2006). Potassium (K) is always present at low concentrations while calcium (Ca) and magnesium (Mg) are present at the highest concentrations. Also, Ca and Mg are typically near the same value. The low and relatively constant K concentrations suggest this cation can be ignored in the calculation of EC. The general annual trend is observed in this figure as salt concentrations reach a minimum during the spring snowmelt period.

Figure 3-2 presents the linear regression of EC against the sum of the 3 major cations (Na, Ca, and Mg, in milliequivalents per liter) at USGS Gage 06306300. The regression provides a strong linear fit (R^2 = 98.3) and shows that an accurate prediction of observed EC can be obtained by using only the 3 major cations. Thus, reconstruction of EC from Ca, Mg, and Na should be sufficient for the LSPC/W2 applications.

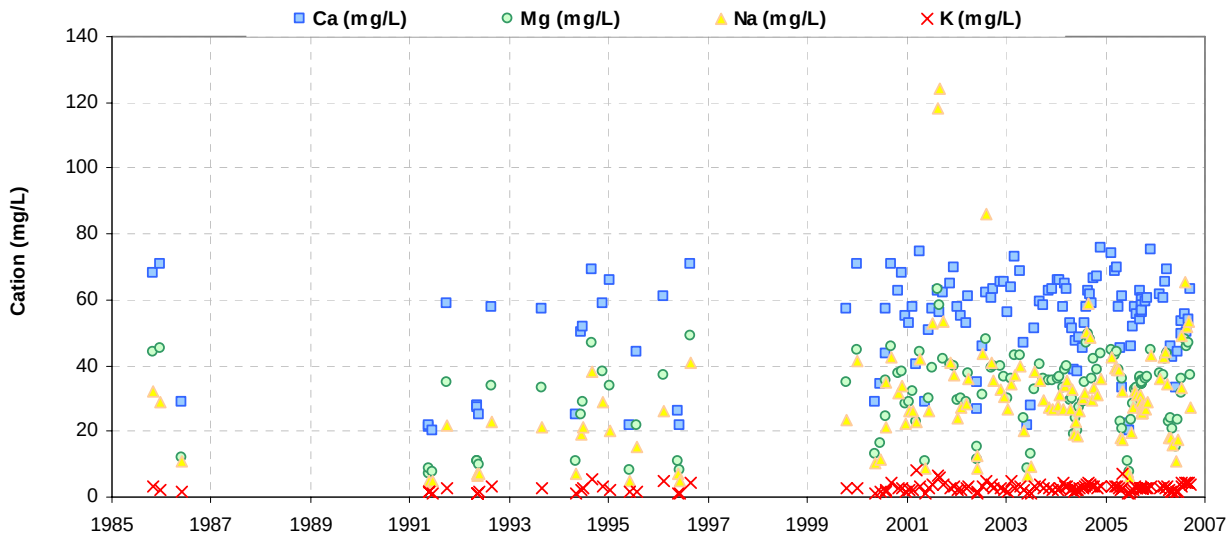


Figure 3-1. Observed cations in the Tongue River at the State Line (USGS Gage 06306300). All data through September 30, 2006 are shown.

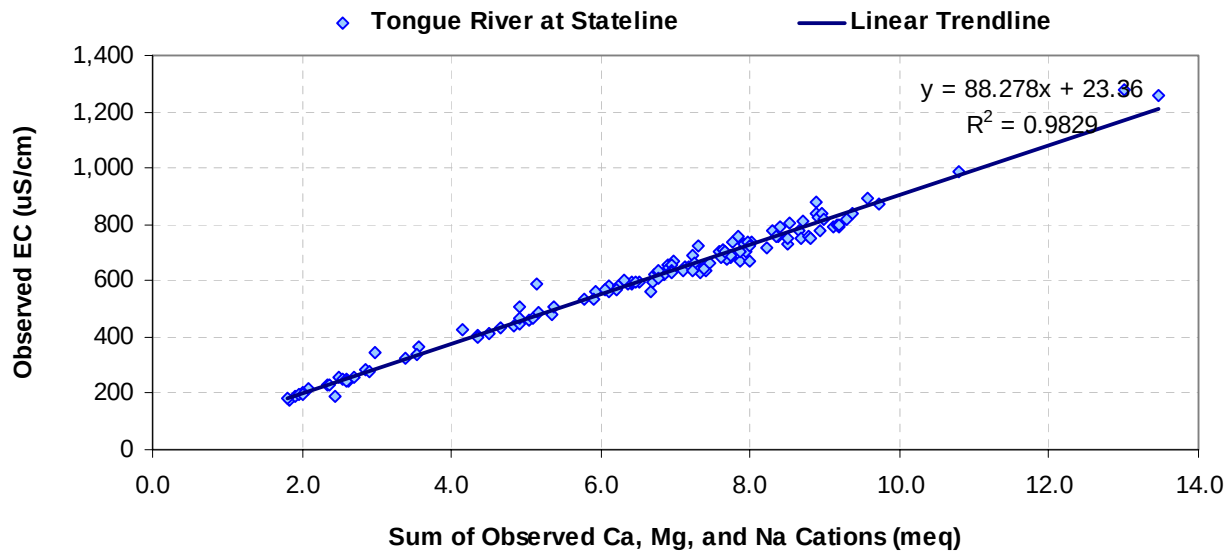


Figure 3-2. Linear regression of observed cations to observed EC at USGS gage 06306300 (Tongue River at the State Line).

Because of the previously discussed relationships for deriving EC from cation concentrations, there was no need to directly model EC or TDS as separate state variables. Salinity (expressed as specific conductance in µS/cm) was simply computed using the observed relationship between EC and the sum of the Na, Ca, and Mg cations. The relationships at selected USGS gages are reported in Table 3-1. As evidenced by the R^2 values, the regressions provide a good fit, indicating that this approximation is satisfactory. The advantage of this approach is two-fold. First, this method reduces the total number of modeled state variables, which reduces model run time and simplifies model structure. Second, this method insures that salinity specifications are consistent with sodium, magnesium, calcium, and SAR values.

Nutrients in the LSPC were modeled as total nitrogen and total phosphorus. Too few calibration data (i.e., stream, precipitation, interflow, groundwater, and point source concentrations) were available to model nutrient species (e.g., nitrate, nitrite, ammonia, and orthophosphorus).

Table 3-1. Relationships between observed EC and the sum of cations (Ca, Mg, and Na in milliequivalents) at selected USGS gages in the Tongue River watershed.

USGS Station Name	USGS Station ID	Modeling Subbasin	Relationship	R^2
Tongue River near Dayton, Wyoming	06298000	3090	EC (µS/cm) = 84.704 (Ca + Mg + Na) + 24.105	0.79
Tongue River at the Montana-Wyoming State Line, Montana	06306300	3006	EC (µS/cm) = 88.278 (Ca + Mg + Na) + 23.36	0.98
Prairie Dog Creek near Acme, Wyoming	06306250	3007	EC (µS/cm) = 73.704 (Ca + Mg + Na) + 174.8	0.98
Goose Creek near Acme, Wyoming	06305700	3022	EC (µS/cm) = 79.405 (Ca + Mg + Na) + 59.692	0.98
Tongue River at the Tongue River Reservoir Dam near Decker, Montana	06307500	3112	EC (µS/cm) = 83.923 (Ca + Mg + Na) + 49.005	0.97
Tongue River at the Birney Day School Bridge, Montana	06307616	3088	EC (µS/cm) = 83.293 (Ca + Mg + Na) + 48.478	0.91
Tongue River near the Brandenberg Bridge, Montana	06307830	1047	EC (µS/cm) = 83.895 (Ca + Mg + Na) + 60.936	0.97
Tongue River at Miles City, Montana	06308500	1002	EC (µS/cm) = 83.096 (Ca + Mg + Na) + 69.933	0.90
Hanging Woman Creek near Birney, Montana	06307600	1095	EC (µS/cm) = 78.801 (Ca + Mg + Na) + 172.9	0.95
Otter Creek at Ashland, Montana	06307740	1059	EC (µS/cm) = 72.625 (Ca + Mg + Na) + 374.36	0.90
Pumpkin Creek near Miles City, Montana	06308400	1007	EC (µS/cm) = 86.408 (Ca + Mg + Na) + 111.35	0.99

3.2 Watershed Segmentation

LSPC was configured to simulate the Tongue River watershed as a series of hydrologically connected subwatersheds. The spatial subdivision of the watersheds allowed for a more refined representation of pollutant sources, and a more realistic description of hydrologic factors. Subwatershed delineation was primarily based on Montana DNRC's Draft 6th Code HUCs, but also took into consideration spatial variation in sources, hydrology, and jurisdictional boundaries (DNRC, 2006a). Output from LSPC is for the most downstream point of each subwatershed (sometimes referred to as the "pour point"). Subwatersheds were therefore delineated to obtain modeling output at key flow or water quality stations and at political boundaries (e.g., the Montana/Wyoming state line and at the upstream and downstream boundaries of the Northern Cheyenne Reservation).

Because of the Tongue River Reservoir, the subwatersheds were classified into three distinct regions:

- *Upper Tongue River* – The portion of the watershed upstream of the Tongue River Reservoir (i.e., headwaters to the confluence with the reservoir). Numbered as LSPC subbasins 3001 to 3108.
- *Lower Tongue River* – The portion of the watershed located downstream of the Tongue River Reservoir (i.e., Tongue River Reservoir Dam to the mouth). Numbered as LSPC subbasins 1001 to 1113.
- *Tongue River Reservoir* – The portion of the watershed draining directly to the Tongue River Reservoir. Numbered as LSPC subbasin 3000.

Relatively large subwatersheds were specified in the model due to the homogenous land use/land cover characteristics, and the fact that fewer subwatersheds reduced computational time. Smaller subwatersheds were delineated in the Bighorn Mountains to reduce the elevation change per subwatershed (which impacts the snow simulation process). Each of the subwatersheds was modeled as a single stream segment that was assumed to be a completely mixed, one-dimensional segment with a trapezoidal cross-section (see Section 3.3). The final subwatersheds and primary streams for the LSPC model are shown in Figure 3-3 and Figure 3-4, as are the location of cities and political boundaries.

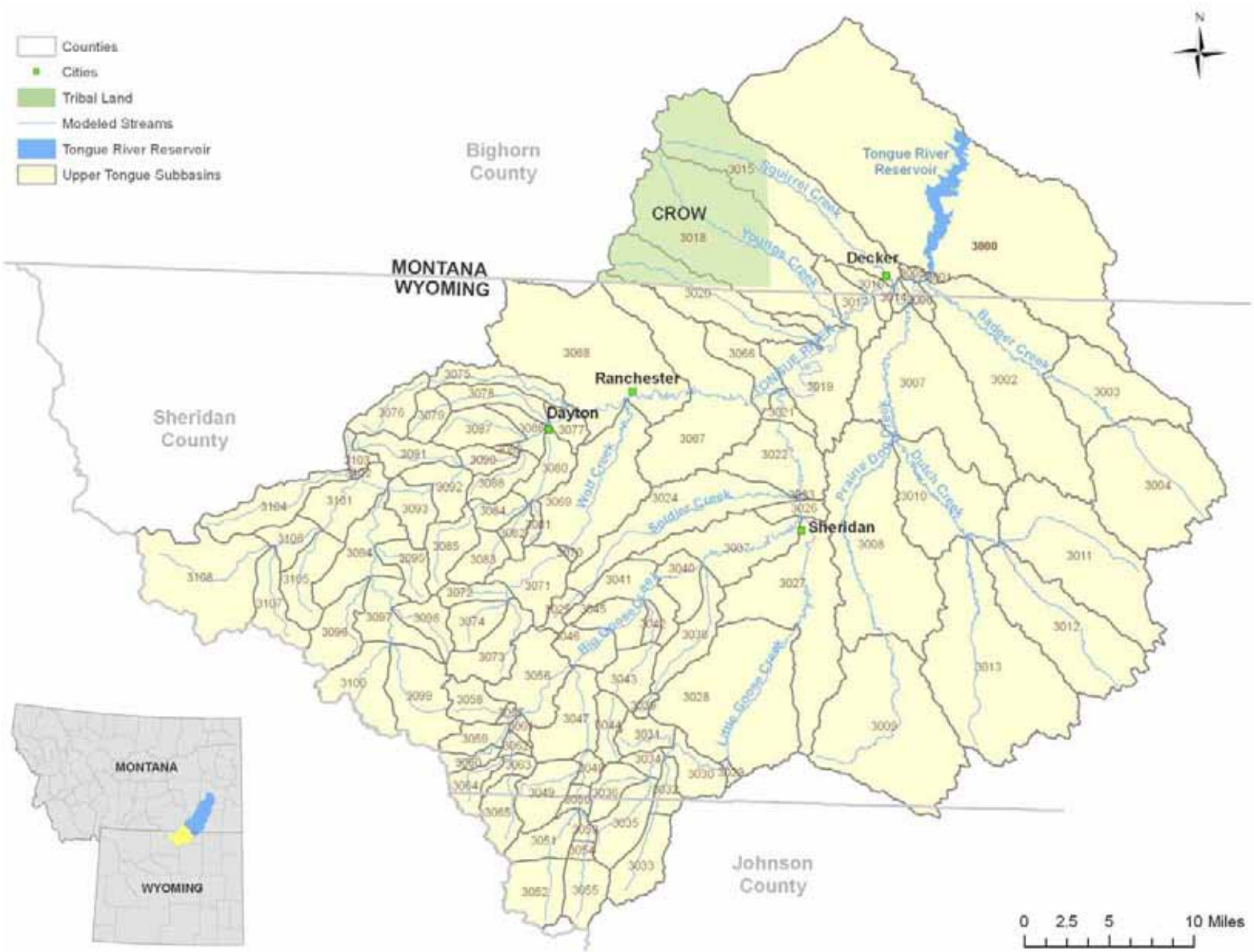


Figure 3-3. Modeling subwatersheds for the Upper Tongue River watershed and Tongue River Reservoir.

Figure 3-4. Modeling subwatersheds for the lower Tongue River watershed.

3.3 Waterbody Representation

LSPC was configured to model both streams and reservoirs in the Tongue River watershed. Section 3.3.1 discusses the information used to model the stream segments, and Section 3.3.2 discusses the setup of the Tongue River Reservoir. High altitude reservoirs located in the Bighorn Mountains are further discussed in Section 3.9.

3.3.1 Streams

Each subwatershed in LSPC was represented with a single stream assumed to be a completely mixed, one-dimensional segment with a trapezoidal cross-section (Figure 3-5). Input parameters for the reaches include initial depth, length, depth, width, slope, Manning's roughness coefficient, and coefficients to describe the shape of the stream channel. The methodology for determining these parameters for the Tongue River watershed is described below:

- IDEPTH (Reach Initial Water Depth) – Assumed to be half the bankfull depth.
- LENGTH (Reach Length) – Determined from the National Hydrography Dataset (NHD) medium resolution stream reach network (available online at http://nhd.usgs.gov/).
- DEPTH (Reach Bankfull Depth) – Reach bankfull depth values were estimated based on the equation 1 (below). The coefficients for "a" and "b" were determined based on cross sections measured by USGS at nine sites in the Tongue River watershed (USGS, 2004).

$$eq.1: BankfullDepth(ft) = a \times (WatershedArea)^b$$

- WIDTH (Reach Bankfull Width) – Reach bankfull width values were estimated based on equation 2. The coefficients for "c" and "d" were determined based on cross sections measured by USGS at nine sites in the Tongue River watershed (USGS, 2004).

$$eq.2: BankfullWidth(ft) = c \times (WatershedArea)^d$$

- SLOPE (Reach Slope) – Calculated based on elevation data from the USGS 30-meter National Elevation Dataset (USGS, 2002).
- MANN (Manning's Roughness Coefficient for the Stream Channel) – Estimated coefficient of 0.02 was applied to each representative stream reach based on typical literature values (Schwab et al., 1993)
- R1 (Reach ratio of Bottom Width to Bankfull Width) – Estimated from USGS, 2004.
- R2 (Reach Side Slope of Floodplain) – Estimated from USGS, 2004.
- W1 (Reach Floodplain Width Factor) – Estimated from USGS, 2004.

Reach dimensions for the Tongue River LSPC model are included in the LSPC model input file, which is available upon request.

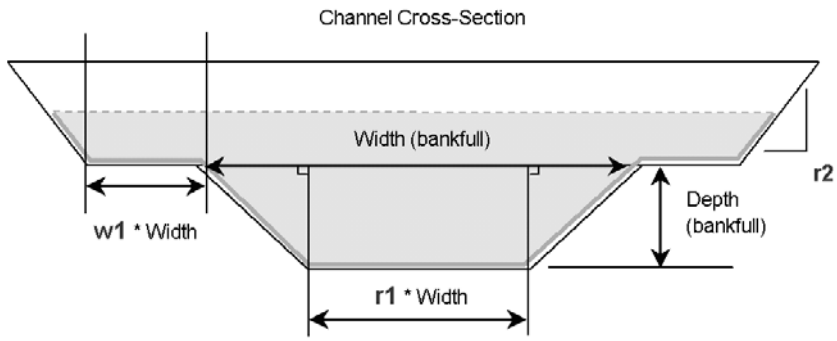


Figure 3-5. Stream channel representation in the LSPC model.

3.3.2 Tongue River Reservoir

As discussed in Section 2.2, major cations (and thus salinity and SAR) were modeled in the Tongue River Reservoir using the lake/reservoir features of LSPC. Nutrients were modeled in the reservoir using the CE-QUAL-W2 program, which is discussed in Section 6.

The Tongue River Reservoir (TRR) was originally completed in 1940 by constructing an earthen dam on the Tongue River north of Decker, Montana (DNRC, 2004). A 1996–1999 rehabilitation project increased the reservoir's active storage capacity from approximately 68,000 acre-feet of water to 79,000 acre-feet of water. An additional spillway was also added during the rehabilitation project so that the maximum potential discharge from the reservoir is now approximately 4,000 cfs. The average depth of the reservoir is 6.1 meters (20 feet) with a length of approximately 12.5 kilometers (7.8 miles) (DNRC, 2005). The average volume of water in the reservoir between 1999 and 2006 was 40,432 acre-feet and the median residence time during this period was approximately 88 days (with longer residence times during the fall, winter, and spring and shorter residence times during the summer) (DNRC, 2006).

Tongue River Reservoir Primary Spillway and Inlet Release Structure
(Photo by Tetra Tech, Inc.)

The primary spillway for the Tongue River Reservoir is a concrete labyrinth spillway (weirwall spillway) with a crest of 3,428.4 feet MSL, corresponding to a storage volume of 79,071 acre-feet of water in the reservoir. The primary spillway was re-constructed in the late 1990's and the first full year of normal operation was 2000 (Personal Communications, Kevin Smith, Montana DNRC, June 14, 2004). Very little water has gone over the spillway since the re-construction. The reservoir also has an emergency spillway with a crest at 3,431.5 feet, or when the reservoir volume is at 91,107 acre-feet of water.

In addition to the primary and emergency spillways, the reservoir has two inlet structures. The first was built in 1940 and the second in 1999 (Personal Communications, Kevin Smith, Montana DNRC, June 14, 2004). Each structure has inlets at two invert elevations (3,375 feet and 3,390 feet) with grills on all sides

and on top. Water flow through these grills is controlled through a central system located within the earthen dam. There is no way to close one grate versus another and water intake through the individual grills is therefore not regulated. At its fullest, the reservoir is drafting water through all grill inlets, the emergency spillway, and the primary spillway. However, normal operation is to draft water over the primary spillway and through the inlets. By the end of summer, water is typically only discharging through the two inlet towers. The reservoir is almost never drawn down below an elevation of 3,404 feet (Personal Communications, Kevin Smith, Montana DNRC, June 14, 2004).

The Tongue River Reservoir was set up in the LSPC model based on data provide by Montana DNRC. The reservoir was not explicitly modeled as a reach segment with fixed dimensions, but was rather simulated with the use of a stage-volume relationship (referred to as an F-Table in LSPC). DNRC provided monthly observed stage and volume data for the time period between 1960 to present (DNRC, 2006). The data between 2000 and 2006 were used to create a stage-volume relationship for the post-construction conditions in the Tongue River Reservoir. Pre-reconstruction conditions were not modeled, which as described in Section 4, provided a limitation to the time period that could be used to calibrate the mainstem Tongue River downstream of the Tongue River Reservoir. Reservoir surface area was calculated using a GIS and CAD files of reservoir bathymetry (also provided by Montana DNRC). The primary overflow spillway height was set at 54.4 feet (elevation of 3,428.4 feet), and the intake structure for managed reservoir releases was set at 53.5 feet (elevation of 3375.0 feet). Figure 3-6 shows the stage-volume-area relationship developed for the Tongue River Reservoir.

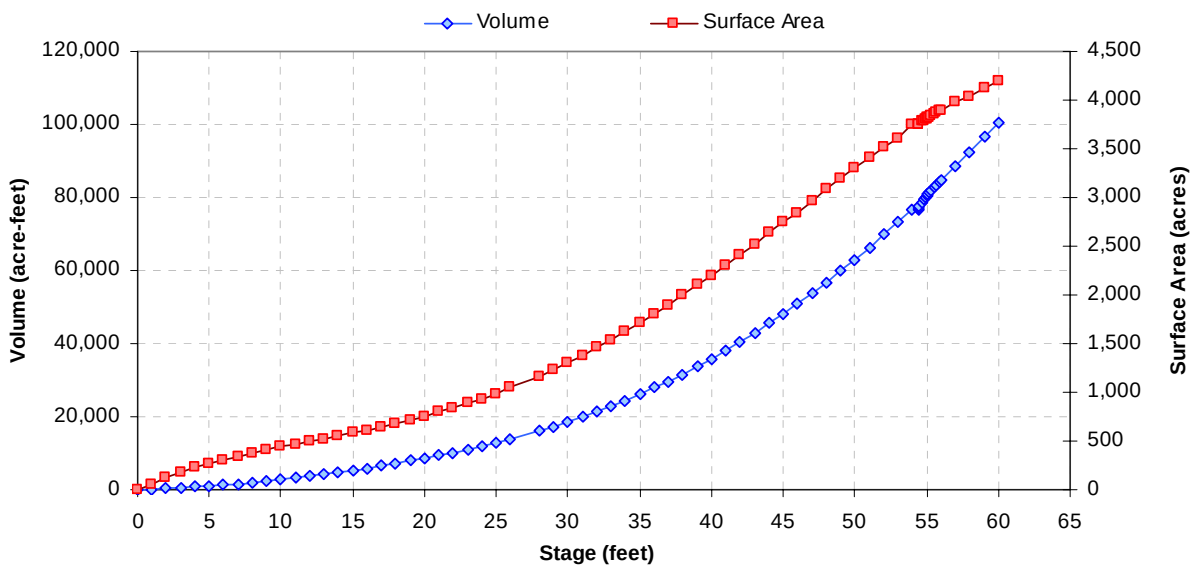


Figure 3-6. Stage-volume-area relationships for the Tongue River Reservoir.

The measured stage and volume data provided the data needed to properly size the Tongue River Reservoir in the model. However, the DNRC data did not provide information about reservoir discharge. Releases from the Tongue River Reservoir are managed, and therefore a simple stage-discharge relationship could not be developed. Water is stored throughout the winter and spring seasons and released in the spring and summer to provide water to downstream irrigators. The USGS gage located in the Tongue River downstream of the Tongue River Reservoir (USGS Gage 06307500) measures the discharge from the reservoir, but it does not differentiate between “managed” water (i.e., water regulated through the two inlet structures) and water that flows over the spillway.

Daily discharge data at the USGS gage downstream of the Tongue River Reservoir Dam were assessed to determine the reservoir releases due to management versus overflow over the spillways. Flow percentiles were calculated for the daily discharge data from October 1, 2000 to September 30, 2006. Based on the calculated flow percentiles, five different model sensitivity runs were conducted where flows less than the 60, 70, 80, 90, and 95th percentiles were defined as "management" (i.e., releases through the inlet structure). The reservoir management time series was withdrawn from the reservoir and input into the next downstream modeling subbasin – 1112. The remaining water volume was allowed to naturally accumulate, evaporate, and discharge over the reservoir spillway. Figure 3-7 shows the results of the five model runs, and the impact the various management scenarios have on reservoir stage.

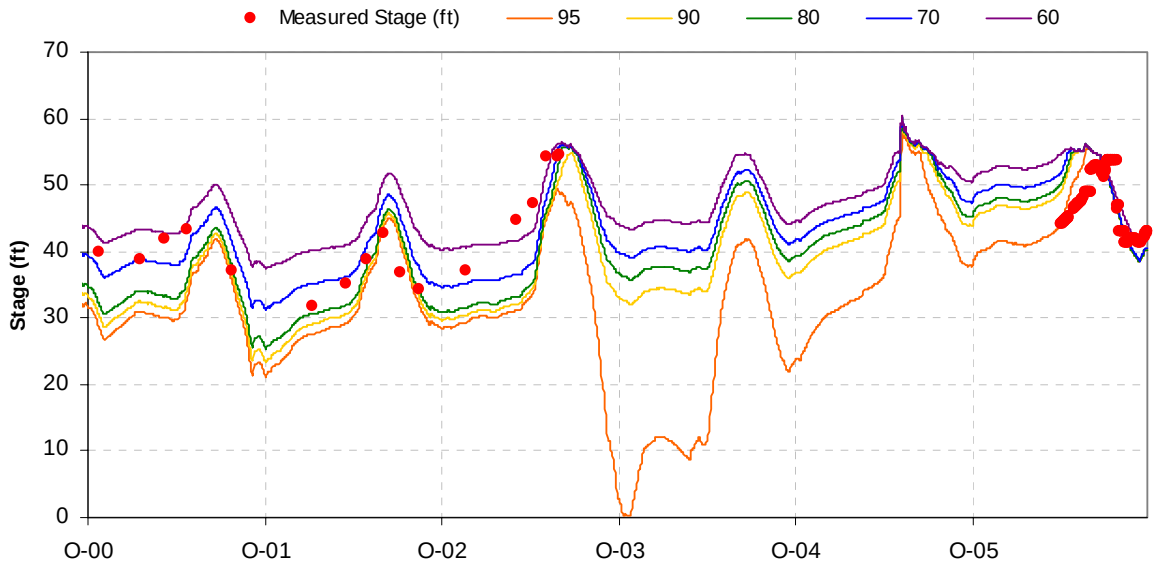


Figure 3-7. Sensitivity analysis of five model runs for water released from the Tongue River Reservoir.

Based on the sensitivity analysis, it was assumed that flows occurring below the 90th percentile were due to managed releases from the reservoir. The time series of flows for USGS Gage 06307500 below the 90th percentile were input into the LSPC model as a managed discharge or "withdrawal" from the reservoir that is reintroduced into the downstream mainstem Tongue River in LSPC subbasin 1112. The remainder of the water in the reservoir is allowed to overflow as needed. Discharge from the spillway was also determined in the F-Table based on the stage of the reservoir and a spillway width of 100 feet.

This method for modeling discharge from the Tongue River Reservoir has one primary advantage – it allows for potential scenarios where reservoir management can be altered or removed. However, as seen in Figure 3-7, this approach does introduce some error into the model. Without observed data from the reservoir outlets, it is impossible to determine what volume of water is manually released versus discharged over the spillway. As seen in Section 4, this had an impact on the main stem Tongue River hydrology and water chemistry calibration downstream of the Tongue River Reservoir Dam.

3.4 Weather Data

The LSPC model is driven by precipitation and other climatologic data (e.g., temperature, cloud cover, wind speed). As a result, meteorological data are a critical component of the watershed modeling effort. Appropriate representation of precipitation, wind movement, solar radiation, potential evapotranspiration, cloud cover, temperature, and dew point are required to develop a valid model.

A number of sources were consulted to determine the availability of weather data – the National Climatic Data Center (NCDC), Natural Resources Conservation Service (NRCS), U.S. Forest Service, and the Bureau of Land Management. Ideal weather stations had daily (or more frequent) data collected recently (i.e., 1980 to present), were located within the watershed boundary, and recorded multiple parameters in addition to precipitation. Appropriate data were determined to be available from 10 NCDC stations and 6 NRCS SNOwpack TELemetry (SNOTEL) stations. Only stations with daily rainfall totals were used in the LSPC model, as NCDC personnel indicated that daily stations were more complete and had more thorough quality control than hourly stations (Personal Communications, NOAA, December 13, 2006). Data from four hourly rainfall stations were used for distribution only, to disaggregate the daily rainfall totals to hourly. Precipitation data were obtained from the daily stations, and weather gages were assigned to each subwatershed using the Thiessen polygon method (Theissen, 1911). At the time of the model setup, weather data were available through September 30, 2006. Additional data may be added to the model as needed.

The weather stations used in the modeling are summarized in Table 3-2 and their locations are shown in Figure 3-8. Figure 3-8 illustrates that large areas must be simulated based on data from single weather stations. In fact, the average area per weather station is 338 square miles. This relatively sparse coverage of weather stations posed one of the most significant limitations of the modeling effort. Substantial variability in meteorology is known to be present across the Tongue River watershed due to its size and topography. Perhaps even more importantly, the timing of individual storms can also be significantly different throughout the region, especially during convective summer thunderstorms. As explained in Section 5.7.1, the extrapolation of precipitation from a limited number of points is believed to be one of the largest sources of model error. Nevertheless, the relatively higher density and high quality of SNOTEL gages for precipitation and temperature in the mountain regions significantly improved the high-altitude snowfall/snowmelt representation, as described in Section 4.1.1. The mountain region is responsible for about 63 percent of all the water in the Tongue River Watershed.

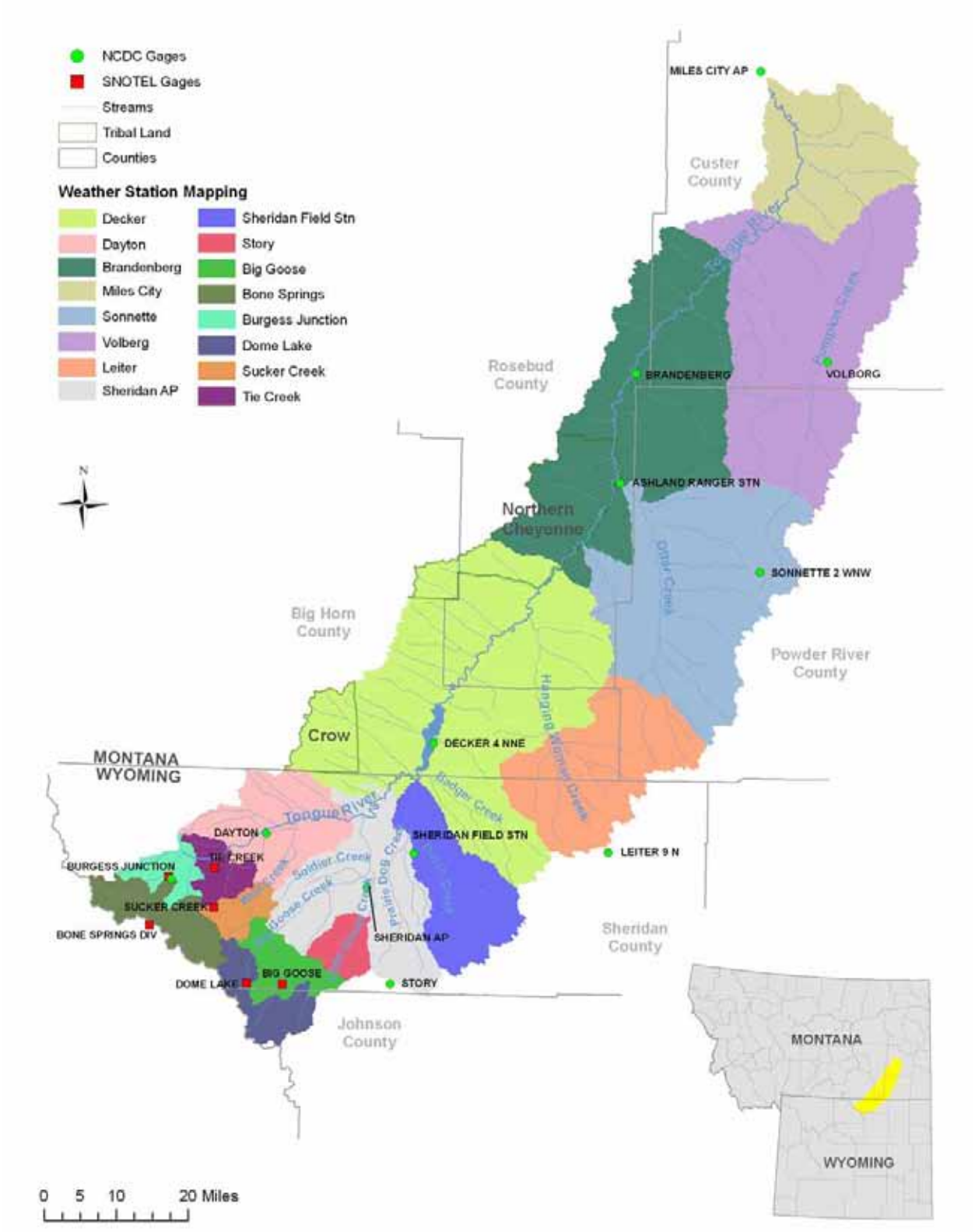


Figure 3-8. Weather station mapping for the Tongue River watershed.

Table 3-2. Weather stations used in the Tongue River watershed modeling.

Station Name	Station ID	Agency [a]	Data Type [b]	Temperature Elevation (ft)	Available Data
Big Goose	07E32S	NRCS	SNOTEL	7990	Precip, Min/Max Temp
Bone Springs	07E18S	NRCS	SNOTEL	9350	Precip, Min/Max Temp
Burgess Junction	07E33S	NRCS	SNOTEL	7880	Precip, Min/Max Temp
Dome Lake	07E34S	NRCS	SNOTEL	8880	Precip, Min/Max Temp
Sucker Creek	07E12S	NRCS	SNOTEL	8880	Precip, Min/Max Temp
Tie Creek	07E39S	NRCS	SNOTEL	6870	Precip, Min/Max Temp
Brandenberg	241084	NCDC	Daily	2770	Precip, Min/Max Temp
Leiter 9 N	485506	NCDC	Daily	4160	Precip, Min/Max Temp
Miles City AP	245690	NCDC	Daily	2624	Precip, Min/Max Temp
Sheridan AP	488155	NCDC	Daily	3945	Precip, Min/Max Temp
Dayton	482399	NCDC	Daily	3945[c]	Precip
Sheridan Field Station	488160	NCDC	Daily	3750	Precip, Min/Max Temp, Evap
Decker 4 NNE	242266	NCDC	Daily	3750[c]	Precip
Sonnette 2 WNW	247740	NCDC	Daily	3900	Precip, Min/Max Temp
Story	488626	NCDC	Daily	5083	Precip, Min/Max Temp
Volborg	248607	NCDC	Daily	5083[c]	Precip
Sheridan AP	24029	NCDC	Hourly	3945	Dewpoint, Wind, Cloud/Solar
Ashland Ranger Station	MT0330	NCDC	Hourly	n/a	Precip
Sheridan AP	WY8155	NCDC	Hourly	n/a	Precip
Story	WY8626	NCDC	Hourly	n/a	Precip

[a] NRCS is the National Resource Conservation Service; NCDC is the National Climatic Data Center
[b] SNOTEL are SNOwpack TELemetry stations (Snow Water Equivalent data are also available, but used for calibration rather than input)
[c] Temperature data was either unavailable or largely missing. The nearest representative surrogate was used (listed above entry).

3.4.1 Patching and Disaggregating Rainfall Data

The Tongue River LSPC models were run at an hourly time step to best capture the impact of individual storm events. However, as shown in Figure 3-8 and Table 3-2, many of the precipitation stations only recorded daily precipitation. In addition, many of the stations contained various intervals of accumulated, missing, or deleted data. Missing or deleted intervals are periods over which either the gage malfunctions or the data records were somehow lost. Accumulated intervals represent cumulative precipitation over several hours or days, but the exact temporal distribution of the data is unknown. The normal-ratio method (Dunn & Leopold, 1978) was used to compute accumulated, missing, and deleted data intervals. The normal-ratio was also used to disaggregate the daily rainfall totals to hourly records based on the hourly rainfall distributions at nearby gages.

The normal-ratio method estimates a missing rainfall value using a weighted average from surrounding stations with similar rainfall patterns according to the relationship:

$$P_A = \frac{1}{n}\left(\sum_{i=1}^{n} \frac{N_A}{N_i} P_i\right)$$

where P_A is the missing precipitation value at station A, n is the number of surrounding stations with valid data at the same specific point in time, N_A is the long term average precipitation at station A, N_i is the long term average precipitation at nearby station i, and P_i is the observed precipitation at nearby station i. For each missing data record at station A, n consists of only the surrounding stations with valid data; therefore, for each record, n varies from 1 to the maximum number of surrounding stations. When no precipitation is available at the surrounding stations, zero precipitation is assumed at station A. The US Weather Bureau has a long established practice of using the long-term average rainfall as the precipitation normal. Since the normal ratio considers the long-term average rainfall as the weighting factor, this method is adaptable to regions where there is large orographic variation in precipitation. Figure 3-9 below shows the 23-water-year annual rainfall totals at a representative station (Decker, Montana).

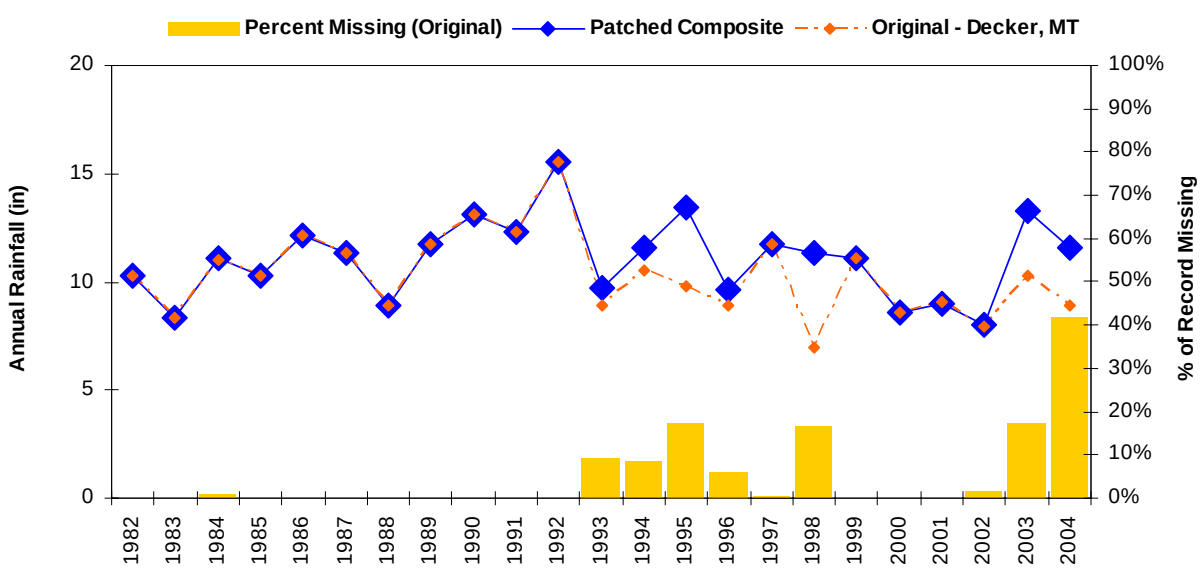


Figure 3-9. Twenty-three years of annual rainfall for weather station 242266 (Decker, Montana).

3.4.2 Potential Evapotranspiration

Evapotranspiration represents the sum of direct evaporation of surface and soil moisture and transpiration of water by plants. In the Tongue River watershed, evapotranspiration is a key component of the hydrologic balance. As a weather input, LSPC requires potential evapotranspiration (PEVT), which is the maximum naturally achievable amount at any given moment.

Although there are some tests available for actually measuring evapotranspiration in the field, most practitioners estimate evapotranspiration using empirical formulations that are a function of other related (and more commonly observed) weather data. Three widely used methods are the Hamon method (1961), the Jensen-Haise method (1963) and the Penman Pan-Evaporation method (1948). The Penman method computes evaporation as a function of temperature, solar radiation, dew point or relative humidity, and wind movement. The other two methods, Hamon and Jensen-Haise, are simplified empirical representations that require fewer observed datasets to compute.

The various potential evapotranspiration methods were assessed in the Tongue River watershed. Based on test of each method, the Penman method predicted evapotranspiration closest to measured data at Sheridan Field Station in Wyoming. Therefore, the Penman equation was used to calculate potential evapotranspiration for the entire Tongue River watershed.

Because PEVT is a key component of the hydrologic balance, it is also a potential source of model uncertainty and error. Few measured PEVT data were available for the Tongue River watershed, and few data were available for calculating PEVT using the previously described methods. Furthermore, the various methods for calculating PEVT give differing results. As explained in Section 5.7.1, the extrapolation of PEVT from a limited number of weather stations, combined with the varying methods for calculating PEVT, is believed to be one of the largest sources of model error.

3.5 Land Cover Representation

LSPC requires a basis for distributing hydrologic and pollutant loading parameters. This is necessary to appropriately represent hydrologic variability throughout each watershed, which is influenced by land surface and subsurface characteristics. It is also necessary to represent variability in pollutant loading, which is highly correlated to soil characteristics and land practices.

Land cover data were obtained from the 2001 National Land Cover Database (NLCD). The NLCD GIS coverage was derived from satellite imagery obtained around 2001 (i.e., late 1990s to 2003) and is the most current and detailed land cover data known to be available at the time of this report (MRLC, 2007). Each 30 m by 30 m (98-foot by 98)-foot pixel contained within the satellite image is classified according to its reflective characteristics into 29 distinct land covers (see Homer et al., 2004). The NLCD land cover data for the Tongue River are shown in Figure 3-10, and data are summarized in Table 3-3.

Table 3-3. NLCD land cover in the Tongue River watershed.

Land Cover	Area		Percent of Watershed
	Acres	Square Miles	
Grassland	1,465,447	2,290	42.39%
Shrubland	1,132,203	1,769	32.75%
Evergreen Forest	645,990	1,009	18.69%
Woody Wetland	67,365	105	1.95%
Pasture and Hay	41,899	65	1.21%
Cropland	34,899	55	1.01%
Emergent Wetland	23,897	37	0.69%
Open Space, Developed	16,694	26	0.48%
Barren	10,240	16	0.30%
Deciduous Forest	8,407	13	0.24%
Low Intensity Development	5,118	8	0.15%
Open Water	2,763	4	0.08%
Medium Intensity Development	1,733	3	0.05%
High Intensity Development	375	1	0.01%
Total	3,457,031	5,402	100.00%

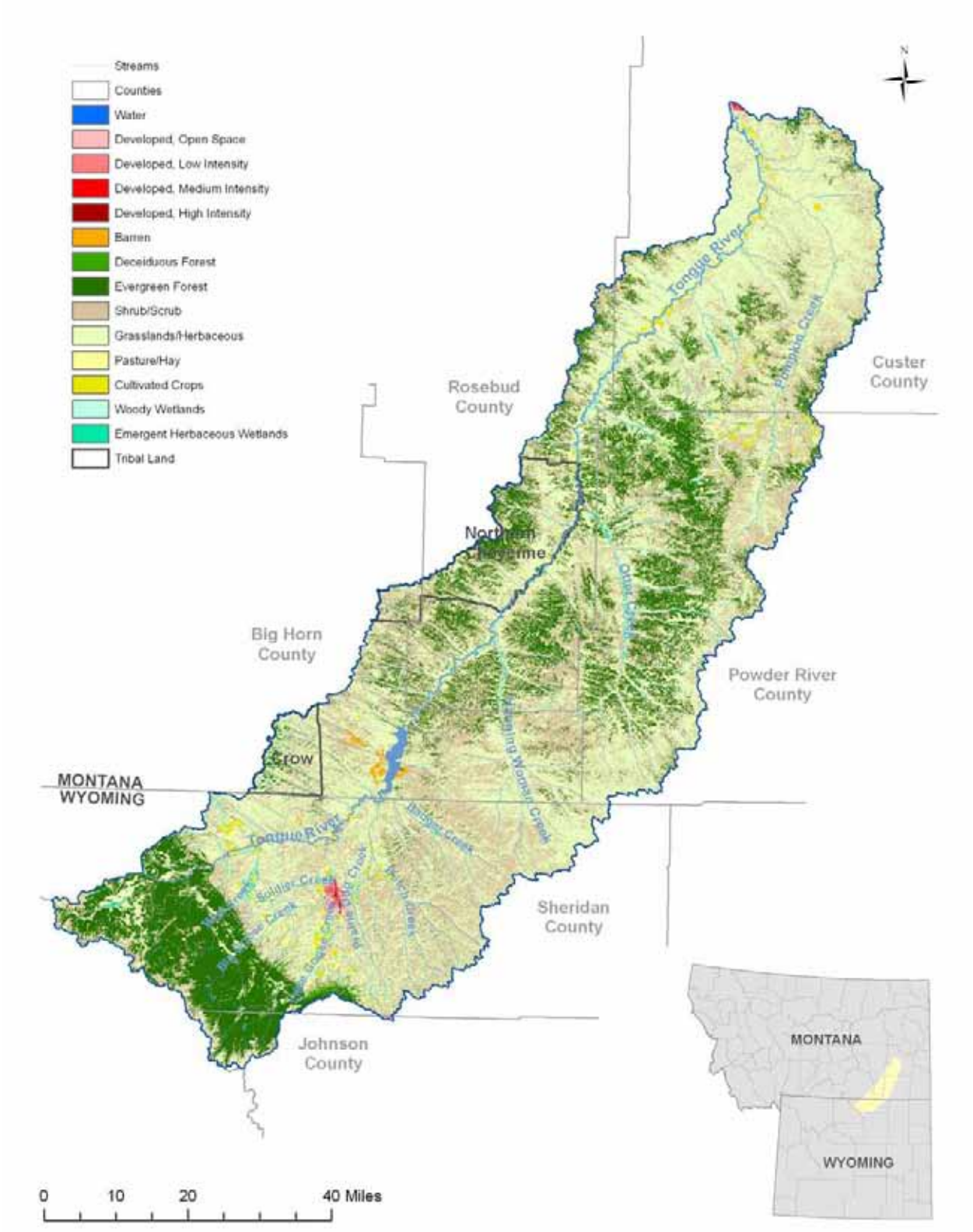


Figure 3-10. NLCD land cover in the Tongue River watershed.

It was important to evaluate the effects of impervious and irrigated land uses. These land uses are not explicitly identified in the NLCD land cover, although certain NLCD classes (such as "commercial/industrial/transportation") provide insight into the specific type of land use and cover (i.e., impervious cover). The following sections describe the modifications made to the NLCD land cover data to represent the impervious and irrigated land uses.

3.5.1 Impervious Lands

LSPC requires that land cover categories be divided into separate pervious and impervious land units for modeling. Separate model algorithms are then used to simulate major hydrologic and pollutant loading processes for both land units – PERLND and IMPLND (respectively), which are further discussed in Section 4.1. The percentage of impervious area for the four urban land use classes is shown in Table 3-4. Values were obtained from the NLCD definitions of impervious cover (Homer et al., 2004).

The percent of impervious land per NLCD land use class was modified during the initial calibration of the LSPC model, as the model is sensitive to the amount of impervious land in the watershed. Specifically, the LSPC model routes water from impervious surfaces directly to the stream segment, and thus requires as input the effective impervious area, rather than the total impervious area. This is typical for larger cities with storm sewer systems and high intensity development, but does not necessarily describe the land use classified by the NLCD data as "impervious surfaces" in the Tongue River watershed. It was assumed that runoff from land areas with a small amount of impervious surface (i.e., small area of developed open space and low intensity development) most likely flows on to adjacent pervious land areas where infiltration can occur prior to discharge into a stream segment. These NLCD land uses were set to 100 percent pervious surfaces. The medium and high intensity land use impervious areas were not modified from the NLCD default values.

Table 3-4. Percentage of impervious cover for developed land use classes.

NLCD Land Use	NLCD Land Use Code	% Pervious	% Impervious
Open Space (developed)	21	100	0
Low Intensity Development	22	100	0
Medium Intensity Development	23	35	65
High Intensity Development	24	10	90
Total		100	100

3.5.2 Irrigated Lands

The NLCD land use coverage does not explicitly identify irrigated land (although some land use classes, like cropland, can indicate the presence of irrigation). An analysis was conducted to specifically identity the amount and location of irrigated land in the Tongue River watershed. Two different methods were employed to identify irrigated land – one for irrigated land in Wyoming and another for irrigated land in Montana.

The Wyoming Water Development Commission conducted a detailed inventory and analysis of water use in the Tongue River watershed in Wyoming. As part of the inventory, aerial photos were obtained and used to identify irrigated land. Irrigated land was delineated into a GIS coverage, and verified with field surveys and interviews. Detailed information about the methodology used to identify irrigated land can be found in the Basin Plan Technical Memoranda, "Appendix C – Irrigated Lands Mapping and Water Rights Data," (WWDC, 2002e). A GIS coverage of irrigated land was obtained from the Powder/Tongue River Basin Plan website, which identified the following irrigated land use classes:

Full & Partial Supply Irrigation & Man-Induced	Man-Induced Beneficial Use from Seepage
Full & Partial Supply Mix of Irrigation	Non-Irrigated Lands enclosed by Irrigated
Full Supply & Man-Induced Beneficial Use	Partial Supply & Man-Induced Beneficial Use
Full Supply Irrigation	Partial Supply Irrigation
Full Supply Irrigation with Development	Partial Supply Irrigation with Development
Idle Lands	Side Tributary - Kick-outs or Ditches
Idle Lands with Development	Spreader Dike - holds water

For modeling purposes, it was assumed that only land identified as having full or partial supply irrigation actually receives supplemental water. The irrigated land was classified into two groups – full supply and partial supply irrigation. The Powder/Tongue Basin Plan defines these as described below (WWDC, 2002e):

- **Full supply irrigation –** Typically receives a full water supply.
- **Partial supply irrigation –** Typically receives a reduced water supply due to limited water availability or the inability to provide complete field coverage.

Both full and partial supply irrigated land uses were added as new land use classes in the LSPC model, and the corresponding NLCD classified land was subtracted from the appropriate subwatershed. All NLCD land uses within the identified irrigated land polygons were reclassified as either full or partial supply irrigation. Based on the WWDC data, 54,402 acres of full supply irrigated land and 14,724 acres of partial supply irrigated land are present in the Tongue River watershed in Wyoming.

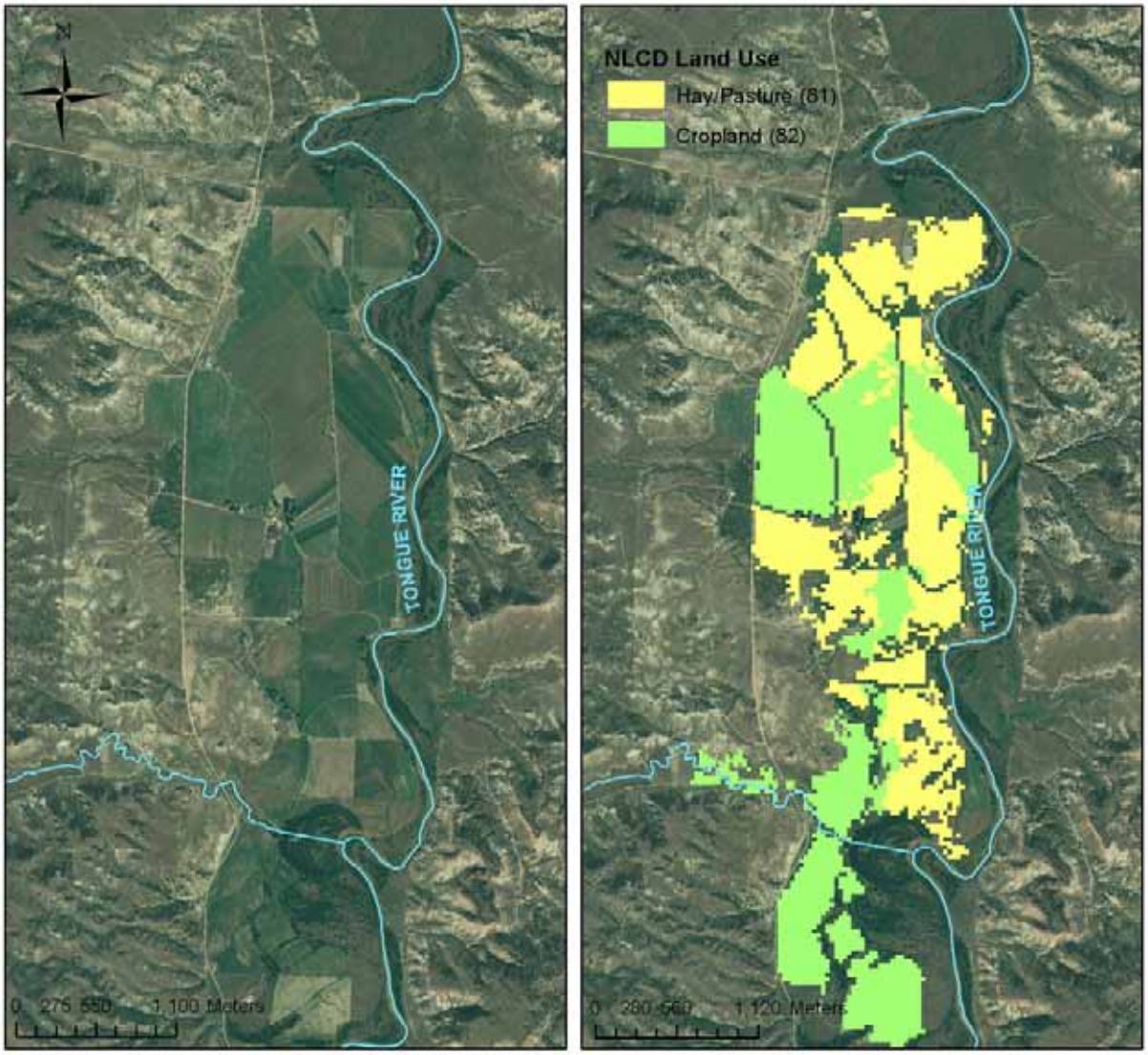
No recent irrigated land analysis was available for the Tongue River watershed in Montana. The Montana Agricultural Statistics Service reported that there were 55,000 acres of irrigated alfalfa hay in Big Horn, Custer, Powder River, and Rosebud Counties in 2001 (MASS, 2002). However, only 22 percent of this area is in the Tongue River watershed. The 1947 Water Resources Survey for Big Horn County, Montana states that approximately 30,000 acres of land are irrigated from the Tongue River between the Tongue River Reservoir Dam and the mouth (Montana State Engineer, 1947).

A GIS analysis was performed to obtain more detailed information about the amount and location of irrigated land in the Tongue River watershed, Montana. The 2001 NLCD land use coverage was overlain on the U.S. Farm Services Agency National Agricultural Imagery Program (NAIP) 1-meter resolution images for Montana. Several irrigated fields in the Tongue River watershed were identified from the aerial photos, and then overlain with the NLCD land use data. The NLCD data appeared to classify irrigated land (as identified in the aerial photos) as one of three land use categories – pasture/hay (81), cropland (82), and emergent herbaceous wetlands (95). This pattern was verified for 20 fields irrigated from either the Tongue River or major tributaries to the Tongue River. Irrigated land along the Tongue River was primarily classified as cropland or pasture/hay. Figure 3-11 illustrates this by showing the aerial photo and NLCD land use for an irrigated field near Ashland, Montana. It was assumed that these two land uses correspond to “full supply irrigation”, as defined by the Powder/Tongue Basin Plan (WWDC, 2002e). Irrigated land classified by the NLCD as “emergent herbaceous wetlands” primarily occurred along the perennial tributaries (e.g., Hanging Woman Creek, Otter Creek, and Pumpkin Creek). Figure 3-12 illustrates an irrigated field in the Otter Creek watershed that is classified as emergent herbaceous wetlands. It was assumed that this land received a partial supply of irrigation water. Based

on this analysis, 31,151 acres of irrigated land were identified in the Tongue River watershed, Montana (Table 3-5). Figure 3-13 shows the location of the irrigated land in Montana and Wyoming.

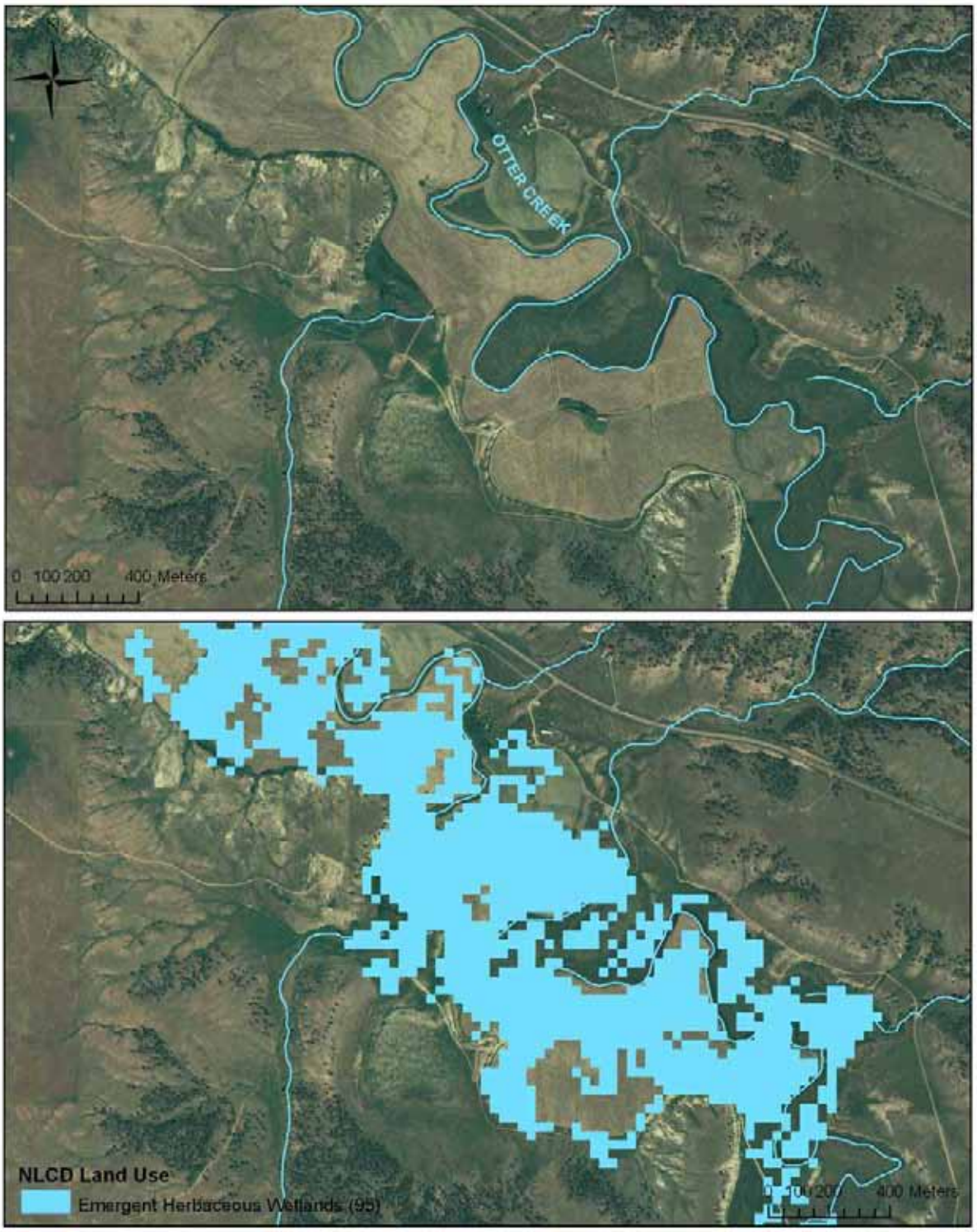
Table 3-5. Total acres of irrigated land in the Tongue River watershed in Montana

Watershed	Full Supply	Partial Supply	Total
Pumpkin Creek	8,044	454	8,498
Otter Creek	1,868	24	1,892
Hanging Woman Creek	305	42	348
Tongue River (Other)	19,167	1,247	20,414
Total	29,384	1,767	31,151



Sources: U.S. Farm Services Agency National Agricultural Imagery Program (NAIP) 1-meter resolution images for Montana
NLCD 2001 Land Use

Figure 3-11. Example area where irrigated land is classified as "hay/pasture" or "cropland" by the NLCD data. Tongue River near Ashland is shown.



Sources: U.S. Farm Services Agency National Agricultural Imagery Program (NAIP) 1-meter resolution images for Montana
NLCD 2001 Land Use

Figure 3-12. Example area where irrigated land is classified as "emergent herbaceous wetlands." Otter Creek near Ashland is shown.

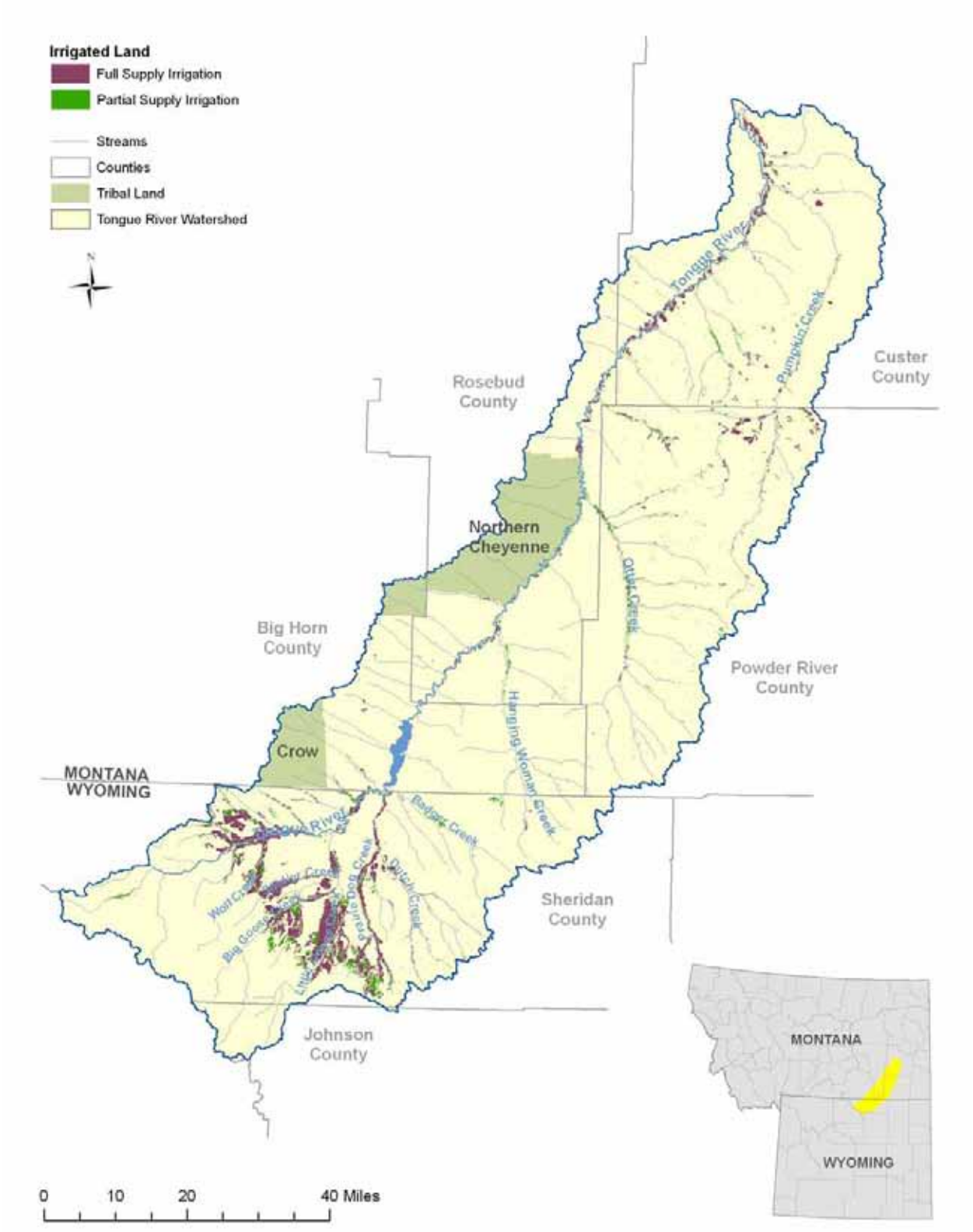


Figure 3-13. Location of irrigated land in the Tongue River watershed.

The accuracy of this methodology was verified with the Wyoming Powder/Tongue Basin Plan irrigated land coverage. The NLCD classified 55,385 acres of land as cropland, pasture/hay, or emergent herbaceous wetlands in the Tongue River watershed in Wyoming. The Wyoming Powder/Tongue Basin Plan indicated that there are 69,126 acres of irrigated land (WWDC, 2002e). This assessment suggests that the current methodology underestimates irrigated land in the Tongue River watershed in Montana. Additional data and field verification is recommended in the future to correct potential errors introduced by this assessment.

3.5.3 Final Modeled Land Uses

The NLCD land uses were grouped by similar characteristics to simplify the LSPC model and improve model run time. The LSPC land use groups and associated NLCD classes are shown in Table 3-6. The total acres per LSPC land use group are shown in Table 3-7.

Table 3-6. LSPC land use groupings and their associated NLCD land use classes.

LSPC Land Group	NLCD Land Use Name and Code
Barren	Bare Rock/Sand Clay (31)
Cropland (non-irrigated)	Cropland (82)
Forest	Deciduous Forest (41) Evergreen Forest (42)
Full Supply Irrigation	NA – Identified Separately
Partial Supply Irrigation	NA – Identified Separately
Pasture/Grassland (non-irrigated)	Grasslands/Herbaceous (71) Pasture/Hay (81)
Shrubland	Shrubland (52)
Urban Impervious	Open Space, Developed (21) Low Intensity Development (22) Medium Intensity Development (23) High Intensity Development (24)
Urban Pervious	Open Space, Developed (21) Low Intensity Development (22) Medium Intensity Development (23) High Intensity Development (24)
Water	Open Water (11)
Wetlands	Woody Wetlands (90) Emergent Herbaceous Wetlands (95)

Table 3-7. Modeled land uses in the Tongue River watershed.

LSPC Group Name	LSPC Group Number	Total Acres	Total Square Miles
Barren	1	10,166	16
Cropland	6	2,861	4
Forest	3	653,630	1,021
Full Supply Irrigation	9	83,787	131
Partial Supply Irrigation	10	16,491	26
Pasture/Grassland (non-irrigated)	4	1,463,287	2,286
Shrubland	5	1,125,334	1,758
Urban Impervious	20	2,207	3
Urban Pervious	7	18,541	29
Water	11	2,744	4
Wetlands	8	77,988	122
Total		3,457,036	5,402

3.6 Watershed Grouping

The LSPC model allows for variation of input parameters by land use (see Section 3.5). Input parameters can also be varied by *watershed groups*. A watershed group is defined as a subset of modeling subwatersheds that have similar soils and geology. The basis for watershed groups in LSPC was initially defined by the NRCS hydrologic soils groups, as defined by the STATSGO data (see Section 2.1.9.2 of the 2003 Status Report). However, initial calibration results showed that further group refinement was needed, primarily because of the complex geochemistry in the Tongue River watershed. In LSPC, groundwater concentrations are varied per watershed group (see Section 3.12.2), and hydrologic soil groups did not always account for the large changes in groundwater quality concentrations from the headwaters of the Tongue River to the mouth, or within the Tongue River tributaries. Groundwater in the Tongue River watershed exhibits a pattern of increasing dissolved solids (i.e., TDS, calcium, magnesium, and sodium) from the Bighorn Mountains to the mouth, with localized impacts from high salinity coal bed aquifers (USDI, 2003). The initial watershed groups were refined to reflect changes in soil hydrology as well as groundwater quality. Final watershed groups are described in Table 3-8, and are shown in Figure 3-14. These groups provided the primary basis for varying input parameters during model calibration (further described in Sections 4.1 and 4.2 – Hydrology Calibration Methodology and Water Quality Calibration Methodology).

Four additional watershed groups were set up to allow for calibration of the areas draining to CBM ponds and stock ponds, and their associated downstream subirrigated areas (see Sections 3.7.2 and 3.8 for additional details about the CBM and stock pond modeling). Groups 5 and 16 represent the areas draining to CBM and stock ponds (i.e., the total watershed area of all of the ponds per subbasin) for the Upper and Lower Tongue River watersheds, respectively. Groups 6 and 17 represent the areas that are subirrigated downstream of CBM and stock ponds in the Upper and Lower Tongue River watersheds, respectively.

Table 3-8. Watershed groups for the Tongue River LSPC model.

Region	Group Name	Group #	Corresponding Model Subbasins
Upper Tongue River and Tongue River Reservoir	Bighorn Mountains – Low Elevation	1	3025, 3029, 3044, 3047-3051, 3056, 3057, 3061-3063, 3071, 3072, 3074, 3076, 3082-3085, 3090-3108
	Bighorn Mountains – Middle Elevation	2	3030, 3031, 3034, 3035, 3036, 3053, 3054, 3058, 3059 , 3064, 3065, 3073
	Bighorn Mountains – High Elevation	3	3032, 3033, 3052, 3055, 3060
	Prairie	4	3000-3024, 3026-3028, 3037-3043, 3045, 3046, 3067-3070, 3075-3081, 3086-3089
	Area Draining to CBM and Stock Ponds	5	13002, 13006, 13007, 13008, 13010, 13012, 13013, 13014, 13017, 13019, 13021, 13022, 20504, 20604, 20804, 20902, 21904, 22004
	Area Subirrigated by CBM and Stock Ponds	6	30504, 30604, 30804, 30902, 31904, 32004
Lower Tongue River	Tongue River Prairie – Coal Region	11	1046-1057; 1079-1092; 1107-1113
	Pumpkin Creek	12	1006-1025
	Otter Creek	13	1058-1078
	Hanging Woman Creek	14	1093-1106
	Tongue River Prairie – Non Coal Region	15	1001-1005; 1026-1045
	Area Draining to CBM and Stock Ponds	16	11104, 11105, 20111, 20113, 20115, 20211, 20212, 20213, 20312, 20315, 20413, 20414, 21812, 21815, 21911, 21914
	Area Subirrigated by CBM and Stock Ponds	17	30111, 30113, 30115, 30211, 30212, 30213, 30312, 30315, 30413, 30414, 31812, 31815, 31911, 31914

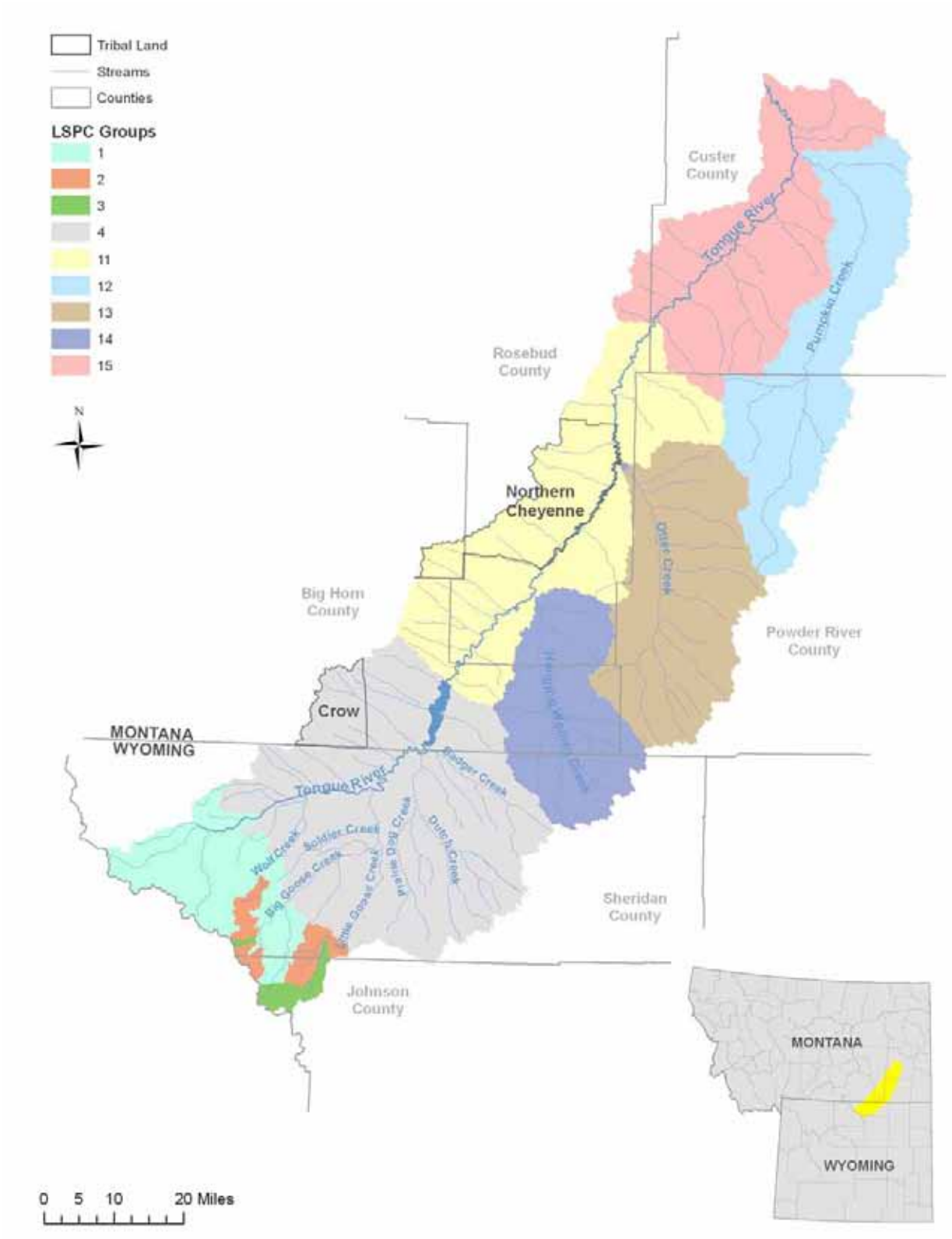


Figure 3-14. Watershed groups for the Tongue River LSPC model.

3.7 Point Sources

There are a number of point source surface water discharges in the Tongue River watershed, including wastewater treatment plants, industrial facilities, coal mines, and coalbed methane. Data for these point sources were compiled from a number of sources including Wyoming DEQ, Montana DEQ, local industry, members of the Modeling Committee, and EPA's Permit Compliance System (PCS). Flows and pollutant concentrations from the point sources were input to the LSPC model as time series and were combined with modeled estimates of surface runoff and subsurface loads to simulate in-stream water chemistry. Each point source category is summarized in the following sections, and additional details are provided in Appendix A. Figure 3-15 shows the location of all of the known point sources in the Tongue River watershed as of September 30, 2006.

Point Sources

A detailed description of all point sources in the Tongue River watershed is presented in Appendix A.

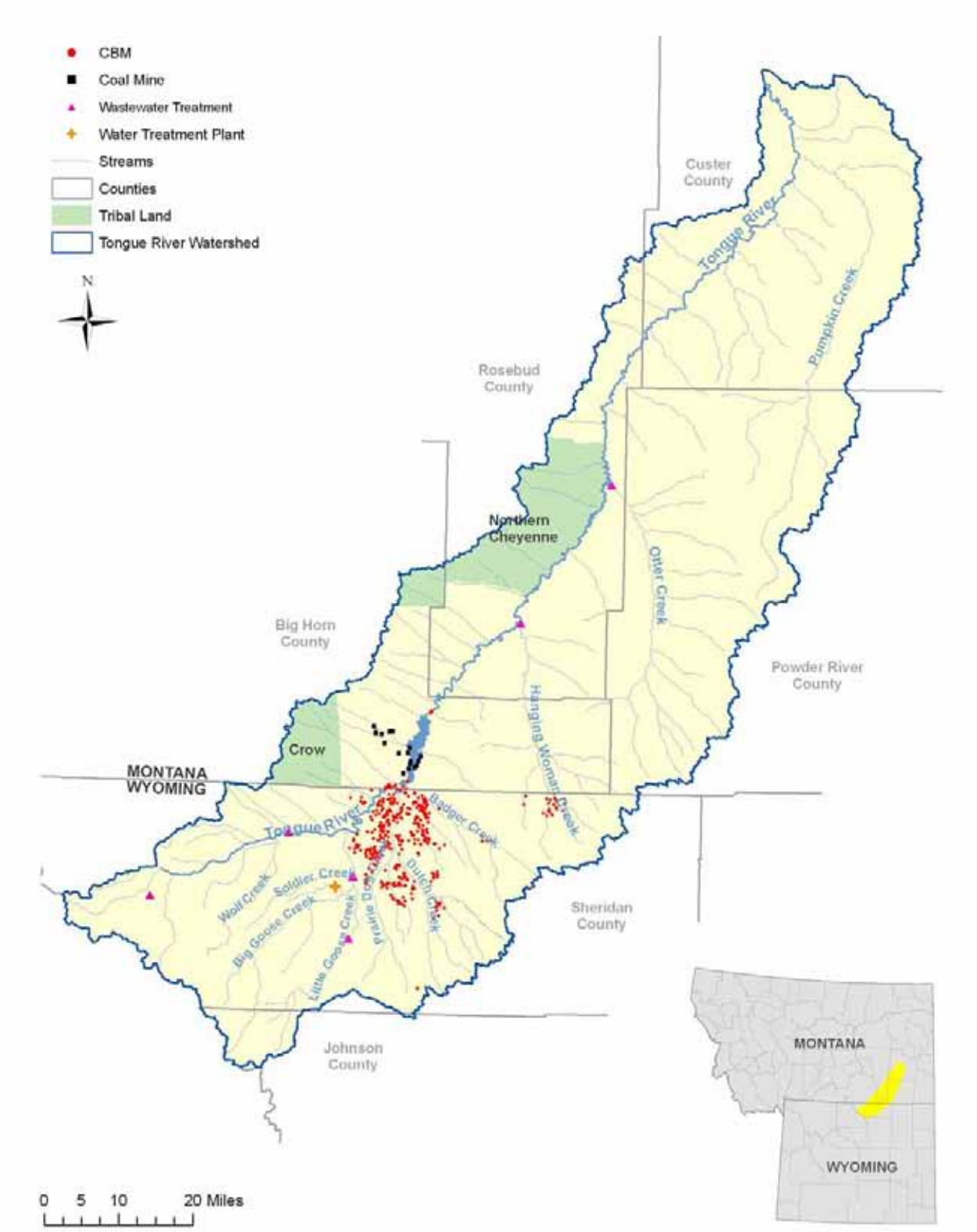


Figure 3-15. Location of the permitted surface water discharges in the Tongue River watershed (as of September 30, 2006).

3.7.1 Wastewater Treatment Facilities

As of September 30, 2006, there were six permitted wastewater treatment plants that discharge in the Tongue River watershed – City of Sheridan, WY; City of Ranchester, WY; City of Dayton, WY; Bighorn Mountain KOA (located near Sheridan, WY), Burgess Junction Dump Station (at Burgess Junction, WY), and the Powder Horn Ranch community (located southeast of Sheridan, WY). Three of the facilities operate lagoons (Dayton, Ranchester, and Burgess Junction), and two of the facilities operate small package plants (Powder Horn Ranch and Bighorn Mountain KOA) (WDEQ, 2003a; 2003b, 2004; 2005a; 2005b). The City of Sheridan operates a larger activated sludge (extended-aeration) facility with an average discharge of 4.6 cubic feet per second (USEPA, 2006b). Plant discharge data for all six facilities is summarized in Table 3-9 and in Appendix A.

Two additional wastewater treatment lagoons (City of Ashland, Montana and City of Birney, Montana) are operated in the Tongue River watershed, but do not require permits from Montana DEQ because of their size and because no direct discharge is anticipated (Personal Communications, USEPA, April 3, 2007). These two lagoons were not modeled.

Table 3-9. Summary of permitted wastewater discharge data in the Tongue River watershed (average values for the available period of record are reported).

Facility	Outfall	Period of Operation	Receiving Waterbody	n[2]	Flow (cfs)	SC (µS/cm)	TDS (mg/L)	SAR	Total N (mg/L)	Total P (mg/L)
Sheridan WWTP (WY0020010)	001	1988 – Present[1]	Goose Creek	60	4.60	838	442	2.73	NA	3.7
Dayton Lagoon (WY0020435)	001	1988 – Present[1]	Tongue River	57	0.12	NA	NA	NA	NA	NA
Ranchester Lagoon (WY0022161)	001	1990 – Present[1]	Tongue River	61	0.16	NA	643	NA	NA	NA
Bighorn Mountain KOA (WY0026441)	001	1990 – Present[1]	Goose Creek	56	0.003	NA	NA	NA	NA	NA
Powder Horn Ranch (WY0036251)	001	2001 – Present	Little Goose Creek	56	0.03	NA	NA	NA	NA	NA
Burgess Junction Dump Station (WY0020931)	001	1981-Present[1]	North Fork Tongue River	56	0.000	NA	NA	NA	NA	NA
	002			56	0.063	NA	NA	NA	NA	NA
	003			56	0.002	NA	NA	NA	NA	NA
City of Ashland Lagoon	None	1990 – Present[1]	Groundwater	NA	NA	NA	NA	NA	NA	NA
City of Birney Lagoon	None	1990 – Present[1]	Groundwater	NA	NA	NA	NA	NA	NA	NA

[1]The actual construction date for the facility is unknown. The period of operation was determined by the first reported compliance monitoring in the online PCS database, and may not reflect the actual construction date.
[2]The total number of samples varied per parameter. The largest sample count is reported.
NA – Not Available

The six permitted treatment facilities were simulated in LSPC as monthly varying continuous loads based on their reported discharge volumes and concentrations. Monthly average discharge and concentration data were obtained from the EPA Permit Compliance System and from Wyoming DEQ (see Appendix A). Few concentration data were available for the facilities; therefore monthly varying concentrations were estimated for most parameters at most times. The assumptions for the estimated concentrations at each facility are presented below:

City of Sheridan WWTP – Cation data (i.e., calcium, magnesium, and sodium) was available from effluent toxicity testing on file with Wyoming DEQ and ranging from 1988 to 1997 (multiple hardcopy reports, WDEQ, 1988-1997). Average monthly cation concentrations were calculated from the available data (n=14) and input into the model as a monthly varying time series through September 30, 2006. Total nitrogen concentrations were based on literature values and set at 14 mg/L (USEPA, 1997).

Total phosphorus concentrations were initially based on the one measured value reported by the facility (3.7 mg/L on May 10, 1988). However, initial model results indicated that the implementation of this value caused an unsatisfactory calibration of TP at the State Line USGS gage, particularly at base flow. Rather than using the reported concentration or literature values, an effective phosphorus contribution was calculated based on concentrations observed at two USGS gages located downstream of the treatment plant. USGS Gage 06305500 (Goose Creek below Sheridan, Wyoming) and 06305700 (Goose Creek near Acme, Wyoming) are 7.45 river miles apart, have paired phosphorus data, and both are downstream of the treatment plant (gage 06305500 is located immediately downstream of the plant, gage 06305700 7.45 miles downstream). A simple mass balance for the two gages and wastewater treatment plant (assuming an average flow of 4.6 cfs) indicated that the effective TP concentration from the treatment plant outfall is 1.2 mg/L. This value was input into the LSPC time series. It should be noted that this value may not represent the actual TP concentration in the treatment plant outfall. However, it represents an effective concentration that takes into consideration the actual concentration discharged from the outfall plus near-field uptake. Future measurements of TP in the treatment plant outfall plus an assessment of algal uptake in Goose Creek could help to refine this assessment.

City of Ranchester Lagoons – Average monthly TDS was reported for the Ranchester Lagoon effluent, but no other cations were reported. Calcium, sodium, and magnesium in the effluent were calculated based on the relationship of the three cations to TDS as measured in the Tongue River at Dayton, Wyoming (USGS gage 06298000), which is the closest gage to the Ranchester drinking water intake. This method assumes that there is no change in the balance of cations as the water moves through the public water system. No recent total phosphorus or total nitrogen data were available for the Ranchester Lagoons. Total phosphorus concentrations were based on literature values and set at 5 (USEPA, 1997). Total nitrogen concentrations were set at the observed ammonia concentrations and at the average observed ammonia concentration where no ammonia data were available.

City of Dayton Lagoons – No recent cation, total phosphorus, or total nitrogen data were available for the City of Dayton Lagoons. Effluent concentrations were therefore set to the same values as at the Ranchester Lagoons (see above).

Bighorn Mountain KOA – No recent cation, total phosphorus, or total nitrogen data were available for the City of Dayton Lagoons. Effluent concentrations were therefore set to the same values as at the Ranchester Lagoons (see above).

Burgess Junction Dump Station – Data from the Burgess Junction Dump Station indicate that the outfall from the lagoon system (outfall 001) does not discharge. Therefore, this outfall was not modeled in LSPC. Outfalls 002 and 003 discharge water from two underdrain systems which do not necessarily represent the effluent in the lagoon system. No relevant water chemistry data were available for this

facility. Furthermore, the facility is only operational from May through September of each year. Therefore, outfalls 002 and 003 were not modeled in LSPC.

Powder Horn Ranch – No recent cation, total phosphorus, or total nitrogen data were available for the Powder Horn Ranch. Effluent concentrations were therefore set to the same values as at the Ranchester Lagoons (see above).

3.7.2 Coalbed Methane

Coalbed methane (CBM) is methane gas found in coal seems and their associated aquifers (Keith et al., 2003). The methane is generally held in the coal seams by pressure from the local aquifers. Pumping water out of the aquifers releases the pressure from the coal seams thereby allowing the methane to rise to the surface. Pumped water from the coal aquifer can be directly discharged to a stream, stored in a containment unit, treated, used for irrigation or stock watering purposes, or re-injected. In the Tongue River watershed, most water from CBM wells is pumped into a series of outfalls that discharge to ponds. One outfall (or pond) can contain effluent from one to hundreds of individual CBM wells.

Montana DEQ and Wyoming DEQ require NPDES permits for CBM facilities discharging to surface waterbodies. Permits are issued for a specified number of outfalls (not individual wells) at specific locations. Facilities are required to monitor effluent from the outfalls and submit discharge monitoring reports (DMRs) to the respective agencies, generally on a monthly basis. Effluent monitoring occurs at the outfall discharge point before it enters a pond or stream, although some facilities are also required to monitor downstream impacts at compliance points. Ponds and pond discharges are rarely considered regulated NPDES compliance points.

The following sections summarize the CBM facilities, outfalls, and ponds located in the Tongue River watershed. Measured discharges and water chemistry at the CBM outfalls are discussed in Section 3.7.2.1, while ponds, pond design, and pond processes are discussed in Section 3.7.2.2. The methods and assumptions used to model the outfalls and ponds in LSPC are discussed in Section 3.7.2.3. Additional information about the permitted CBM facilities is provided in Appendix A.

3.7.2.1 CBM Outfalls

CBM permits and DMR data were obtained from Montana DEQ and Wyoming DEQ. Data for Montana CBM facilities were provided by Montana DEQ in Microsoft Excel spreadsheets. The spreadsheets contained DMR data for three facilities having 18 CBM outfalls, all of which have direct discharges to the mainstem Tongue River (MDEQ, 2006c). Figure 3-16 shows the location of the 18 direct discharges in Montana. Data were available from January 5, 2000 to October 31, 2006. Additional details about the Montana discharges are provided in Appendix A.

The Montana Board of Oil and Gas (MBOG) indicates that Fidelity Exploration and Production Company (Fidelity) began CBM operations in the Tongue River watershed in March 1997 (MPDES Permit MT0030457) (MBOG, 2006). At the time, no MPDES permit was required, and Montana DEQ did not issue a permit until June 16, 2000 (MDEQ, 2000). Because of this, no DMR data was submitted between March 1997 and January 2000. Several assumptions were therefore made about the timing and amount of discharge occurring between March 1997 and January 2000 at the Fidelity facility:

- According to DMR records, outfalls 001 through 009 were discharging in January, 2000. It was assumed that these 9 outfalls were also discharging from April 1, 1997 to January 1, 2000.

- It was assumed that flows from April 1, 1997 to January 1, 2000 were equal to the average long-term reported flow from each outfall, using all available data.
- It was assumed that water chemistry concentrations from April 1, 1997 to January 1, 2000 were equal to the long-term average concentration from each outfall, using all available data.

It is acknowledged here that this is most likely an overestimate of the actual amount of discharged water because new wells were drilled over time and not all at once. However, it is considered a conservative estimate for this analysis.

Wyoming DEQ provided a Microsoft Access database (dated January 23, 2007) of data for CBM facilities in the Tongue River watershed, Wyoming. The database contained over one million records of CBM DMR data dating from March 1, 1999 to January 1, 2007. Wyoming DEQ personnel indicated that the database contains information for all of the permitted CBM facilities in the Tongue River watershed through January 1, 2007 (Personal Communications, Wyoming DEQ, March 19, 2007). The database contained data for 420 CBM outfalls that discharge to ponds and 7 outfalls that discharge directly to streams. An estimated 222 of the outfalls discharge to off-channel ponds, and 198 discharge to on-channel ponds (WDEQ, 2007) (further discussed in Section 3.7.2.2). Of the 427 outfalls, only 410 had reported flows. The other 10 outfalls either had no reported data or had reported discharges of zero. Wyoming personnel indicated that this was common, as outfalls are often permitted and built but not used (Personal Communications, Wyoming DEQ, March 19, 2007). Additional information about CBM facilities located in Wyoming is provided in Appendix A, and Figure 3-16 shows the location of the known CBM outfalls as of September 30, 2006

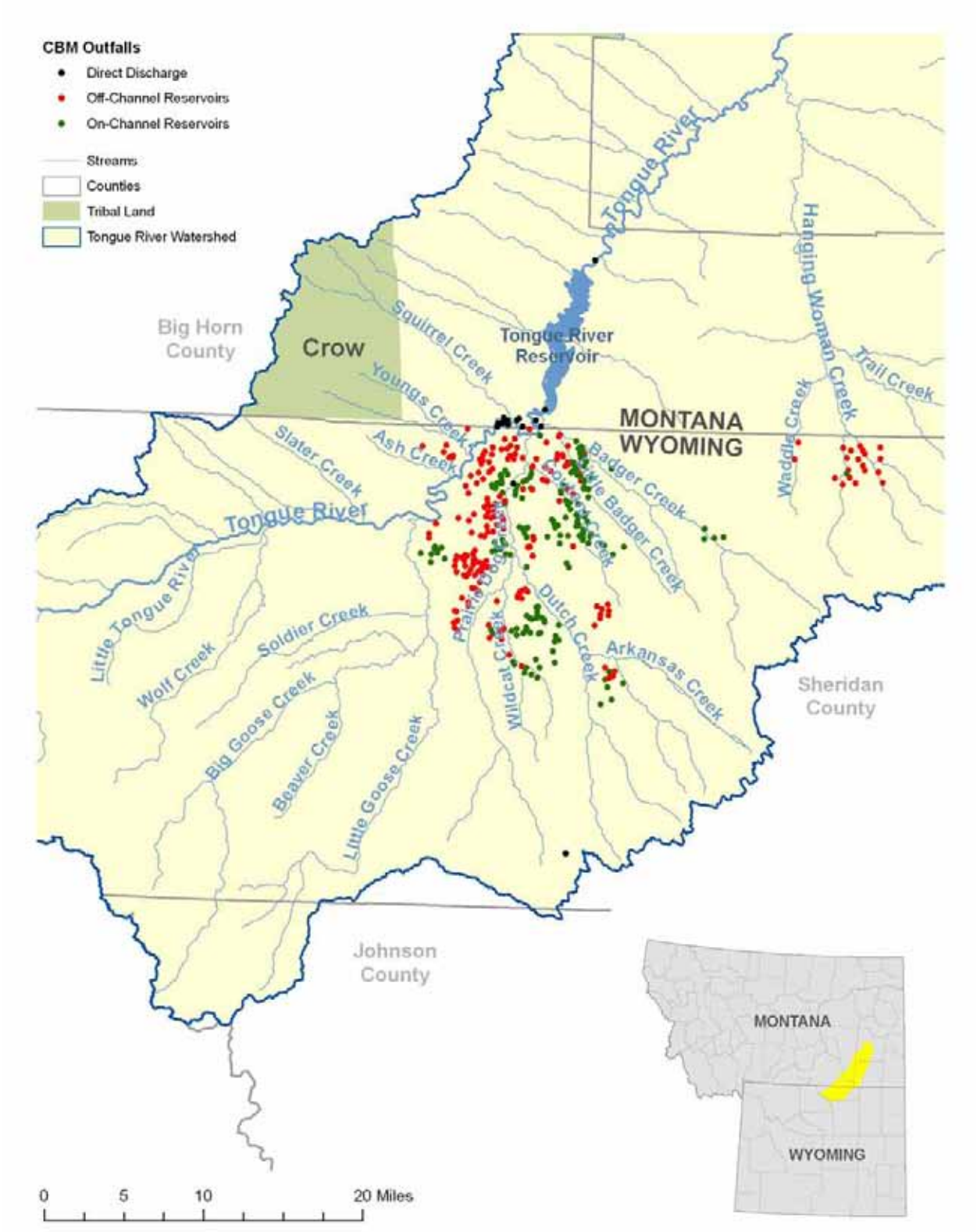


Figure 3-16. Location of known CBM outfalls in the Tongue River watershed as of September 30, 2006.

A summary of the reported flows for all Wyoming and Montana CBM outfalls is presented in Figure 3-17. Flows from the Montana CBM facilities began in 1997 and remained relatively constant with an average flow of 2.3 cubic feet per second. The average SC and SAR from the Montana facilities was 1,935 µS/cm and 41.1, respectively. CBM facilities were first constructed in Wyoming in 1999, and discharges have increased over time to a peak of 13.0 cubic feet per second in November of 2004. The average SC and SAR from the Wyoming facilities was 1,900 µS/cm and 38.1, respectively. The total yearly effluent volumes from Wyoming CBM outfalls within the Tongue River watershed (as reported by the Wyoming Oil and Gas Commission) are also displayed in Figure 3-17 for comparison.

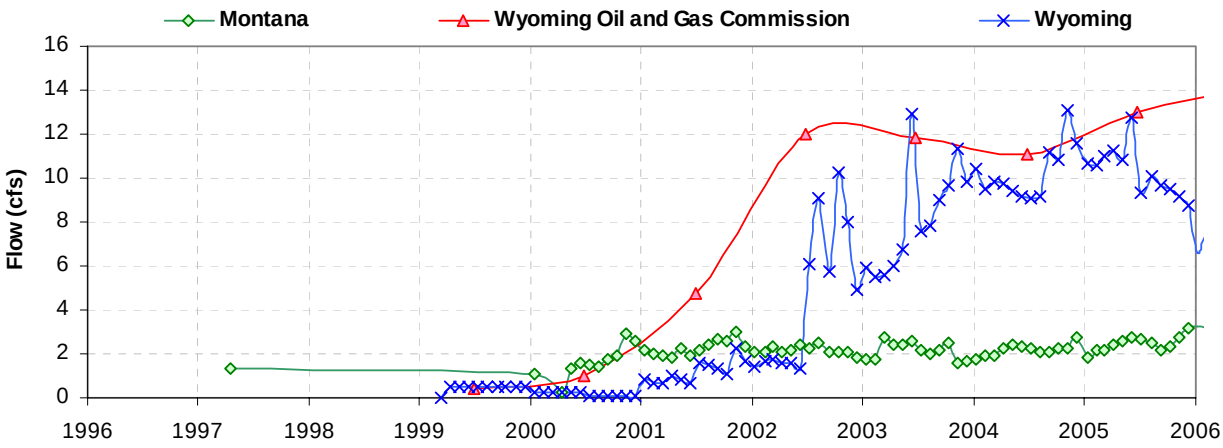


Figure 3-17. Summary of total monthly CBM discharge from Montana and Wyoming facilities (all available data from 1997-2006)

3.7.2.2 CBM Ponds

Most CBM effluent is discharged into ponds. Ponds are designed to contain, infiltrate, and evaporate discharge water. At times, the ponds may have a surface water discharge from overtopping or pond failure. Wyoming DEQ allows both on-channel and off-channel CBM ponds in the Tongue River watershed (Montana currently does not have any MPDES permitted CBM ponds in the Tongue River watershed). On-channel ponds are defined by Wyoming DEQ as "an impoundment sited on or within a distance of 500 feet of a designated water feature as defined on a United States Geologic Survey (USGS) 1:24,000 scale topographic map, or within a distance of 500 feet of the floodplain or mapped alluvium (including alluvial mixtures) of a stream system as defined on a Wyoming State Geological Survey 1:100,000 scale surficial geology map," (WDEQ, 2006a). Off-channel ponds are defined as any pond not meeting the requirements of an on-channel pond. Pond sizing and design varies per CBM facility. Designs can vary from complete discharge of CBM effluent to complete containment of all CBM effluent plus water from up to a 100-year storm event (Various permits, WDEQ, 2000-2006). Several examples from the CBM NPDES permits are presented below to illustrate the variety of permitted pond designs:

- ***Permit WY0038628 –*** *All eleven outfalls authorized under this permit will discharge into on-channel reservoirs as described in Table 1 (Part I.B.12) of the permit. While the reservoirs receive effluent from this CBM facility, the permit does not require containment of the effluent within the reservoirs. This permit anticipates discharge of effluent to Goose Creek, with the limits specified below. In addition, neither the reservoirs nor their spillways will constitute regulated discharge points under this permit (WDEQ, 2005c).*
- ***Permit WY0051811 –*** *The permittee has committed to containment of all CBM effluent within a series of on-channel reservoirs. The permittee is required to contain all effluent within the reservoirs, and may not discharge except during periods of time in which stormwater runoff enters the reservoir, causing it to overtop and spill (WDEQ, 2005d).*
- ***Permit WY0052345 –*** *The permittee has submitted information to demonstrate that all produced effluent from this facility will be contained in 7 on-channel reservoirs. The water budget for this facility confirms that these reservoirs will have sufficient capacity to contain all of the estimated effluent from this facility as well as storm runoff from up to a 100-year/24-hour event (WDEQ, 2005e).*
- ***Permit WY0046540 –*** *Under this permitting option, the produced water is immediately discharged to a confined, off channel pit, stock pond or other man made containment unit (class 4 water) that will not flow into any other waters of the state. The permittee has demonstrated through a water balance study that, considering CBM well inflow, natural precipitation, evaporation and infiltration, the off channel containment unit will be adequate to contain all CBM discharge water and stormwater up to a 25 year 24 hour event. In addition, the permittee has committed to the complete containment of all discharged water (WDEQ, 2005f).*
- ***Permit WY0052043 –*** *The permittee has committed to, and will be required to, contain all of the CBM produced water and stormwater runoff up to and including the runoff from a 100 year, 24 hour storm event in the playa. The permittee has also submitted a water balance which demonstrates that , considering CBM well production, natural precipitation, and evaporation and infiltration, and other facilities that these wells are linked to in the immediate vicinity, the playa will be adequate to contain all estimated CBM discharge water discharged to it. To allow the permittee the maximum flexibility in the use of the playa lake for CBM produced water containment, no flow limit will be established in this permit. However, the permittee has committed to the complete containment of all discharged water within the topographically closed basin (WDEQ, 2004c).*

A literature review was conducted to better understand the hydrological and chemical processes occurring in the CBM ponds. The physical setup for CBM ponds is similar to stock ponds (and indeed some CBM ponds are former stock ponds): they tend to be located on ephemeral channels and discharge directly to downstream perennial waters only during storm events. The major difference is that CBM ponds receive near continuous inputs of produced water, while stock ponds primarily rely on natural inflow events.

A major effect of CBM ponds is to raise the water table in the alluvial aquifer. Payne and Saffer (2005) found that infiltration was a major part of the water budget; however, this infiltration occurred to a much greater extent in the ephemeral stream channels than in the ponds themselves. Infiltration from the ponds was limited by a variety of factors, including compaction, settling of fine-grained material to the pond bottom, and presence of a mounded water table under the ponds. In 2003, analysis over a travel distance of about 1500 meters partitioned the flow into 46 percent infiltration plus transpiration, 44 percent surface flow, and 10 percent direct evaporation (Payne and Saffer, 2005). However, the balance will shift further toward infiltration and away from surface flow with additional travel distance. Field calculated estimates of infiltration ranged from 0.032 to 0.132 cfs/mi. The authors judged that a typical industry value for infiltration losses of about 0.1 cfs/mi may be a slight overestimate. It is important to note that these estimates of "infiltration" actually refer to total losses, and so are the sum of infiltration and evapotranspirative losses, which may be high due to the presence of riparian vegetation.

Water discharged over the dams goes into what were ephemeral stream channels, where much of it infiltrates into the alluvial aquifer or is lost to evapotranspiration (Payne and Saffer, 2005). Water also exfiltrates through the bottom of the pond into the alluvial aquifer. The resulting increase in water volume can establish perennial flow and wetlands in the receiving channel, but typical operation appears to result in a condition in which continuous surface flow does not reach natural perennial streams (Payne and Saffer, 2005). However, during storm events significant amounts of direct surface flow may proceed through the system.

Flow associated with CBM ponds reaches perennial stream reaches by four potential pathways: direct overflow (O_p), direct infiltration (I_p), interflow (I_c), and groundwater (G_c). Each of these pathways will have different water chemistry characteristics. Wheaton and Brown (2005) make a number of points regarding these issues in relation to CBM ponds. Experiments reported by Wheaton and Brown first indicate that the water chemistry of the groundwater associated with CBM ponds is more strongly related to the chemistry of the receiving hydrogeology than to the characteristics of the source water. CBM-produced water is typically high in bicarbonate, very low in sulfate, has low concentrations of calcium and magnesium, and relatively high concentrations of sodium (and thus a high SAR). In general, infiltration into the shallow groundwater results in increases in Ca and Mg due to dissolution of calcium and magnesium carbonates in the formerly unsaturated overburden, potentially followed by exchange of Ca and Mg for Na where sodic shales are contacted. Wheaton and Brown (2005) conclude that "the increase in TDS is likely associated with the dissolution of minerals present in the overburden material and is not directly associated with the [CBM] production water. In fact, similar TDS levels would be expected if a surface water source, or rainwater, had been pumped into the pond." The increases in TDS during infiltration are largely due to dissolution of Ca and Mg, while Na seems to be approximately conservative.

A second point is that the effect of increased groundwater flows will change over time as available salts are flushed from the system by exchange of one or more porewater volumes. In large aquifers, this effect will take place over very long time frames; however, it may be an important consideration in small, confined alluvial aquifers or along the flowpaths through overburden for infiltration from ponds.

Preliminary conclusions by Wheaton and Brown (2005) suggest that water chemistry immediately beneath an infiltration pond can be approximated by a simple mixing model of pond water and ambient

ground water. However, as flowpaths become longer, the resulting groundwater discharge will become more and more similar to ambient groundwater. The primary impact of ponds on baseflow water chemistry would thus seem to be an increase in groundwater flow, rather than a significant change in the ionic concentrations. Impacts from individual ponds are likely to be highly variable, dependent on local geology, and hard to generalize.

3.7.2.3 Modeling CBM Outfalls and Ponds

The DMR data obtained from Wyoming DEQ and Montana DEQ for CBM outfalls (as discussed in Section 3.7.2.1) were entered into the LSPC model as monthly varying time series based on the reported flow and water chemistry concentrations. Average monthly flows, salinity, and SAR were reported for most Montana and Wyoming CBM outfalls. However, additional parameters required for the LSPC modeling (i.e., calcium, magnesium, sodium, total nitrogen, and total phosphorus concentrations) were not always reported. Where missing, these parameters were set to the average concentration for that particular outfall or facility. If no data were reported for a facility, data from nearby CBM facilities were used to supplement the missing information. No total nitrogen (TN) or total phosphorus (TP) data were available for any of the Wyoming CBM wells. Wyoming DEQ personnel indicated that no nutrient monitoring has ever been required of CBM facilities (Personal Communications, Wyoming DEQ, March 20, 2007). The average TN and TP concentrations from the 16 Fidelity outfalls (Montana MPDES permit MT0030457) were therefore used for all Wyoming CBM outfalls (1.40 and 0.10 mg/L, respectively). A summary of all modeled CBM outfall data are presented in Table 3-10.

Table 3-10. Summary of modeled CBM flow and concentrations.

Parameter	Average	Min	Max
Flow (cfs)	0.18	0.00	5.55
Calcium (mg/L)	7.8	0.2	131.9
Magnesium (mg/L)	4.0	0.1	114.3
Sodium (mg/L)	476.7	4.3	1,428.0
Total Nitrogen (mg/L)	1.49	0.10	3.30
Total Phosphorus (mg/L)	0.10	0.05	0.12

In all, 428 CBM outfalls had at least one month with a reported flow, and 428 time series (18 in Montana and 410 in Wyoming) were input into the LSPC model. Discharges from the outfalls were either routed into a stream or pond, depending on the permit. Nineteen of the outfalls were direct discharges, and 409 discharges were routed into ponds. It was assumed that one outfall discharged to one pond; therefore 409 ponds were input into the LSPC model.

As discussed in Section 3.7.2.2, there are a variety of CBM pond designs. Ponds can be located on or off-channel, contain 0 to 100 percent of CBM effluent, and contain 0 to 100 percent of flow from major storm events. Because of the varying pond designs, several assumptions were made to simplify pond modeling processes. Each pond was assumed to be rectangular shaped with a triangular profile, and a full pool depth of 10 feet. It was also assumed that infiltration from all ponds is 15 mm/day (based on literature reviews: Payne and Saffer, 2005; Neff, 1980). These assumptions (along with the pond design, CBM discharge, and precipitation data) provided the information for calculating pond sizes.

For modeling purposes, the ponds were classified into three groups based on the frequency of overflows. The groups and number of ponds per group are described below and are shown in Figure 3-18:

- **Group 1 – "Complete Containment" –** Group 1 contains both on channel and off channel ponds that are designed for complete containment of CBM effluent plus water from storm events. This assumes that infiltration and any resulting changes to the groundwater are the same from either on or off channel ponds. This assumption is appropriate because of the scale of the LSPC model (i.e., large, watershed scale model that is not appropriate for field scale assessments) (272 ponds).
- **Group 2 – "No Containment" –** Group 2 consists of CBM ponds that are designed to simply "dissipate energy" from CBM discharges (25 ponds). Ponds in this group are not designed to store CBM effluent or storm event runoff.
- **Group 3 – "Partial Containment" –** This group consists of on-channel ponds that are designed for complete containment of CBM effluent, but allow overflow during storm events (112 ponds).

Each group was modeled with a different set of rules and assumptions. The primary difference among the groups was the sizing of the ponds. Group 1 ponds were sized in the LSPC model large enough to capture all effluent and storm events up to a 100-year flood, Group 2 were sized to contain flow from one day of CBM effluent (based on best professional judgment), and Group 3 were designed to contain 100 percent of the CBM effluent, but overflow with storm events.

Individual CBM ponds were not modeled in LSPC; rather, ponds and CBM discharges to ponds were lumped per modeling subbasin (as defined in Section 3.2). One surrogate pond was created for each Pond Group, resulting in zero to three surrogate ponds per modeling subbasin (depending on the type of ponds present in the subbasin). The total volume of effluent discharging to a specified group in a specified subbasin was summed to create the surrogate pond. LSPC currently does not allow for varying pond sizes over time, therefore the total volume of CBM ponds as of September 30, 2006 was used to compute pond sizes. It is recognized that this introduces error into the model, particularly between 1999 and 2006 when CBM experienced rapid growth in the watershed.

It should be noted that some modeling subbasins had no CBM outfalls, while others had one or more particular group of ponds. The number of surrogate ponds per subbasin ranged from zero to three based on the type of ponds present in the subbasin. The total number of ponds per modeling subbasin and Pond Group is shown in Table 3-11. The CBM time series were routed into the surrogate pond for each subbasin, and water was allowed to infiltrate, evaporate, and overflow.

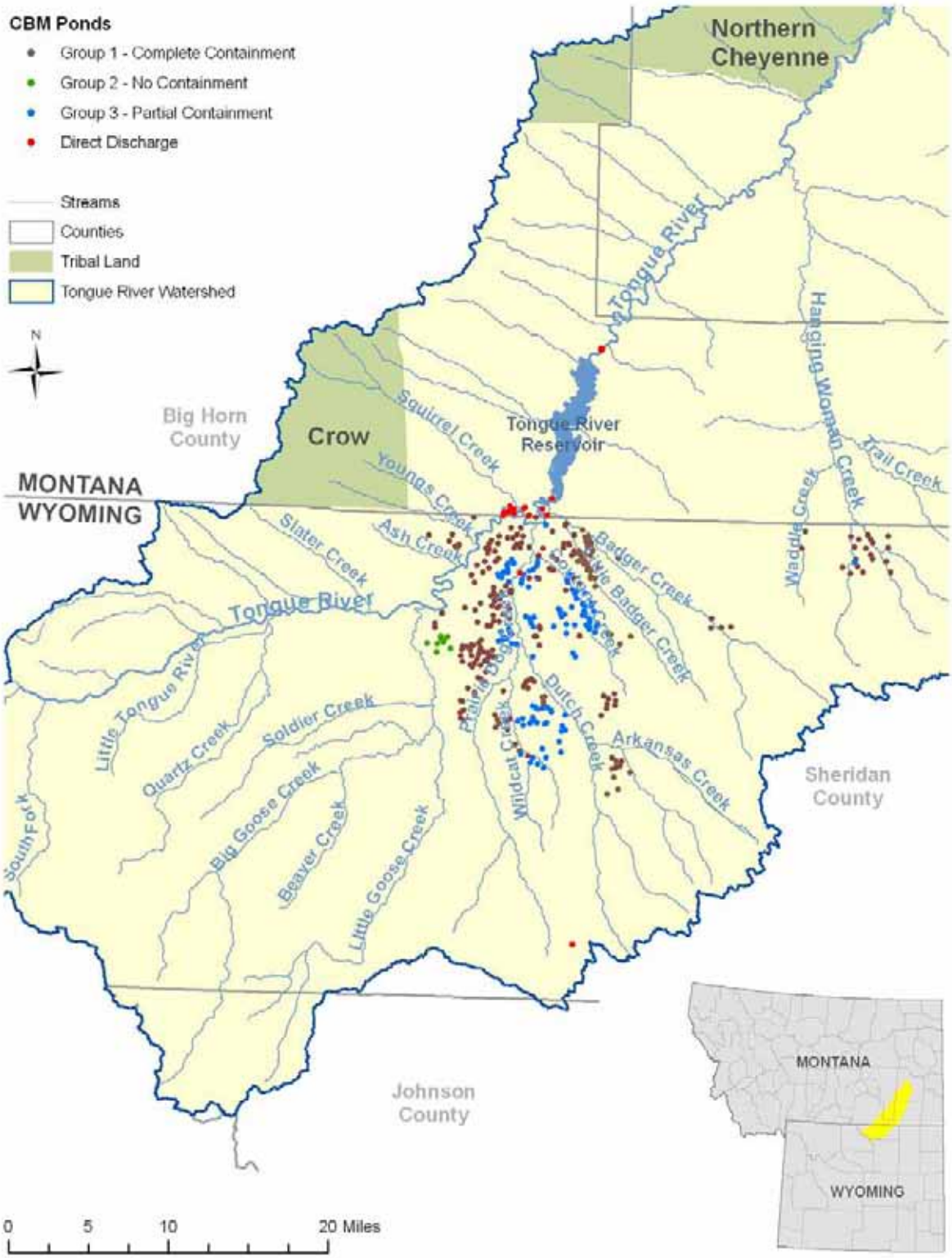


Figure 3-18. Location of CBM ponds and pond groups.

Table 3-11. Summary of modeled CBM outfalls per LSPC subbasin.

LSPC Subbasin ID	Subbasin Name	Direct Discharge	Group 1 (Complete Containment)	Group 2 (No Containment)	Group 3 (Partial Containment)	Total
1104	Hanging Woman Creek	0	10	0	0	10
1105	Hanging Woman Creek	0	8	0	0	8
1106	Hanging Woman Creek	0	2	0	0	2
1112	Tongue River	1	0	0	0	1
3002	Badger Creek	0	54	0	0	54
3005	Tongue River	1	0	0	0	1
3006	Tongue River	4	1	0	3	8
3007	Prairie Dog Creek	1	68	3	73	145
3008	Prairie Dog Creek	0	50	0	16	66
3009	Prairie Dog Creek	0	0	0	0	0
3010	Prairie Dog Creek	0	16	0	20	36
3012	Prairie Dog Creek	0	9	0	0	9
3013	Prairie Dog Creek	0	2	0	0	2
3014	Tongue River	3	2	0	0	5
3016	Tongue River	9	4	0	0	13
3017	Tongue River	0	13	0	0	13
3019	Tongue River	0	32	9	0	41
3021	Goose Creek	0	1	10	0	11
3022	Goose Creek	0	0	3	0	3
Total		**19**	**272**	**25**	**112**	**428**

On-channel ponds have an associated watershed area upstream of the pond. This area was estimated by delineating watersheds for a subset of ponds in a GIS, which yielded an average watershed area of 120 acres per on-channel CBM pond. For modeling purposes, it was assumed that this area is composed of 50 percent grasslands and 50 percent shrubland (based on the GIS analysis). The CBM pond watershed area was subtracted from the modeling subbasin watershed and routed directly into the surrogate ponds as dictated by the location of the ponds and their associated permitted design.

Downstream of the ponds, it was assumed that infiltrated water is added to the active groundwater storage, which then raises the water table and provides subirrigation (i.e., irrigation provided by the presence of a higher than normal water table) to plants downstream of the ponds (Payne and Saffer, 2005; Wheaton and Brown, 2005). The infiltrated water is also subject to loss to deep aquifers and evaporation, and excess water is discharged back to the stream. Based on the research of Wheaton and Brown (2005), it was assumed that water infiltrated from the CBM ponds equilibrates with the ambient groundwater. Therefore, the water chemistry of the subirrigated area was set to the same interflow and groundwater concentrations as the rest of the watershed group, which varied depending on the location within the Tongue River watershed (see Section 3.12.2).

This subirrigated area (like the area subirrigated by stock ponds – see Section 3.8) was assumed to follow the stream channel for a maximum distance of 1,000 meters, subirrigating a 30 meter wide area of land downstream of the ponds. Based on a GIS analysis, it was assumed that all areas subirrigated by CBM ponds were composed of NLCD land use classes 95 (emergent herbaceous wetlands) and 71 (grassland). Using these assumptions, the subirrigated area was discretely represented in the LSPC model, and water infiltrated from CBM ponds was routed into this area. It is recognized that this approach is an oversimplification of pond infiltration and subirrigation processes, and that actual subirrigation amounts

will vary based on the size of the pond, infiltration rate, soils, vegetation, groundwater, and in-stream flow.

Overflow from stock ponds and type 3 CBM ponds are assumed to go directly to the stream segment. This is because overflow from these ponds are mostly driven by storms. If a storm is large enough to cause one of these types of ponds to overflow, then it is reasonable to assume that all pervious land surfaces are saturated, with little opportunity for additional infiltration. However, Type 2 CBM ponds, which are designed for continuous overflow, discharge to the sub-irrigated land surface. This water is subject to additional infiltration because the timing of these controlled discharges does not necessarily follow the timing of wet weather events that would otherwise saturate the ground.

Figure 3-19 presents a summary of the CBM pond processes described in the previous paragraphs and modeled in LSPC.

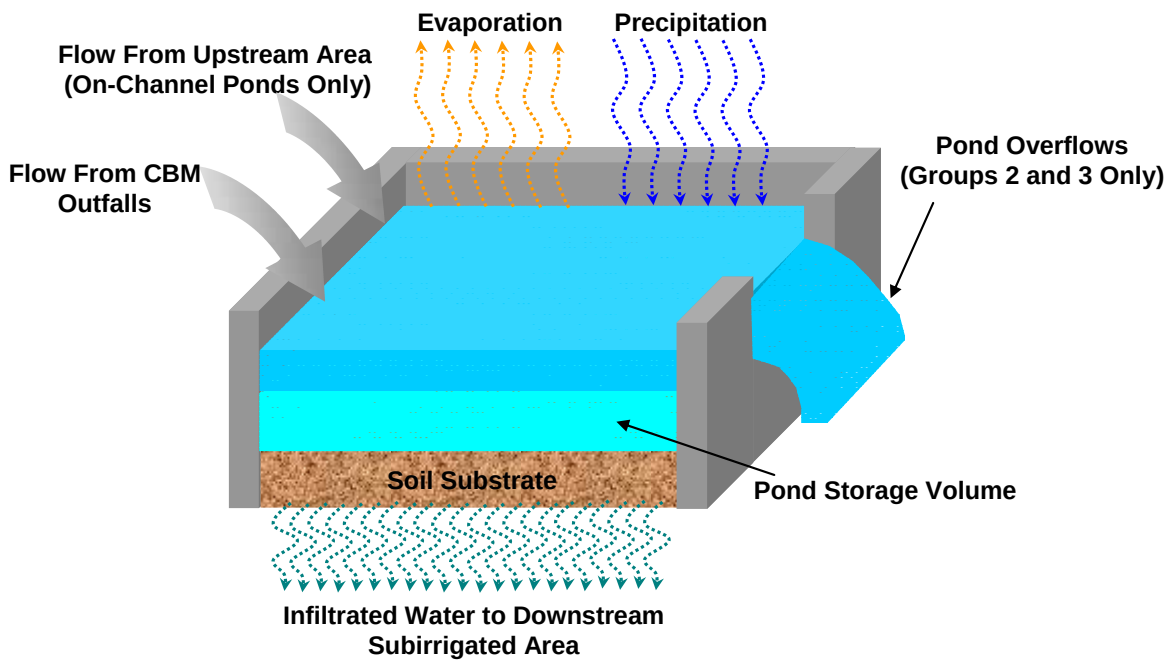


Figure 3-19. CBM pond processes modeled in LSPC.

3.7.3 Coal Mines

Three strip coal mines are currently operating in the Tongue River watershed – Spring Creek, Decker East, and Decker West. The Bighorn Mine Coal Mine was operational until 2000, and is now undergoing reclamation. Additional details about all four strip mines are included in Appendix A.

Only two outfalls were modeled in LSPC – Decker West outfall 007 and Decker East outfall 002. Both outfalls discharge to the Tongue River Reservoir. According to the discharge monitoring reports (DMRs) and information from the Montana DEQ Industrial and Energy Minerals Bureau (IEMB), these are the only two outfalls that continuously discharge (see Appendix A). The remaining outfalls have intermittent, unpredictable discharges and therefore were not included in the LSPC model. None of the Spring Creek outfalls discharge on a regular basis. Decker West outfall 007 and Decker East outfall 002 were modeled as monthly varying continuous loads based on their reported discharge volumes and concentrations (obtained from the online PCS database and from the IEMB). Summary statistics from the time series is presented in Table 3-12. Total nitrogen data for both outfalls was calculated as the sum of the ammonia plus nitrate plus nitrite data.

Table 3-12. Summary of modeled coal mine outfalls and data.

Outfall	Parameter	Average	Min	Max
Decker West #007	Flow (cfs)	2.25	0.03	26.90
	Calcium (mg/L)	158.8	58.3	242.1
	Magnesium (mg/L)	117.5	53.6	155.0
	Sodium (mg/L)	297.2	90.8	510.2
	Total Nitrogen (mg/L)	1.92	0.03	7.56
	Total Phosphorus (mg/L)	0.05	0.01	0.23
Decker East #002	Flow (cfs)	1.39	0.69	2.37
	Calcium (mg/L)	72.9	27.0	102.0
	Magnesium (mg/L)	60.6	44.7	76.7
	Sodium (mg/L)	538.9	296.2	791.4
	Total Nitrogen (mg/L)	1.88	0.43	3.45
	Total Phosphorus (mg/L)	0.04	0.01	0.18

3.8 Stock Ponds

Stock ponds are small human-made water impoundments that serve as water supply for livestock and crops. Stock ponds are found throughout the Tongue River watershed (Figure 3-21) and have the ability to affect hydrologic processes in the following ways:

- Delay response to storms by capturing runoff and then releasing via overflow.
- Reduce overall stream flows due to loss of water from evaporation or use of water.
- Reduce downstream sediment loads through settling.
- Infiltrate water, thereby increasing downstream baseflow, and potentially increasing downstream dissolved solid concentrations.

In the LSPC model, stock pond setup was similar to the CBM ponds. One surrogate pond was created for every subbasin with a stock pond. Table 3-13 summarizes the LSPC modeling subbasins with stock ponds and the total volume per subbasin. The surrogate pond was sized to be the sum of the volumes of the stock ponds in the subbasin based on information provided by Montana DNRC and the Wyoming State Engineers Office (DNRC, 2003; WWDC, 2002c). Sizing and infiltration assumptions were similar to the CBM ponds:

- The pond is rectangular with a triangular profile.
- The full pool depth is 10 feet.
- Each pond has a trapezoidal weir to accommodate overflows.
- Infiltration from all ponds is 15 mm/day (based on literature reviews: Payne and Saffer, 2005; Neff, 1980).
- The length to width ratio of the pond is 4:3.

The upstream drainage area was calculated in a GIS for a subset of stock ponds. Based on the subset of data, the relationship between the known pond total volume and watershed area was calculated (Figure 3-20). The upstream watershed area was assumed to be composed of 50 percent shrubland and 50 percent grassland.

It was assumed that stock pond infiltration raises the water table and provides subirrigation to plants downstream of the ponds. This subirrigated area was assumed to follow the stream channel for 1,000 meters, subirrigating a 30 meter wide area of land. It was assumed that the 30,000 square meter area was composed of grassland and emergent herbaceous wetlands.

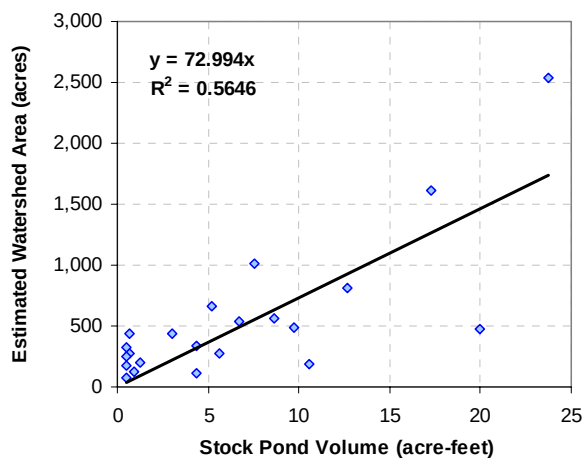


Figure 3-20. Relationship between watershed area and stock pond volume.

Table 3-13. Total volume of stock ponds per modeling subbasin

Subbasin	Total Stock Pond Volume (Acre-feet)	Subbasin	Total Stock Pond Volume (Acre-feet)	Subbasin	Total Stock Pond Volume (Acre-feet)	Subbasin	Total Stock Pond Volume (Acre-feet)
3002	83	3068	1,308	1031	87	1070	238
3003	28	3069	115	1032	85	1071	37
3004	105	3075	55	1033	96	1072	101
3007	245	3077	6	1034	42	1073	15
3008	351	3078	474	1035	142	1074	50
3009	450	3079	0	1037	15	1075	41
3010	391	3080	6	1038	20	1076	16
3011	101	3086	146	1039	24	1077	27
3012	241	3087	46	1040	31	1078	18
3013	110	3088	3	1042	1	1079	16
3015	165	1002	86	1043	176	1081	34
3017	44	1003	57	1044	89	1083	103
3018	26	1005	126	1045	48	1084	310
3019	271	1007	16	1046	1	1085	25
3020	62	1008	15	1047	1	1087	113
3021	23	1009	4	1049	100	1089	1
3022	1,603	1010	46	1050	43	1091	28
3024	58	1011	79	1051	194	1092	1
3026	41	1012	66	1052	27	1094	115
3027	390	1015	46	1053	10	1095	22
3028	253	1016	39	1057	16	1096	107
3031	16	1018	24	1059	20	1097	30
3034	70	1019	26	1060	143	1098	18
3037	57	1020	26	1061	223	1101	25
3038	33	1022	24	1062	103	1102	33
3040	121	1023	26	1063	110	1106	1
3041	10	1024	48	1064	31	1107	36
3043	1	1025	48	1065	47	1108	45
3045	6	1026	62	1066	136	1109	186
3046	4	1027	1	1067	96	1110	126
3066	15	1029	34	1068	167	1111	52
3067	214	1030	40	1069	166	1112	16
						1113	1

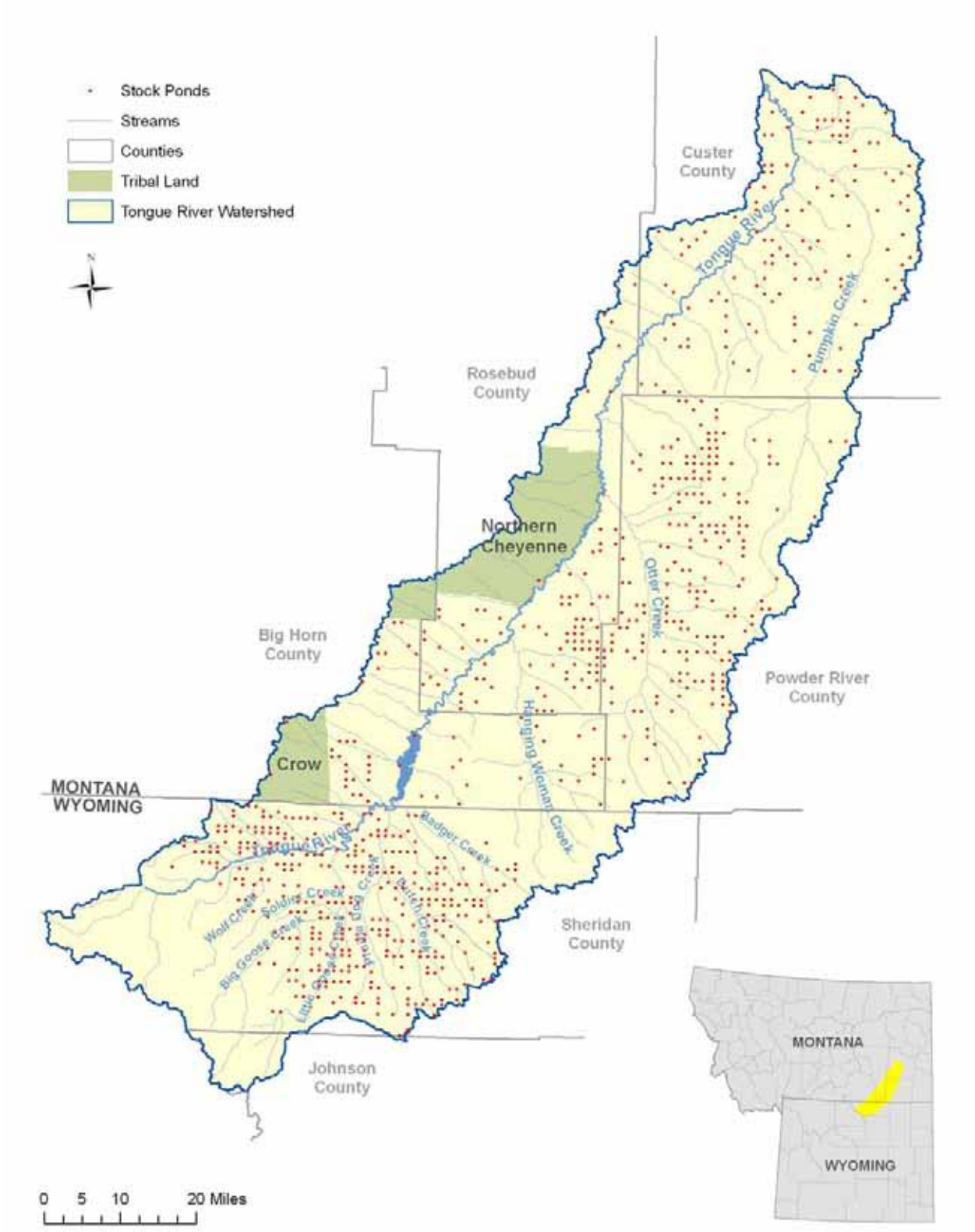


Figure 3-21. Location of stock ponds in the Tongue River watershed.

3.9 High-Altitude Reservoirs and Diversions

Small lakes and reservoirs are prolific throughout the Bighorn Mountains, particularly in the Goose Creek watershed (southeast portion of the Tongue River watershed in the Bighorn Mountains). Several of the reservoirs store mountain snowmelt and are regulated to provide irrigation and drinking water to downstream users. A series of dams, diversions, and ditches exist to store and move irrigation water as needed. Figure 3-22 provides a simplified schematic of the reservoirs and diversions in the Goose Creek watershed.

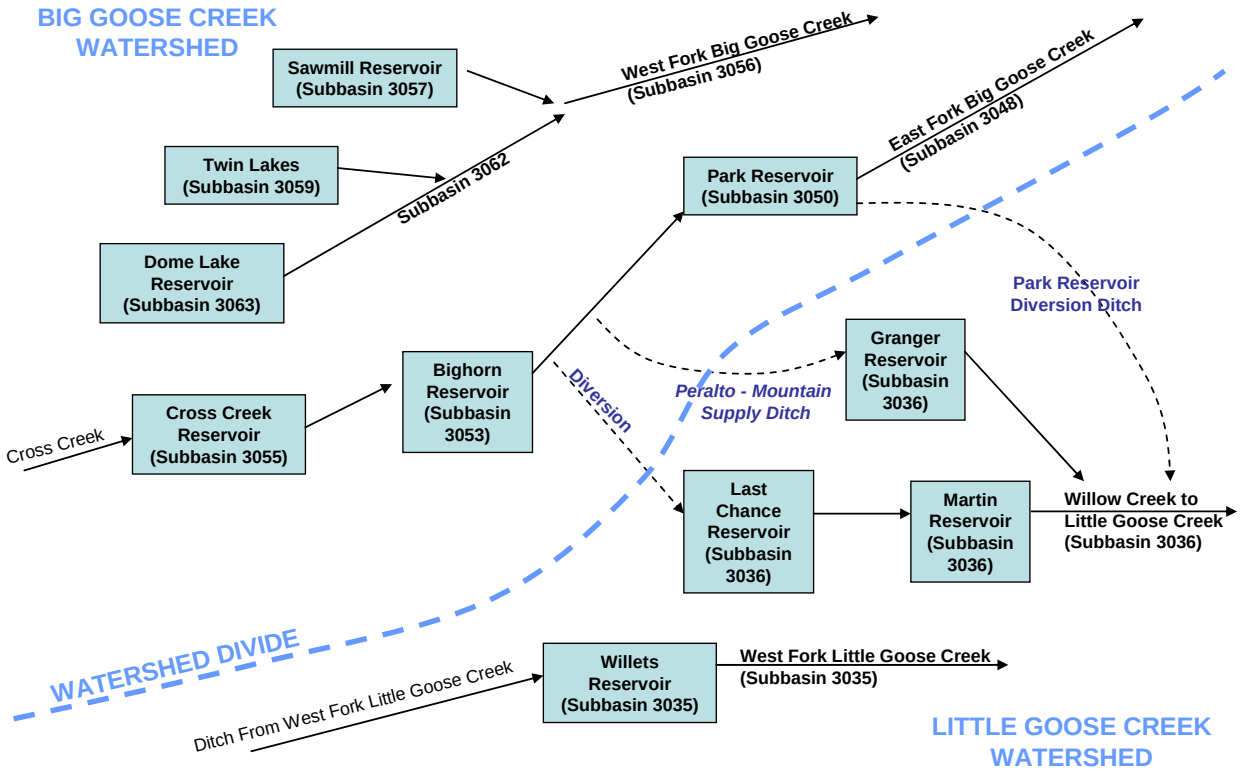


Figure 3-22. Simplified schematic of high-altitude reservoirs and diversions in the Goose Creek watershed (not to scale).

The five major high-altitude reservoirs in the Goose Creek watershed were included in the LSPC model – Bighorn, Dome Lake, Park, Sawmill and Twin Lakes Reservoirs. The remaining smaller reservoirs (i.e., Willets, Last Chance, Martin, Cross Creek, and Granger Reservoirs) were not modeled because information indicates that the reservoirs are too small to have a substantial impact on watershed hydrology (i.e., Last Chance and Granger Reservoirs have a 90 and 146 acre-foot capacity, respectively), reservoirs are not always filled (e.g., Willets, Martin, and Granger Reservoirs), or reservoir operation is captured in a more downstream reservoir (i.e., Cross Creek and Last Chance Reservoirs) (USFS, 2005) (SEO, 2001;2002;2003;2004;2005).

The five reservoirs were established in the LSPC model based on the reported reservoir storage, depth, and outlet information summarized in the Powder/Tongue River Basin Plan, Technical Memoranda J – Storage Operation and Description (WWDC, 2002g). Model input parameters are summarized in Table 3-14.

Table 3-14. Summary of modeled high-altitude reservoirs and their associated input parameters.

Reservoir Name	LSPC Subbasin	Year Completed	Dam Height (ft)	Modeled Storage (acre-feet)
Bighorn	3053	1909	29	4,629
Dome Lake	3063	1907	23	1,506
Park	3050	1933	71	10,362
Sawmill	3057	1960	31	1,275
Twin Lakes	3059	1937	67	4,042

The high altitude reservoirs are all managed to store mountain snowmelt and supply water to downstream users when needed. Managed releases were simulated in LSPC based on measured release data, diversion data, and high altitude USGS gages. The simulation of releases for each reservoir is described below.

- **Bighorn Reservoir –** Modeled releases from this reservoir were based on the times series of data for the Mountain Supply Diversion (obtained from the Wyoming SEO and Tongue/Powder Basin Plan) (WWDC, 2002g). An average of 25 cfs is released from the reservoir (subbasin 3053) between June and September of each year. Water is diverted into the Little Goose Creek watershed (subbasin 3036) via the Mountain Supply Ditch. Any overflows were allowed to spill over and were routed downstream to subbasin 3050.
- **Dome Lake –** A daily time series of releases from 2001 to 2005 was available from the Wyoming SEO. This time series was directly used to model releases from Dome Lake (from subbasin 3063 to 3062). The average monthly flow was calculated from the daily time series and applied to the years 1990-2000. An average of 12 cfs is released between June and September of each year. Any overflows were allowed to spill over and were routed downstream to subbasin 3062.
- **Park Reservoir –** The Park Diversion Ditch diverts water from the Park Reservoir (subbasin 3050) into the Little Goose Creek watershed (subbasin 3036). Wyoming SEO data state that an average of 16 cfs is diverted into this ditch between June and September of each year. The reservoir operator is also required to maintain a minimum of 4.5 cfs of water in the East Fork Big Goose Creek during the irrigation season (WWDC, 2002g). This withdrawal was routed out of the reservoir and into subbasin 3048. Any overflows were allowed to spill over and were routed downstream to subbasin 3048.
- **Sawmill Lake –** There were no available monitoring data for releases from the Sawmill Reservoir. The Tongue/Powder Basin Plan states that 15 cfs is initially released from the reservoir in late July (from subbasin 3057), and that the flow tapers to 5 cfs by the end of the season (WWDC, 2002g). Releases were modeled as 15 cfs starting on July 25 of each year and decreasing to a flow of zero on September 30. Water is released into subbasin 3056. Any overflows were allowed to spill over and were routed downstream to subbasin 3056.
- **Twin Lakes –** There were no available daily or monthly monitoring data for releases from the Twin Lakes Reservoir. The Tongue/Powder Basin Plan states that the reservoir is used to maintain 1 to 6 cfs of water in the West Fork of Big Goose Creek, with three days of flushing flows each year, generally in May or June (WWDC, 2002g). A time series of releases was created for the LSPC model to mimic this description. The 50 cfs of flushing flow was modeled as occurring on May 30-June 1 of each year. Water is released from the reservoir (subbasin 3059) to subbasin 3062. Any overflows were allowed to spill over and were routed downstream to subbasin 3062.

Three major high altitude diversions move water from the Big Goose Creek to the Little Goose Creek watersheds (see Figure 3-22). The Park Diversion diverts flow from Park Reservoir to Willow Creek and the Mountain Supply Diversion diverts water from the East Fork of Big Goose Creek to the Granger

Reservoir and Willow Creek (WWDC, 2002g). Another diversion moves water from the West Fork of Big Goose Creek to the Last Chance Reservoir and Willow Creek.

Flow data for the Park and Mountain Supply Diversions were obtained from the Tongue/Powder River Basin Plan Technical Memoranda A – Irrigation Diversion Operation and Description (WWDC, 2002d). Continuous flow data for the Park Diversion and Mountain Supply Diversion were also obtained from the Wyoming State Engineer's Office (SEO, 2006). Diversions were modeled based on the reported flow data and period of operation for each year. Water is withdrawn and the specified flow and modeled concentration and input into the appropriate LSPC subbasin. The diversion from the West Fork of Big Goose Creek to the Last Chance Reservoir was not modeled because data indicate that the Last Chance Reservoir is only periodically filled (SEO; 2001-2006).

3.10 Other Diversions

Diversions are prolific throughout the Tongue River watershed, and are generally used to supply irrigation water to cropland near the point of diversion. The amount of diverted flow widely varies, and can range from less than 1 to more than 100 cfs of water (WWDC, 2002d). In Wyoming alone, 248 points of diversion were identified in the Tongue River watershed by the Powder/Tongue Basin Plan (WWDC, 2002a). Similar data were not available for Montana.

Little flow data are available for diversions. Some larger diversions have continuous flow meters, and Wyoming SEO and Montana DNRC personnel periodically obtain spot measurements on smaller diversions. For the most part, the location, volume of timing of diverted water in the Tongue River watershed is largely unknown. Furthermore, in the case of larger diversions serving multiple users, it is not clear which fields are irrigated from the diversion at what time and volume.

Because of the large uncertainty in the diversion data, a simplified approach was chosen for modeling diversions in LSPC. Only diversions that move a large amount of water (i.e., more than 10 cfs) between modeling subbasins were included in the LSPC model. The remaining diversions were not explicitly modeled, but were implicitly captured in the irrigation module (further described in Section 3.11). Water for irrigated land was withdrawn directly from the modeled stream segment (as opposed to from a diversion). This method assumes that irrigated land within a modeling subbasin (as defined in Section 3.2) receives water from the stream segment in the same modeling subbasin.

Two of the major high altitude diversions (Mountain Supply and Park Diversions) were previously discussed in Section 3.9. The other five modeled diversions are discussed individually in Sections 3.10.1, 3.10.2, and 3.10.3.

3.10.1 Mead-Coffeen, Piney-Cruse, and Prairie Dog Diversions

Three ditches (Mead-Coffeen, Piney-Cruse, and Prairie Dog) divert water from the Powder River watershed (Piney Creek near Story, WY) to the Tongue River watershed (WWDC, 2002d). Water is delivered to the Prairie Dog Creek and Little Goose Creek subwatersheds, as shown in Figure 3-23. The diversions were setup in the LSPC model based on flow records obtained from the Tongue/Powder River Basin Plan and Wyoming SEO (WWDC, 2002d; SEO, 2006b). Average monthly flow data were available through 2000, and daily data were available from 2001 to 2005. An estimated average monthly flow was used for 2006. Both the Piney-Cruse and Prairie Dog Ditches divert water solely to the Prairie Dog Creek watershed. These diversions were routed to modeling subbasin 3009. The Meade-Coffeen Ditch provides irrigation water to both the Prairie Dog Creek and Little Goose Creek subwatersheds. Based on the irrigation data provided in the Tongue/Powder River Basin Plan, 40 percent of the flow from

the Meade-Coffeen Ditch was routed to the Little Goose Creek watershed (LSPC modeling subbasin 3027) and 60 percent was routed to the Prairie Dog Creek watershed (LSPC modeling subbasin 3009) (WWDC, 2002d). Table 3-15 summarizes the ditches and average monthly flows.

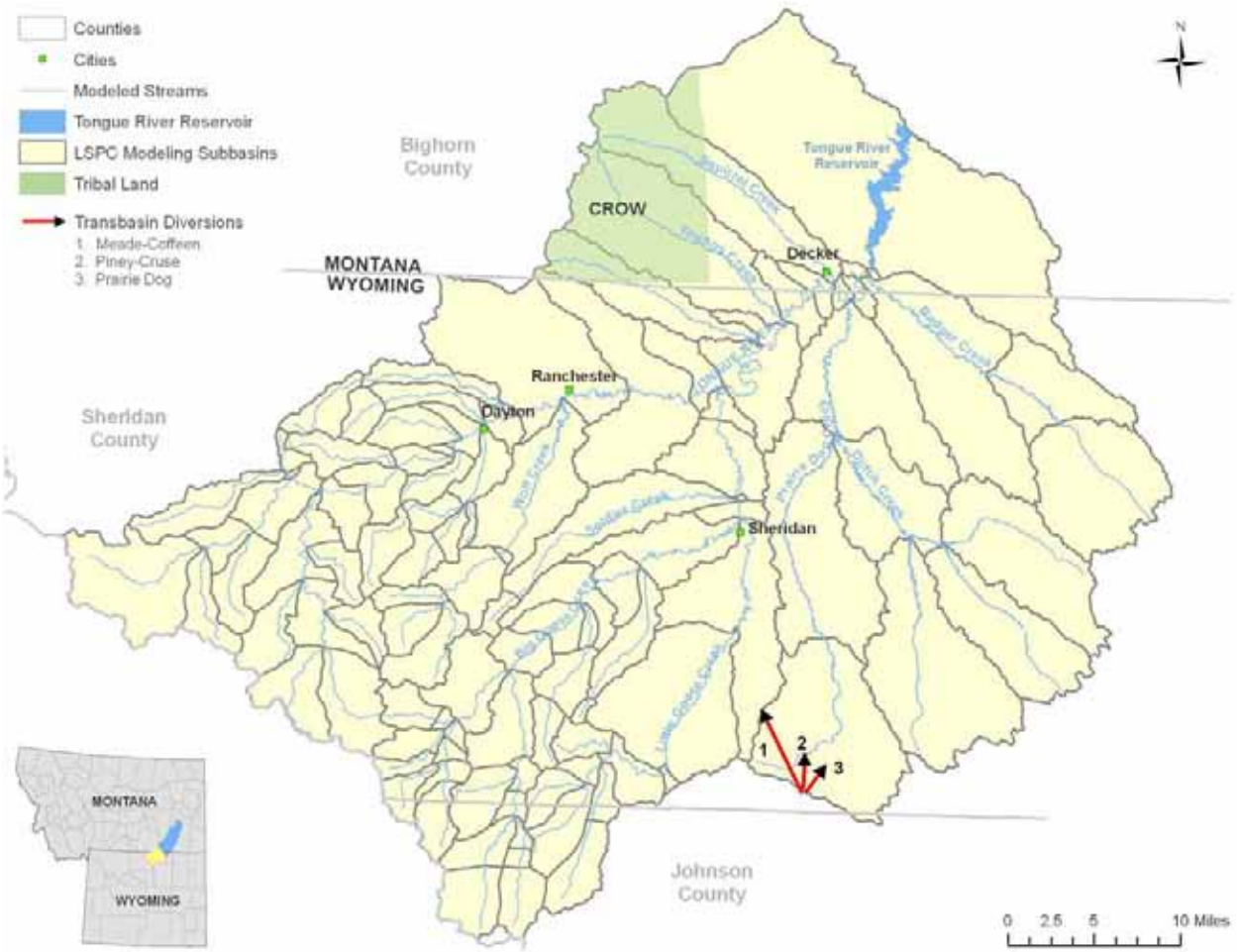


Figure 3-23. Transbasin diversions from the Powder River watershed to the Tongue River watershed.

Table 3-15. Average monthly flow (cfs) for the three diversions from the Powder River watershed.

Diversion	LSPC Subbasin	Apr	May	Jun	Jul	Aug	Sep	Oct
Meade-Coffeen (To Prairie Dog Creek)	3009	1.6	3.2	6.4	8.4	8.2	5.6	0.0
Meade-Coffeen (To Little Goose Creek)	3027	1.0	2.1	4.3	5.6	5.5	3.7	0.0
Piney-Cruse	3009	3.0	7.1	11.5	14.5	14.5	9.8	0.0
Prairie Dog	3009	15.1	39.6	48.4	53.8	50.0	25.3	0.0
Total Flow Imported from Piney Creek		**20.7**	**52.0**	**70.7**	**82.3**	**78.2**	**44.4**	**0.0**

WWDC, 2002d

No water chemistry data were available for the three diversions, and few data were available for Piney Creek (Personal Communications, Michael Whitaker, Wyoming SEO, December 26, 2006). Water chemistry data from the Tongue River at Dayton (USGS Gage 06298000) were used in the LSPC model to represent the water chemistry of the diverted water from Piney Creek. This gage was chosen because it is geographically similar to Piney Creek near Story, Wyoming. Both locations are at the base of the Bighorn Mountains and consist primarily of mountain runoff. Both are also located before any major influences from anthropogenic sources (e.g., irrigation, point sources, etc.). Finally, the Tongue River at Dayton was chosen because it has a robust set of water chemistry data from 1966 to 2002, and all of the parameters of concern (i.e., calcium, magnesium, sodium, total nitrogen, and total phosphorus) are available. Average monthly values of calcium, magnesium, sodium, total nitrogen, and total phosphorus were obtained from this gage and input into the LSPC transbasin time series.

It is acknowledged that this approach introduces some error and uncertainty into the model. The Tongue River at Dayton is located more than 25 miles from Story, Wyoming, and undoubtedly has different water chemistry concentrations than observed in Piney Creek. Second, there is year-to-year variability in water chemistry data which is not being represented by using a monthly average approach. Future collection of water chemistry data in Piney Creek and/or the three diversions could help to strengthen model performance and reduce error.

3.10.2 Tongue and Yellowstone Diversion

The Tongue River Diversion Dam is located on the Tongue River near the confluence of Pumpkin Creek and approximately 12 miles upstream of Miles City. Water is diverted out of the Tongue River at the dam for use in both the Tongue River watershed and the Yellowstone River watershed. The diversion was input into the LSPC model based on daily flow data provided by Montana DNRC (DNRC, 2006b). Data were only available from 1997 to 2005. Average monthly values were calculated and input into the model for 1990 to 1996. Water was diverted out of subbasin 1026 and routed out of the watershed. The average flow for the diversion was 129 cfs, and it was generally operational from May to October of each year.

3.10.3 Sheridan Water Treatment Plant

The City of Sheridan diverts water out of Big Goose Creek near the canyon for use in the city's public water supply (WDEQ, 2006d). Flow data for the diversion were obtained from the Powder/Tongue Basin Plan and the Wyoming SEO. Daily flow data were available from 2001 to 2005, and average monthly data were available from 1990 to 2000. Diverted flow ranges from 4 to 19 cfs, with an average of 8 cfs (WWDC, 2002d; SEO, 2006). Flow is diverted year-round and exhibits a seasonal pattern, with more flow diverted in the summer and less in the winter. In the LSPC model, water was diverted out of subbasin 3046 and ultimately routed out of the model. Returns from Sheridan's water supply were captured as part of the Sheridan Wastewater Treatment Plant discharge to Goose Creek (see Section 3.7.1).

3.11 Irrigation

Irrigation and other water withdrawals/diversions are a potential source of pollutants in the Tongue River watershed. Through irrigation, crops uptake water and concentrate salts in the root zone. Additional leaching then moves salts out of the root zone, where they mix with alluvial groundwater (MDEQ, 2001). The net effect to the surface-groundwater system is a loss of water (by plant uptake) and a higher concentration of salts. However, water withdrawals have another indirect effect on in-stream concentrations. Any water withdrawal results in less surface water volume, as only some, but not all of the water is returned to the river via return flows, springs, and groundwater recharge. Because there is less surface water, evaporation and additional high salinity inputs (from tributaries, point sources, and/or groundwater) can lead to higher in-stream salinity concentrations. Irrigation practices also alter the timing of natural hydrology due to diversions and reservoir releases.

Adequately simulating the impacts of irrigation is critical to obtaining a thorough understanding of both current and "natural" water chemistry issues in the Tongue River watershed. However, there is little available information about the amount of water applied to irrigated land. Major diversions often have flow gages or flow grab samples, but they do not indicate how much water is actually applied to the land, when the water is applied, and which specific parcel of land is irrigated from the diversion. Water rights information was available from both the Montana DNRC and Wyoming SEO, but rights are often over-appropriated, and again do not indicate the exact volume of water withdrawn at a specific time. The irrigated land analysis (as described in Section 3.5.2) defines the location of irrigated land, but even this information has associated errors. The amount of irrigated land can change per year based on development, fallowed land, and precipitation. Because it was not in the scope of this analysis to precisely define the volume and timing of applied irrigation water, a simplified method for simulating irrigation was chosen for the LSPC model.

Irrigation withdrawal volumes were modeled in LSPC as a function of the irrigation demand (defined as the difference between effective-crop-potential evapotranspiration [PEVT] and precipitation [PREC] evaluated over a user-specified window of days). Since local field data were available for consumptive irrigation requirements (CIR), which have already taken into account demand and transport losses, irrigation rate (direct withdrawal volume) was used instead of computing demand. A weighted average withdrawal volume was computed based on the consumptive irrigation requirements (CIR) for alfalfa, beans, corn, and pasture at Sheridan, Wyoming. Table 3-16 shows the computed weighted average CIR used in the LSPC model for all irrigated land.

Table 3-16. Crop irrigation requirements for irrigated land in the Tongue River watershed.

Weight:	0.884	0.020	0.003	0.093	Weighted Average
Month	**Alfalfa**	**Beans**	**Corn**	**Pasture**	**Typical CIR (in)**
Jan	0.0000	0.0000	0.0000	0.0000	**0.0000**
Feb	0.0000	0.0000	0.0000	0.0000	**0.0000**
Mar	0.0000	0.0000	0.0000	0.0000	**0.0000**
Apr	0.0000	0.0000	0.0000	0.0000	**0.0000**
May	1.8381	0.0000	0.0000	0.1738	**2.0120**
Jun	3.5084	0.0560	0.0070	0.3346	**3.9058**
Jul	5.6912	0.1197	0.0199	0.5532	**6.3841**
Aug	4.6749	0.0712	0.0196	0.4682	**5.2339**
Sep	2.1916	0.0000	0.0097	0.2177	**2.4191**
Oct	0.6186	0.0000	0.0000	0.0579	**0.6765**
Nov	0.0000	0.0000	0.0000	0.0000	**0.0000**
Dec	0.0000	0.0000	0.0000	0.0000	**0.0000**
Total CIR	**18.5228**	**0.2469**	**0.0562**	**1.8054**	**20.6314**

Adapted from Trelease et al., 1970

Based on the irrigated land analysis described in Section 3.5.2, full-supply and partial-supply irrigation areas were input as independent land use categories in the LSPC model. Areas defined as having full supply irrigation were assumed to be irrigated at 100 percent of the CIR, while partial supply irrigation areas were assumed to be irrigated at 50 percent of the CIR. Full-supply irrigation was assumed to be 60 percent sprinkler and 40 percent flood irrigation, while partial supply assumed to be 100 percent flood irrigation.

The difference between sprinkler and flood irrigation in the model is the storage compartment or pathway where irrigation water is reintroduced to the land segment. Sprinkler irrigation is subject to interception storage (trapping by plant leaves or branches) in the same way as direct precipitation. Flood irrigation bypasses interception and is applied directly to the land surface.

The irrigation rate in the model is computed using a monthly variable multiplier for the PEVT time series such that the long-term monthly CIRs, as defined in Table 3-16, are maintained. Years with higher PEVT will require more irrigation, while years with lower PEVT will require less; however, the long-term monthly CIR relationship is preserved. This method also assumes that irrigated acreage does not change over the modeling time period, that the same land is irrigated every year, the same crops are grown, and the same type of irrigation (flood versus sprinkler) is the same from year to year. It was also assumed that irrigation does not occur if the stage of the stream falls below 0.1 ft, reflecting that fact that irrigation relies on a minimum volume of water in the stream to be viable.

3.12 Surface and Subsurface Water Chemistry Concentrations

The LSPC model simulates flow to perennial streams by three different pathways: surface runoff, interflow, and groundwater discharge. Surface runoff, by definition, proceeds across the land surface when infiltration capacity is exceeded. Interflow represents short-distance lateral subsurface pathways, typically occurring on hill slopes when capacity for deep infiltration is exceeded. Interflow proceeds laterally through soils beneath the root zone (typically via the B or upper C soil horizon), and, in a model at the large scale represented by the Tongue, typically emerges to join surface flow within the physical dimensions of model subbasins. Groundwater discharge represents slower discharge from the surficial aquifer. Groundwater flow proceeds through the saturated zone at and below the water table.

Flows from these three pathways encounter different geologic media that have different chemical compositions. The varying chemical compositions result in varying surface runoff, interflow, and groundwater concentrations. Concentrations also vary spatially as soils and geology formations change throughout the Tongue River watershed. The following sections describe the methodology used for assigning water chemistry concentrations to surface runoff, interflow, and groundwater pathways in the LSPC model.

3.12.1 Surface Runoff Concentrations

Concentrations of cations in direct surface runoff are generally not of major concern. Except in areas of high water tables or confined depressions, precipitation tends to leach salt from the surface into the subsurface, rather than creating high concentrations in runoff, and runoff from intense precipitation events may not have time to achieve equilibrium with soil salt concentrations (Tuteja et al., 2002). Because of this, it was assumed that surface runoff concentrations are equal to the concentrations in precipitation. Average concentrations of calcium, magnesium, and sodium in precipitation were obtained from the National Atmospheric Deposition Program's (NADP) Little Bighorn Battlefield monitoring gage (located southeast of Billings, Montana) and average values were initially applied in the LSPC model (NADP, 2006). Average values were 0.182 mg/L Ca, 0.026 mg/L Mg, and 0.059 mg/L Na. Values were then slightly varied during calibration. Nutrient surface runoff concentrations were modeled using build-up wash-off routines, as described in Section 4.2.2.

3.12.2 Subsurface Concentrations

Both interflow and groundwater concentrations are difficult to characterize in the Tongue River watershed because of the wide spatial and vertical variations. The various sources of interflow and groundwater chemistry data are discussed below (literature review), followed by the rationale and assumptions used for setting concentrations in the LSPC model.

3.12.2.1 Literature Review

In the arid climate of the Tongue River, the water table can be at considerable depth below the ground surface – except in alluvial and irrigated areas (WWDC, 2002f). Outside of alluvial areas, groundwater concentrations should reflect the geochemistry of the surface aquifer – as either determined from wells screened in the upper aquifer or by geochemical modeling of the uppermost saturated geologic formation. Within alluvial/irrigated areas with higher water tables, the groundwater discharge concentrations most likely reflect the concentrations observed or calculated at the bottom of the soil C horizon, which consists of fractured but unweathered regolith.

Bedrock geology of the Tongue River basin in Montana is primarily occupied by the Fort Union formation with a small amount of the Wasatch formation (Lewis and Roberts, 1978; WWDC, 2002b). These two formations have similar Tertiary deposits containing interbedded layers of sandstone, siltstone, mudstone, limestone, coal, and carbonaceous shale deposited by fluvial and swampy systems (USGS, 1999). In the Wyoming portion of the basin the plains area is primarily Wasatch east of Sheridan. To the south and west the uplift of the Bighorn Mountains exposes older Fort Union shales along the margins, with limestone, dolomite, and plutonic rocks, among others, at higher elevations. Groundwater geochemistry is expected to be generally similar in the Wasatch and Fort Union areas (although subject to significant local variability), but is likely to be quite different in the Bighorn Mountains.

Recent USGS studies of ground water in the Wasatch and Fort Union formations in the Powder River basin (Bartos and Ogle, 2002) report median values of 225 mg/L Na, 15.5 mg/L Ca and 15.4 mg/L Mg, while samples from coalbed aquifers had median values of 210 mg/L Na, 26 mg/L Ca, and 15 mg/L Mg. The interquartile range for Na is 90 to 480 mg/L. Ca and Mg concentrations in these samples are apparently lower than expected in discharge because both ions (unlike Na) have a significant negative correlation with depth. Shallow wells, which are the ones most likely associated with discharging groundwater, tend to have much higher concentrations of Ca and Mg.

Very few well samples appear to be available from the Bighorn Mountains. However, Larson and Daddow (1984) do report five samples from the Madison Limestone, which is present across much of the western portion of the Upper Tongue area. These samples are highly depleted in Na (0-1 mg/L) with 15-30 mg/L Mg and 40-88 mg/L Ca.

Detailed information on ion concentrations in irrigated alluvial soils at 15 sites in the Tongue basin is provided in the 2006 Agronomic Monitoring and Protection Program (AMPP) report (Schafer et al., 2006). The authors conclude that ion concentrations (as meq) at the base of the soil profile are little affected by irrigation and, as noted above, these saturation paste results can potentially be used to estimate discharging groundwater concentrations. The results for these soils show considerable variability from site to site (Figure 3-24), particularly for Na which ranges from 81 to 6250 mg/L. Median concentrations are shown in Table 3-17.

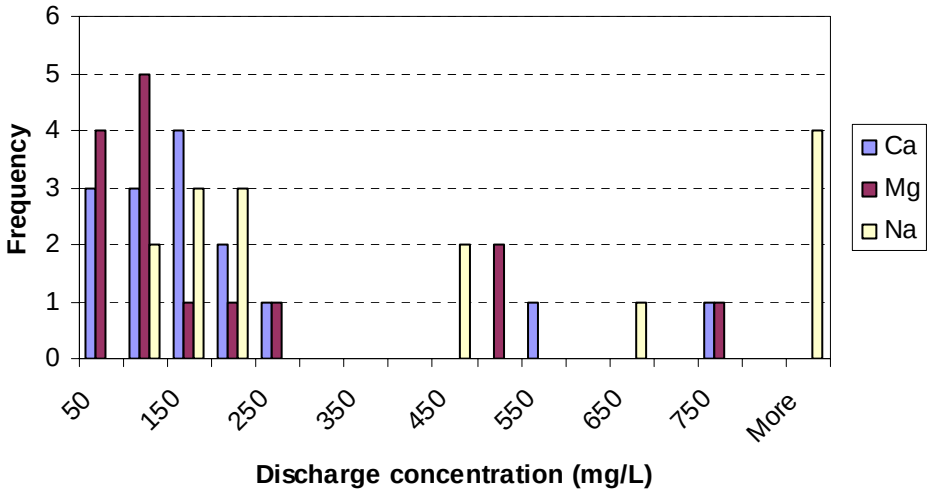


Figure 3-24. Histogram of Discharge Concentrations from Base of C Horizon, AMPP Alluvial Soils (calculated from data in Schafer et al., 2006)

Table 3-17. Summary of Discharge Concentrations (mg/L) from Base of C Horizon, AMPP Alluvial Soils (calculated from data in Schafer et al., 2006)

Parameter	Median	Mean	Geometric Mean
Calcium	112.2	175.3	119.7
Magnesium	82.7	175.4	96.3
Sodium	197.7	1,154.7	386.7

The NRCS soil surveys provide information on salinity (as SC) and SAR for soils throughout the nation. This provides some insights into the expected spatial variability of subsurface salt concentrations, but the information turns out to be of somewhat limited value for the following reasons:

- SAR and SC results are reported only as relatively broad ranges (e.g., SC of 1 to 8 µmhos/cm). The use of broad ranges does not provide sufficient precision to accurately resolve the Na concentration using the equations given above.
- Upland soil profiles often do not extend to the full extent of the overburden. Further, except in alluvial areas, the water table position is likely to be in the bedrock, so that soil profile data tells us little about saturated flow concentrations.
- Given only SAR and SC, there is no firm basis for assumptions about the ratio of Ca to Mg equivalence or the concentration of minor cations.

Despite these calculations, some qualitative comparisons can be made. Estimated discharge concentrations from the basal horizon of alluvial soils in the prairie region of the watershed in Montana (Map Unit MT668) and Wyoming (Map Unit WY055) are compared in Table 3-18, using weighted percentages of the Map Units ID (MUID) components, and with the additional assumptions that the concentration of minor cations is 5 mg/L and that the ratio (in meq) of Ca:Mg is 60:40.

Table 3-18. Calculated discharge concentrations from alluvial soils.

Soil MUID	Ca (mg/L)	Mg (mg/L)	Na (mg/L)
MT668	233	256	592
WY055	268	294	121

These results suggest that prairie ground water in the Upper Tongue watershed (i.e., predominantly in Wyoming) should have a lower concentration of Na, lower SAR, and higher Ca and Mg than ground water in the Lower Tongue. The difference between the MT668 and WY055 results in Table 3-18 is primarily due to the presence of three soils with elevated SAR (Map Units MT0106, MT0286, and MT0181), the last two of which also have elevated salinity, that compose about 17 percent of the MUID. In contrast, basal horizon SAR values in Wyoming alluvial soils are low, and generally similar to the remaining soil components in MT668. This suggests that the aerial extent of high-SAR soils (at bottom of soil profile) could provide a useful basis to vary groundwater concentrations by watershed.

3.12.2.2 Modeled Subsurface Concentrations

Based on the research discussed in Section 3.12.2.1, there is no clear and precise external source of information available to set subsurface cation concentrations generally throughout the LSPC Tongue River modeling domain. There are, however, a variety of sources of information that help inform and constrain potential concentrations. These constraints were used to help calibrate the subsurface concentrations (described in 4.2). The rationale and assumptions for setting subsurface concentrations in the LSPC model are described below. Final calibrated values are discussed in Section 4.2.

Ground Water

Groundwater concentrations were assumed to primarily reflect chemistry of the underlying aquifer – especially the chemical characteristics near the discharge point.

Prairie. Concentrations were set based on local spring data obtained from the USGS NWIS Database. Median values were used as constant annual values for all land uses. Limited data were available for most of the region, and this is believed to be a major source of uncertainty in the LSPC model (see Section 5.7.7)

Mountains. Available evidence suggests that ground water from this area has low sodium concentrations and moderate Ca and Mg. Concentrations were set as annual average values for all land uses using the data reported by Larson and Daddow (1984). As with the prairie region, limited data were available.

Irrigated Land. For groundwater discharges from irrigated lands cation concentrations are primarily determined by soil characteristics (under current irrigation water chemistry). The best available evidence for this component appeared to be the median values derived from the AMPP study (Schafer et al., 2006), as summarized in Table 3-17. These were used as starting values for the model but subsequently adjusted during calibration.

Alluvial Channels downstream of Ponds. Infiltration from ponds sub-irrigates the ephemeral channel downstream (see Section 3.7.2.2 and 3.8). Given the assumption that groundwater concentrations are determined primarily by the underlying bedrock – but influenced by the elevation in water table, these groundwater concentrations were set equal to those for irrigated land.

Interflow

Interflow represents shorter lateral flow pathways through the subsoil. Concentrations should differ from those in ground water due to mineralization of Ca and Mg, but Na concentrations are likely to be similar (Wheaton and Brown, 2005). It should be noted that LSPC (and the HSPF model from which it is derived) route interflow from surface detention storage prior to entry into the soil profile. Functionally, however, interflow is used to represent lateral subsurface flow through the soil that occurs more rapidly than groundwater flow from the water table. This occurs when vertical infiltration capacity is exceeded at some point in the unsaturated soil profile. In arid climates, this conversion to lateral flow may occur at a significant depth – despite the way it is represented in LSPC – allowing time for desorption of salts in the upper soil profile.

Prairie. Sodium concentrations in interflow were set equal to those in groundwater. Calcium and magnesium concentrations are, however, likely to be enriched due to the shorter flow pathways, whereas concentrations in ground water are reduced by mineralization. Assuming that mineralization rates of Ca

and Mg are approximately similar, the interflow concentrations were adjusted upward by a single calibration factor, K_I.

Mountains. For the Upper Tongue Mountains, cation concentrations are low and soil profiles are short. For this region it was appropriate to set equal groundwater and interflow concentrations.

Irrigated Land. Schafer et al. (2006) demonstrate a peak in cation concentrations at an average depth of 3 feet, likely coincident with the main locus of lateral flow under saturated conditions. (The result could, however, be an artifact of the drought conditions of recent years.) As with groundwater, this source appears to be the best information currently available. For irrigation with existing river water, interflow concentrations were initially set to the average 3-ft peak shown in Figure 5-10 of Shafer et al. (2006), which has an SAR of 4.0 and SC of 5.4. This translates to discharge cation concentrations of 521 mg/L Ca, 389 mg/L Mg, and 1012 mg/L Na. As with groundwater discharge from irrigated land, these concentrations were adjusted during calibration.

Alluvial Channels Downstream of Ponds. Water exfiltrating from ponds is assumed to be applied to soil storages and is available for plant ET, but not for interflow. Interflow will occur only in response to direct precipitation (or snowmelt) on the channel area. The subirrigation will, however, raise the water table, and any simulated interflow will likely be mixed with ground water. Therefore, infiltration concentrations were set equal to groundwater concentrations for this area.

4.0 LSPC CALIBRATION

Calibration is defined as "the process of adjusting model parameters within physically defensible ranges until the resulting predictions give the best possible fit to the observed data" (USEPA, 2003). For LSPC, calibration is required for both hydrology (flow) and water chemistry and is an iterative procedure of parameter evaluation and refinement as a result of comparing simulated and observed values at specified locations in a watershed. Calibration is required for parameters that cannot be deterministically and uniquely evaluated from topographic, climatic, physical, and chemical characteristics of the watershed and compounds of interest. Because these characteristics vary throughout a watershed, calibration generally occurs at more than one site. Also, calibration generally covers several years to capture a variety of climactic conditions. The calibration procedure results in parameter values that produce the best overall agreement between simulated and observed values throughout the calibration period.

Several different methods were employed to judge the adequacy of the model fit to the observed data. Hydrologic calibration followed the standard operating procedures for the model described in Donigian et al. (1984) and Lumb et al. (1994). Daily, monthly, seasonal, and total modeled flows were compared to observed data, and error statistics were calculated for the percent difference (i.e., [Modeled – Observed]/[Observed] *100). The percent errors were then compared to recommended tolerance targets from Donigian et al. (1984) and Lumb et al. (1994). Tolerance targets for the flow simulation were modified slightly from the literature values to better assess the Tongue River watershed calibration. Donigian et al. (1984) and Lumb et al. (1994) recommend seasonal targets (e.g., spring, summer) of ±30 percent. The targets were used to assess monthly results (e.g., January, February) and growing season results (i.e., growing season versus non-growing season), which are the basis for the Montana salinity and SAR water quality standards. Targets are show in Table 4-1. Model results were also visually compared to observed data, and daily and monthly data were plotted as scatter plots with regression analyses.

Table 4-1. Recommended criteria for the Tongue River watershed hydrology calibration.

Category	Recommended Criteria (%)
Error in total volume:	**±10**
Error in the mean of the 10% lowest flows:	**±10**
Error in the mean of the 10% highest flows:	**±15**
Error in Monthly Volumes:	**±30**
Error in Growing Season Volumes:	**±30**
Error in Nongrowing Season Volumes:	**±30**

Modified from Lumb et al., 1994 and Donigian et al. 1984

Fewer water chemistry data were available for most calibration locations. Where daily data were available, water chemistry calibration followed the standard operating procedures previously described for the hydrologic calibration. Donigian et al. (1984) suggest targets for the percent error in mean water chemistry data. The authors specifically note, however, that "tolerance ranges should be applied to mean values and that individual events or observations may show larger differences, and still be acceptable". Water chemistry at all locations was also judged with graphs, box plots, and scatter plots.

Table 4-2. Recommended criteria for the Tongue River watershed chemistry calibration.

Parameter	% Difference Between Simulated and Measured Values		
	Very Good	Good	Fair
Water Temperature	< 7	8 - 12	13 - 18
Water Quality/Nutrients	< 15	15 - 25	25 - 35

Source: Donigian et al. (1984)

The following sections discuss the methodology for calibrating the Tongue River LSPC model. Section 4.1 discusses the hydrologic calibration process, Section 4.2 discusses the water quality calibration process, Section 4.3 summarizes the results, and Section 4.4 presents information on the evaluation of the model. Final calibrated values for all input parameters in the LSPC model are included in the model input file, which is available upon request. All evaluated calibration tables and plots are included in Appendix B.

4.1 Hydrologic Calibration Methodology

Hydrologic calibration was performed at 13 USGS gages selected because they had continuous flow records for multiple years and were located in strategic positions throughout the Tongue River watershed. Table 4-3 summarizes the 13 USGS gages, and gages are shown in Figure 4-1.

Table 4-3. USGS monitoring sites used for the Tongue River LSPC model hydrology calibration.

Site Name	Station ID	Altitude (ft)	Drainage Area (mi^2)	LSPC Subbasin
Tongue River near Dayton, WY	06298000	4,060	206	3090
Tongue River at the Montana-Wyoming State Line, MT	06306300	3,429	1,453	3006
Tongue River at Tongue River Dam near Decker, MT	06307500	3,344	1,770	3112
Hanging Woman Creek near Birney, MT	06307600	3,150	470	1095
Otter Creek at Ashland, MT	06307740	2,917	707	1059
Tongue River near the Brandenberg Bridge, MT	06307830	2,760	3,948	3047
Pumpkin Creek near Miles City, MT	06308400	2,490	697	1007
Tongue River at Miles City, MT	06308500	2,360	5,379	1002
Wolf Creek at Wolf, Wyoming	06299950	4,525	38	3070
Big Goose Creek near Sheridan, Wyoming	06302000	4,505	120	3046
Little Goose Creek near Bighorn, Wyoming	06303500	4,860	52	3029
East Fork Big Goose Creek near Bighorn, Wyoming	06300500	8,320	20	3051
Coney Creek above Twin Lakes near Bighorn, Wyoming	06301480	8,690	3.4	3060

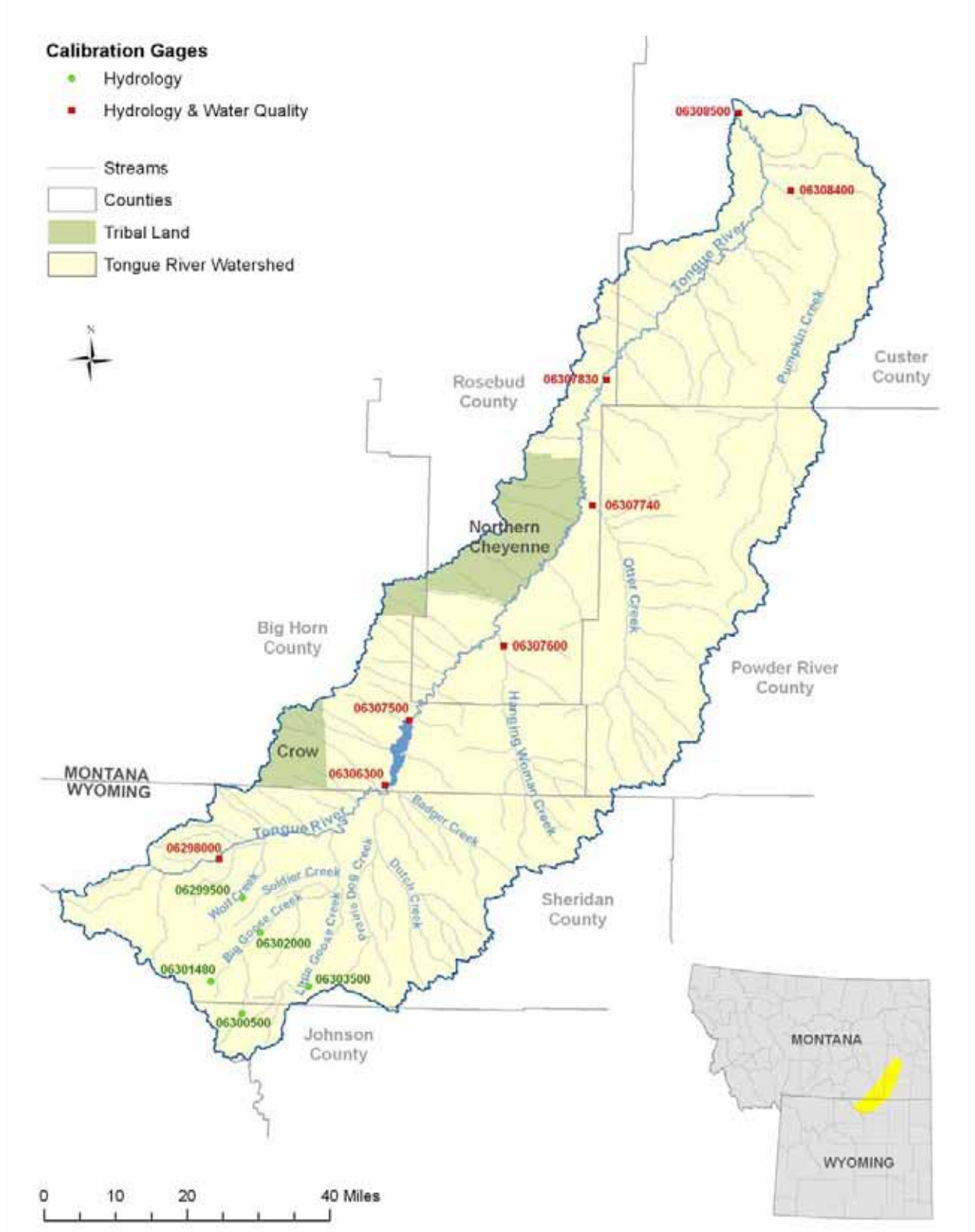


Figure 4-1. LSPC calibration sites for the Tongue River watershed.

The hydrologic calibration proceeded from upstream gages to downstream gages (as illustrated in Figure 4-1) and involved a comparison of observed data to modeled in-stream flow and an adjustment of key parameters. Modeling parameters were varied within generally accepted bounds and in accordance with observed temporal trends and soil and land cover characteristics. An attempt was made to remain within the guidelines for parameter values set out in BASINS Technical Note 6 (USEPA, 2000). The hydrology calibration initially focused on the period between water years 1992 and 1998 and the 1999 through 2006 period served as an informal validation period (it should be noted that the 1999 to 2006 period is not considered a formal validation period because, during calibration, model results for the entire period of record were also evaluated).

For the purpose of this report, the hydrologic calibration is further discussed in the two following sections – High Altitude (i.e., Bighorn Mountain) gages (Section 4.1.1) and Prairie gages (Section 4.1.2).

4.1.1 High-Altitude Hydrologic Calibration Methodology

Hydrologic calibration began in the Bighorn Mountains. Because most of the flow in the Tongue River (about 63% of all the water in the watershed) originates in the mountains, it was important to obtain an adequate calibration in this region to achieve calibrated results in the downstream region. Specifically, it was important to achieve an adequate snow budget (snow accumulation and melt processes). Snow accumulation and melting were calibrated by comparing model output to a computed snow budget based on the NRCS SNOTEL data. Key calibration parameters were revised from defaults during optimization and included the snow catch factor (SNOWCF, ratio that accounts for under-catch of snow in standard precipitation gages), the field adjustment parameter for heat accumulation in the snow pack (CCFACT), the maximum rate of snow melt by ground heating (MGMELT), and the difference between the mean elevation of a subwatershed and the gage elevation (ELDAT, to correct for temperature changes between the gage elevation and subwatershed elevation). Calibration at two SNOTEL gages (Dome Lake and Sucker Creek) show that snow processes are well represented in the Bighorn Mountains from 1989 through 2006 (Figure 4-2 and Figure 4-3).

Daily flow records at two USGS gages were used to further refine the high-elevation hydrologic calibration. Input parameters were varied to achieve calibrated results at USGS gages on Coney Creek and East Fork Big Goose Creek (USGS gages 06301480 and 06300500, respectively). Calibrated results are presented in Appendix B.

Downstream of the Coney Creek and East Fork Big Goose Creek gages, reservoirs, lakes, and diversions significantly alter stream flows. Water is stored and released from reservoirs to meet water supply demands, while diversions move water among various subbasins (i.e., from Big Goose Creek to Little Goose Creek) (see Section 3.9). Calibration at gages downstream of the reservoirs was reliant upon an adequate understanding of volume in the reservoirs and timing of releases. Four USGS Gages (USGS gages on Big Goose Creek, Little Goose Creek, Tongue River, and Wolf Creek) located at the base of the Bighorn Mountains were used to assess the final calibration for the high-altitude region.

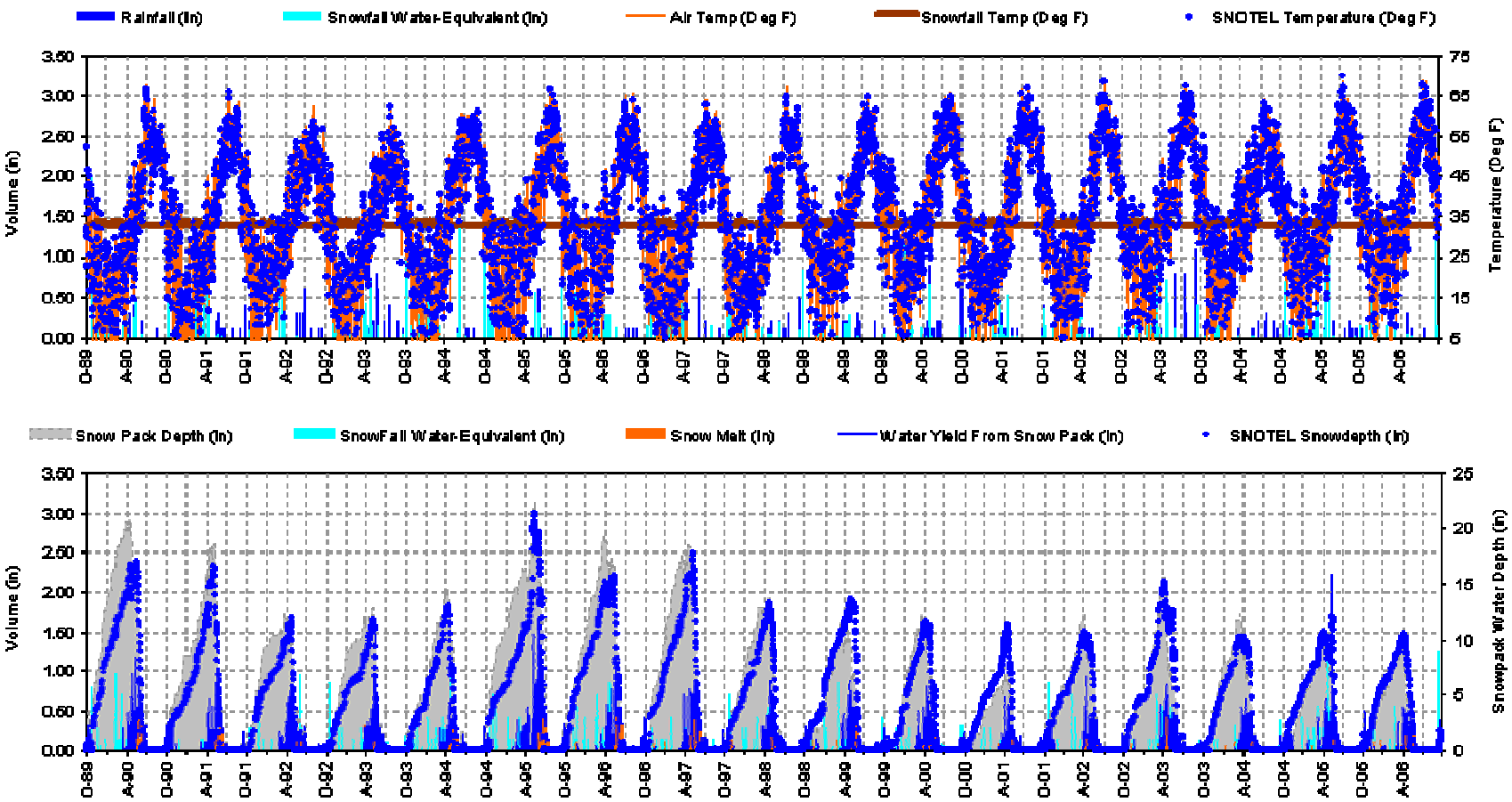


Figure 4-2. Snow budget for the Dome Lake SNOTEL gage.

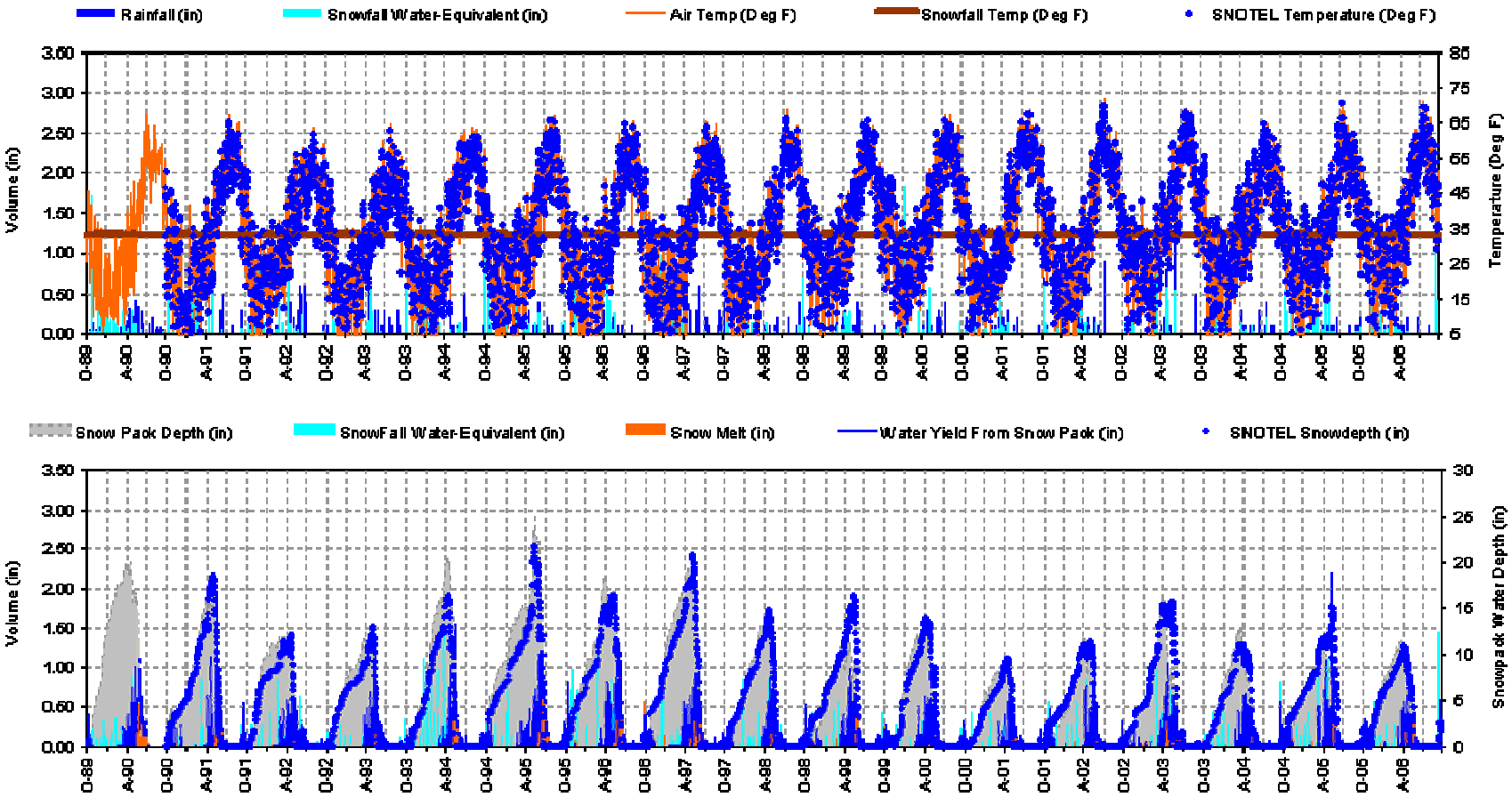


Figure 4-3. Snow budget for the Sucker Creek SNOTEL gage.

4.1.2 Prairie Hydrologic Calibration Methodology

In the Prairie region of the Tongue River watershed, model performance is sensitive to the specification of the water-holding capacity within the root zone of the soil profile (expressed through LZSN, the nominal lower-zone storage) and the infiltration rate index (INFILT), which together control the partitioning of water between surface and subsurface flow. Values for LZSN in the three watersheds ranged between 5 and 9 inches depending primarily on soil conditions.

INFILT in HSPF is an *index* of infiltration rate and is not directly interpretable from measured field infiltration rates. BASINS Technical Note 6 recommends values in the range of 0.1 to 0.4 in/hr for B soils, 0.05 to 0.1 in/hr for C soils, and 0.01 to 0.05 in/hr for D soils. Values were re-optimized by starting from the center of the recommended ranges and modifying the value for each soil class proportionately. Final values ranged between 0.008 and 0.24.

Interception of precipitation in LSPC is represented by a storage capacity (CEPSC) factor, which accounts for moisture that is retained by vegetation or other ground cover and not available for infiltration or overland flow. Calibrated values ranged between 0.00 and 0.40 inches, depending on land use and time of year.

Key parameters for the subsurface flow response include the ground water recession coefficient (AGWRC), and the interflow inflow and recession parameters (INTFW and IRC). AGWRC was set by optimizing model performance for baseflow recession, with relative variation among land uses based on past experience, resulting in values from 0.90 to 0.998. Interflow should be fairly high in this landscape, and the interflow recession constant parameter was specified as gradually varying between 0.3 and 0.85. The interflow inflow factor ranged from 1 to 3 depending on soils, topography, and land use.

Deep aquifer infiltration (DEEPFR) represents the fraction of infiltrating water that percolates to deep aquifers and is therefore “lost” water removed from the system. Within these watersheds, DEEPFR is usually higher in headwater areas far away from the main stem. The range of DEEPFR values was optimized accordingly during the calibration process and ranged between 0.0 and 0.2.

Overland flow in LSPC is simulated using the Chezy-Manning equation and an empirical expression that relates outflow depth to detention storage. Monthly variations of Manning’s “n” were specified to account for changing ground cover conditions and values ranged between 0.10 (barren lands) and 0.2 (forest).

Monthly variability in hydrologic response was specified by setting monthly values for the upper zone nominal soil storage and the lower zone ET parameter. In each case, the values specified are consistent with the range recommended in BASINS Technical Note 6 (USEPA, 2000).

All final calibrated values for the Tongue River LSPC model are included the model input file, which is available upon request.

4.2 Water Chemistry Calibration Methodology

After hydrology was sufficiently calibrated, water chemistry calibration was performed. The water chemistry calibration consisted of running the watershed model, comparing output to available observation data, and adjusting pollutant loading and in-stream water quality parameters within a reasonable range.

Water chemistry calibration occurred at eight USGS gages selected because there were sufficient data. Table 4-4 summarizes the gages assessed during the calibration process, and the gages are shown in Figure 4-1.

Table 4-4. USGS monitoring sites used for the Tongue River LSPC model water chemistry calibration.

Site Name	Station ID	Altitude (ft)	Drainage Area (mi^2)	LSPC Subbasin
Tongue River near Dayton, WY	06298000	4,060	206	3090
Tongue River at the Montana-Wyoming State Line, MT	06306300	3,429	1,453	3006
Tongue River at Tongue River Dam near Decker, MT	06307500	3,344	1,770	3112
Hanging Woman Creek near Birney, MT	06307600	3,150	470	1095
Otter Creek at Ashland, MT	06307740	2,917	707	1059
Tongue River near the Brandenberg Bridge, MT	06307830	2,760	3,948	1047
Pumpkin Creek near Miles City, MT	06308400	2,490	697	1007
Tongue River at Miles City, MT	06308500	2,360	5,379	1002

Similar to hydrologic calibration, the water chemistry calibration process for each watershed proceeded from upstream gages to downstream gages and involved a comparison of observed data to modeled in-stream water quality and an adjustment of key parameters. Modeling parameters were varied within generally accepted bounds and in accordance with observed temporal trends and soil and land cover characteristics. The water chemistry calibration relied on data for the entire period of record at each location (Table 4-4), but focused primarily on data collected since 2004 when continuous data became available at many monitoring locations.

The following sections discuss the water chemistry calibration for salinity and SAR (as modeled by calcium, magnesium, and sodium concentrations) (Section 4.2.1) and nutrients (Section 4.2.2). Water temperature was also calibrated in the Tongue River upstream of the Tongue River Reservoir (Section 4.2.3), as it is needed for the CE-QUAL-W2 reservoir model (further discussed in Section 6.2.3).

4.2.1 Salinity and SAR

As discussed in Section 3.1, salinity (measured as specific conductance [SC]) and SAR are not directly simulated in the Tongue River application of LSPC. Instead, the model predicts concentrations of the primary cations that compose the two indicators (calcium, magnesium, and sodium). Cations are modeled using constant (surface and interflow) and monthly varying (groundwater) concentrations in outflow from land units. Since little mineralization is expected, a decay rate of zero was assumed.

Calibration points for the Upper Tongue watershed (i.e., upstream of the Tongue River Reservoir) were at Dayton (USGS gage 06298000) and State Line (USGS gage 06306300). Dayton was calibrated first to

isolate the mountain watershed Group 1. Subsequent watershed groups associated with the mountains (Groups 2 and 3) were assigned concentrations resulting from the Dayton calibration, as there were few other water chemistry data collected near the Bighorn Mountains. Interflow and groundwater concentrations in LSPC Group 1 were set to values consistent with data from the Madison limestone formation and springs data (see Section 3.12.2.1). Initially, values were set as constant parameters by month, land use, and flow component. During calibration, groundwater and interflow concentrations were adjusted slightly for all but irrigated land uses. In addition, the observed data suggested decreased groundwater concentrations in portions of summer. To account for this trend, constituents associated with groundwater outflow were decreased in June through August (July and August at State Line).

In the Upper Tongue watershed, assignments associated with prairie groups (Groups 4, 5, and 6) were based on calibration at State Line for Group 4: Prairie. In the Lower Tongue watershed, parameters were then based on the calibration of Group 4 (Prairie) in the Upper Tongue watershed. Parameters were then varied to achieve calibrated results for the main stem Tongue River and tributaries.

As described in Section 3.12, initial surface, interflow, and groundwater concentrations for calcium, magnesium, and sodium were based on a variety of sources. Concentrations in surface outflow from land units (SOQC) were based on data from the National Atmospheric Deposition Program (as described in Section 3.12.1). Small adjustments were made during calibration. Higher concentrations were assigned to the prairie region, where the sedimentary soils have naturally higher salt concentrations than the Bighorns Mountains.

Soil cation concentrations cited in Schafer et al (2006) provided initial concentrations in interflow and groundwater concentrations associated with irrigated land uses. While initial values were based on median values from Schafer et al. (2006), calibration resulted in much lower assignments to outflow, particularly for sodium. Sodium concentrations in interflow were reduced by an order of magnitude. Irrigation likely flushes salts below the simulated interflow region into groundwater where it re-equilibrates with the soil matrix, resulting in lower outflow concentrations. Calibration reduced interflow concentrations of calcium and magnesium by 70 to 75 percent. Groundwater concentrations were adjusted to values near those for the other simulated land uses.

4.2.2 Nutrients

Nutrients in the LSPC model were simulated using buildup/washoff functions for the surface runoff contribution of nutrients, and concentration assignments for interflow and groundwater outflow. General first order decay processes describing the in-stream loss rate were specified for each constituent, which in this system likely represents uptake and trapping by periphyton to a large degree. In the Upper Tongue watershed, the station at Dayton was calibrated first followed by State Line. Nutrients were not modeled in the Lower Tongue River watershed because none of the 303(d) listed stream segments downstream of the Tongue River Reservoir were listed as impaired for nutrients.

First-order decay rates were taken from the USGS SPARROW work (Smith et al., 2003) for streams with flow less than 28 m^3/s; TN at 0.455 per day and TP at 0.258 per day. The rate for TN was unchanged during calibration. First-order decay rates for TP varied spatially. Subbasins 3022 and 3068 (which receive effluent from the Sheridan WWTP and Ranchester/Dayton Lagoons, respectively), were assigned a decay rate of 0.8 per day during calibration. It was assumed that there was extra uptake possibly due to periphyton mats very near to the discharge location of these point sources. All other reaches within subbasins were set to 0.4 per day. The effects of seasonality were represented with the use of an Arrhenius temperature correction coefficient on the decay rate, which was set at 1.04 for TN and TP (USEPA, 1985). Water temperature simulation was performed using a regression equation with air

temperature. The equation was developed from observed water and air temperatures at the State Line station on a monthly basis (further described in Section 4.2.3).

Initial nutrient concentrations of interflow and groundwater were based on observed data during baseflow periods. Adjustment to the initial concentrations in interflow and groundwater were made during the calibration process. While phosphorus levels are expected to be low in groundwater discharge, the groundwater component of the model also represents baseflow transport through small, unmodeled stream reaches. These reaches are not explicitly represented due to the scale of the Tongue River model. During the groundwater-dominated receding limb of the late spring and summer period, organic and sorbed phosphorus continue to be mobilized by flow in these small reaches, resulting in apparent higher "groundwater" concentrations of TP. To capture this pattern in observed data at Dayton and State Line, ground water values assigned for TP were set from observed data at Dayton and State Line respectively. Then the concentrations were adjusted during the calibration process.

Initial values for buildup/washoff parameters were based on several sources. Land uses other than cropland and urbanized land were assigned initial TN values based on concentration data collected by the National Atmospheric Deposition Program, converted to corresponding accumulation factors (Butcher, 2003). For cropland and urban land, the initial TN concentration values were based on data summarized in Haith et al. (1992), with a similar conversion to accumulation rates. Likewise, initial concentration values of TP for crop land were derived Haith et al. (1992) and converted to accumulation rates. For urban land, typical accumulation rates were provided by Haith et al., and were assigned an accumulation of zero. Calibrated concentrations for both TN and TP were slightly higher than the initial values. It is recognized that in this system, overland runoff, when compared to base flow, is relatively small and infrequent.

Maximum storage (SQOLIM) equal to five times the accumulation rate was assigned across land uses. Values typically range from approximately 5 to 8 times the accumulation (Sartor and Boyd, 1972). The rate of surface runoff that removes 90 percent of stored nutrient (WSQOP) typically ranges from 0.4 to 0.7 in/hr. A value of 0.6 in/hr was assumed for this model application. Since the model was not particularly sensitive to the SQOLIM and WSQOP, these parameters in the model were held constant across land uses and parameters during calibration, except for default ID 4 in which three land uses were assigned a maximum storage at nine times the accumulation rate.

4.2.3 Water Temperature

Water temperature in the Upper Tongue watershed was simulated in LSPC by use of regression equations which make each surface, interflow, and groundwater water temperature the dependent variable and air temperature the independent variable. An analysis was performed on the observed water and air temperature data at State Line. The data of each were worked into monthly averages and then plotted in Excel. A linear regression was performed which set the monthly average air temperature as the independent variable and monthly average water temperature as the dependent variable (Figure 4-4). LSPC allows for unique specification of water temperature for the three components: surface, interflow, and groundwater. However, in this application, and lacking adequate observed data to describe the forcing, each of these three components were assigned the same regression equation using air temperature from the meteorological forcing files as the independent variable.

The temperature simulation was further defined by using default assumptions. The model was developed with an assumption that 80 percent of all reaches are exposed to solar radiation (CFSAEX). The longwave radiation coefficient (KATRAD) was set to 9.5. The conduction-convection heat transport coefficient (KCOND) was set to 6.12. And lastly, the evaporation coefficient (KEVAP) was set to 2.24.

Water temperature was not calibrated for the lower Tongue watershed because temperature dependant parameters (i.e., nutrients) were not modeled.

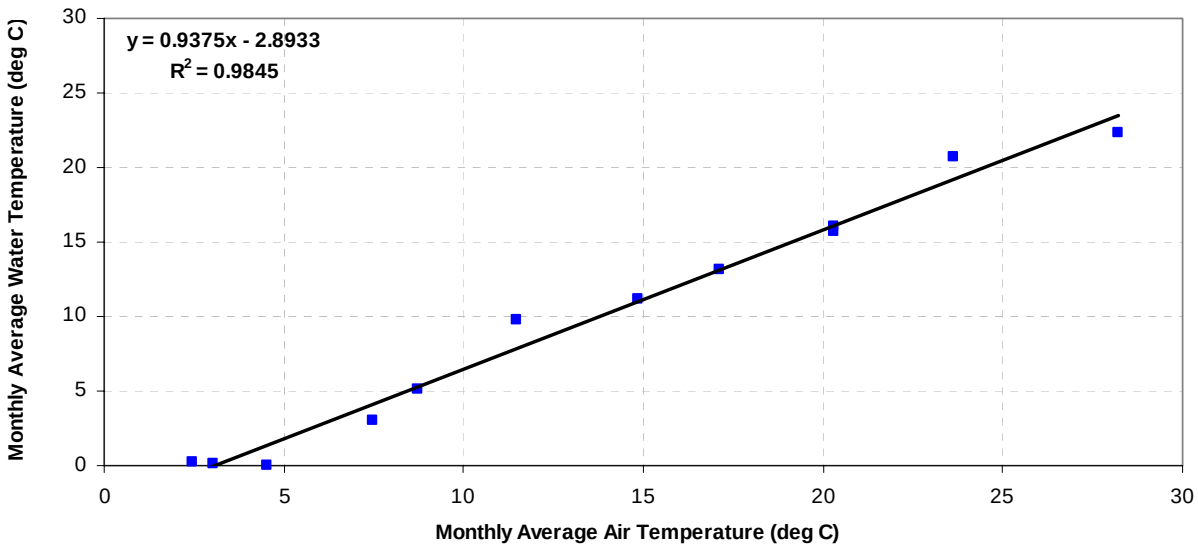


Figure 4-4. Water versus air temperature regression at State Line (06306300)

5.0 PERFORMANCE AND EVALUATION OF THE CALIBRATED MODEL

The process whereby model performance was optimized (i.e., calibration) was described in Section 4.0. An evaluation of model performance (i.e., how well the model represents the real world) is presented in this section.

Typically, the performance of a calibrated model is evaluated through "validation". Model validation is defined as "subsequent testing of a pre-calibrated model to additional field data, usually under different external conditions, to further examine the model's ability to predict future conditions" (USEPA, 1997). Its purpose is to ensure that the calibrated model properly assesses all the variables and conditions that can affect model results, and demonstrate the ability to predict field observations for periods separate from the calibration effort (Donigian, 2003).

Model Evaluation Results

The LSPC model results were evaluated at USGS monitoring gages located throughout the Tongue River watershed. USGS gages had observed data for varying time periods, and included both grab samples and continuous (average daily) observations. As part of the model evaluation, over 130 graphs and tables were generated to compare model results to observed data. Where sufficient data were available, statistics showing mean values and percent error were also generated. A summary of the results is presented in Section 5.0, and the complete set of data used to calibrate both hydrology and water chemistry is included in Appendix B.

The Tongue River LSPC model was not strictly validated in the traditional sense. First, limited data precluded validation in many cases. With the exception of discrete periods of time (that vary from monitoring station to monitoring station) when continuous chemistry data have been collected, chemistry data is limited in the Tongue River Watershed. As a result, it was not possible to select one period of time, and one set of data for calibration and another for validation. Also, given the large watershed area and extreme variability in model forcing functions across the watershed (e.g., geography, climate, precipitation, hydrogeology, rainfall/runoff relationships, etc.), it was necessary to calibrate over the entire period of record to ensure that model output was not calibrated to a condition derived from limited data over a short period of space and time. The calibration period represented a wide range of conditions/events (e.g., high flows, low flows, variable dam operation practices, variable rates of permitted discharges, high snow periods, low snow periods, etc.) resulting in an informal form of validation.

Model performance has been evaluated through qualitative and quantitative comparisons of predicted to observed data from the calibration time period (i.e., full period of record). A summary of model performance relative to the prediction of average SC, SAR, and flow at time periods including the full period of record, the growing season, the non-growing season, and monthly is presented below. Detailed comparisons of predicted and observed data are presented in Appendix B. The criteria in Table 5-1 were used to rank model performance in cases where sufficient observed data were available for quantitative comparisons (Donigian, 2000).

Table 5-1. Model performance criteria (Adapted from Donigian, 2000).

Parameter	% Difference Between Predicted and Observed Values		
	Very Good	Good	Fair
Hydrology/Flow	<10	10-15	15-25
Water Quality/Nutrients	< 15	15 - 25	25 - 35

5.1 Flow

Hydrology is well calibrated for the main stem of the Tongue River upstream of the Brandenburg Bridge. Simulated flows mimic daily and seasonal patterns. For example, a time series of predicted daily mean flow and observed daily mean flow is shown in Figure 5-1 (Tongue River at State Line). Similar figures for all of the evaluated locations are presented in Appendix B. As shown in Table 5-2, with the exception of March through May, model performance relative to the prediction of average flow is generally good to very good at the evaluated time scales upstream of the Brandenburg Bridge.

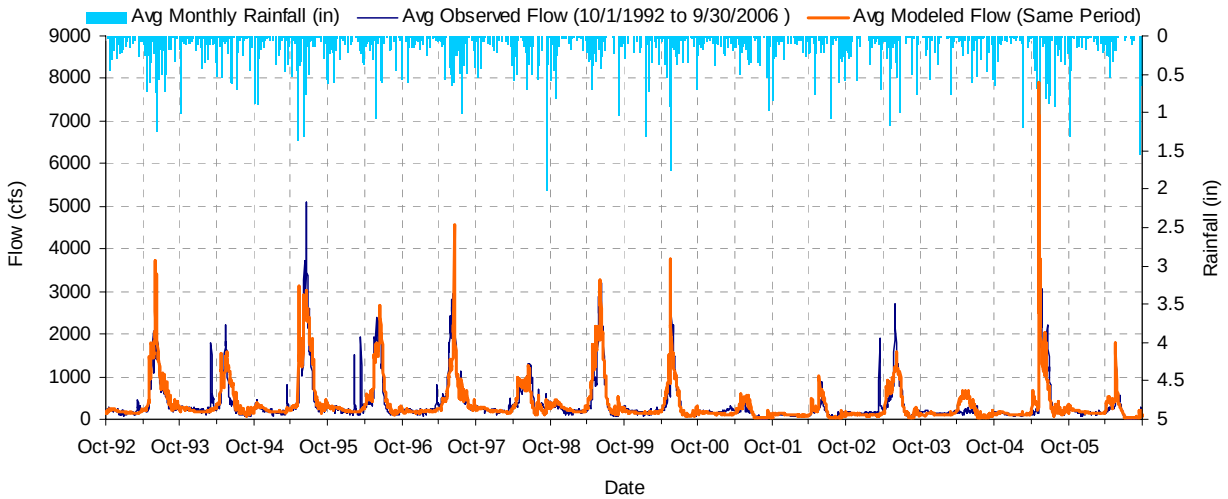


Figure 5-1. Time series of daily mean predicted and observed flow for the Tongue River at State Line near Decker, Montana (USGS gage 06306300).

At Miles City, the observed seasonal patterns are generally mimicked by the predicted results, but May is over predicted and February through April, June, and August are under predicted. In Hanging Woman Creek flow predictions were fair to good for the entire period of record, the growing season and during the 10 percent of the highest flows. Flow predictions were poor for the remaining time periods in Hanging Woman Creek and for all time periods in the other two tributaries shown in Table 5-2.

Table 5-2. Model performance – average flow at various timescales.

Time Period	Tongue River near Dayton, WY	Tongue River near State Line	Tongue River below TRR Dam	Tongue River below Brandenburg Bridge	Tongue River at Miles City	Hanging Woman Creek near Birney	Otter Creek near Ashland	Pumpkin Creek near Miles City
All Data	Very Good	Very Good	Very Good	Very Good	Good	Fair	Poor	Poor
Growing Season	Very Good	Very Good	Very Good	Very Good	Fair	Good	Poor	Poor
Non-growing Season	Very Good	Very Good	Very Good	Very Good	Very Good	Poor	Poor	Poor
January	Good	Very Good	Very Good	Very Good	Very Good	Poor	Poor	Poor
February	Good	Good	Very Good	Very Good	Poor	Poor	Poor	Poor
March	Very Good	Poor	Very Good	Poor	Poor	Poor	Poor	Poor
April	Poor	Poor	Very Good	Very Good	Poor	Poor	Poor	Poor
May	Very Good	Very Good	Poor	Poor	Poor	Poor	Poor	Poor
June	Very Good	Very Good	Fair	Good	Poor	Poor	Poor	Poor
July	Fair	Very Good	Very Good	Very Good	Fair	Poor	Poor	Poor
August	Good	Fair	Very Good	Very Good	Poor	Poor	Poor	Poor
September	Very Good	Very Good	Very Good	Very Good	Very Good	Poor	Poor	Poor
October	Very Good	Good	Very Good	Good	Fair	Poor	Poor	Poor
November	Fair	Very Good	Very Good	Very Good	Very Good	Poor	Poor	Poor
December	Very Good	Very Good	Very Good	Very Good	Very Good	Poor	Poor	Poor
10% Highest Flows	Very Good	Very Good	Very Good	Very Good	Fair	Fair	Poor	Poor
10% Lowest Flows	Very Good	Good	Very Good	Poor	Poor	Poor	Poor	Poor

5.2 Specific Conductance

As shown in Table 5-3, where sufficient data are available for comparison, model performance relative to the prediction of average SC is generally good to very good at time scales ranging from the entire period of record to monthly. The exceptions are the months of April, May and June in the Tongue River at State Line and June and July in Hanging Woman Creek where poor to fair ranks were attained. Insufficient data were available for a quantitative evaluation of model performance in the Tongue River near Dayton, Wyoming and for the non-growing season and winter months in the Tongue River at Miles City, and Hanging Woman, Otter and Pumpkin Creeks. Line graphs comparing predicted to observed values are presented in Appendix B to facilitate a qualitative evaluation.

Table 5-3. Model performance – average SC at various time scales.

Time Period	Tongue River near Dayton, WY	Tongue River near State Line	Tongue River below TRR Dam	Tongue River below Brandenburg Bridge	Tongue River at Miles City	Hanging Woman Creek near Birney	Otter Creek near Ashland	Pumpkin Creek near Miles City
All Data	NA	Very Good	Very Good	Very Good	Very Good	Good	Very Good	Very Good
Growing Season	NA	Very Good	Very Good	Very Good	Very Good	Good	Very Good	Very Good
Non-growing Season	NA	Very Good	Very Good	Very Good	NA	NA	NA	NA
January	NA	Very Good	Good	Very Good	NA	NA	NA	NA
February	NA	Very Good	Very Good	Very Good	NA	NA	NA	NA
March	NA	Very Good	Very Good	Very Good	Very Good	NA	NA	NA
April	NA	Fair	Very Good	Very Good	Very Good	Very Good	Very Good	Poor
May	NA	Fair	Very Good	Very Good	Good	Very Good	Very Good	Poor
June	NA	Poor	Very Good	Very Good	Good	Fair	Very Good	Very Good
July	NA	Very Good	Very Good	Very Good	Good	Fair	Very Good	Poor
August	NA	Very Good	Very Good	Very Good	Very Good	NA	Good	NA
September	NA	Very Good	Very Good	Very Good	Very Good	NA	Very Good	NA
October	NA	Good	Very Good	Very Good	Very Good	Poor	Good	Poor
November	NA	Very Good	Very Good	Very Good	NA	NA	NA	NA
December	NA	Very Good	Very Good	Good	NA	NA	NA	NA

5.3 SAR

As shown in Table 5-4, where sufficient data are available for comparison, model performance relative to the prediction of average SAR is generally good to very good at time scales ranging from the entire period of record to monthly. The exceptions are the months of April through August in the Tongue River at State Line, May and June in the Tongue River at Miles City, and June and July in Hanging Woman Creek where poor to fair ranks were attained. Insufficient data were available for a quantitative evaluation of model performance in the Tongue River near Dayton, Wyoming and below the Tongue River Reservoir Dam. Insufficient data were also available for the non-growing season and winter months in the Tongue River at Miles City, and Hanging Woman, Otter and Pumpkin Creeks. Line graphs comparing predicted to observed values are presented in Appendix B to facilitate a qualitative evaluation.

Table 5-4. Model performance – average SAR at various timescales.

Time Period	Tongue River near Dayton, WY	Tongue River near State Line	Tongue River below TRR Dam	Tongue River below Brandenburg Bridge	Tongue River at Miles City	Hanging Woman Creek near Birney	Otter Creek near Ashland	Pumpkin Creek near Miles City
All Data	NA	Very Good	NA	Very Good	Good	Good	Very Good	NA
Growing Season	NA	Very Good	NA	Very Good	Good	Good	Very Good	NA
Non-growing Season	NA	Very Good	NA	NA	NA	NA	NA	NA
January	NA	Very Good	NA	NA	NA	NA	NA	NA
February	NA	Very Good	NA	NA	NA	NA	NA	NA
March	NA	Very Good	NA	Very Good	Good	NA	NA	NA
April	NA	Poor	NA	Very Good	Very Good	Good	Very Good	NA
May	NA	Poor	NA	Good	Poor	Good	Very Good	NA
June	NA	Fair	NA	Good	Poor	Fair	Very Good	NA
July	NA	Poor	NA	Very Good	Good	Poor	Very Good	NA
August	NA	Fair	NA	Very Good	Very Good	NA	Very Good	NA
September	NA	Very Good	NA	Good	Very Good	NA	Very Good	NA
October	NA	Very Good	NA	Very Good	Very Good	NA	Very Good	NA
November	NA	Good	NA	NA	NA	NA	NA	NA
December	NA	Good	NA	NA	NA	NA	NA	NA

5.4 Total Nitrogen

Insufficient data were available for a quantitative evaluation of model performance with regards to total nitrogen. Line graphs comparing predicted to observed values are presented in Appendix B to facilitate a qualitative evaluation. Figure 5-2 shows an example line graph from the total nitrogen calibration, where observed grab samples are compared to model output for the Tongue River at the State Line. Calibration of total nitrogen in the Tongue River Reservoir is discussed in Section 6.3.

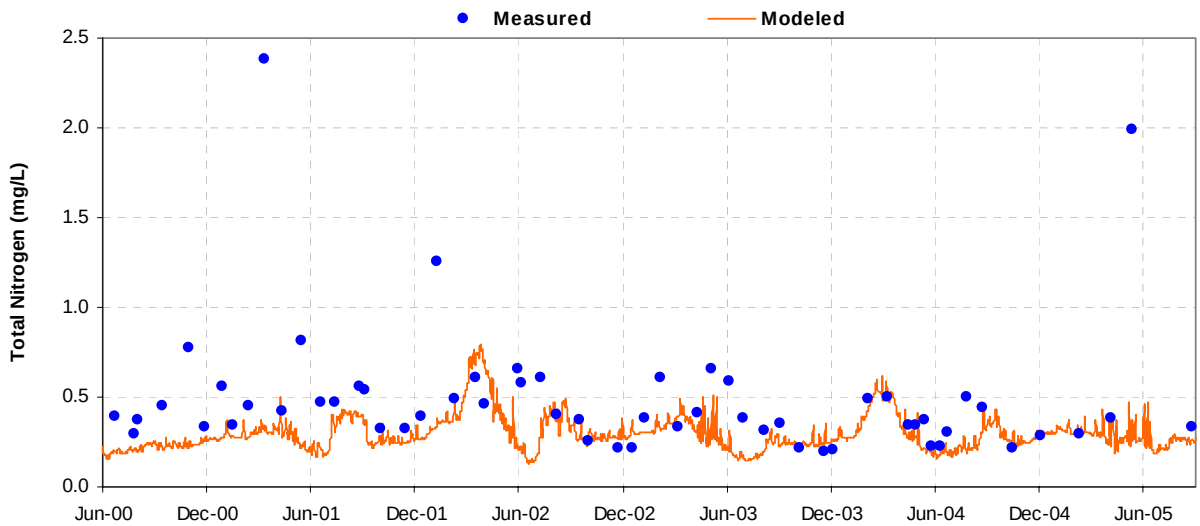


Figure 5-2. Time series of TN data for the Tongue River at State Line near Decker, Montana (USGS gage 06306300).

5.5 Total Phosphorus

Insufficient data were available for a quantitative evaluation of model performance with regards to total phosphorus. Line graphs comparing predicted to observed values are presented in Appendix B to facilitate a qualitative evaluation. Figure 5-3 shows an example line graph from the total phosphorus calibration, where observed grab samples are compared to model output for the Tongue River at the State Line. Calibration of total phosphorus in the Tongue River Reservoir is discussed in Section 6.3.

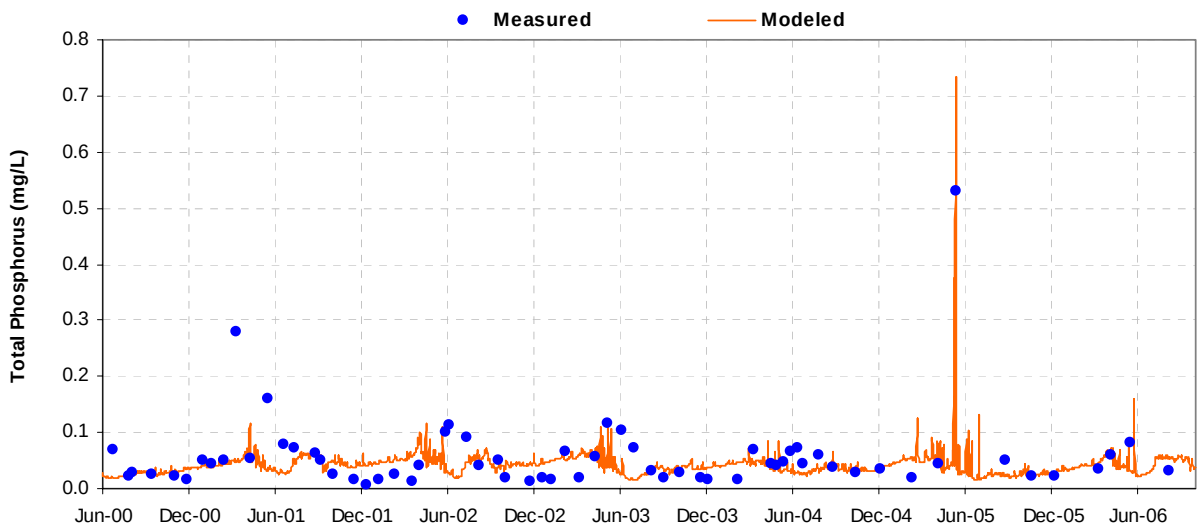


Figure 5-3. Time series of TP data for the Tongue River at State Line near Decker, Montana (USGS gage 06306300).

5.6 Salinity and SAR Calibration in the Tongue River Reservoir

There are few salinity and SAR data available for the Tongue River Reservoir. Because of this, the salinity and SAR calibration of the reservoir occurred at the USGS gage located just downstream of the Tongue River Reservoir Dam. The CE-QUAL-W2 model and calibration of nutrients in the reservoir are discussed in Section 6.0.

Simulated flows mimic daily and seasonal patterns at the USGS gage downstream of the Tongue River Reservoir, and hydrology calibration targets (as described in Table 4-1) are met for most months and seasons. The exception is during May, where the model tends to over predict flows (see Appendix B).

Daily observed salinity and SAR data at the gage downstream of the Tongue River Reservoir provided a robust dataset for calibration. Trends for both parameters were well matched over the available period (October 1, 2000 to September 20, 2006), and the mean error targets were met for most of the evaluated periods. April, May, and June were the exception (and July for SAR), where the model tended to under predict both salinity and SAR values.

5.7 Model Limitations

The Tongue River LSPC model is only capable of representing processes that are captured in the model input data (see Section 3). Events that are unknown to the models, such as storm events, undocumented point source discharges, or undocumented flow alterations, cannot be replicated. Therefore, limitations in the input data drive the limitations, error, and uncertainty in the LSPC models. The following sections summarize the known limitations in the model input data, and how these data limitations potentially affect model output.

5.7.1 Weather Data

As discussed in Section 3.4, weather data (e.g., temperature, precipitation, cloud cover, PEVT, wind speed) are critical for running the LSPC model. Precipitation data are the source for all modeled flows, while other weather data control temperature, snowfall, and evaporation processes. Therefore, the accuracy of modeled flows (and water quality, indirectly) tends to increase as the number of weather gages increases. Unfortunately, as described in Section 3.4, weather gages near the Tongue River watershed are sparse. On average, a single weather gage provides data for an average area of 338 square miles, and several thousand feet of elevation change (depending on location). The lack of weather gages was most evident when trying to calibrate storm events and snowmelt events. Nevertheless, the SNOTEL gages in the mountain region were more densely distributed. This significantly improved the quality of the high-altitude snowfall/snowmelt representation, which accounts for about 63 percent of all the water in the Tongue River watershed.

5.7.2 Flow Alterations

Flow alterations (diversions, storage, releases) are pervasive throughout the Tongue River watershed. The location of the flow alteration, as well as the volume and timing of flow, is required to accurately model stream flows and water quality. While some diversions and reservoirs had daily flow data, most had little to no data. The lack of data affected the flow calibration process, particularly during the summer months when flow alterations are present. The storage and management of water from the Tongue River Reservoir also proved to be a major limitation to the model performance. Detailed data about reservoir management and overflows would help to strengthen model performance in the Tongue River downstream of the Tongue River Reservoir.

5.7.3 Point Sources Discharges

As described in Section 3.7, point source discharges have the potential to affect flow and water quality in a stream. The LSPC model can account for these sources by using time-series inputs of flow and concentrations. However, most point sources only report data on a monthly basis (or less frequently), and data was extrapolated to provide daily model input. In other cases, very little information was available about the point source, and best professional judgment was used to estimate flow, timing, water quality, and/or outfall location. Point source uncertainties have the greatest potential to affect model output during low flow events, when point sources make up a larger percentage of the load.

5.7.4 Physiographic Characteristics

LSPC is driven by the basic physiographic characteristics that make up a watershed – land use, soils, slopes, and geology (see Section 3.5). Therefore, physiographic data must be accurate and complete for each watershed. Potential errors were introduced into the model because several of these physiographic characteristics were simplified to facilitate modeling. Also, physiographic characteristics change over time, and may or may not be represented by the available data and the chosen calibration period. However, this process most likely does not introduce much modeling error when compared to the other potential sources or error.

5.7.5 Observation Data

There is always the possibility of analytical uncertainty in any reported observation that derives from the inherent imprecision of analytical techniques, and, occasionally, from laboratory analysis and reporting

errors. Perhaps more importantly, grab samples submitted for chemical analyses represent a specific location and point in time that is not entirely consistent with the spatial and temporal support of the model. LSPC represents waterbodies as discrete reaches, which are assumed to be fully mixed. Real waterbodies vary continuously in both longitudinal and lateral dimensions, as well as in time. A sample taken from a specific location may not be representative of the average concentration across the stream cross-section, and even less representative of the average across an entire model reach. Further, a sample taken at a discrete point in time may not be representative of the average concentration that would be observed across a modeling time step – particularly when the sample is taken near a source of discharge or during the course of a runoff event. This phenomenon most likely introduces model error during storm events or during periods with short-term discharges.

5.7.6 Hydrology Calibration Data

A lack of hydrology calibration data were one source of model error. Few flow gages met the LSPC calibration criteria (i.e., gages had too little data and/or not enough recent data). For example, there was generally a lack of current data with which to calibrate the tributaries, and no long-term calibration gages were available for smaller Great Plains subwatersheds. The result of the lack of flow gages is that varying flow errors are introduced throughout the watersheds. The errors are not quantifiable, simply because there are no other flow gages with which to validate the hydrologic calibration.

5.7.7 Water Chemistry Calibration Data

While there were over 100 stations with water chemistry data in the Tongue River watershed, most had few recent data. Stations with the most recent data were used to calibrate water chemistry. The available data at most stations generally consisted of discrete grab samples collected over a period of several years. As a result, there was generally insufficient data to calibrate to all potential conditions throughout the watershed, such as storm events, low flows, high flows, and spring snowmelt. Specifically, the following water chemistry data gaps were identified:

- Few recent nitrogen and phosphorus monitoring data were available for streams throughout the Tongue River watershed. Specifically, few data regarding nitrogen and phosphorus species (i.e., nitrate, nitrite, organic nitrogen, and orthophosphorus) were available. Because of this, the model could only be calibrated to total nitrogen and total phosphorus concentrations (which were also limited throughout the watershed).
- Aside from the 12 stations with continuous sampling, most stations had few recent salinity or SAR data. On average, one water chemistry station was used to calibrate 450 square miles of watershed area.
- Monitoring data for all parameters of concern in the Tongue River Reservoir were limited, and depth profiles were only available from a small number of sampling events in 2001 and 2003.
- Groundwater chemistry data were limited for all parameters of concern.
- No water chemistry data were available for the high altitude reservoirs, high altitude diversions, and interbasin diversions.
- Limited water chemistry data were available for irrigation return flows and irrigation impacts to groundwater quality.

6.0 CE-QUAL-W2 MODEL SETUP AND CALIBRATION

As described in Section 2.5, a CE-QUAL-W2 (W2) model was chosen to simulate nutrient and eutrophication processes in the Tongue River Reservoir. Two different types of models were necessary to simulate conditions within the Tongue River watershed. A watershed model (LSPC) was used to address the generation of loads over the land surface, through groundwater, and to predict the resulting impact on stream water chemistry upstream of the Reservoir. A separate model was necessary to simulate nutrients within the Tongue River Reservoir. The U.S. Army Corps of Engineers CE-QUAL-W2 (W2) model was selected (see Section 2.5 for a description of the W2 model) and the setup and calibration of the Tongue River Reservoir model is described in the following section.

6.1 CE-QUAL-W2 Model Configuration

Configuration of the W2 model involved setting up a computational grid using available bathymetry data and setting initial conditions, boundary conditions, and hydraulic and kinetic parameters for the hydrodynamic and water chemistry simulations. This section describes the configuration and key components of the model.

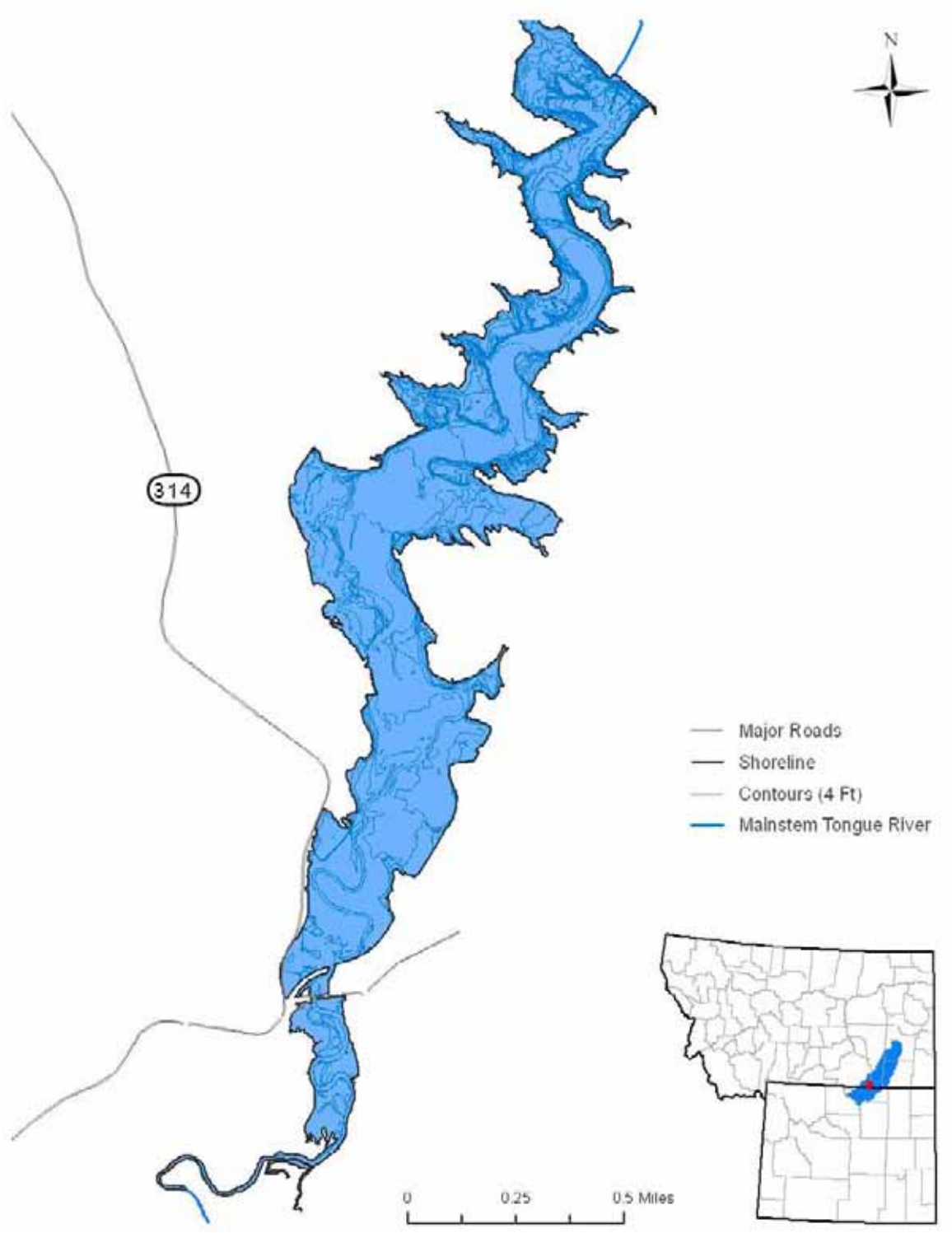


Figure 6-1. Tongue River Reservoir bathymetry.

6.1.1 CE-QUAL-W2 Segmentation/Computational Grid Setup

The computational grid defines how the Tongue River Reservoir is represented in the W2 model. The reservoir was represented as a single main branch based on its long and narrow shape. Montana DNRC provided information on the reservoir's bathymetry following the 1996—1999 rehabilitation project and this was used to generate the computational grid for the W2 model (DNRC, 2005). The average segment width, depth, and orientation information were derived from the bathymetry information and bottom roughness and initial water surface elevation was assigned for each segment. The initial water surface was set at the maximum of 1028 meters and the default bottom roughness of 70 suggested in the W2 manual was assigned.

It should be noted that a portion of the upstream area defined by the Montana DNRC bathymetry file is usually dry, which poses a limitation for W2. Since this area contributes a very small portion of the overall volume of the reservoir, it was not included in the model setup. The difference between the actual reservoir volume and the volume in the model bathymetric file was less than one percent.

The model was configured with 15 longitudinal segments with lengths ranging from 435 to 930 meters. The model also contains up to a maximum of twelve 1-meter thick vertical layers. The model segmentation and longitudinal profile of the reservoir is shown in Figure 6-2 and Figure 6-3. Note that only the active cells are shown in the figures, and the first and last cells are not shown. The active cells represent the cells that may contain water during the simulation. W2 requires that the user also specify boundary cells (having zero widths) as part of the computational grid.

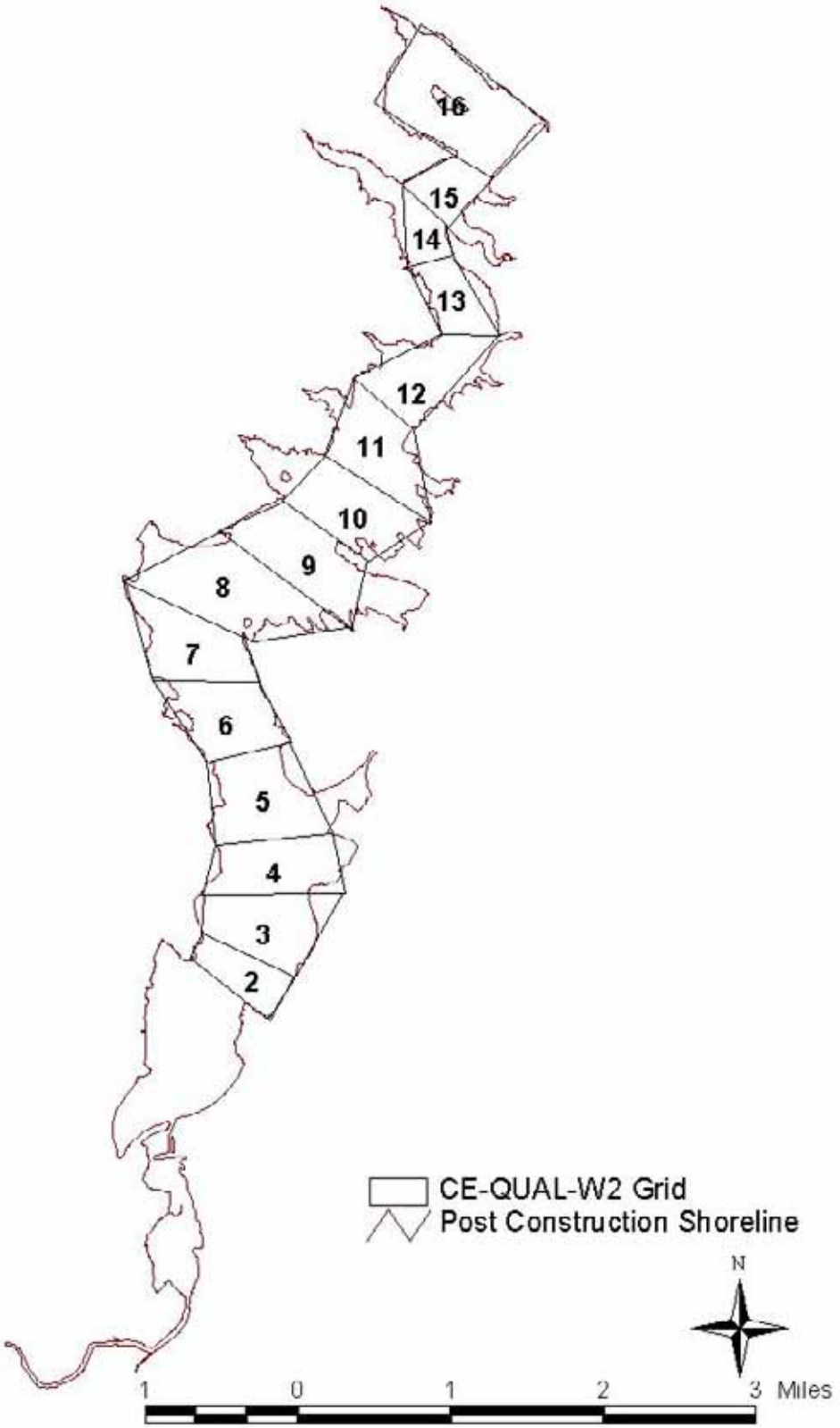


Figure 6-2. Tongue River Reservoir segmentation.

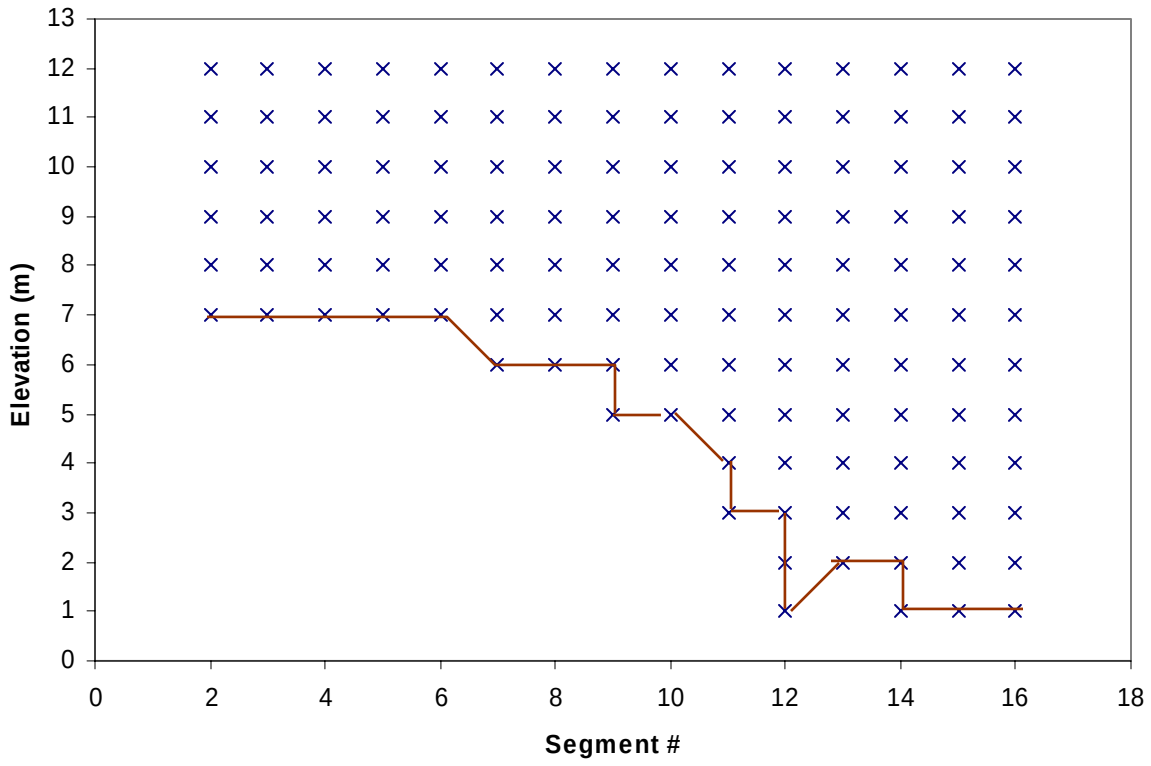


Figure 6-3. Longitudinal profile of the Tongue River Reservoir

6.1.2 Initial Conditions

The W2 model requires the user to specify initial temperature and water chemistry conditions at the start of the model run. A constant initial temperature of 0° C (January 2000) was specified throughout the reservoir and initial condition values for water chemistry parameters were based on observed in-reservoir monitoring data from sampling conducted in the year 2000.

The number and location of inflow/outflows also must be specified when defining initial conditions in the W2 model. For the Tongue River Reservoir, inflows were specified at segments 2 (branch inflow), 4 (tributary inflow), and 7 (tributary inflow). Outflow was specified at segment 16. An initial water surface elevation was specified as 1028 meters (which is equal to the deepest point in the reservoir).

6.1.3 Boundary Conditions

Boundary conditions are required as inputs for the W2 model and represent external contributions of flow and pollutants into the reservoir. The upstream boundary for the Tongue River Reservoir was set at the USGS gage near the Montana-Wyoming state line (gage 06306300), which is approximately 3 miles upstream of the reservoir (depending on reservoir storage). The downstream boundary condition of the reservoir was established using the daily flow record for the USGS gage located immediately downstream of Tongue River Reservoir Dam (gage 06307500).

6.1.4 Reservoir Outflow

Outflows from the model were computed based on a selective withdrawal algorithm in W2 that withdraws water from each of the different vertical layers. The purpose of using this algorithm is to account for the mixing and hydrodynamics in the system for each layer.

6.1.5 Point Sources

Three permitted point source discharges were input directly into the reservoir model (permit IDs shown in parentheses):

- Spring Creek Coal Company (MT0024619)
- Decker Mine West (MT0000892)
- Decker Mine East (MT0024210)

EPA's Permit Compliance System (PCS) database reported no flow data for the Spring Creek Coal Company for the calibration period; therefore no flow was input for this point source. Flows from outfall 007 of the Decker Mine West were assigned to segments 2 of the reservoir model, and flows from outfall 002 from the Decker Mine East were assigned to segment 4 (Figure 6-4). A distributed tributary with a very small flow (1 cfs) was also configured for the model to account for nonpoint sources directly adjacent to the reservoir.

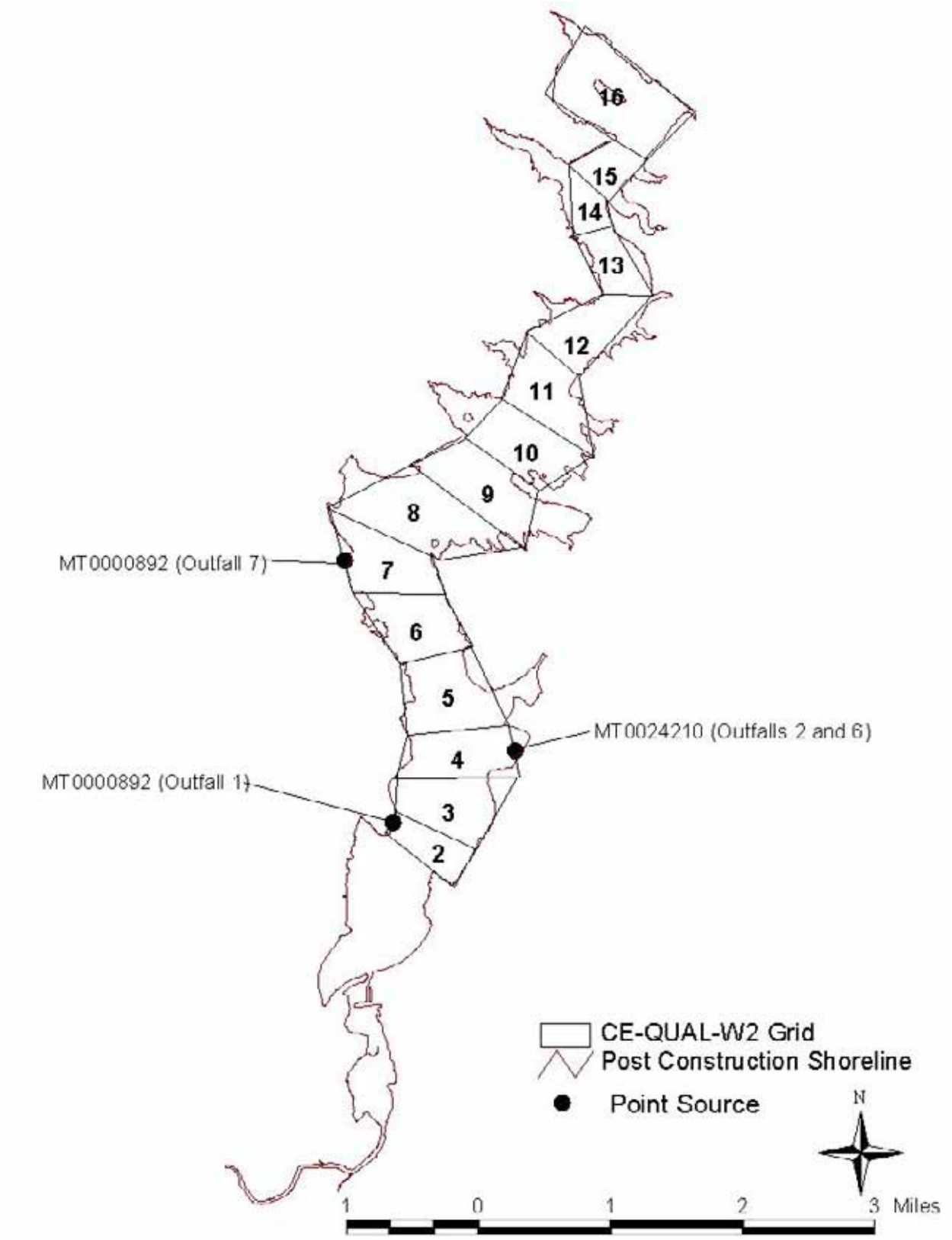


Figure 6-4. Point source locations in Tongue River Reservoir model.

6.1.6 Meteorological Data

Meteorological data are an important component of the W2 model because the surface boundary conditions are determined by weather conditions. The meteorological data required by the W2 model are hourly air temperature, dew point temperature, wind speed, wind direction, and cloud cover. The nearest weather station with these data at the hourly scale is the Sheridan County Airport station located approximately 25 miles south of the reservoir (Figure 6-5). Data from this station were also more complete than data from other potential weather stations.

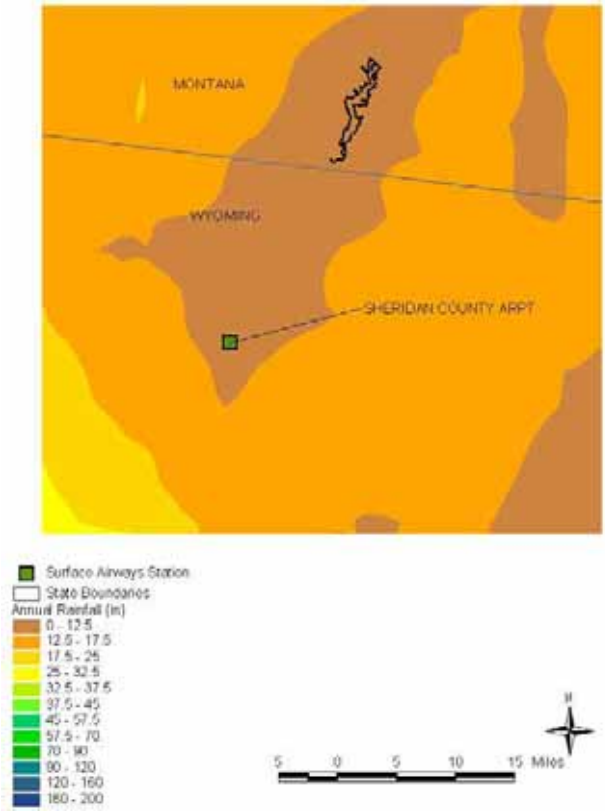


Figure 6-5. Location of weather station used for Tongue River Reservoir modeling.

6.1.7 CE-QUAL-W2 Calibration Time Period

Calibration of the Tongue River Reservoir was complicated because the reservoir was rehabilitated between 1996 and 2000, which changed the dam height, reservoir dimensions, and storage volume. Because CE-QUAL-W2 cannot account for changing dimensions and capacity, the Tongue River Reservoir was calibrated to post-rehabilitation conditions only (i.e., 2000 through 2006). The model was calibrated to water chemistry data from the year 2001 and then validated to data from the year 2003.

6.2 Upstream Conditions

Flow and nutrient output from the Tongue River LSPC model provided the initial input for the Tongue River Reservoir CE-QUAL-W2 model. Therefore, any uncertainties or error in the Upper Tongue River LSPC model were carried through to the Tongue River Reservoir during preliminary calibrations. To improve the Tongue River Reservoir calibration, the reservoir was calibrated as a separate system that was not directly linked to the Upper Tongue River LSPC model. Rather, flow and water chemistry data from the Upper Tongue River watershed model were simulated by using measured data from USGS gage 06306300 (Tongue River at the Montana-Wyoming State Line). Daily flows were available at this gage from 1960 to present, while water chemistry data was collected at varying frequencies (quarterly or monthly). For days with no water chemistry data, concentrations were interpolated from the two nearest concentrations. Using this method, the Tongue River Reservoir could be calibrated without the bias from the Upper Tongue River LSPC model. The following sections describe the methodology for determining the upstream inputs to the CE-QUAL-W2 model.

6.2.1 Flow

Upstream flow was simply derived from the daily flow records available at USGS gage 06306300. By using this methodology to calibrate the reservoir, potential flow errors from the Upper Tongue River LSPC model were removed. However, the disadvantage to this method is that it assumes that there are no additional flows or withdrawals between the USGS gage and the reservoir boundary. In reality, Badger Creek flows into this segment, and several industrial outfalls are present.

6.2.2 Water Chemistry

The water chemistry component of the W2 model requires loading of dissolved and particulate organic material, ammonia, nitrate-nitrite, ortho-phosphorous and dissolved oxygen. Data at USGS gage 06306300 were available from 2000 to 2003 (collected approximately once per month) and linear interpolation was used to estimate daily concentrations between sampling dates.

Concentrations of organic matter were not available from the USGS gage and thus had to be estimated. Based on previous modeling applications, dissolved organic material (DOM) loadings were estimated to be one-half of the organic nitrogen load and particulate organic material (POM) loadings were estimated to account for the remaining half of the organic nitrogen and the total organic phosphorous. The DOM and POM form the source of carbon for the model. Table 6-1 presents the annual average water chemistry concentrations for the various parameters for the period 2000 to 2003.

Table 6-1. Annual average water chemistry concentrations (mg/L) at the USGS gage along the Tongue River at Decker, Montana (gage ID 06306300).

Date	Count	TDS	PO4	NH4	NOx	LDOM	LPOM	DO
2000	16	393.55	0.007	0.041	0.068	0.172	0.211	10.29
2001	12	508.21	0.032	0.064	0.108	0.271	0.326	9.15
2002	10	410.09	0.009	0.038	0.061	0.216	0.252	9.66
2003	9	399.73	0.010	0.039	0.057	0.179	0.224	10.20

Notes: TDS = Total Dissolved Solids; PO4 = Orthophosphorus; NH4 = Ammonia; NOx = Nitrate + Nitrite; LDOM = Labile Dissolved Organic Matter; LPOM = Labile Particulate Organic Matter; DO = Dissolved Oxygen.

6.2.3 Temperature

Daily temperatures for each inflow into the reservoir were derived from historical temperature data (i.e., 33 in-stream measurements from 1974 to 2003). A polynomial equation was fitted to the observed historical data and a temperature time series for each Julian day was calculated using the derived equation (Figure 6-6).

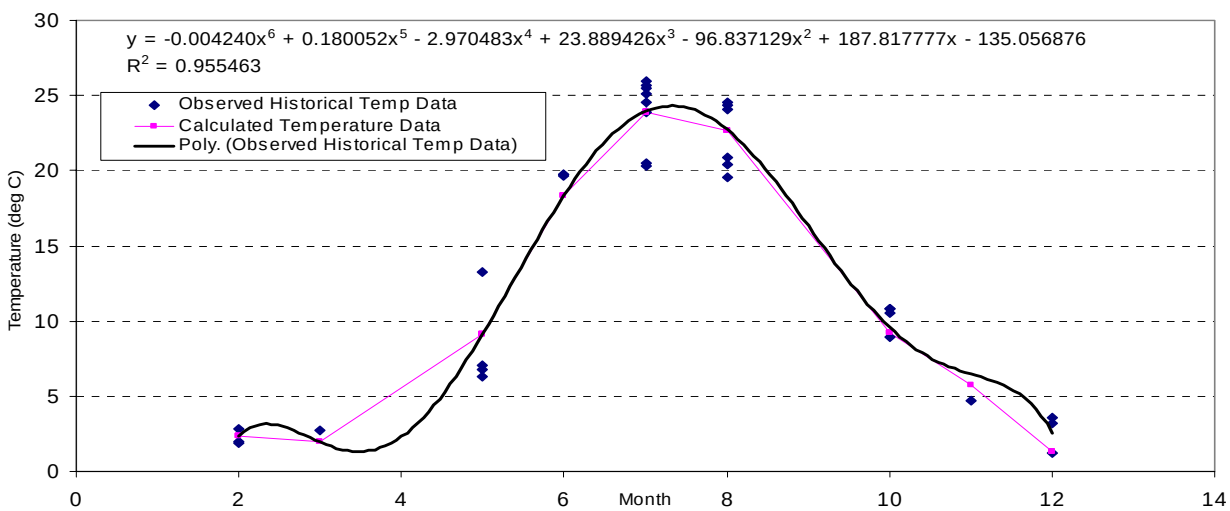


Figure 6-6. Polynomial fit used to derive temperature time series from observed historical data

6.3 CE-QUAL-W2 Model Calibration and Validation

After establishing the CE-QUAL-W2 input conditions (Section 6.2), the first step in the model calibration process was to match observed reservoir water surface elevations and temperatures in the year 2000 to maintain the water balance and reproduce the thermal structure of the reservoir. This step is known as the hydrodynamic calibration. Water chemistry was calibrated following the successful hydrodynamic calibration and then the model was run for the year 2003 (without changing any parameters) as part of the model validation process.

Daily water surface elevation data for the calibration and validation time periods were not available for the Tongue River Reservoir. However, monthly water surface elevation data were estimated from monthly storage volumes provided by Montana DNRC. Daily water surface elevations calculated by the model were converted to monthly values and evaluated against the estimated monthly water surface elevation data (Figure 6-7). The model results follow the seasonal trend fairly well and have an estimated absolute mean error of only 0.75 meters.

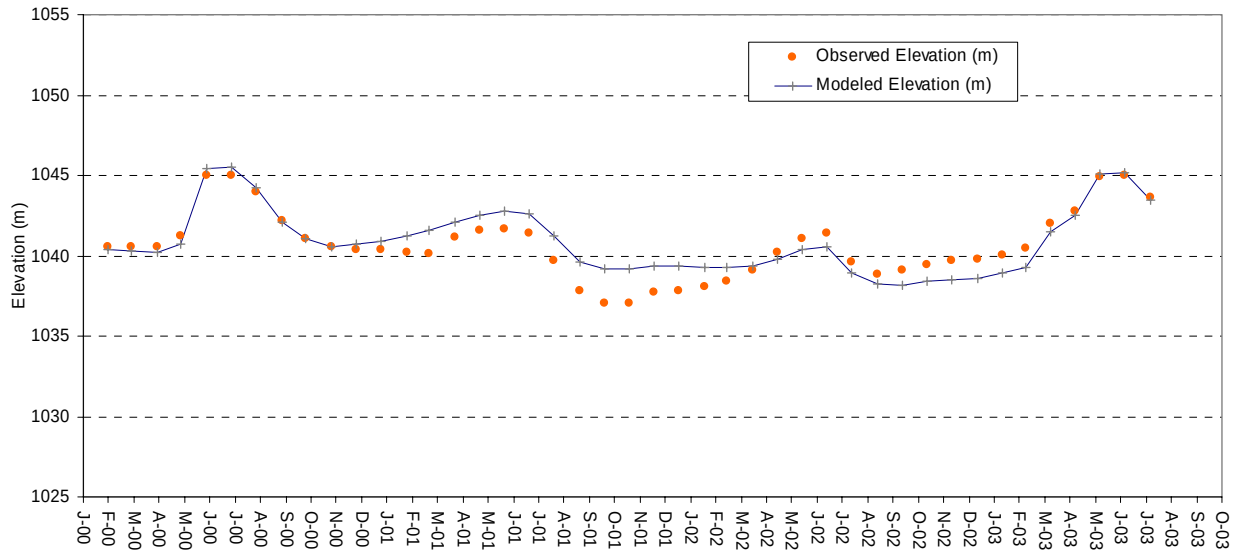


Figure 6-7. Water Surface Elevation Calibration.

During model calibration it became apparent that the reservoir was significantly affected by highly dynamic and flashy weather patterns reported at the Sheridan County Airport. For example, wind speeds were reported as greater than 20 meters/second during some months and diurnal air temperature was also found to vary by as much as 30 °C on some days in October.

W2 allows for spatially adjusting the wind-sheltering coefficient (WSC) and values ranging from 0.60 to 0.85 were used in the model to address the dynamic weather patterns. The W2 model uses wind speed to calculate evaporation.

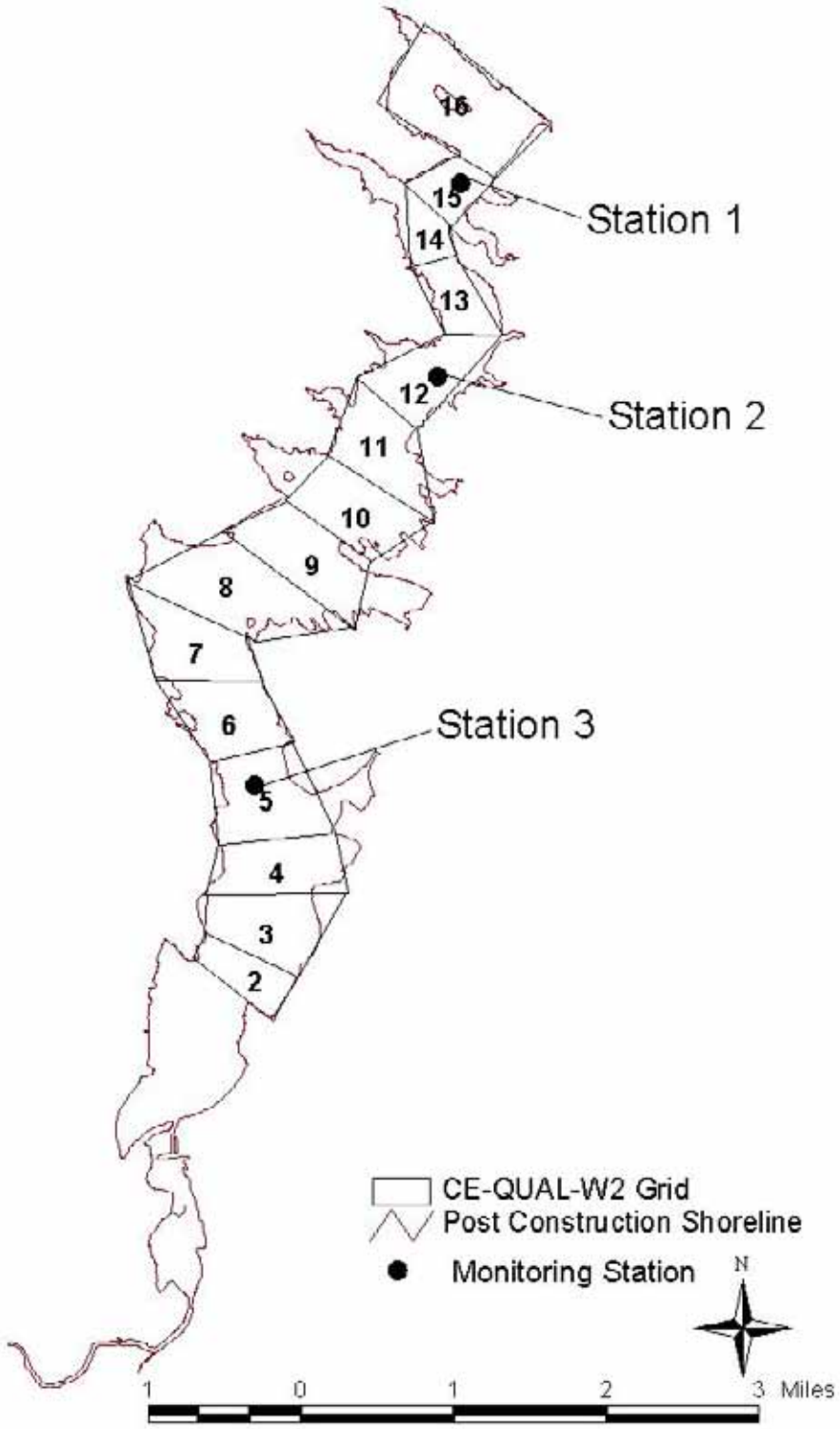


Figure 6-8. Monitoring station locations.

Water chemistry and temperature data were available at three locations along the Tongue River Reservoir. Figure 6-8 shows the monitoring station locations used for calibration[1.] Temperature and dissolved oxygen monitoring profile data (at a 1 meter vertical resolution) for the years 2001 and 2003 were available. Vertical profile data for salinity (EC) were available only in 2003.

Figure 6-9 and Figure 6-10 show the temperature calibration and validation respectively at each of the three sampling locations. In general the model represents the summer stratification and fall turnover fairly well and captures the temperature trend in the months with the highest evaporation (July and August). However, the model does overestimate temperatures in September and October. This may be due to a combination of errors in the estimated temperature boundary conditions and differences between the meteorological data reported for Sheridan and those that occurred at the reservoir.

Calibration of the water chemistry model involved minor adjustments to the default recommended rate coefficients. Figure 6-11 to Figure 6-12 compare the observed versus predicted dissolved oxygen for the calibration and validation time periods, respectively. Considering the sparse boundary conditions, the agreement was considered to be reasonable with the model representing the annual trend in the reservoir's response and capturing the critical summer period (especially in 2003). However, the 2001 dissolved oxygen trends in July and August do not seem to follow the observed trends as well. Figure 6-11 and Figure 6-12 indicate that the model predicts hypolimnetic anoxic conditions fairly well except for several periods in 2001. This is probably due to a variety of factors including the hydrodynamic calibration, boundary conditions, lateral averaging of the model, etc.

The model was also run to predict nutrient (orthophosphorus) and algae concentrations, although only a preliminary calibration was possible due to the limited data. Figure 6-13 and Figure 6-14 display the results and indicate a fair agreement between observed and simulated conditions.

[1] The data in 2001 were collected by MDEQ and the data in 2003 were collected by EPA. Due to differences in naming conventions for the stations by EPA and MDEQ the stations are named Station 1, 2, and 3 in this report.

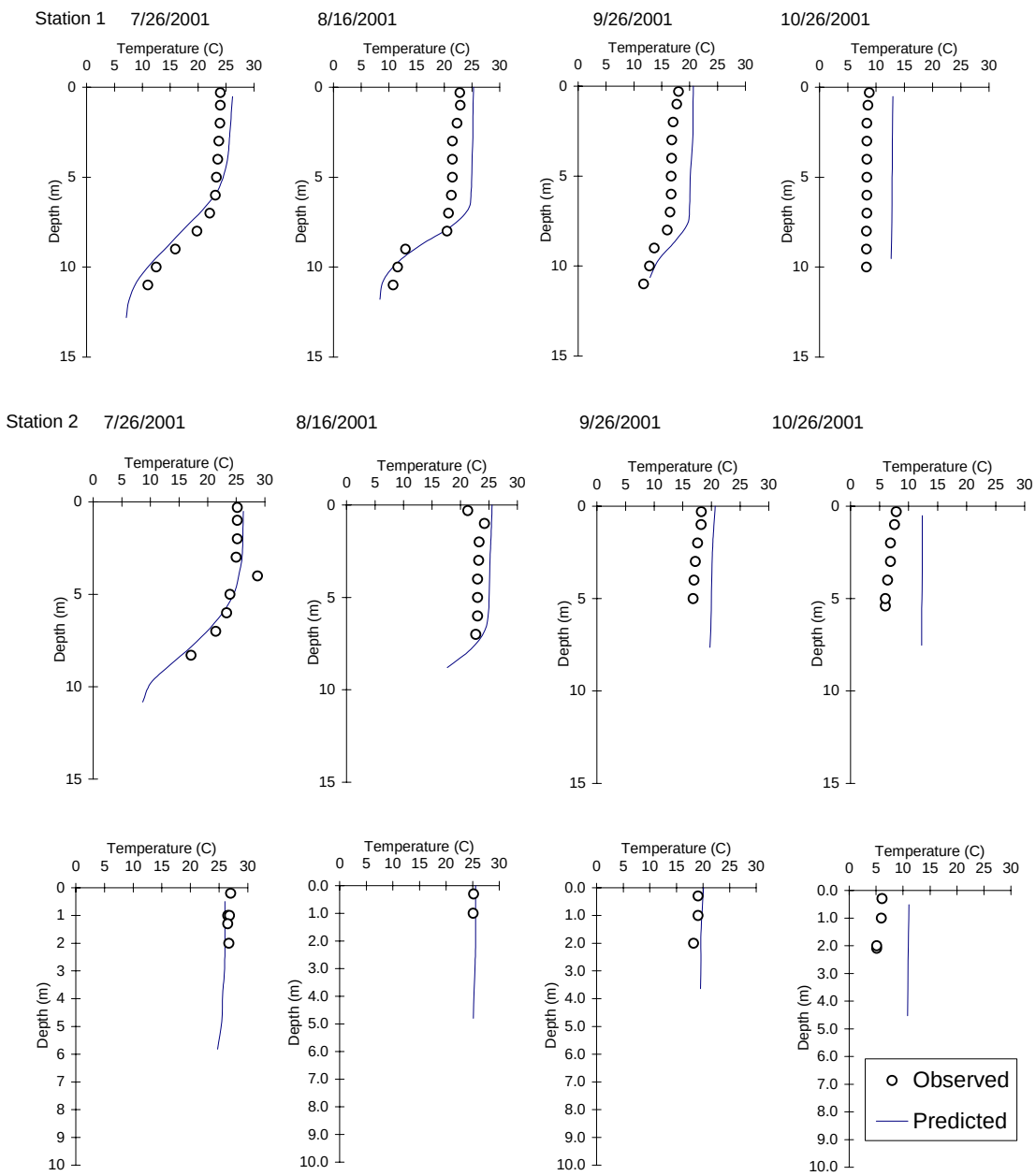


Figure 6-9. Temperature (deg C) calibration (2001).

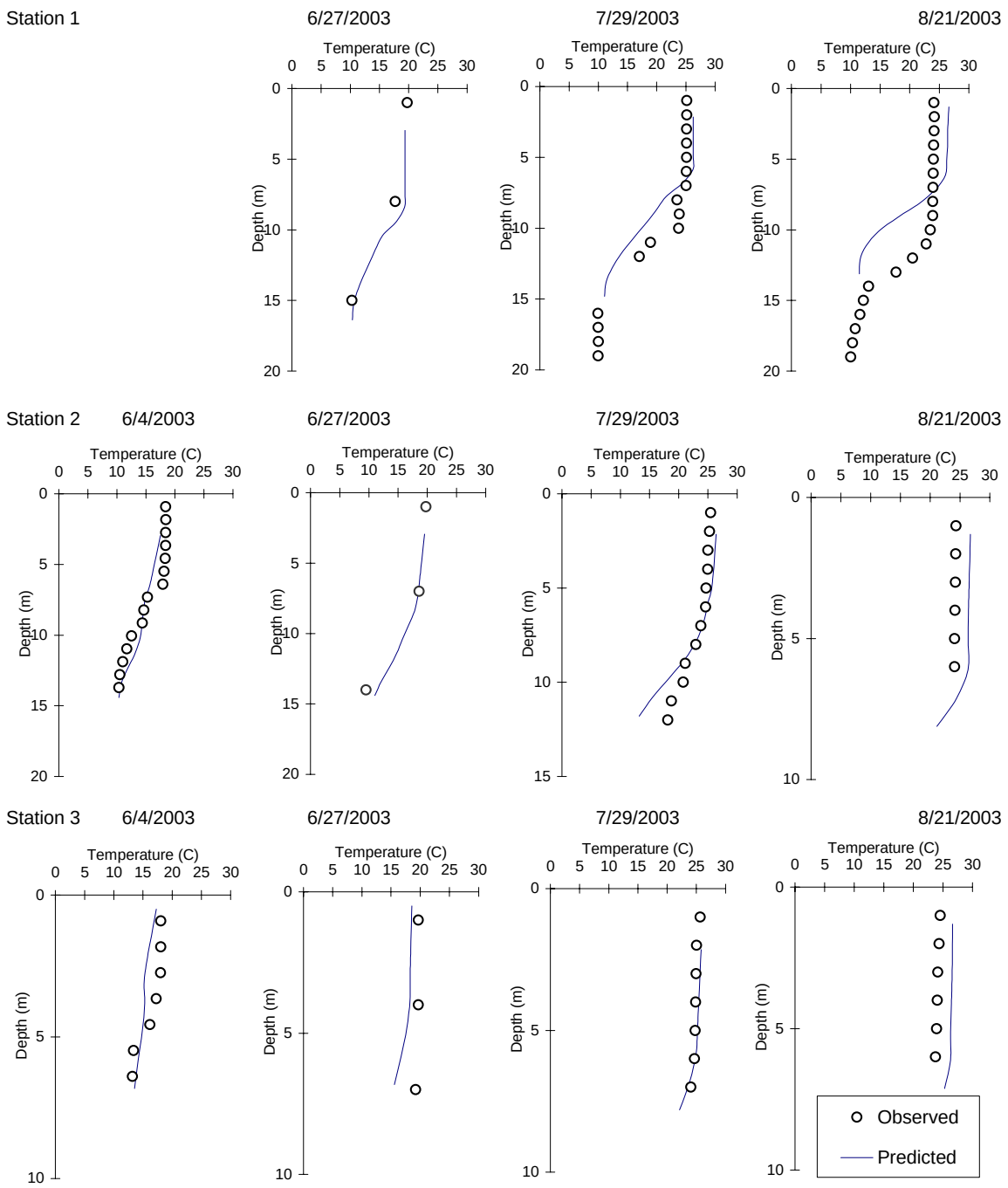


Figure 6-10. Temperature (deg C) validation (2003).

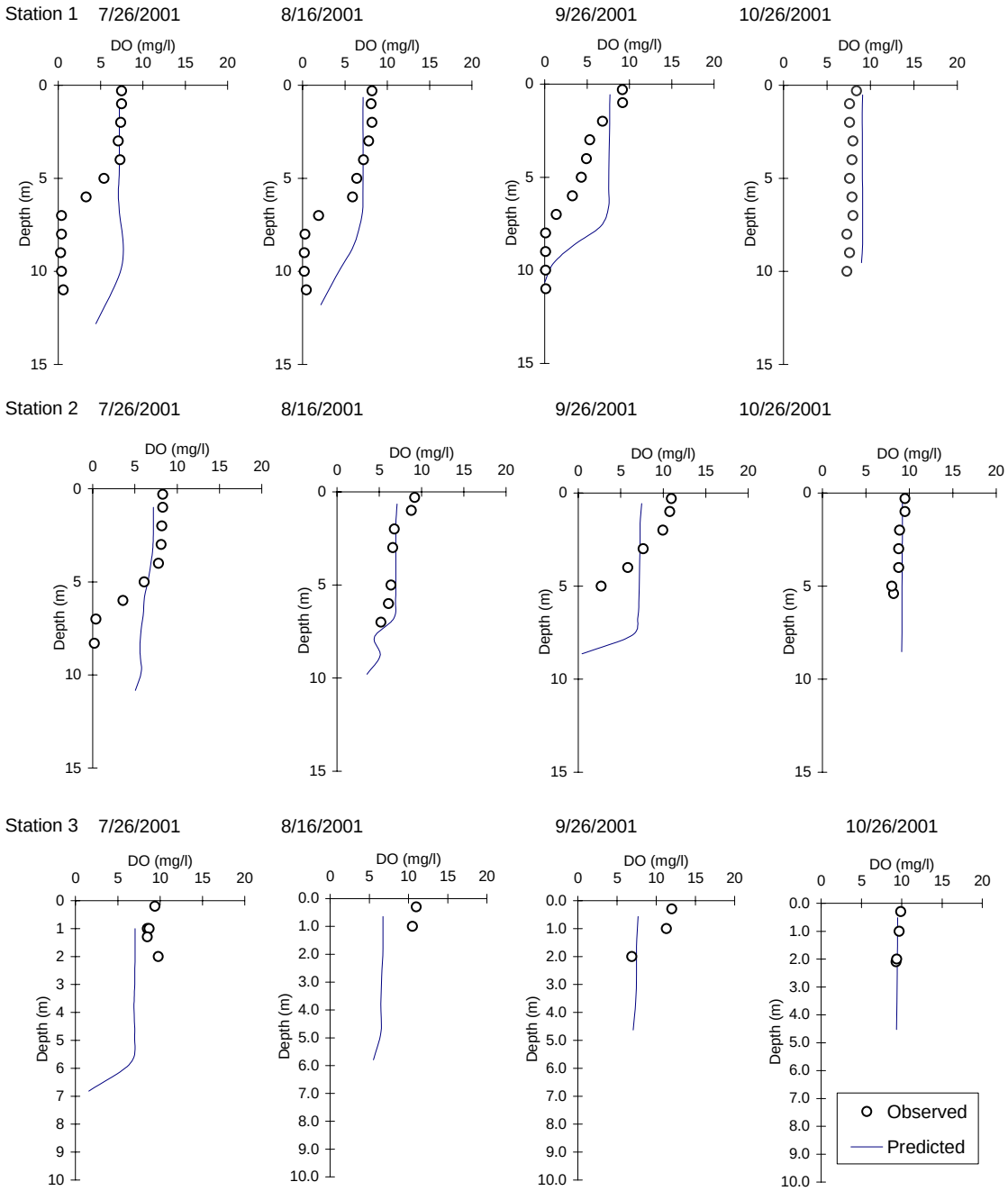


Figure 6-11. Dissolved oxygen calibration (2001).

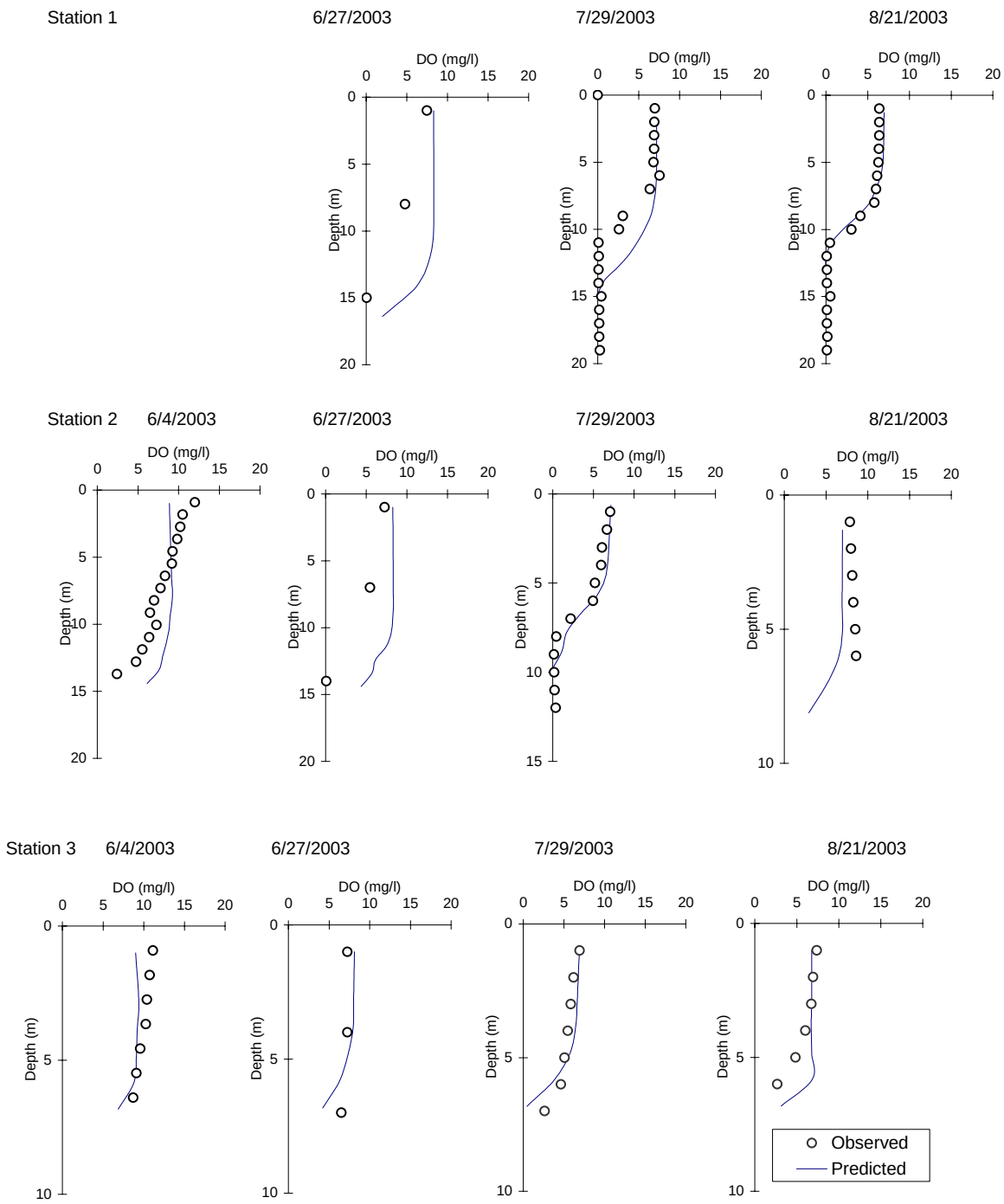


Figure 6-12. Dissolved Oxygen validation (2003).

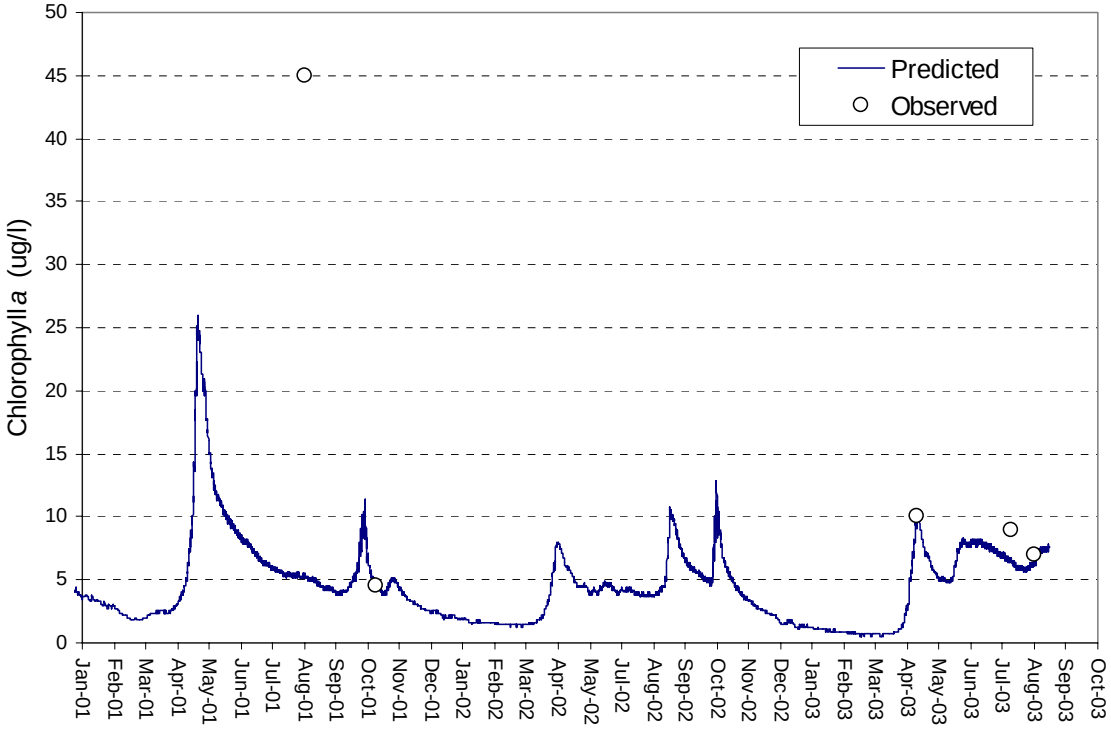


Figure 6-13. Chlorophyll-*a* calibration/validation at Station 1.

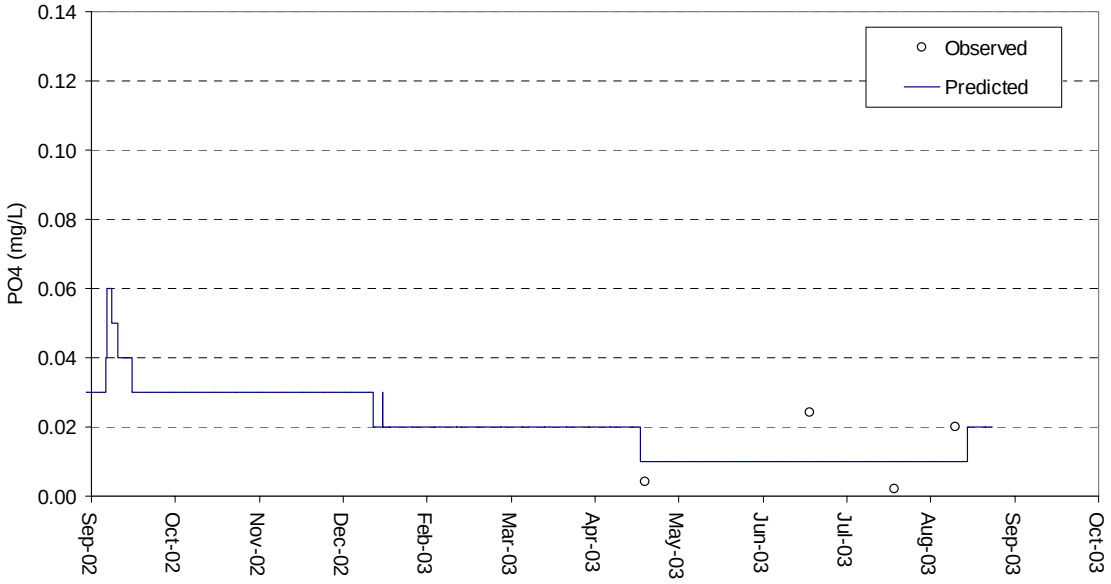


Figure 6-14. PO_4 calibration/validation at Station 1.

6.4 CE-QUAL-W2 Modeling Coefficients

Various modeling coefficients are needed to describe the water chemistry reaction rates in the reservoir. Initial estimates were obtained from W2 default values, general literature values (USEPA, 1985), and from the W2 User's Manual (Cole, 2003). These coefficients were then refined, as necessary, through iterative model simulations until the model captured the major processes influencing the reservoir and reasonably predicted the observed data.

The hydrodynamic calibration mainly involved adjusting the wind sheltering coefficients. W2 allows for spatially adjusting the wind-sheltering coefficient (WSC). The hydrodynamic calibration was found to be sensitive to the wind. The Tongue River system has highly dynamic and flashy weather patterns with wind speeds greater than 20 m/s during some months and diurnal air temperatures were found to vary by approximately 30 deg C in October. A WSC of 0.6 to 0.85 was used in the model.

The water chemistry calibration coefficients as well as the phytoplankton calibration coefficient data for the reservoir are presented below in Table 6-2. Default W2 parameters were in general found to be acceptable. The model was also sensitive to the SOD values. A value of 1.25 g-cm^{-2}day^{-1} was found to achieve the most reasonable DO calibration. No sediment oxygen demand measurements have been made for the Tongue River Reservoir and this value was within the range of that reported in the literature (Cole, 2003). Minor adjustments were made to the temperature bounds for the algal rates to better mimic the observed dissolved oxygen concentration observations in the lake.

Table 6-2. Kinetic Coefficients used in the calibration of Tongue River Reservoir.

Parameter	Description	Units	Value
PO4R	Sediment release rate of phosphorous	fraction of SOD	0.015
NO3DK	Nitrate decay rate	day^{-1}	0.050
NO3T1	Lower temperature for nitrate decay	^oC	5
NO3T2	Upper temperature for nitrate decay	^oC	30
NO3K1	Lower temperature rate multiplier for nitrate decay	Unitless	0.10
NO3K2	Upper temperature rate multiplier for nitrate decay	Unitless	0.99
NH4DK	Ammonium decay rate	day^{-1}	0.12
NH4R	Sediment release rate of ammonium	Fraction of SOD	0.05
NH4T1	Lower temperature for ammonium decay	^oC	5
NH4T2	Upper temperature for ammonium decay	^oC	30
NH4K1	Lower temperature rate multiplier for ammonium decay	Unitless	0.10
NH4K2	Upper temperature rate multiplier for ammonium decay	Unitless	0.99
SOD	Sediment Oxygen Demand	$gO_2\ cm^{-2}day^{-1}$	1.25
AG	Growth rate	day^{-1}	2.0
AR	Dark respiration rate	day^{-1}	0.04
AE	Excretion rate	day^{-1}	0.04
AM	Mortality rate	day^{-1}	0.10
AS	Settling rate	day^{-1}	0.1
AHSP	Phosphorous half-saturation coefficient	$g.m^{-3}$	0.003
AHSN	Nitrogen half-saturation coefficient	$g.m^{-3}$	0.014
ASAT	Light saturation	$W.m^{-3}$	100
AT1	Lower temperature for minimum algal rates	^oC	1
AT2	Lower temperature for maximum algal rates	^oC	25
AT3	Upper temperature for minimum algal rates	^oC	28
AT4	Upper temperature for maximum algal rates	^oC	30
AK1	Lower temperature rate multiplier for minimum algal rates		0.10
AK2	Lower temperature rate multiplier for maximum algal rates		0.99
AK3	Upper temperature rate multiplier for minimum algal rates		0.99
AK4	Upper temperature rate multiplier for maximum algal rates		0.10

6.5 CE-QUAL-W2 Data Limitations

The Tongue River Reservoir CE-QUAL-W2 model is only capable of representing processes that are captured in the model input data (see Section 6.1). Events that are unknown to the model, such as storm events, illicit discharges, or flow alterations, cannot be replicated. Therefore, limitations in the input data drive the limitations, error, and uncertainty in the CE-QUAL-W2 model. The following sections summarize the known limitations in the model input data, and how these data limitations potentially affect model output.

6.5.1 Point Sources Discharges

As described in Section 6.1.5, point source discharges have the potential to affect flow and water chemistry in the Tongue River Reservoir. The CE-QUAL-w2 model can account for these sources by using time-series inputs of flow and concentrations. However, most point sources only report data on a monthly basis (or less frequently), and data was extrapolated to provide daily model input. In other cases, little information was available about the point source, and best professional judgment was used to estimate flow, timing, water chemistry, and/or outfall location.

6.5.2 Observation Data

There is always the possibility of analytical uncertainty in any reported observation that derives from the inherent imprecision of analytical techniques, and, occasionally, from laboratory analysis and reporting errors. Perhaps more importantly, grab samples submitted for chemical analyses represent a specific location and point in time that is not entirely consistent with the spatial and temporal support of the model. Real reservoirs vary continuously in both longitudinal and lateral dimensions, as well as in time. A sample taken from a specific location may not be representative of the average concentration across the cross-section, and even less representative of the average across an entire model reach. Further, a sample taken at a discrete point in time may not be representative of the average concentration that would be observed across a modeling time step – particularly when the sample is taken near a source of discharge or during the course of a runoff event.

6.5.3 Water Chemistry Calibration Data

There were few recent water chemistry data for the Tongue River Reservoir. Post-rehabilitation data were only available for 2001 (4 sampling events) and 2003 (6 sampling events), and samples were only collected between April and October of each year. Samples were obtained at three sites during each event. Dissolved oxygen depth profiles were available for both years, but nutrient depth profiles were only available for 2003. The lack of data for the reservoir proved to be a major complication for calibration. No data was available for calibrating winter conditions (November through March), and few data were available to describe water chemistry concentrations at depth.

7.0 UNCERTAINTY

Uncertainties in the scientific sense are a component of all aspects of the modeling process and are due to (USEPA, 2003):

- uncertainty in the underlying science and algorithms of a model (model framework uncertainty)
- data uncertainty
- uncertainty regarding the appropriate application of a model

Identifying the types of uncertainty that significantly influence model outcomes and communicating their importance is critical to successfully integrating information from models into the decision-making process. This report has attempted to identify the key aspects of uncertainty associated with the Tongue River modeling effort by:

- Reporting model uncertainty (discrepancy between observation and prediction) for both the hydrologic and water quality calibration results (see Appendix B and Section 6.3).
- Documenting the known data limitations and uncertainty used for model inputs (see Section 5.7 and 6.5).
- Discussing the potential implications of model uncertainty as they relate to the intended use of the model (see Section 7.1).

7.1 Model Use

To date, the LSPC model's primary purpose has been to support the development of the Tongue River Assessment Report. Specifically, the purpose of the model is to:

1) Simulate stream flows in Hanging Woman, Otter, and Pumpkin Creek for time periods when no monitoring data were available to assist in the evaluation/description of drought conditions.
2) Estimate the magnitude of hydrologic change associated with anthropogenic flow alterations associated with stock ponds and irrigation withdrawals/returns in the Hanging Woman, Otter, and Pumpkin Creek and the Tongue River watersheds.
3) Estimate daily and average monthly SC and SAR under various scenarios (i.e., existing conditions and the "natural" condition) for comparison to the Montana numeric instantaneous maximum and average monthly SC and SAR standards.
4) Estimate nutrient loads from the Upper Tongue River watershed to the Tongue River Reservoir.

Based on the data limitations and uncertainty, the model is better suited to answer some of these questions than others. Each of the model uses are presented separately below followed by a discussion of model uncertainly and limitations.

(1) Simulate stream flows in Hanging Woman, Otter, and Pumpkin Creek for time periods when no monitoring data were available to assist in the evaluation/description of drought conditions.

Over the long term, as shown in Table 5-2, prediction of average flow was fair (-20%) in Hanging Woman Creek. For the growing season, predicted average flow was good (-12%) in Hanging Woman Creek. Therefore, the model is reasonably well-suited for long-term predictions of average stream flows in Hanging Woman Creek. Model performance regarding the prediction of stream flow in Otter and Pumpkin Creeks, however, was generally poor.

It should be noted that the purpose of these model predictions (see Appendix H of the Assessment Report) was informational only. So long as the uncertainty is acknowledged, it is felt that use of the model results is appropriate.

(2) Estimate the magnitude of hydrologic change associated with anthropogenic flow alterations associated with stock ponds and irrigation withdrawals/returns in the Hanging Woman, Otter, Pumpkin Creek, and Tongue River watersheds.

The assumptions associated with simulation of irrigation and stock ponds are presented in Sections 3.8 and 3.11 and in Appendix J of the Assessment Report. In the absence of field data describing their hydrologic characteristics, it was not possible to specifically calibrate hydrology associated with these two sources of human-caused flow alteration. The hydrologic processes and fate and transport of chemical constituents were characterized by the LSPC model using a literature-based understanding combined with best professional judgment and consideration in the overall hydrologic calibration. The inability to specifically calibrate precludes an assessment of how well the model has simulated these features.

Donigian (2000) points out that factors such as the availability of alternative assessment procedures and the purpose of the model application need to be considered when allowing for uncertainty. In this case, at the watershed scale, there is no alternative assessment procedure for estimating the potential magnitude of hydrologic change associated with anthropogenic flow alteration. While the simulations of these two sources are not calibrated, it is felt that it provides the best means for assessing the hydrologic effects of irrigation and stock ponds in the absence of monitoring data.

Given the un-quantified uncertainty, model predictions associated with potential impacts of anthropogenic flow alteration should be used with caution.

(3) Estimate daily and average monthly SC and SAR under two scenarios (i.e., existing conditions and the "natural" condition) for comparison to the Montana numeric instantaneous maximum and average monthly standards (i.e., relative comparisons between two modeled scenarios).

The performance of the model for the prediction of SC and SAR is summarized in Section 5.2 and 5.3 and in Appendix B. The "existing condition" and "natural condition" scenarios are described in Appendix J of the Assessment Report.

Existing Condition SC

For the "existing condition", performance of the model relative to prediction of average monthly and instantaneous maximum SC can be determined directly through examination of the calibration results. The calibration results vary by water body and site. As shown in Table 5-3, for most months and time periods greater than one month, model performance for the prediction of average SC is very good (i.e., plus or minus 15 percent or less) in the Tongue River near the State Line, below the Tongue River Reservoir, and at Miles City. Insufficient data were available to quantitatively evaluate model performance in the Tongue River at Dayton, Wyoming. The time series chart showing predicted and observed SC in the Tongue River at Dayton (Figure B-7 in Appendix B), however, qualitatively suggests that the LSPC predictions of SC are good at this location.

Insufficient data were available for a quantitative analysis of model performance during the non-growing season and associated months in the Tongue River at Miles City and Hanging Woman Creek, Otter Creek, and Pumpkin Creek. At the long-term (annual or greater) and growing season time scales at these four

locations, the LSPC predictions of average SC were good (i.e., plus or minus 15 to 25 percent) and very good (i.e., plus or minus 15 percent or less).

Model performance at the daily time step was evaluated by comparing observed average daily values to predicted average daily values using regression analysis and box plots (see Appendix B). R-squared values ranged from 0.01 in Pumpkin Creek to 0.51 in the Tongue River at State Line indicating a general poor fit of observed to predicted average daily values. The poor correlations between observed and predicted daily average values likely reflects the difficulties in exactly duplicating the timing of flows, given the uncertainties in the timing of model inputs, mainly precipitation.

The box plot analysis, among other things, allows for ready examination of the model performance relative to the prediction of maximum and minimum values. In most cases, the maximum and minimum values are over or under predicted (see Appendix B for magnitude) suggesting that model results should be used with caution for daily maximum or minimum values (Table 7-1).

Table 7-1. Qualitative comparison of predicted and observed minimum and maximum SC values (Symbols indicate under or over prediction)

Location	Minimum	Maximum
Tongue River at Dayton, WY	▼	▼
Tongue River at State Line	▼	▼
Tongue River below the TRR	▲	▲
Tongue River below Brandenberg Bridge	▼	▲
Tongue River at Miles City	▼	–
Hanging Woman Creek near Birney	▼	–
Otter Creek at Ashland	▼	▲
Pumpkin Creek near Miles City	▼	▼

▲ = Over prediction
▼ = Under prediction
– = Approximately equal

In summary, use of the LSPC model developed for the Tongue River watershed for the prediction of average daily SC for a given day would likely be unreliable. On the other hand, predictions at the monthly or greater time step are generally good to very good.

Existing Condition SAR

As with SC, performance of the model relative to prediction of average monthly and instantaneous maximum SAR under the "existing condition" scenario can be determined directly through examination of the calibration results. The calibration results vary by water body and site. As shown in Table 5-4, where sufficient data were available for a quantitative evaluation, for most months and time periods greater than one month, model performance for the prediction of average SAR is good to very good (i.e., plus or minus 25 percent or less). The exceptions are the Tongue River at State Line and Miles City and Hanging Woman Creek during some of the spring and summer months were model performance was poor to fair.

Insufficient data were available for a quantitative evaluation of model performance for SAR at the Tongue River near Dayton, below the Tongue River Reservoir Dam, Pumpkin Creek, and during many of the non-growing season months at the other site shown in Table 5-4.

Model performance at the daily time step was evaluated by comparing observed average daily values to predicted average daily values using regression analysis and box plots (Appendix B). Sufficient data were

only available for regression analysis in Otter and Hanging Woman Creeks and the Tongue River at State Line, below Brandenberg Bridge, and Miles City where R-squared values ranged from 0.04 in Hanging Woman Creek to 0.45 in the Tongue River at State Line indicating a general poor fit of observed to predicted average daily values. The poor correlations between observed and predicted daily average values likely reflects the difficulties in exactly duplicating the timing of flows, given the uncertainties in the timing of model inputs, mainly precipitation.

The box plot analysis, among other things, allows for ready examination of the model performance relative to the prediction of maximum and minimum values. In most cases, the maximum and minimum values are over or under predicted (see Appendix B for magnitude) suggesting that model results should be used with caution for daily maximum or minimum values (Table 7-2).

Table 7-2. Qualitative comparison of predicted and observed minimum and maximum SAR values (Symbols indicate under or over prediction)

Location	Minimum	Maximum
Tongue River at Dayton, WY	▼	▼
Tongue River at State Line	–	▲
Tongue River below the TRR	–	▼
Tongue River below Brandenberg Bridge	–	▲
Tongue River at Miles City	–	–
Hanging Woman Creek near Birney	–	▲
Otter Creek at Ashland	▲	–
Pumpkin Creek near Miles City	–	▼

▲ = Over prediction
▼ = Under prediction
– = Approximately equal

In summary, use of the LSPC model developed for the Tongue River watershed for the prediction of average daily SAR for a given day would likely be unreliable. On the other hand, predictions at the monthly or greater time step are generally good to very good.

Natural Condition SC and SAR

As described in Appendix J of the Assessment Report, a number of anthropogenic factors such as irrigation, agriculture, CBM discharge, wastewater treatment discharge, mining, etc. were removed from the model to estimate the potential magnitude of human affect.

In the absence of field data describing the hydrologic and pollutant fate/transport characteristics associated with many of these factors, it was not possible to specifically calibrate SC and SAR loading from these sources. These sources were addressed in the model using a literature-based understanding of their characteristics.

However, the potential magnitude of change between the existing and natural conditions was based on a relative comparison of two model scenarios, thereby minimizing the error/uncertainty associated with model fit to the observed data. As a result, the uncertainty associated with comparisons of SC and SAR between the two scenarios is largely a function of the model's ability to simulate each of the various anthropogenic factors. While it is not possible to evaluate the model's ability to simulate each of these sources, no other assessment methodology is currently available to estimate what water quality conditions might have been like in the absence of man's influence. As a result, the model provides one of the only means for evaluating the impact of human's actions at the watershed scale.

(4) Estimate nutrient loads from the Upper Tongue River watershed to the Tongue River Reservoir.

Two model scenarios were developed; one for the existing condition and one for the natural condition (i.e., the absence of human actions). For the existing condition, performance of the LSPC model relative to prediction of nutrient loads to the Tongue River Reservoir can be evaluated by examination of the flow and water quality calibration results for the Tongue River at the State Line near Decker, Montana. As summarized in Table 5-2, model performance with regards to flow at the State Line was very good (± < 10%) for time periods greater than monthly (i.e., growing season, non-growing season, full period of record). However, as shown in Appendix B (Section B.3.2.3 and B3.2.4), the LSPC model appears to under predict TN and over predicts peak TP.

Similar to SC and SAR (Number 3 above), a number of anthropogenic nutrient sources were then removed from the model to estimate the potential magnitude of human affect (i.e., define the "natural condition).

In the absence of field data describing the hydrologic and pollutant fate/transport characteristics associated with many of the nutrient sources, it was not possible to specifically calibrate TN and TP loading from these sources. These sources were addressed in the model using a literature-based understanding of their characteristics.

However, the potential magnitude of change between the existing and natural conditions was based on a relative comparison of two model scenarios, thereby minimizing the error/uncertainty associated with model fit to the observed data. As a result, the uncertainty associated with comparisons of nutrient loading between two model scenarios is largely a function of the model's ability to simulate each of the various anthropogenic factors. While it is not possible to evaluate the model's ability to simulate each of these sources, no other assessment methodology is currently available to estimate what water quality conditions might have been like in the absence of man's influence. As a result, the model provides one of the only means for evaluating the impact of human's actions at the watershed scale.

7.2 Conclusions

As described above, the model has been used primarily to; 1) fill-in spatial and temporal gaps where no monitoring data are available for SC, SAR, and flow and 2) to make relative comparisons between two or more model scenarios considering SC, SAR, nutrients, and flow. The former use has been largely for descriptive purposes. While acknowledging uncertainty is still important, the consequences of prediction error are relatively insignificant. The later use has been to answer "what if" questions such as what would SC, SAR, nutrient, and/or temperature levels be in the absence of human influence? Since answers to these types of questions may be used to inform future decisions, uncertainty and an understanding of prediction error may be important.

However, is should be noted that the purpose of the model has been to answer questions that can only be answered through simulation since sufficient monitoring data do not exist to answer the questions by other means. For example, no data exist from a period in time prior to the onset of human influence. The only way to estimate what water quality conditions may have been like at that time, in the absence of monitoring data from that period in time and/or data from a suitable reference stream, is through model simulation. Thus, the models described in this document have been developed and used because there is no alternative method for obtaining answers to the questions that need to be asked to ultimately interpret Montana's water quality standards (i.e. estimate "natural conditions") and/or assess the potential magnitude of impact associated with man's past, current, and future influences on water quality.

In general, the fit between observed and predicted SC and SAR is good to very good at time scales greater than one month at most locations and there is greater uncertainty associated with the non-growing season months than the growing season months. Uncertainty associated with daily predictions and for prediction of instantaneous maximum values is relatively high and the model should only be used with caution at these time scales.

Qualitatively, it appears that a reasonable fit between predicted and observed TN and TP values was obtained in the Upper Tongue River. So long as the model results are used with caution and in combination with other data and information the model is adequately suited for the intended purpose relative to nutrients.

In summary, the current quality of fit is sufficiently good that the model is judged ready for supporting the development of the Tongue River Assessment Report. If a higher level of “proof” (validation or corroboration) is required for regulatory application, it is recommended that appropriate data quality objectives be pre-defined and tested on new sampling data obtained after the period used for model calibration.

8.0 STEPS TO IMPROVE MODEL PERFORMANCE

The Tongue River LSPC and CE-QUAL-W2 models were set up and calibrated primarily to support the specific purposes associated with the Tongue River water quality assessment. Despite model uncertainties, the models are believed to be appropriate for water quality assessment purposes, especially since model output was only one of several types of information used to make the assessment decisions (i.e., a weight-of-evidence approach was employed that also relied on a variety of other data). The models also have the potential to support a variety of future watershed management needs, such as TMDL development, water quality standards compliance, and watershed-based permitting activities. However, a detailed re-analysis of the modeling quality objectives should be undertaken to determine the suitability of the existing modeling framework to support these potential decision needs. Additional model refinements are likely necessary to achieve the new modeling quality objectives. For example, several potential model refinements were identified during the calibration process including the following:

- The modeling of salt transport might be improved by incorporating a geochemical representation of salt leaching and transport into the LSPC model. In this way the modeling of groundwater discharges could be improved by taking into account geochemistry, water table elevation, and soil characteristics.
- The modeling of nutrients in the Upper Tongue River could possibly be improved with more information on point source discharges and stream characteristics that might affect nutrient transport to the reservoir (e.g., location and extent of large periphyton beds).

A variety of data limitations also limited model performance and the following data needs were identified:

- Weather data is believed to be the primary limitation in the Tongue River LSPC model (particularly in the prairie region). Long-term use of the models would greatly benefit from additional weather stations throughout the Tongue River watershed.
- Information on the location, timing, and volume of water diverted and returned from the main stem Tongue River was limited and inconsistent. Studies to better understand this important characteristic of the watershed would help the modeling process.
- Information on point source discharge characteristics was also limited and inconsistent. Better data on key point sources would help to determine the magnitude of their impact.
- Additional nutrient and salinity sampling should be performed to update the LSPC and CE-QUAL-W2 models. For example, sampling of Tongue River in-stream concentrations for PO_4 and NO_x would help to determine the characteristics of incoming nutrient loads.

9.0 REFERENCES

Anderson , E.A., 1968: Development and Testing of Snow Pack Energy Balance Equations. Water Resources Research, 4, 19-37.

Anderson, E.A. and N.H. Crawford. 1964. The Synthesis of Continuous Snowmelt Runoff Hydrographs on a Digital Computer. Technical Report No. 36, Department of Civil Engineering, Stanford University, Stanford, CA.

APHA. 1992. Standard Methods for the Examination of Water and Wastewater. 18th ed. American Public Health Association, Washington, DC.

Bartos, T.T. and K.M. Ogle. 2002. Water Quality and Environmental Isotopic Analyses of Ground-Water Samples Collected from the Wasatch and Fort Union Formations in Areas of Coalbed Methane Development – Implications to Recharge and Ground-Water Flow, Eastern Powder River Basin, Wyoming. Water-Resources Investigations Report 02-4045. U.S. Geological Survey, Cheyenne, WY.

Bedient, P. B., and Huber, W. C., 1992, Hydrology and Floodplain Analysis: Addison-Wesley Publishing Company, Reading, Massachusetts, 692 p.

Bicknell, B.R., J.C. Imhoff, J. Kittle, A.S. Donigian, and R.C. Johansen. 1996. *Hydrological Simulation Program–FORTRAN, User's Manual for Release H*. U.S. Environmental Protection Agency, Environmental Research Laboratory, Athens, GA.

BLM. 2003. Final Environmental Impact Statement and Proposed Plan Amendment for the Powder River Basin Oil and Gas Project. U.S Department of Interior Bureau of Land Management, Wyoming State Office, Buffalo Field Office. Document WY-070-02-065. Buffalo, Wyoming. Available online at http://www.wy.blm.gov/nepa/prb-feis/.

Butcher, J.B. 2003. Buildup, Washoff, and Event Mean Concentrations. Journal of the American Water Resources Association. 39(6): 1521-1528.

Cole, T.M., and S. A. Wells. 2003. CE-QUAL-W2: A two-dimensional, laterally averaged, Hydrodynamic and Water Quality Model, Version 3.1. Instruction Report EL-03-1. US Army Engineering and Research Development Center, Vicksburg, MS.

Crawford, N.H. and R.K. Linsley. 1966. Digital Simulation in Hydrology: The Stanford Watershed Model IV. Palo Alto, CA: Dept. of Civil Engineering, Stanford University; Tech. Rep. No. 39.

DNRC. 2003. *Pond data for Southeast Montana [Computer File]*. Montana Department of Natural Resources and Conservation [Producer and Distributor]. Helena, Montana.

DNRC. 2004. DNRC Water Resources Division Annual Report – 2004. Montana Department of Natural Resources and Conservation. Helena, Montana. Available online at http://dnrc.mt.gov/About_Us/publications/2004/wrd.pdf (accessed February 26, 2007).

DNRC. 2005. CAD files for the Tongue River Reservoir [Computer File]. Montana Department of Natural Resources and Conservation [Producer and Distributor]. Helena, Montana.

DNRC. 2006a. Draft Montana Watershed Boundaries 6th Code HUCs (Dated November 2006) [Computer File]. Montana Department of Natural Resources and Conservation [Producer and Distributor]. Helena, Montana. Available online at http://nris.state.mt.us/nsdi/watershed/index.html (Accessed December 12, 2006).

DNRC. 2006b. Daily Flow Data for the T&Y Diversion near Miles City, Montana [Computer File]. Montana Department of Natural Resources and Conservation [Producer and Distributor]. Helena, Montana.

Donigian, A. S., Jr., J. C. Imhoff., B.R. Bicknell, and J. L. Kittle, Jr. 1984. Application Guide for the Hydrological Simulation Program - FORTRAN. EPA 600/3-84-066. U. S. EPA, Environmental Research Laboratory, Athens, Georgia.

Donigian, Jr., A.S., 2000. HSPF Training Workshop Handbook and CD. Lecture #19. Calibration and Verification Issues. Presented and prepared for U.S. EPA, Office of Water, Office of Science and Technology, Washington, D.C.

Donigian. A.S. 2003. Watershed Model Calibration and Validation: The HSPF Experience.

Dunn, T. and Leopold, L.B. 1978. Water in Environmental Planning Freeman Press, San Francisco, 818 p.

Fidelity Exploration & Production Company. 2004. DMR Data for CBM Outfalls near Decker, Montana [Computer File]. Fidelity Exploration & Production Company [Producer and Distributor]. Sheridan, Wyoming.

Haith, D.A., R. Mandel, and R.S. Wu. 1992. GWLF, Generalized Watershed Loading Functions, Version 2.0, User's Manual. Dept. of Agricultural & Biological Engineering, Cornell University, Ithaca, NY.

Homer, C., C. Huang, L. Yang, B. Wylie, and M. Coan. 2004. Development of a 2001 National Land-Cover Database for the United States. Photogrammetric Engineering & Remote Sensing, 70(7): 829-840.

Jensen, M.E. and Haise, H.R. 1963. Estimating Evapotranspiration from Solar Radiation. Journal of the Irrigation and Drainage Division of the American Society of Civil Engineers. 89(IR4):15-41.

Keith, Kristen, J. Bauder, and J. Wheaton. 2003. Frequently Asked Questions – Coal Bed Methane. Montana State University. Available online at http://waterquality.montana.edu/docs/ methane/cbmfaq.shtml (accessed March 8, 2007).

Larson, L.R. and R. L. Daddow. 1984. Ground-Water-Quality Data from the Powder River Structural Basin and Adjacent Areas, Northeastern Wyoming. Open-File Report 83-939. U.S. Geological Survey, Cheyenne, WY.

Lewis, B.D., and Roberts, R.S. 1978. Geology and Water-yielding Characteristics of Rocks of the Northern Powder River Basin, Southeastern Montana: U.S. Geological Survey Miscellaneous Investigations Map I-847-D, scale 1:250,000, 2 sheets.

Lumb, A.M., R.B. McCammon, and J.L. Kittle, Jr. 1994. Users Manual for an Expert System (HSPEXP) for Calibration of the Hydrological Simulation Program–Fortran. Water-Resources Investigations Report 94-4168. U.S. Geological Survey. Reston, VA.

Mao, K. How To Select A Computer Model For Storm Water Management. Pollution Engineering, Oct. 1, 1992, pp. 60-64.

MASS. 2002. Montana Agricultural Statistics Volume XXXIX October 2002. Montana Agricultural Statistics Service. Helena, Montana.

MBOG. 2006. Online Oil & Gas Information System – Coal Bed Methane [Online]. Montana Board of Oil and Gas Conservation. Available online at http://bogc.dnrc.state.mt.us/default.asp (Accessed December 8, 2006).

MDEQ. 1996. Montana 303(d) List – Streams. Montana Department of Environmental Quality; Planning, Prevention, and Assistance Division, Monitoring and Data Management Bureau, Helena, Montana.

MDEQ. 2000. Authorization to Discharge Under the Montana Pollutant Discharge Elimination System – Redstone Gas Partners, LLC [Permit #MT0030457]. Montana Department of Environmental Quality. Helena, Montana.

MDEQ. 2001. Water Quality Impacts from Coal Bed Methane Development in the Powder River Basin, Wyoming and Montana. Montana Department of Environmental Quality Water Quality Technical Report. Helena, Montana.

MDEQ. 2003. Total Maximum Daily Load (TMDL) Status Report Tongue River TMDL Planning Area. Montana Department of Environmental Quality. Helena, Montana. Available online at http://deq.mt.gov/wqinfo/TMDL/TonguePowderRosebudTMDL.asp.

MDEQ. 2006a. 2006 Integrated 303(d)/305(b) Water Quality Report for Montana. Water Quality Planning Bureau, Montana Department of Environmental Quality. Available online at http://www.deq.state.mt.us/CWAIC/default.aspx (Accessed March 5, 2007).

MDEQ. 2006b. Administrative Rules of Montana – Chapter 30 Subchapter 6 – Surface Water Quality Standards and Procedures. Helena, Montana. Available online at http://arm.sos.state.mt.us/.

MDEQ. 2006c. Fidelity Exploration and Production Company MPDES Permit MT0030457 DMR Data [Computer File]. Montana Department of Environmental Quality [Producer and Distributor]. Helena, Montana.

Montana State Engineer. 1947. Water Resources Survey – Big Horn County, Montana. Helena, Montana.

MRLC. 2007. National Land Cover Database 2001 [Online]. Multi-Resolution Land Characteristics Consortium. Sioux Falls, South Dakota. Available online at http://www.mrlc.gov/ (Accessed December 2, 2006).

NADP. 2006. Annual Data Summaries for Site MT00 – Little Bighorn Battlefield National Monument. NADP Program Office, Illinois State Water Survey, Champaign, IL. Available online at http://nadp.sws.uiuc.edu/ (Accessed December 2, 2006).

Neff, Earl L. 1980. Using Sodium Carbonate to Seal Leaky Stock Ponds in Eastern Montana. Journal of Range Management. Volume 33(4). p. 292-295.

NRCS. 1986. Urban Hydrology for Small Watersheds Technical Release 55. June 1986.

NRCS. 2005. SNOTEL Data Collection Network Fact Sheet [Online]. Natural Resources Conservation Service. Portland, Oregon. Available at http://www.wcc.nrcs.usda.gov/snow/ (Accessed April 22, 2005).

Payne, A.A. and D. M. Saffer. 2005. Surface water hydrology and shallow groundwater effects of coalbed natural gas development, upper Beaver Creek drainage, Powder River Basin, Wyoming. Chapter 1 *in* Zoback, M.D., ed., Western Resources Project Final Report – Produced Groundwater Associated with Coalbed Natural Gas Production in the Powder River Basin. Report of Investigations No. 55. Wyoming State Geological Survey, Laramie, WY.

Penman, H.L. 1948. Natural Evaporation from Open Water, Bare and Grass. Proceedings from the Royal Society of London, Series A. Volume 193. pp. 120–145.

Sartor J. and G. Boyd. 1972. Water Pollution Aspects of Street Surface Contaminants. U.S. Environmental Protection Agency EPA-R2-72-08. Washington, D.C.

Schafer, W.M., N. Fehringer, and K. Harvey. 2006. 2006 Progress Report, Tongue River Agronomic Monitoring & Protection Program.

Schwab, G.O., D.D. Fangmeier, W.J. Elliott, and R.K. Frevert. 1993. *Soil and Water Conservation Engineering*. Fourth Edition.

SEO. 2001. Division II Annual Hydrographer's Report – 2001. Wyoming State Engineer's Office. Sheridan, Wyoming.

SEO. 2002. Division II Annual Hydrographer's Report – 2002. Wyoming State Engineer's Office. Sheridan, Wyoming.

SEO. 2003. Division II Annual Hydrographer's Report – 2003. Wyoming State Engineer's Office. Sheridan, Wyoming.

SEO. 2004. Division II Annual Hydrographer's Report – 2004. Wyoming State Engineer's Office. Sheridan, Wyoming.

SEO. 2005. Division II Annual Hydrographer's Report – 2005. Wyoming State Engineer's Office. Sheridan, Wyoming.

SEO. 2006a. Daily Flow Data for the Park Diversion [Computer File]. Wyoming State Engineer's Office (Producer and Distributor). Cheyenne, Wyoming. Obtained December 26, 2006.

SEO. 2006b. Daily Flow Data for the Meade-Coffeen, Piney-Cruse, and Prairie Dog Transbasin Diversions [Computer File]. Wyoming State Engineer's Office (Producer and Distributor). Cheyenne, Wyoming. Obtained December 27, 2006.

Smith, R.A., Alexander, R.B., and Schwarz, G.E., 2003. Estimating the natural background concentrations of nutrients in streams and rivers of the conterminous United States. Environmental Science and Technology. Vol. 37, 3039-3047.

Theissen, A.H., 1911, Precipitation Averages for Large Areas. Monthly Weather Review, v. 39, p. 1082–1084.

Trelease, Frank J., T. Swartz, P. Rechard, and R. Burman. 1970. Consumptive Use of Irrigation Water in Wyoming. Wyoming Water Planning Report No. 5. Water Resources Series No. 19. Cheyenne, Wyoming. Available online at http://library.wrds.uwyo.edu/wrs/wrs-19/ (accessed December 29, 2006).

Tuteja, N.K., G.T.H. Beale, G. Summerell, and W.H. Johnston. 2002. Development and Validation of the Catchment Scale Salt Balance Model – CATSALT (Version 1). New South Wales Dept. of Land and Water Conservation, Parramatta, New South Wales, Australia.

United States Army Corps of Engineers. 1956. Snow Hydrology. Portland, OR.

U.S. Bureau of Reclamation. 2006. Great Plains Cooperative Agricultural Weather Network – AgriMet Data [Online]. Available at http://www.usbr.gov/gp/agrimet/ (Accessed February 14, 2006)

USDI. 2003. Final Statewide Oil and Gas EIS and Proposed Amendment of the Powder River and Billings RMPs. United State Department of the Interior – Bureau of Land Management. Miles City and Billings, Montana Field Offices. Billings, Montana.

USEPA. 1985. Rates, Constants, and Kinetics Formulations in Surface Water Quality Modeling (Second Edition). U.S. Environmental Protection Agency Document EPA/600/3-85/040. Office of Research and Development. Athens, Georgia.

USEPA. 1997. Technical Guidance Manual for Developing Total Maximum Daily Loads: Book 2, Rivers and Streams; Part 1 - Biochemical Oxygen Demand/Dissolved Oxygen & Nutrient Eutrophication EPA 823/B-97-002.

USEPA. 2000. *BASINS Technical Note 6. Estimating Hydrology and Hydraulic Parameters for HSPF*. EPA-823-R00-012. U.S. Environmental Protection Agency. Office of Water. July 2000.

USEPA. 2003. Draft Guidance on the Development, Evaluation, and Application of Regulatory Environmental Models. Prepared by The Council for Regulatory Environmental Modeling. U.S. Environmental Protection Agency, Office of Science Policy, Office of Research and Development. Washington, D.C.

USEPA. 2006. Permit Compliance System Database [Online]. U.S. Environmental Protection Agency. Washington D.C. Available online at http://www.epa.gov/enviro/html/pcs/pcs_overview.html (Accessed October 18, 2006).

USEPA. 2007. Water Quality Assessment for the Tongue River Watershed, Montana. U.S. Environmental Protection Agency, Montana Operation Office. Helena, Montana.

USGS. 2002. 30-Meter National Elevation Dataset for Montana [Computer File]. U.S. Geological Survey EROS Data Center [Producer] and Montana State Library [Distributor]. Helena, Montana. Available online at http://nris.state.mt.us/gi.asp.

USGS. 2004. Channel-Morphology Data for the Tongue River and Selected Tributaries, Southeastern Montana, 2001-02. Open-File Report 2004-1260. U.S. Geological Survey. Reston, Virginia. Available online at http://pubs.usgs.gov/of/2004/1260/ (Accessed December 2, 2006).

WDEQ. 2003a. Authorization to Discharge Under the National Pollutant Discharge Elimination System – Dayton Wastewater Treatment Lagoon [Permit #WY0020435]. Wyoming Department of Environmental Quality. Cheyenne, Wyoming.

WDEQ. 2003b. Authorization to Discharge Under the National Pollutant Discharge Elimination System – Bighorn Mountain KOA Sewage Plant [Permit #WY0026441]. Wyoming Department of Environmental Quality. Cheyenne, Wyoming.

WDEQ. 2004a. Authorization to Discharge Under the National Pollutant Discharge Elimination System – Burgess Junction Dump Station [Permit # WY0020931]. Wyoming Department of Environmental Quality. Cheyenne, Wyoming.

WDEQ. 2004b. Authorization to Discharge Under the National Pollutant Discharge Elimination System – AC Ranch N and E, Option 1B Facility [Permit #WY0052043]. Wyoming Department of Environmental Quality. Cheyenne, Wyoming.

WDEQ. 2005a. Authorization to Discharge Under the National Pollutant Discharge Elimination System – Sheridan Wastewater Treatment Plant [Permit #WY0020010]. Wyoming Department of Environmental Quality. Cheyenne, Wyoming.

WDEQ. 2005b. Authorization to Discharge Under the National Pollutant Discharge Elimination System – Ranchester Wastewater Treatment Lagoon [Permit #WY0022161]. Wyoming Department of Environmental Quality. Cheyenne, Wyoming.

WDEQ. 2005c. Authorization to Discharge Under the National Pollutant Discharge Elimination System – Wrench Ranch Goose Creek On-Channel [Permit #WY0038628]. Wyoming Department of Environmental Quality. Cheyenne, Wyoming.

WDEQ. 2005d. Authorization to Discharge Under the National Pollutant Discharge Elimination System – Hape 14 Option 2 [Permit #WY0051811]. Wyoming Department of Environmental Quality. Cheyenne, Wyoming.

WDEQ. 2005e. Authorization to Discharge Under the National Pollutant Discharge Elimination System – Pipeline Ridge [Permit #WY0052345]. Wyoming Department of Environmental Quality. Cheyenne, Wyoming.

WDEQ. 2005f. Authorization to Discharge Under the National Pollutant Discharge Elimination System – Dunning Facility [Permit #WY0046540]. Wyoming Department of Environmental Quality. Cheyenne, Wyoming.

WDEQ. 2006a. Authorization to Discharge Under the National Pollutant Discharge Elimination System – Powder Horn Ranch LLC [Permit #WY0036251]. Wyoming Department of Environmental Quality. Cheyenne, Wyoming.

WDEQ. 2006b. Authorization to Discharge Under the National Pollutant Discharge Elimination System – Sheridan Water Treatment Plant [Permit #WY0001392]. Wyoming Department of Environmental Quality. Cheyenne, Wyoming.

WDEQ. 2007. Microsoft Access Database of Point Sources in the Tongue River Watershed [Computer File]. Wyoming Department of Environmental Quality [Producer and Distributor]. January 26, 2007.

Wheaton, J.W. and T.H. Brown. Predicting Changes in Groundwater Quality Associated with Coalbed Natural Gas Infiltration Ponds. Chapter 2 *in* Zoback, M.D., ed., Western Resources Project Final Report – Produced Groundwater Associated with Coalbed Natural Gas Production in the Powder River Basin. Report of Investigations No. 55. Wyoming State Geological Survey, Laramie, WY.

WWDC. 2002a. 1:24,000-Scale Irrigation Points of Diversion (Service Areas), in Decimal Degrees – NAD 1927 [Computer File]. Wyoming Water Development Commission [Distributor]. Cheyenne, Wyoming. Available online at http://waterplan.state.wy.us/.

WWDC. 2002b. Bedrock Geology in Decimal Degrees - NAD 1927 [Computer File]. Wyoming Water Development Commission [Distributor]. Cheyenne, Wyoming. Available online at http://waterplan.state.wy.us/.

WWDC. 2002c. Wyoming Stock Pond Permit Locations through December 2000, in Decimal Degrees - NAD 1927 First Edition [Computer File]. Wyoming Water Development Commission [Distributor]. Cheyenne, Wyoming. Available online at http://waterplan.state.wy.us/.

WWDC. 2002d. Powder/Tongue River Basin Water Plan Technical Memoranda A – Irrigation Diversion Operation and Description. Wyoming Water Development Commission. Cheyenne, Wyoming. Available online at http://waterplan.state.wy.us/.

WWDC. 2002e. Powder/Tongue River Basin Water Plan Technical Memoranda C – Irrigated Lands Mapping and Water Rights Data. Wyoming Water Development Commission. Cheyenne, Wyoming. Available online at http://waterplan.state.wy.us/.

WWDC. 2002f. Powder/Tongue River Basin Water Plan Technical Memoranda D – Agricultural Water Use. Wyoming Water Development Commission. Cheyenne, Wyoming. Available online at http://waterplan.state.wy.us/.

WWDC. 2002g. Powder/Tongue River Basin Water Plan Technical Memoranda J – Storage Operation and Description. Wyoming Water Development Commission. Cheyenne, Wyoming. Available online at http://waterplan.state.wy.us/.