Tongue River Watershed Salinity Modeling Report

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Stakeholder Draft

Greg Gianforte, Governor
Christopher Dorrington, Director DEQ

Prepared by:
DEQ Water Quality Planning Bureau, Standards and Modeling and TMDL Sections
In collaboration with Tetra Tech, Inc.

Contributors:

DEQ:
Eric Regensburger, modeler
Christina Staten, coordinator and TMDL Supervisor
Christy Meredith, Water Quality Scientist
Katie Makarowski, Standards and Modeling Supervisor
Andy Ulven, Bureau Chief
Kristy Fortman, Former TMDL Supervisor
Dean Yashan, Former TMDL Supervisor
Erik Makus, Former Modeler

Tetra Tech:
Cole Blasko, Modeler
Sam Sarkar, Former Modeler
Kevin Kratt, Project Coordination
Jon Butcher, Modeling Quality Control Officer

Cover Photo:
Tongue River near confluence with Sand Creek
Photo by: Montana DEQ

Montana Department of Environmental Quality
Water Quality Planning Bureau
1520 E. Sixth Avenue
P.O. Box 200901
Helena, MT 59620-0901

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ACRONYMS

Acronym	Definition
AMSL	Above Mean Sea Level
cfs	cubic feet per second (a unit of flow)
ARM	Administrative Rules of Montana
Ca	calcium cation
CBM	Coalbed Methane
cms	cubic meters per second (a unit of flow)
DEQ	Department of Environmental Quality (Montana)
DNRC	Department of Natural Resources & Conservation
EC	Electrical Conductivity
EMC	Event Mean Concentration
EPA	Environmental Protection Agency (US)
ET	Evapotranspiration
GIS	Geographical Information System
GWIC	Ground Water Information Center (Montana)
ha	Hectares (a unit of area)
HUC	Hydrologic Unit Code
LOADEST	USGS Load Estimator
Mg	magnesium cation
MBOGC	Montana Board of Oil & Gas Conservation
MUID	Map Unit Identifier
NASS	National Agricultural Statistics Service
NCDC	National Climatic Data Center
NED	National Elevation Dataset
NEXRAD	Next Generation Radar Data
NHD	National Hydrography Dataset
NLCD	National Land Cover Dataset
NRCS	Natural Resources Conservation Service
NOAA	National Oceanic and Atmospheric Administration
NSE	Nash-Sutcliffe Coefficient of Efficiency
PET	Potential evapotranspiration
RAWS	Remote Automated Weather Station
RE	Relative Error
RM	River Mile
SAR	Sodium Adsorption Ratio
SC	Specific Conductance
SCS	Soil Conservation Service
SNOTEL	NRCS Snowpack Telemetry
SSURGO	Soil Survey Geographic Database

Acronym	**Definition**
SWAT	Soil and Water Assessment Tool
TMDL	Total Maximum Daily Load
TPA	TMDL Planning Area
µS/cm	microsiemens per centimeter
USFS	United States Forest Service
USGS	United States Geological Survey
WDEQ	Wyoming Department of Environmental Quality
WOGCC	Wyoming Oil & Gas Conservation Commission
WRCC	Western Regional Climate Center

EXECUTIVE SUMMARY

The Tongue River forms in the Big Horn Mountains west of Sheridan, Wyoming, flows across the Wyoming-Montana state border near Decker, Montana and ends at its confluence with the Yellowstone River in Miles City, Montana. Two segments within Montana are currently on Montana's 303(d) list of impaired waters due to elevated levels of salinity, which impacts the agricultural uses along the Tongue River. This study was undertaken to help understand the sources of salinity, and to identify potential solutions towards reducing salinity.

Geologically, the Tongue River lies in an area of shales and coalbeds that underlies parts of Wyoming, Montana, and the Dakotas. The upper portions of the watershed are the Bighorn Mountains, which are some of the highest mountains in the region. These mountains receive large amounts of precipitation and snow in the winter. The late spring/early summer runoff from the Bighorn Mountains supplies most of the annual water supply in the Tongue River. Water from the Bighorn Mountains has relatively low salinity. The Tongue River Reservoir captures flows from Wyoming for summer/fall irrigation use in Montana. The reservoir also provides recreational fishing and boating. Much of the Tongue River watershed below the Bighorn Mountains is composed of relatively saline bedrock, with low rainfall and high evapotranspiration. This has resulted in relatively saline soils and groundwater as well as tributaries. The saline water limits the ability to use tributary water in Montana and parts of Wyoming for irrigation purposes, with tributary area watershed irrigation often limited to high precipitation and snowmelt events. Tongue River water quality is much better than the tributaries and is usually acceptable for irrigation of crops grown in the watershed. Irrigation water from the Tongue River is used throughout the watershed, and the largest Tongue River diversion is at the 12 mile dam (referred to as the T & Y diversion) about 12 miles upstream of Miles City.

The Tongue River has a long history of human interest. The area has been inhabited by Native Americans for several thousand years, and was first settled by European Americans in the 1880s. In the 1880s, livestock and agriculture (cattle grazing and irrigated crops) was introduced to the watershed and continues to the present day. Due to the large amount of coal reserves in the watershed, coal mining has occurred in the watershed for over 100 years. Since about the 1990s, coalbed methane (CBM) extraction has also occurred. Concern over land use impacts on water quality has led to increased water quality monitoring. This monitoring data includes flow as well as salinity-related parameters such as specific conductance from multiple locations throughout the watershed.

To help evaluate salinity loads in the Tongue River watershed, DEQ applied the Soil and Water Assessment Tool (SWAT) water quality model. DEQ used a version of SWAT that includes the ability to simulate salt ions; therefore, the model is referred to as SWATSalt. DEQ compiled several types of data to build the SWATSalt model, including climate data, land use, soils, and both stream flow and water quality data. The model was then calibrated to the observed flow and water quality data. Several calibration parameters, including those that impact the rain/snow balance, overall discharge volumes, range of flows, and other modeling parameters, were adjusted so that model output adequately matched observed data. While individual storm volumes were difficult to accurately simulate, overall the model performed well at re-creating flow conditions in the watershed. Water quality was also calibrated to an acceptable level, matching up closely with the ranges and statistical measures of the observed data.

Following calibration, the model was modified to simulate several scenarios. These included removal and alteration of industrial practices in the watershed (coalbed methane, coal mining), removal and alteration of livestock and agricultural practices in the watershed, Tongue River Dam operational changes, and a natural (historical) scenario. These scenarios show that human activities including coal and coalbed methane extraction affect salinity concentrations along the Tongue River. However, even after removing these sources, salinity levels still exceeded current water quality standards.

1.0 INTRODUCTION

This document describes the development and results for salinity modeling in the Tongue River watershed using the Soil and Water Assessment Tool (SWAT).

The Tongue River watershed is located in southeastern Montana and northern Wyoming and includes portions of both the Northern Cheyenne and Crow Indian Reservations (**Figure 1-1**). The Tongue River forms in the Big Horn Mountains west of Sheridan, Wyoming; flows across the Wyoming-Montana border north of Sheridan; and ends at its confluence with the Yellowstone River in Miles City, Montana. Agriculture represents a major land use within the Tongue River watershed in both Montana and Wyoming, with much of the agriculture relying on irrigation water from the Tongue River or tributaries for crop production. Two segments of the Tongue River in Montana (Assessment Unit ID MT42C001_011 and MT42C001_014, **Figure 1-1**) are not fully supporting their agricultural beneficial use due to probable causes of salinity impairment(EC) (MT DEQ 2021)).

The Montana Department of Environmental Quality (DEQ) determined that a modeling approach was the most effective way to identify the contributions of natural and anthropogenic salt loads in the Tongue River watershed. DEQ began modeling in the early 2000s and initiated several efforts towards completion of a model. The model chosen by DEQ was the SWATSalt model originally developed by Texas A & M. DEQ set up the model and started model development but never finished an earlier calibration of a SWATSalt model for the Tongue River watershed. In 2021, EPA provided funding to DEQ to update and complete the model through a contract with Tetra Tech. DEQ and EPA worked with Tetra Tech on model development, including parameterizing, calibrating, and summarizing the model. Many of the inputs were based on work done in previous DEQ modeling efforts on the Tongue River.

The principal study questions answered by the Tongue River watershed SWAT salinity model included:

1. What are the baseline flow and salinity conditions in the watershed, including the relative contributions of natural, anthropogenic nonpoint, and anthropogenic point sources of salinity?

2. What anthropogenic sources, cumulatively or individually , can be managed to reduce salinity and result in meeting salinity water quality standards for the model time period?

The Tongue River salinity model was developed to inform the potential development of one or more salinity Total Maximum Daily loads (TMDLs) for the Tongue River to satisfy both Montana State Law and Federal Clean Water Act requirements. TMDLs define a pollutant “budget” and include pollutant loading allocations to major sources or source categories, with a goal of developing a path toward meeting applicable water quality standards. By further quantifying the contribution of point sources, modeling results may also be used in the development of future permit limits under the Montana Pollutant Discharge Elimination System (MPDES).

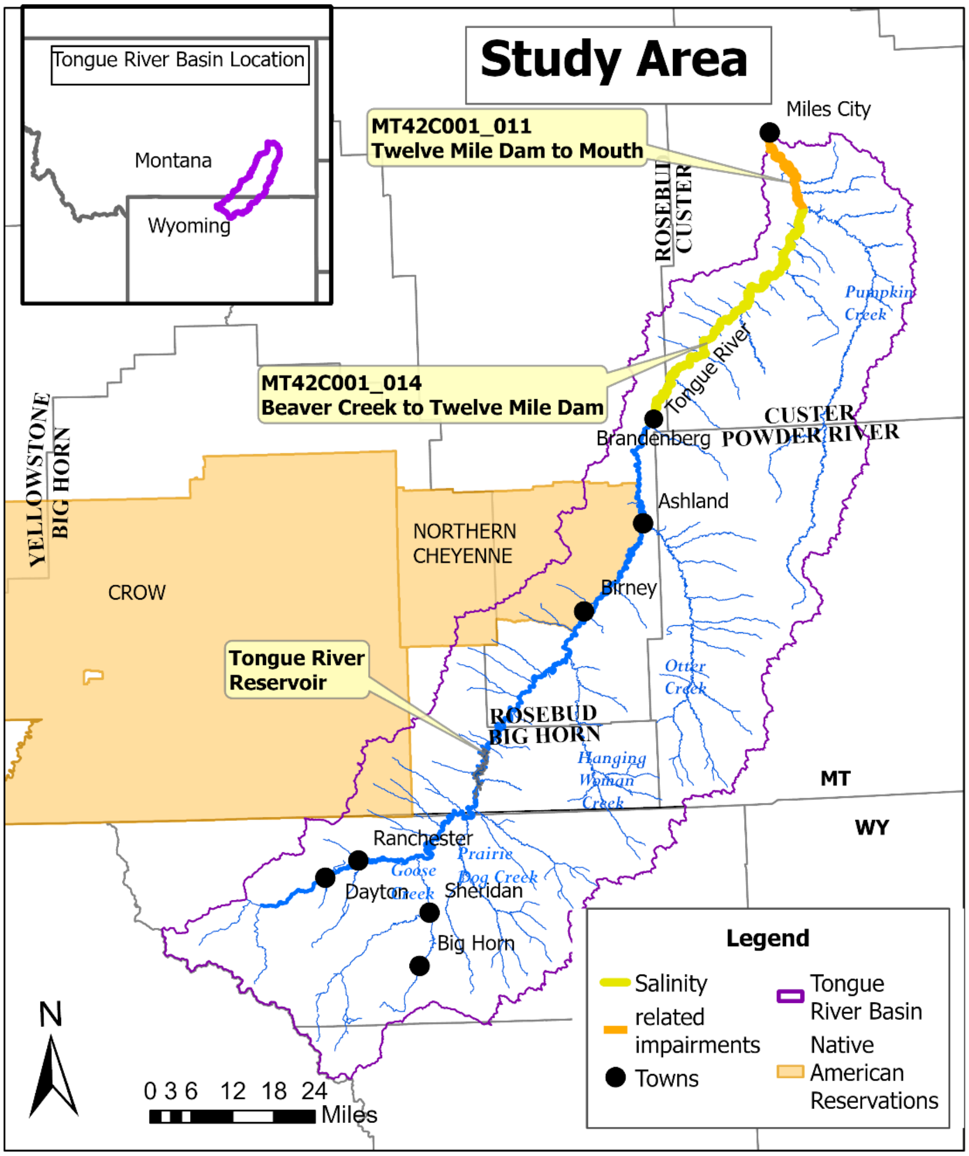


Figure 1-1. Tongue River watershed

2.0 Tongue River Watershed Description

The Tongue River is located in southeastern Montana and northern Wyoming, and flows northward approximately 265 miles from the Bighorn Mountains of Wyoming to its mouth at Miles City, Montana, where it joins the Yellowstone River **(Figure 1-1).** The watershed is approximately 5,400 square miles (14,000 square kilometers), or about 3.56 million acres in size. Elevations in the watershed range from approximately 2,300 feet at Miles City to approximately 11,750 feet in the Bighorn Mountains (USGS 2022).

2.1 Climate

Much of the Tongue River watershed is classified as a cold semi-arid steppe climate according to the Koppen system (Plantmaps 2023). Valleys tend to be moderately arid while hillier regions are slightly wetter, and the mountains are very wet. Annual precipitation is approximately 12-15 inches throughout most of the basin valley. Annual precipitation in the Bighorn Mountains can exceed 40 inches. Snowfall in the valleys is moderate, with snowpack rarely exceeding 12 inches. Snowpack can exceed 10 feet or more in the mountains and can last well into June in some years (USDA 2023).

2.2 Geology

The Tongue River basin is located in the northern end of The Powder River Basin in southeast Montana and northeast Wyoming, spanning about 120 miles east to west and 200 miles north to south. As the Big Horn mountains uplifted over geologic time they uplifted and tilted sedimentary rocks, which were then eroded away, creating the plains that span to the east into the area of the Tongue River (Ashley 2005).

Older sedimentary layers are present closer to the mountains and younger layers are present farther away. In the Big Horn Mountains, the Tongue River originates in a mountain canyon of Madison Limestone, deposited approximately 350 million years ago. As the Tongue leaves the mountains it flows through younger formations, including the distinctive thick red Chugwater Formation, deposited approximately 225 years ago. The Tongue River then enters an area dominated by a thick layer of sandstones and silty clay. This sedimentary layer is named for the Tongue River itself, “Tongue River Sandstone”, because its outcrops are dominant in the basin. The Tongue River Sandstone is the youngest of three "members" which form the Fort Union Formation which dominates in the Tongue River basin. The other two members are the Lebo Shale Member and the Tullock sedimentary Member, which are found near the surface closer to Miles City. The Tongue River Member contains extensive coal reserves, including at least 32 coal seams (Ashley 2005).

Saline soils are naturally occurring in the Tongue River watershed due to weathering of marine sediments, low precipitation, and high evapotranspiration. High salt concentrations in soil can limit the amount of plant available water and cause plant mortality, but this varies depending on the type of plant, soil, root depth, and history of agricultural practices (Thompson 1991) .

2.3 History and Land Use

The Tongue River has a long history of human interest. The area has been inhabited by Native Americans for several thousand years, including the Crow and Northern Cheyenne tribes (Hanson 1998). The area was first settled by European Americans in the 1880s when agriculture (cattle grazing and irrigated crops) was quickly introduced to the watershed. This agricultural tradition continues to the present day. Additionally, due to the large amount of coal reserves in the watershed, coal mining has had an active presence in the watershed for over 100 years. Since about the 1990s, coalbed methane (CBM) extraction has also had an active role in the watershed as well.

Figure 2-1 provides land cover information for the watershed. Note that a large portion of the watershed is public grazing allotments. Agricultural lands used for irrigated crop production represent about 3% of the Wyoming portion of the watershed and about 2% of the Montana portion of the watershed (Wyoming Framework Water Plan 2007; FLU 2019). Much of the crop production is to grow hay and alfalfa for cattle feed in support of ranching operations.

Urban development represents only a minor portion of the watershed (~2%) (**Figure 2-1**), with Sheridan, WY being the largest city completely within the watershed with a population of 17,860 in 2017. Other cities and communities include Dayton, WY (population 824 in 2017), Ashland, MT (population 464 in 2000), and Birney, MT (population 108 in 2000). A portion of Miles City, MT is located within the watershed along the Tongue River near the mouth where the Tongue River flows into the Yellowstone River (Figure 1-1).

Land ownership is a mix of private, state, federal, and tribal lands (**Figure 2-2.)** Significant portions of the state and federal lands support grazing. Coal mining and oil and gas production, including coalbed methane extraction, occur on a mix of the private, state and federal lands within Wyoming and Montana.

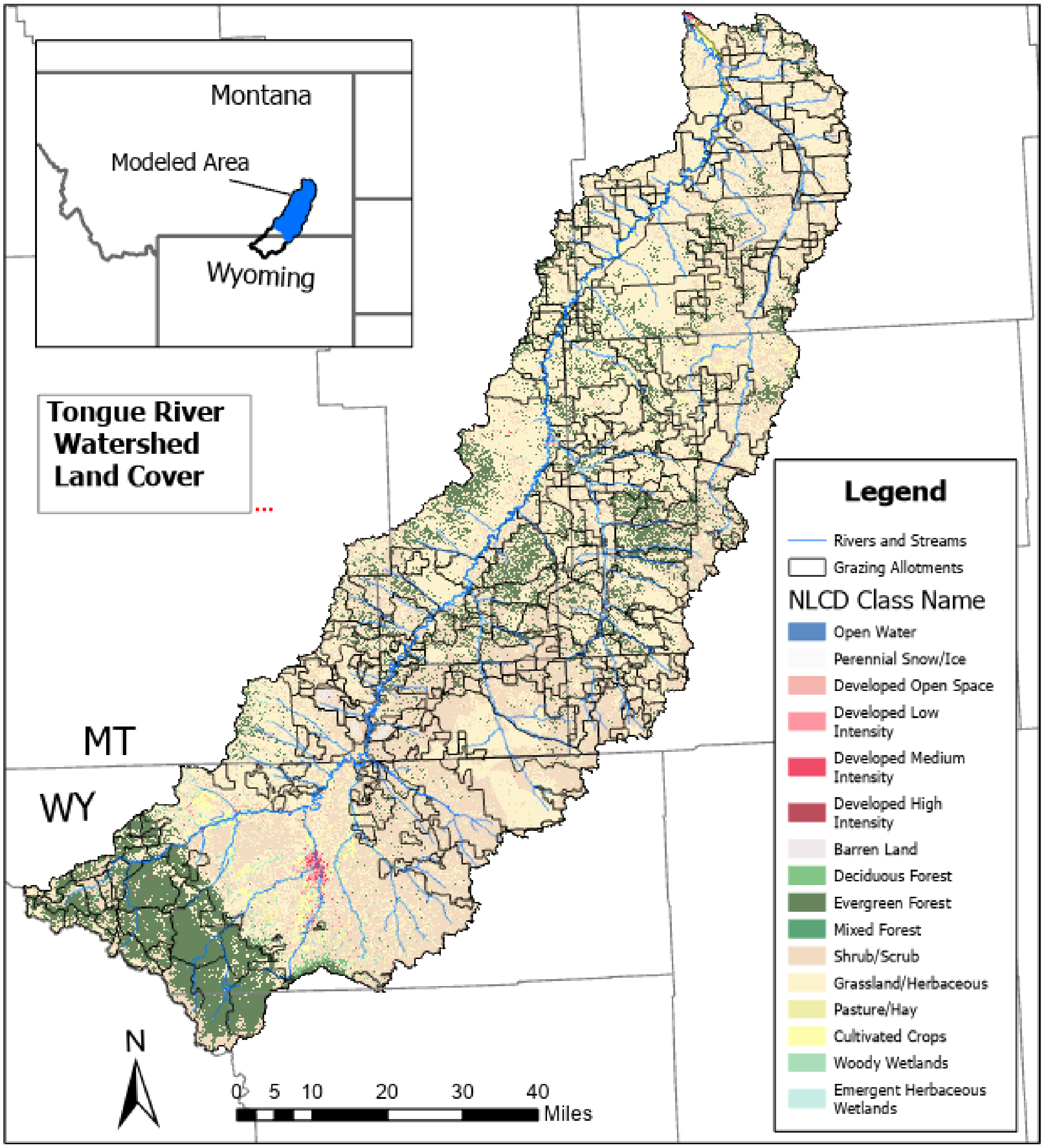


Figure 2-1. Land cover in the Tongue River watershed according to the 2006 NLCD which was used to develop the model.

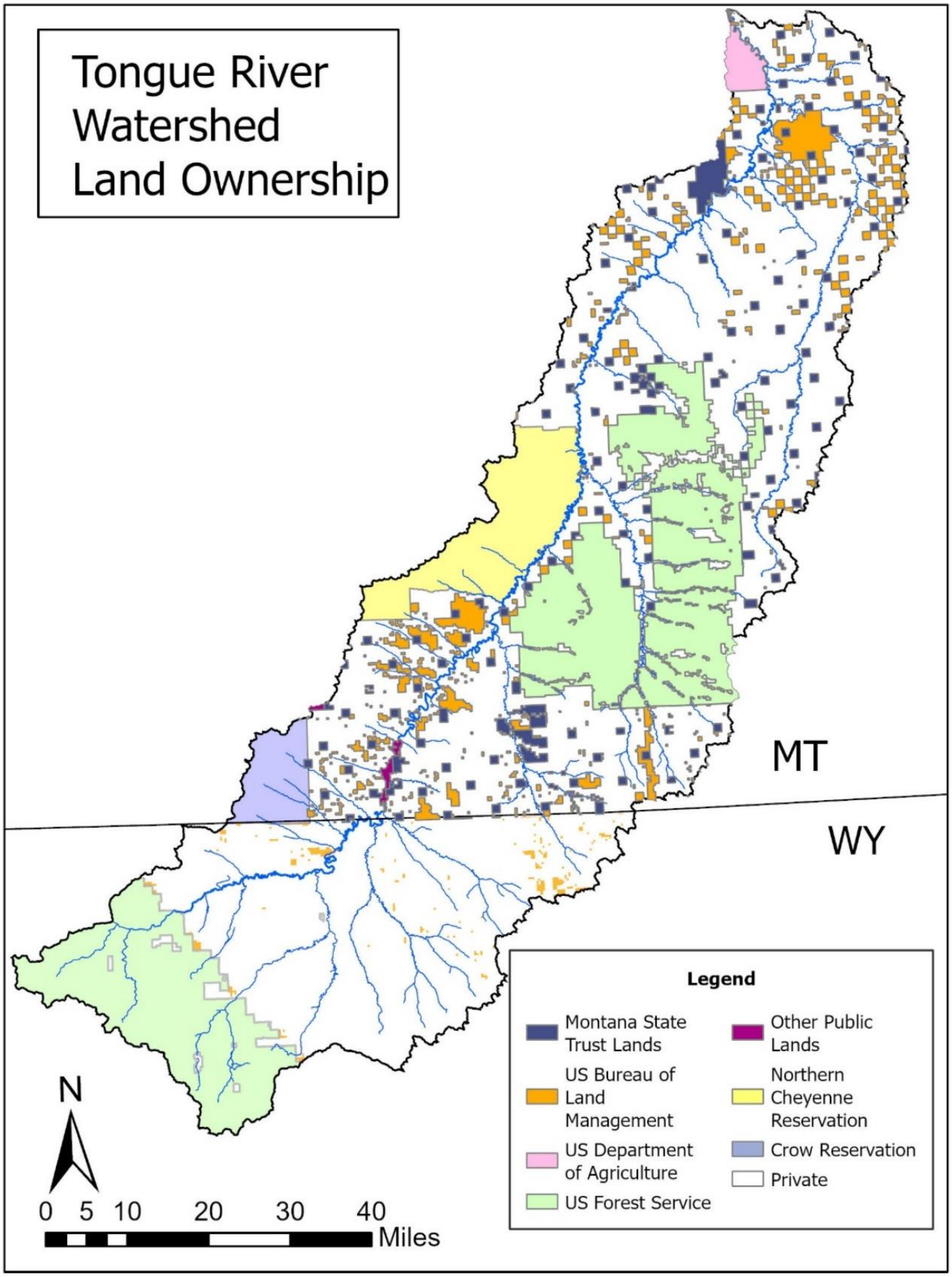


Figure 2-2. Land ownership in the Tongue River watershed.

2.4 HYDROLOGY

The hydrology of the Tongue River watershed is a complex interconnection of fairly regular snowmelt from the Bighorn Mountains, irregular precipitation, groundwater recharge and discharge, check dams, and irrigation practices. The Tongue River flows a total distance of about 265 miles, meeting the Yellowstone River at Miles City, Montana. Major tributaries to the Tongue River within Wyoming include Goose Creek and Prairie Dog Creeks (**Figure 2-3**). Badger Creek is located predominately within Wyoming, entering the Tongue River in Montana a few miles downstream of the Montana-Wyoming border. Three major tributaries entering the Tongue River in Montana include Hanging Woman, Otter, and Pumpkin Creeks. Both Otter and Pumpkin Creek watersheds are contained completely within Montana, whereas approximately 30% of the upper portion of the Hanging Woman Creek watershed is within Wyoming (**Figure 2-3**). The Montana tributaries exhibit prairie stream characteristics with flashy high flows linked to snow melt and/or precipitation events. Baseflows are low, occasionally resulting in dry channel conditions throughout the length of a tributary during dry periods after snowmelt. These same prairie characteristics also apply to a few of the major tributaries originating in Wyoming outside of the Big Horn Mountains, notably Prairie Dog and Badger Creeks.

The Tongue River Reservoir is a 12-mile long, 642 acre impoundment used to store irrigation water and provide recreation opportunities. The reservoir generally stores excess water during spring runoff with subsequent discharge for downstream irrigation season use primarily along the Tongue River corridor. Releases from the reservoir are managed by DNRC in partnership with the Tongue River Water users Association and are subject to the requirements of the Yellowstone River Compact (Bach 1982).

Streamflow has been monitored by the United States Geological Survey (USGS) at nine locations along the Tongue River in Montana, and at additional stations in Wyoming (**Figure 2-3**). The average daily discharge at the State Line near Decker (USGS 06306300) is approximately 438 cubic feet per second (cfs), ranging from a low of less than 10 cfs (August 1961 and August 2001) up to a daily high of over 15,000 cfs (May 1978). The average daily discharge near the mouth at Miles City (USGS gage 06308500) is approximately 437 cubic feet per second (cfs), ranging from a low of 2.2 cfs (May 1981) up to a daily high of over 12,000 cfs (May 2011).

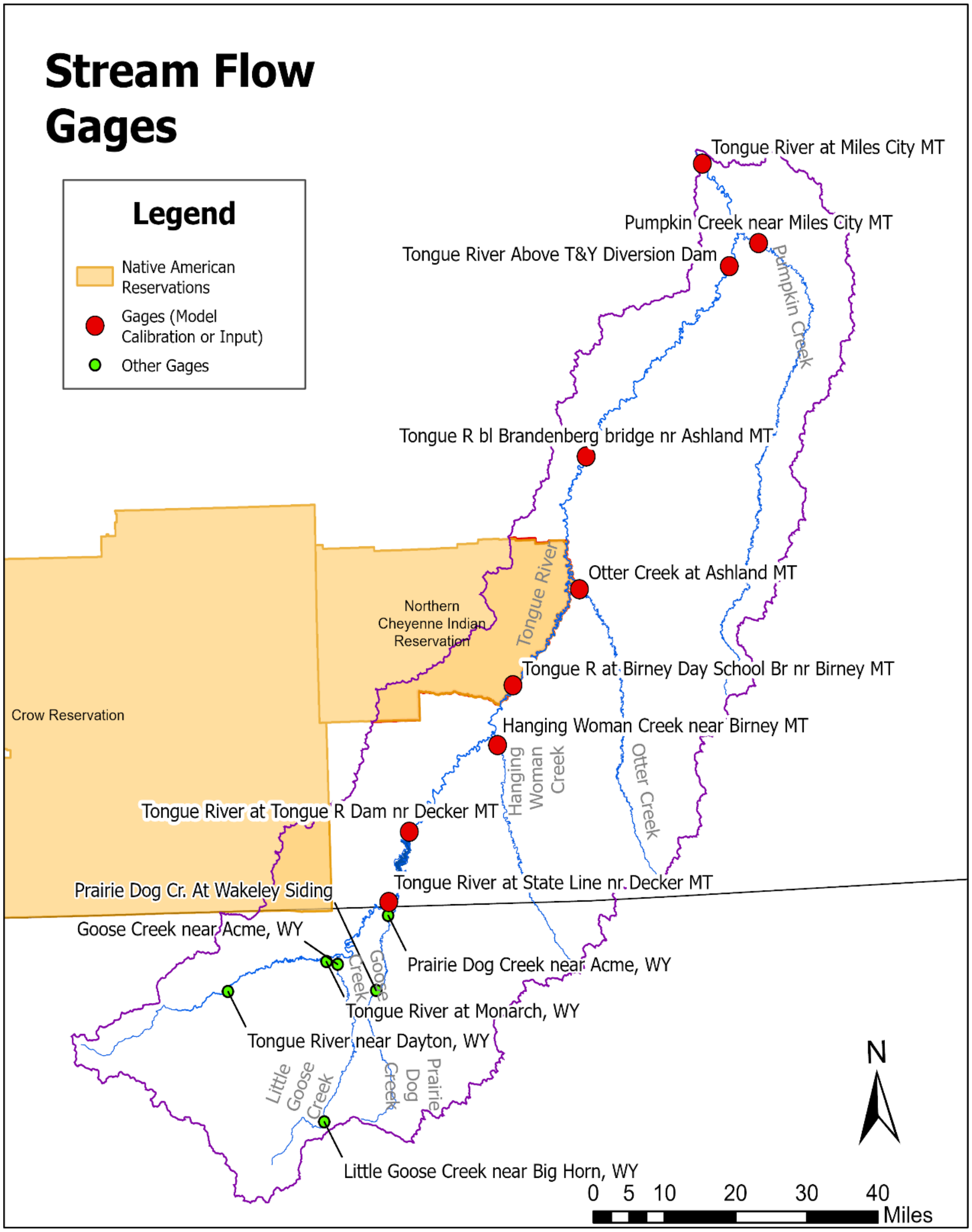


Figure 2-3. Location of USGS Gage Stations in the Tongue River Watershed

The average daily hydrograph at the Tongue River at state line nr Decker (state line) USGS gage shows that streamflow peaks in late May-July due to snowmelt and runoff from the Bighorn Mountains, and (to a lesser degree) precipitation events (**Figure 2-4**). Baseflow conditions typically occur from about August through April. The typical annual hydrograph shows a small peak in March due to prairie snowmelt and runoff, rain on snow events, etc., and then a larger peak from the mountain snowmelt in May-July (**Figure 2-4**). The hydrograph below the reservoir shows more erratic peaks and dips throughout the year (**Figure 2-5**). These are likely due to the many prairie streams that enter the river below the dam. As discussed above, these streams are very flashy and can vary considerably in flow volume in short periods of time. Pumpkin Creek is a good example – it flows into the Tongue River about 12 miles upstream of Miles City, and has a median flow value of 0.2 cfs, but has peaked at 4,660 cfs. Although over the course of the year the prairie streams have very little influence on the cumulative flow of the Tongue River, at times they can represent the majority of the flow at of the mouth of the Tongue River at Miles City and at upstream locations where specific tributaries enter the Tongue River. These tributary impacts on flow can also have short-term significant influences on water quality in the Tongue River given the variable nature of water quality in many of these Tongue River tributaries in comparison to the quality of the water released from the Tongue River Reservoir.

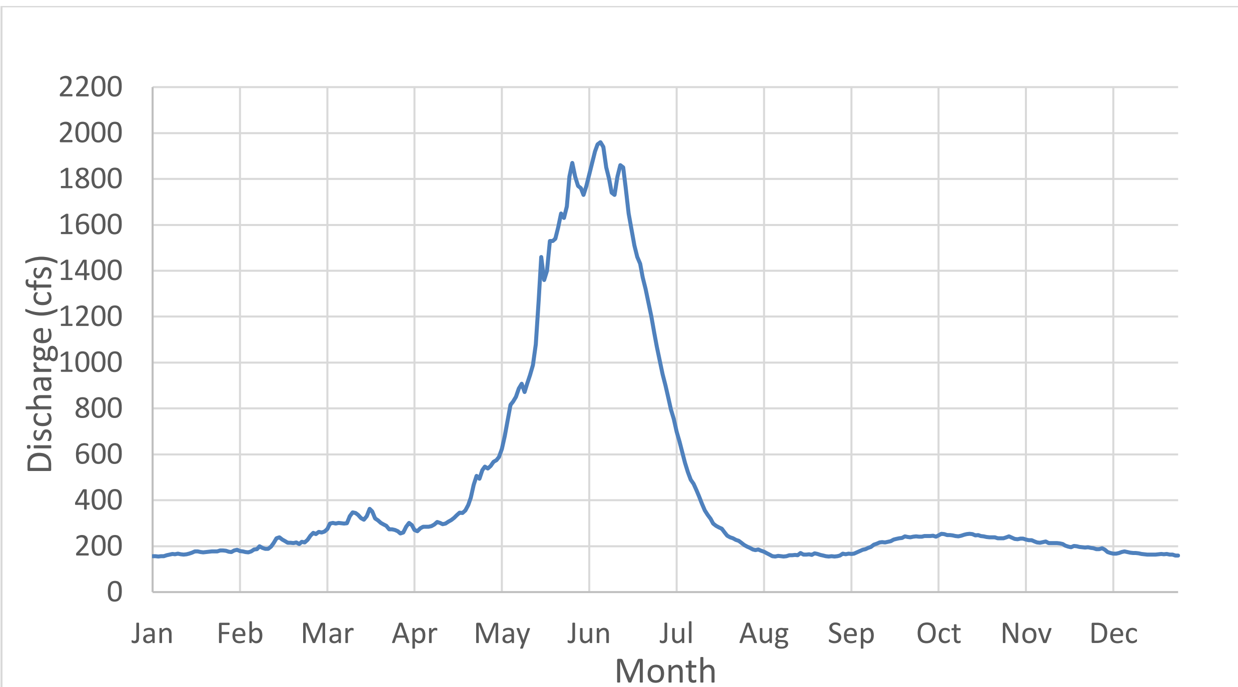


Figure 2-4. Average daily discharge (1960-2022) at USGS gage 06306300 (Tongue River at State Line nr Decker)

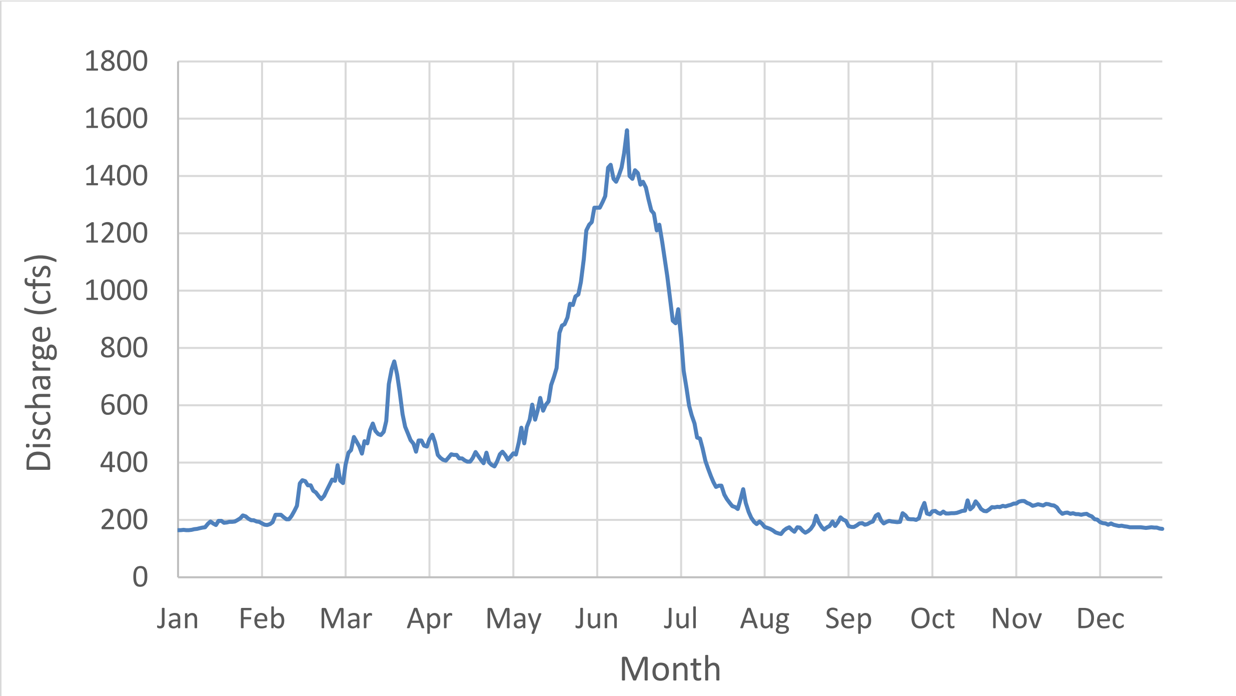


Figure 2-5. Average daily discharge (1960-1922) at USGS gage 06308500 (Tongue River at Miles City)

2.5 Coalbed Methane Activity

Coalbed methane (CBM) is methane gas found in coal seams. The gas is usually held in the coal seams in a near liquid state and is adsorbed to the coal particles (Meredith et al. 2012). Pumping water out of the aquifers releases the pressure from the coal seams. As the pressure within the coal seam declines due to natural production or the pumping of water from the coalbed, both gas and produced water come to the surface. This produced water is typically high in salinity and/or sodium (Ruckelshaus Institute 2005). While the gas is harvested, the water is typically discharged directly into a stream (with or without treatment), held in a constructed pond, or used for other purposes such as dust suppression and livestock watering. Produced water from multiple wells are typically combined before discharging via one of those methods. Discharges directly to waterbodies are referred to as outfalls in their state-issued discharge permits. Ponds which do not discharge directly to waterbodies can either be “on-channel” ponds or “off-channel" ponds (Ruckelshaus Institute 2005), and are also considered outfalls in discharge permits. On-channel ponds are typically located in ephemeral channels where a dam is constructed and the water can evaporate or seep into the channel. On-channel ponds are designed to overflow during precipitation events and potentially discharge to downstream perennial streams when large runoff events occur. Off-channel ponds are located away from channels where the produced water evaporates or seeps into the soil where it can be either be used by plants or enter groundwater which can provide a pathway to surface water. Off-channel ponds are designed to overflow only during extreme precipitation events. Ponds can also be lined or unlined. Unlined ponds allow impounded water to infiltrate back to groundwater more easily, but can also cause deterioration of water quality below the ponds (Meredith et al 2012).

The Tongue River watershed experienced rapid development and rapid decrease of CBM development throughout the last 20 years. Starting in the late 90s, CBM development began in the watershed and steadily increased until about 2008 or 2009, when it peaked at over 3,000 wells and then quickly dropped as natural gas prices dropped (**Figure 2-6**). As of 2022, CBM development in the watershed is limited. Note that produced water rates have a similar trend to the number of active wells in **Figure 2-6**.

For more information about how CBM activity is accounted for in this model effort, refer to **Sections 5.9.2 and 7.2**.

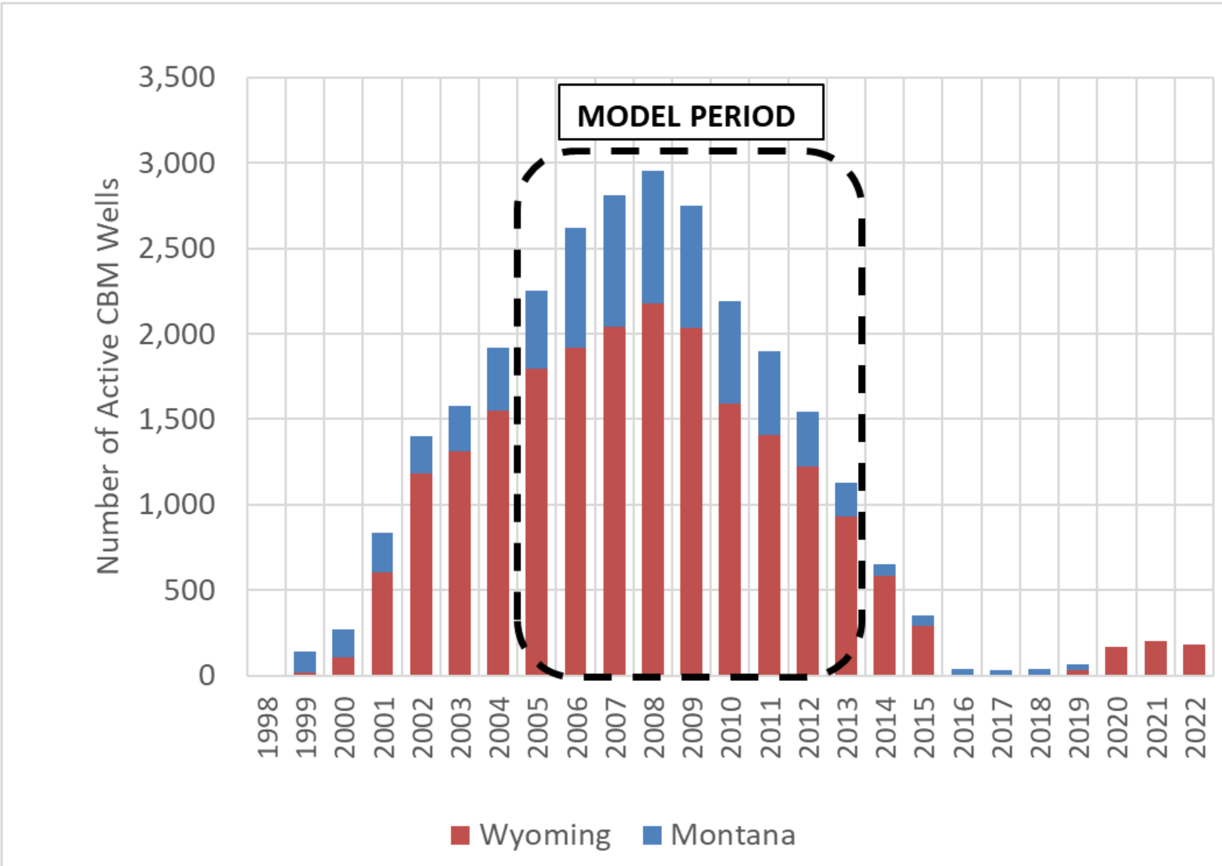


Figure 2-6. Bar graph illustrating number of active wells in the Wyoming and Montana portion of the Tongue River watershed over time, with the model period (2005-2013) highlighted (Source: MT Board of Oil and Gas Conservation and WY Oil and Gas Conservation Commission).

2.6 Coal Mining Activity

The larger Powder River Basin, of which the Tongue River watershed is a part, is one of the most productive coal-producing regions in the world (Luppens et al. 2013).

Three active coal mines were present in the Tongue River watershed in Montana during the modelling period (2000-2013) include Decker West, Decker East, and Spring Creek, (**Figure 2-7**). All are located in Montana and discharge to the Tongue River Reservoir or tributaries of the reservoir. Decker West (MT0000892) and Decker East (MT0024210) have been discharging since mining operations began in the 1970s. Their discharges are permitted under the Montana Pollutant Discharge Elimination System (MPDES). MPDES records goes back to the late 1990s. Spring Creek (MT0024619) only discharged for two days during the 14-year study period (during May and June 2005), and both of those discharges only had observed flows related to rain events with no measured flow rates or concentrations. In addition to these mining operations Wolf Mountain (MT0031411) is a coal buyer and seller in the Montana portion of the watershed that had no discharges during the model period.

In the Wyoming portion of the watershed, Wyoming's Big Horn Coal Company had a permit (WY0022519) for Sheridan Mine through 2003. However, no discharges from the mine occurred after 1999. A permit (WY0096288) was issued for the Youngs Creek mine in 2018, which is currently held by Navajo Traditional. However, the site remains undeveloped and no permit has been reported thusfar (Personal Communication, Jason Thomas, February 26, 2023).

For information on how discharges from coal mines were accounted for in the model, refer to **Section 5.9.3** and **Section 7.2**. It is worth noting that Decker's discharges decreased considerably since 2016, when they stopped discharging from West Decker, and East Decker hit a dry seam. West Decker has not discharged since 2019, and East Decker has not discharged since 2021. All discharges are currently halted while the mine pursues reclamation activities, but may resume in the future in order to drain the ponds when those activities ensue (Personal Communication, Heather Henry, Montana DEQ, February 16, 2023).

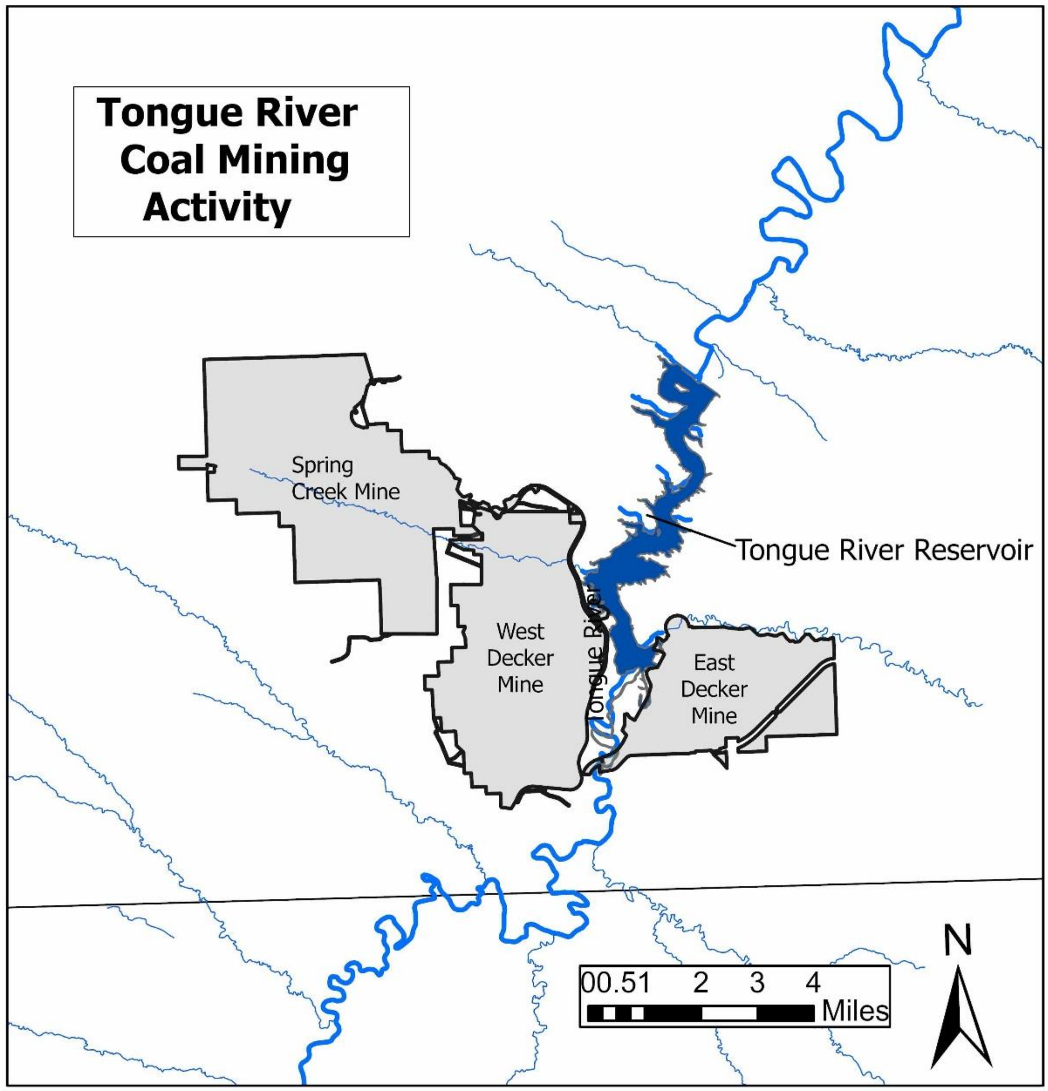


Figure 2-7. Coal mines in the Montana portion of the Tongue River watershed during 2000-2013.

3.0 WATER QUALITY PARAMETERS OF CONCERN

The water quality parameters of concern in this report are linked to salinity, which is a measure of saltiness in the water. These parameters include electrical conductivity (EC), specific conductance (SC), and sodium adsorption ratio (SAR). The main concern is the potential negative effects that elevated levels of EC, SC and SAR can have on agricultural crop production.

3.1 SALINITY, ELECTRICAL CONDUCTIVITY, AND SPECIFIC CONDUCTANCE

Salinity is the concentration of salt in water. It can be determined by taking a filtered sample and drying it out to measure the amount of total dissolved solids (TDS) in the water. However, it is much easier to measure the conductivity of the water, and then correlate conductivity to salinity. The greater the salinity, the more easily it conducts electricity due to more electrostatically charged particles (e.g., anions and cations) in solution. Pure water by itself is a poor conductor of electricity.

Electrical conductivity (EC) is a measure of the ability of water to conduct electricity (Rhoades et al. 1999). The unit of measure for EC is microsiemens per centimeter (µS/cm), which is a measure of electrical potential (conductance) over a specified distance. EC will vary with temperature since the ability to conduct electricity is influenced by temperature (it is easier to conduct electricity at higher temperatures due to greater movement of molecules in solution and an increase in solubility of many salts). All EC measures used in this report and for modeling purposes are temperature corrected to 25 ^{o}C. EC values corrected to 25^{o}C are defined as SC. Because EC meters commonly provide measures that are corrected to 25 ^{o}C, and because the Montana definition of EC is temperature corrected to 25 ^{o}C (ARM 17.30.602(7)); EC, SC, and conductivity are all used to describe the same measure and the terms are used interchangeably in this report. These three terms also describe the extent of saline conditions or salinity in the water given the strong correlation between TDS and SC/EC measurements in the Tongue River watershed (**Figure 3-1**). As shown by **Figure 3-1**, relatively high TDS values will equate to relatively high SC or EC values and sources that increase TDS in the water will also proportionally increase SC and EC. Thus, the term 'salinity' is often used interchangeably with EC and SC when discussing the general saltiness of a waterbody.

Salinity is important to irrigators, because of potential negative effects on crops. Agricultural plants have difficulty absorbing water from the soil when it is high in salinity, thus when salinity rises above a specific crop-dependent threshold, crop yields start to decrease. Salinity can be elevated in soils due to short term application of highly saline irrigation water and/or from a buildup of salinity in soils from irrigation water when soils are not properly leached (Thompson 1991). Therefore, irrigators want to irrigate with low salinity water as much as they can, and avoid irrigating with high salinity water when possible.

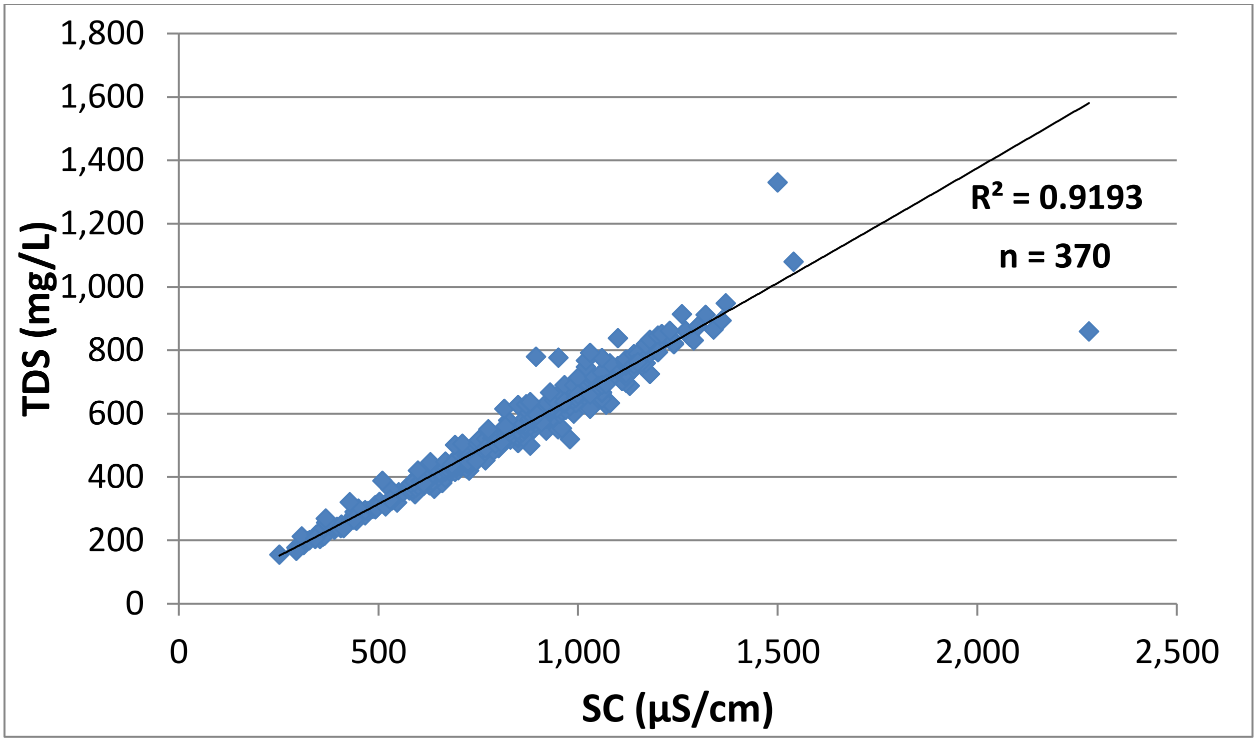


Figure 3-1. Relationship between TDS and SC (or EC corrected to 25 °C) in the Tongue River watershed at Miles City USGS gage 06308500 (1962-2016)

3.2 Sodium Adsorption Ratio

Sodium adsorption ratio (SAR) is a measure of the ratio of sodium to calcium and magnesium. These three cations (positively charged particles) make up the majority of cations in most natural waters. SAR is unitless and is calculated using the following equation:

$$SAR = \frac{[Na]}{\sqrt{([Ca]+[Mg])/2}} \quad \textbf{(EQ-1)}$$

Where:

- [Na] = sodium concentration in meq/L (milliequivalents per liter)
- [Ca] = calcium concentration in meg/L
- [Mg] = magnesium concentration in meq/L

Water with an elevated SAR can cause soils to become sodic. Sodic soils typically display a loss of soil structure, and form a water-tight crust that will dry out the soils (Qadir and Schubert 2002). Highly sodic soils inhibit most types of agriculture. Sandy soils are less susceptible to effects of elevated SAR than finer-grained soils.

3.3 Montana's Water Quality Standards for EC and SAR

The state of Montana has developed both EC and SAR numeric water quality standards for water bodies within the Montana portion of the Tongue River watershed (ARM 17.30.670). These standards were approved by the Environmental Protection Agency (EPA) as being protective of the agricultural use for the specific crops grown in the watershed. In the Tongue River during the March 2 through October 31 period when irrigation is most likely (irrigation season), the monthly average numeric standard for EC is 1000 µS/cm and the monthly average numeric standard for SAR is 3.0. For the period of November 1 through March 1 (non-irrigation season), the monthly average values increase to 1500 µS/cm for EC and 5.0 for SAR. For the Tongue River Reservoir, the monthly average numeric standard throughout the year for EC is 1000 µS/cm and the monthly average numeric standard throughout the year for SAR is 3.0. ARM 17.30.670 also includes numeric EC and SAR standards applicable to the tributaries as well as numeric standards that define individual values (vs. monthly averages) that are not to be exceeded at any time for the tributaries, Tongue River, and Tongue River Reservoir. Montana's water quality standards define EC as being corrected to 25 °C, thus being the equivalent of SC.

The Northern Cheyenne Tribe also has EC and SAR standards where the Tongue River flows through the Reservation. Both sets of standards are summarized in **Table 3-1**.

Table 3-1. EC and SAR Water Quality Standards for the Tongue River in Montana

Area of Interest	EC (mthly avg)	EC (max)	SAR (mthly avg)	SAR (max)	EC (mthly avg)	EC (max)	SAR (mthly avg)	SAR (max)
Montana	**Irrigation Season (3/2 - 10/31)**				**Non-Irrigation Season (11/1 - 3/1)**			
Tongue River	1000	1500	3.0	4.5	1500	2500	5.0	7.5
Tributaries	500	500	3.0	4.5	500	500	5.0	7.5
Tongue River Reservoir	1000	1500	3.0	4.5	1000	1500	3.0	4.5
Northern Cheyenne	**Irrigation Season (4/1 – 11/15)**				**Non-Irrigation Season (11/16 – 3/31)**			
Tongue River	1000	1500	-	2.0	-	1500	-	2.0
Tributaries	1000	1500	-	2.0	-	1500	-	2.0
Wetlands	-	-	-	2.0	-	-	-	2.0

4.0 MODEL OVERVIEW

4.1 SWAT MODEL DESCRIPTION

SWAT is a physically-based model that uses topography, climate, soil, land cover, land use, and management data to calculate a wide range of hydrologic and water quality outputs through physical equations and laws (Arnold et al. 2012a; Arnold et al. 2012b). SWAT operates at the basin scale making it a semi-distributed model. Subbasins are defined by topography and a user specified minimum stream drainage area threshold. Each subbasin contains a reach of the stream that will transfer its loadings at its outlet to the inlet of the next downstream subbasin therefore creating a stream network.

Within each subbasin, hydrologic response units (HRUs) define unique combinations of land use, soil, and slope categories. These HRUs are not spatially connected but rather represent a percentage of each subbasin. HRUs and their unique combination of parameters are used to calculate subbasin outlet loadings. Driven by water balance equations, the hydrology of a watershed can be simulated by land and routing phases of the hydrologic cycle. The land phase accounts for climate, hydrology, land cover, erosion, nutrients, pesticides, salts, and management of each subbasin to calculate loadings into the stream reach within that subbasin (each subbasin has one stream reach). The routing phase accounts for water and loadings as they travel through the stream network to the next stream reach or out of the watershed (Arnold 2012b).

The advantages of SWAT include:

- It is physically based and uses readily available inputs.
- It is computationally efficient in that computers can complete simulation calculations within a reasonable amount of time.
- It incorporates comprehensive processes by using mathematical equations to represent flow, fate, and transport and other physical, chemical, and biological interactions.
- It can be used to study long-term effects and to simulate management scenarios.
- It has globally-validated model code, as both the model and its code are publicly available for free and widely used.

Pollutant yields, water balance, water yield, and sediment yield are computed at the HRU level, and then are aggregated for subsequent routing through the channel system. SWAT simulates streamflow, sedimentation, and water quality. Six general compartments are incorporated into the model to describe the flux of water through the landscape; these include: (1) snow accumulation and melt, (2) surface runoff, (3) unsaturated zone processes/evapotranspiration, (4) lateral flow, (5) shallow groundwater flow, and (6) deep aquifer flow. Hydrologic computations are completed using a modified version of the curve number[1] (CN) where daily CN is adjusted according to the previous day's soil water content (Neitsch et al, 2011 Arnold et al, 201a).

The SWAT modeling project for the Tongue River watershed involves three major phases: 1) model setup, 2) simulation and calibration and 3) scenario evaluation.

[1] The runoff curve number (also called a curve number or simply CN) is an empirical parameter used in hydrology for predicting direct runoff or infiltration from precipitation.

Phase 1: Model setup: determining input files and parameters that represent land-use, soils, climate, and point sources

Phase 2: Model simulation and calibration: comparing flow and water chemistry collected at key locations to model predictions, and adjusting parameters of the model within reasonable ranges so that predicted values are within a certain range of data collected under a variety of seasonal and flow conditions

Phase 3: Model scenario evaluation: modifying land use and point sources to determine the influence on resulting flows, concentrations, and loads to better understand what factors contribute to the water chemistry and how management changes could influence salinity concentrations at specific locations along the Tongue River.

4.2 SWATSalt Model Modification

The SWAT program was modified to create SWATSalt, a module written specifically for Montana DEQ to specifically model conservative constituents within SWAT. It allows up to 10 separate salt cations to be simulated and routed through the channel and regressions for converting salt concentrations to SC and SAR. All the other functionality of the original SWAT model remain in the updated model called SWATSalt.

SWATSalt does not specifically model SC. Instead, it models individual ions and integrates this information to determine SC. The SC is dependent upon the sum of all cations and anions in the water column, and also the fraction of each ion and its charge in the mixture. These relationships are used as the basis of estimating SC. SWATSalt allows a simple regression to be used to convert the modeled salt cations to SC.

Generation of cations in the SWATSalt model is done in the HRUs using a simple event mean concentration (EMC), which is the average concentration in runoff from various land uses multiplied by runoff volume (with appropriate conversions) to create a mass loading to the water column. One of the simplifications used in SWATSalt is that water does not retain its mass loading of salt when moving between water pathways within a sub-basin. For example, if surface runoff pools in a small depression and slowly infiltrates to groundwater, it loses its EMCs and mass loading attributed to surface water, and instantly assume the EMCs and mass loading associated with groundwater (usually much higher). This primarily affects the flow from surface to interflow to groundwater.

SWATSalt includes a simplifying assumption that salts are conserved in the water column, meaning that they do not precipitate out of the water column (e.g., salts lining the sides of a pond after the water dries up). Salts are only removed from the modeled stream reaches when water is also removed due to irrigation diversions or temporary bank storage. This approach likely over-estimates salt loads during dry times of the year, but averages out over longer time scales at longer time scales (Anning and Flynn 2014)

5.0 Model Setup

This section of the report describes the setup and initial simulation portion of the Tongue River SWATSalt model.

5.1 SWATSalt Development

The original SWATSalt model code was based on revision 663 of SWAT 2012 which was created by Texas A & M University. As part of this project, Tetra Tech made several needed improvements to the SWATSalt model in collaboration with DEQ and Texas A & M. These are documented in **Appendix A**. The Water Quality Standards and Modeling Section of Montana DEQ can be contacted for more information. Note that similar capabilities have been added as part of a SWATSalt module that now automatically comes with the current version of SWAT (Bailey 2019). For the purposes of this report, we refer to the model developed by DEQ and Tetra Tech for the Tongue River as SWATSalt. The new version available online is also called SWATSalt and has many of the same features, but may not be exactly the same as the version described in this report.

A previous model for the entire watershed was completed by EPA (2007a) for USEPA. That project used the River Loading Simulation Program C (LSPC) but was not used for this project because it did not include the peak CBM production years (although it could have been updated to include that period), and because the SWATSalt model has a much more detailed management options and databases for crops, livestock and irrigation. Given that agriculture is one of the major anthropogenic landuses in the watershed, that advantage over LSPC was determined to be important to accurately simulate agricultural and livestock management.

Salt can be added in SWATSalt from two different sources: point sources/inlets and HRUs. For the point sources/inlets, the concentrations of up to ten salt ions can be included on a daily basis Salt inputs from the HRUs can be specified as concentrations in surface runoff, lateral flow, groundwater flow, and tile flow. Defining the salt concentrations at HRU level allows the user to vary them by land use, soil type, and slope.

For routing through the system, salt cations are assumed to be conservative in the water column (Anning and Flynn 2014). However, the user can define a delivery ratio to account for settling and temporary storage within the stream. Also, a monthly adjustment factor can be applied to the HRU loadings to vary them by month. For this model the delivery ratio and monthly factors were not used to alter salt cation concentrations.

Generation of cations in the SWATSalt model is done in the HRUs using a simple event mean concentration (EMC), which is the average concentration in runoff from various land uses multiplied by runoff volume (with appropriate conversions) to create a mass loading to the water column. SWATSalt allows a different EMC value (all in mg/L) to be assigned to each land use, for each type of water pathway (surface, interflow, groundwater, tile flow), and for each ion (Ca, Mg, Na). Determination of EMC values for this project is discussed in **Section 6.3**.

Up to ten salt constituents can be simulated and included in the model results. The user can specify whether salt loads will be written on a daily, monthly, or yearly time step. SWATSalt also includes the SAR values in the model results. From water quality data collected in the Tongue River, a strong correlation was found between the sum of the three major cations (Ca, Mg, Na – in milliequivalents per liter) and SC (**Section 6.3**) and used outside the model in estimating SC (**Section 6.5).**

The SWATSalt guidance document (TAMU 2017; **Appendix A**) provides additional information on integrating SWATSalt into SWAT and SWAT Editor. It should be noted that during the calibration process Tetra Tech discovered and fixed several errors or over-simplification of processes in the SWATSalt code resulting in differences between the initial DEQ calibration and the final calibration. A description of these can also be found in **Appendix A**.

5.2 Model Discretization and Boundaries

This modeled area is defined as the Tongue River watershed. However, the SWAT model itself simulated processes within the mainstem portion of the Tongue River downstream of the Tongue Reservoir Dam, while inputs from tributaries and Wyoming (**Section 5.9.1**) were based on other models and relationships (**Figure 6-1**).

To adequately simulate spatial processes in the SWAT model portion of the watershed, each sub-basin is based on the 6th code hydrologic unit code (HUC) boundary. This resulted in a total of 67 sub-basins within the SWAT model (**Figure 5-1**), which ranged in size from 668 to 39,869 acres (**Figure 5-1**). Mean elevations within sub-basins varied, with approximately 1,500 feet of elevation difference between the highest subbasin and the mouth (**Appendix B**). Inlet files were used to provide data related to flow and salinity sources from key tributaries and the Tongue River Reservoir (**Section 5.9**). USGS gauging station with relatively complete flow and EC data during the model period (2005-2013) were used as calibration stations (**Section 6.5**).

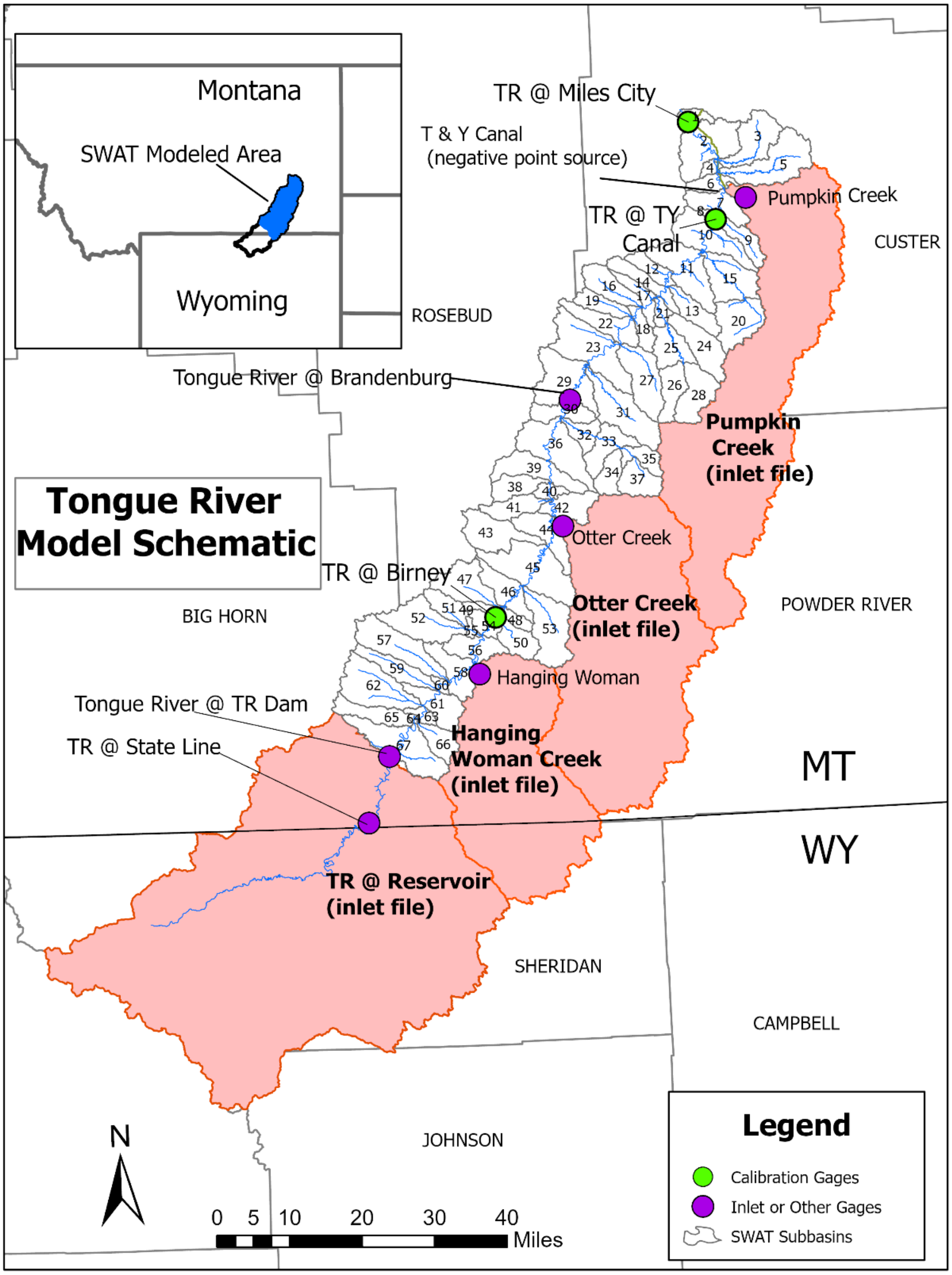


Figure 5-1. Model schematic used in the Tongue River modeling effort. The white region indicates the portion estimated within the SWAT model, while the pink portion was estimated using other models or methods and added as inlet files.

5.3 Digital Elevation Model

The USGS National Elevation Dataset is a 30 meter gridded, high-resolution compilation of elevation data used that was used for watershed delineation, flow accumulation processing, and slope determination.

5.4 Soils and Slopes

Soils in the Tongue River watershed exhibit considerable spatial variability. Soil Survey Geographic Database (SSURGO) soil data was processed independently for use in the model. A total of 449 soil map unit IDs (MUIDs) occur in the calibration area, as defined by the U.S. Department of Agriculture Soil Survey Geographic Database (SSURGO; https://data.nal.usda.gov/dataset/soil-survey-geographic-database-ssurgo D). Most of the SWAT-modeled portion of the watershed belongs to the B (silt loam) and C (sandy clay loam) hydrologic soil groups (HSGs) (**Figure 5-2**), indicating moderate to low infiltration capacities. Soils tend to have more clay content near the mouth of the Tongue River, and especially in the irrigated areas along the T&Y canal.

A multiple slope classification scheme was used in the model setup (**Table 5-1**). Topographic slope in much of the watershed (approximately 85%) exceeds 5%, indicating moderate to high slope. Runoff simulation in SWATSalt is based on the empirical Natural Resources Conservation Sources (NRCS) curve number method.

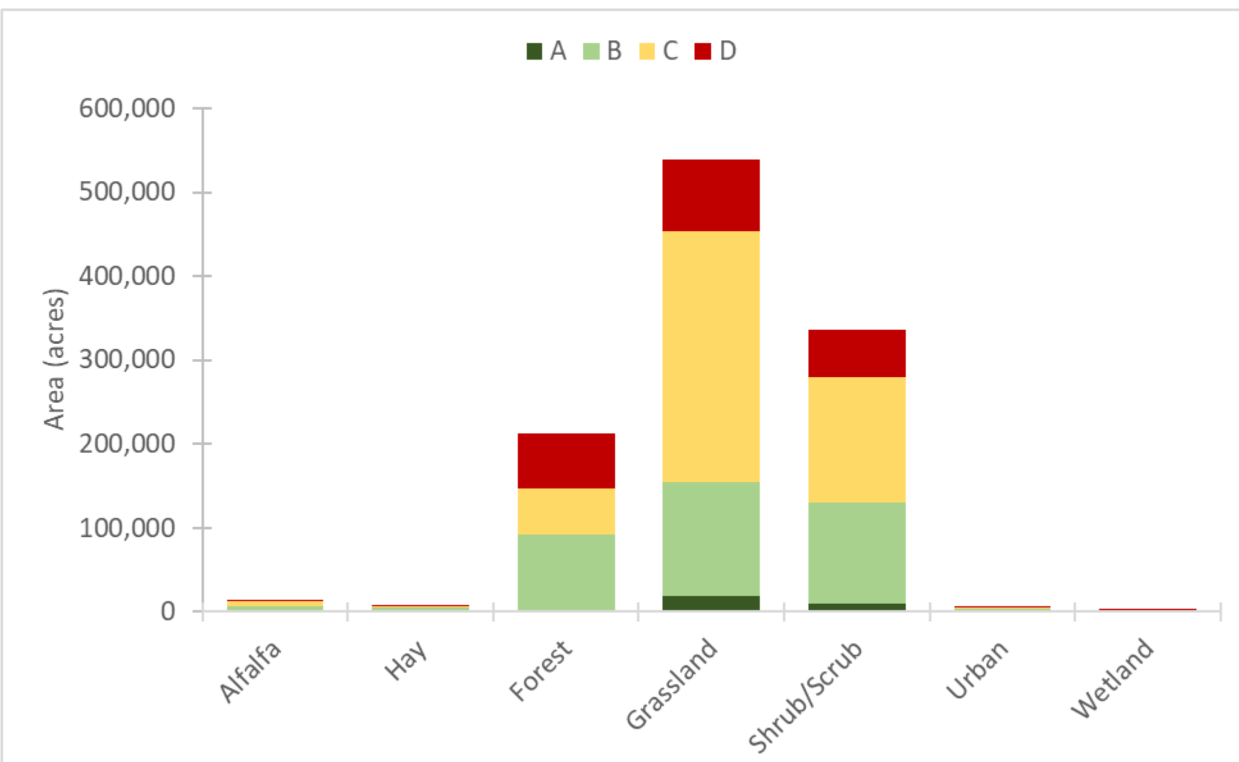


Figure 5-2. Distribution of Hydrologic Soil Groups by land use categories in the Tongue River SWATSalt model

Table 5-1. Distribution of slope classes in the model setup

Slope Category (%)	Watershed Percent
0-2	3%
2-5	10%
5-10	23%
10-9999	65%

5.4 LAND COVER

Land cover in the model was based on the National Land Cover Database NLCD 2006 data set (**Table 5-2; Figure 5-3).** SWAT uses land cover to model uptake by plants, which can ultimately affect the amount and timing of the water entering the stream network (Engida et al. 2021). For the model calibration area (portion of the watershed below the Tongue River Dam), over 95% of the area is classified as forest, grassland, or shrubland. Cultivated crops and pasture/hay areas are generally found along the Tongue River and account for approximately 1.8% of the SWAT-modeled watershed area (**Table 5-2**). Cultivated crops and pasture/hay categories were simulated as irrigated hay or alfalfa in the SWATSalt model. While a smaller percentage of cropland is non-irrigated or of a different crop type, alfalfa and hay comprised the large majority of cropland in the watershed based on National Agricultural Statistic Service (NASS) statistics and a previous survey of growers. Therefore, other low acreage crops were not included in the model.

Urban-residential development occurs in the lower modeled area in and around Miles City, and is virtually absent from the remainder of the modeled area. The majority of the urban land cover consists of roads. Overall, urban land cover, which also includes the towns of Birney and Ashland (**Figure 1-1**) only accounts for about 0.5% of the modeled area.

Land use in the watershed has not changed significantly during the model period, therefore the 2006 NLCD land-use data is considered adequate to reflect the actual land use within the watershed during the model period.

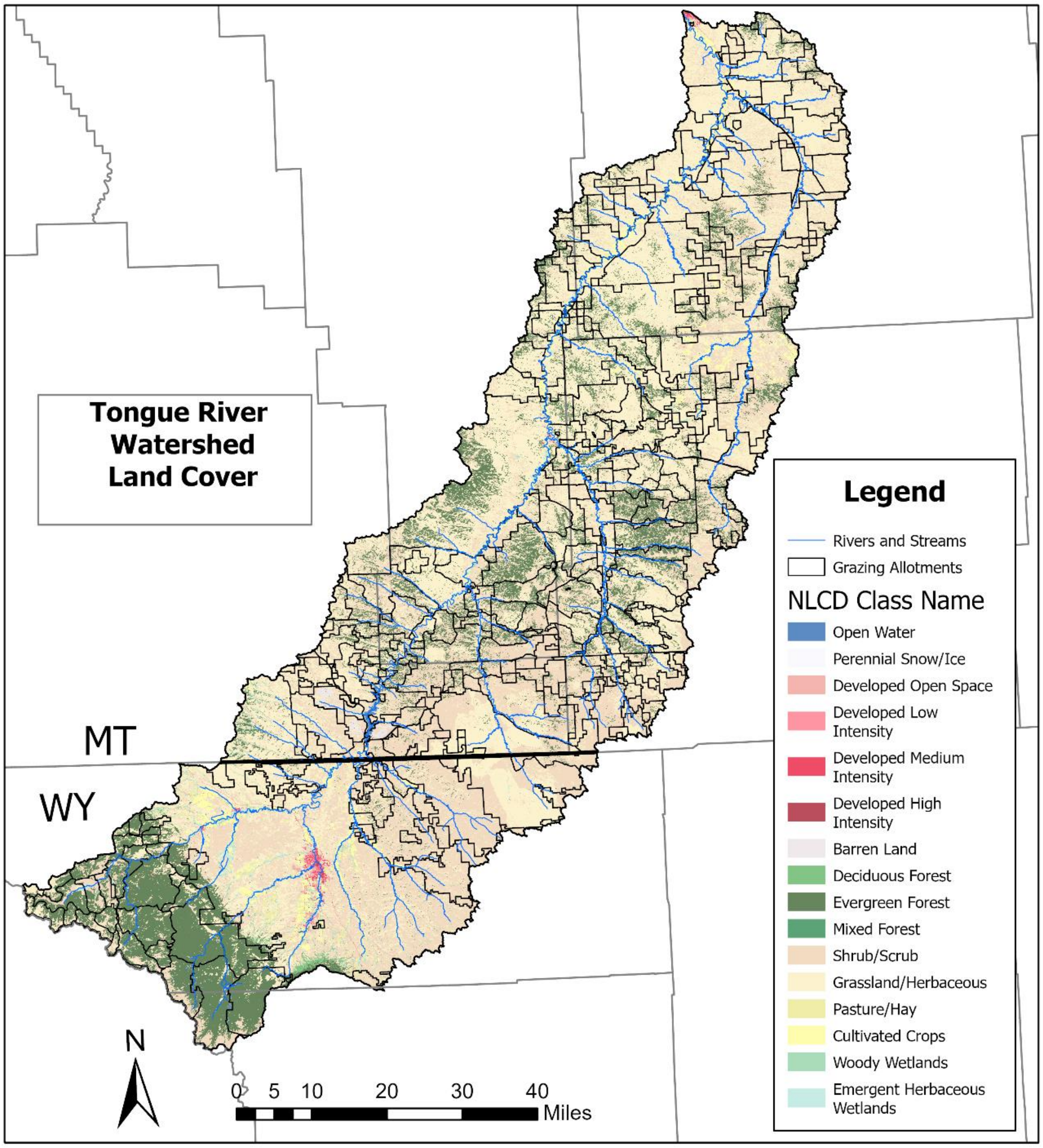


Figure 5-3. Land cover in the Tongue River watershed

Table 5-2. Tongue River land use based on NLCD version 2006, which was used in model development

Land use Type	Land use Code (SWAT)	Area (ha)	Area (acres)	Area (% of total)
Water	WATR	297	734	0.1%
Residential-Low	URLD	1,599	3,952	0.4%
Residential-High	URHD	264	651	0.1%
Arid Rangeland	SWRN	680	1,681	0.2%
Forest-Deciduous	FRSD	118	292	0.0%
Forest-Evergreen	FRSE	84,910	209,817	18.8%
Range-Brush	RNGB	133,047	328,765	29.5%
Range-Grasses	RNGE	212,247	524,472	47.0%
Hay	HAY	2,744	6,781	0.6%
Ag Land - Row Crops	AGRR	5,220	12,899	1.2%
Wetlands-Forested	WETF	7,481	18,484	1.7%
Wetlands-Non-Forested	WETN	2,559	6,323	0.6%
Totals		**451,166**	**1,114,852**	***100%**

***Due to rounding, the sum of this column is slightly over 100.**

5.5 HRU Generation

In SWAT, Hydrological Response Units, or HRU's are unique combinations of land cover, soil and/or slope classes distributed over a subwatershed, and a single HRU can be found at different locations within that subwatershed. It is an effective way to simplify representation and simulation of watershed processes in modeling (Gassman 2007).

HRU thresholds were used to delineate areas that comprised a small proportion of the study area. For the Tongue River SWAT Model, thresholds of 5 and 10% were imposed on land use, soil and slope, respectively. Pixels that comprised a smaller proportion of the study area were redistributed into the other HRU's that met the threshold criteria, which is a common practice (Frankenberger et al. 2015). However, developed land, cultivated crops, and hay land uses were exempt from the thresholding process. This resulted in 1,839 hydrologic response units (HRUs) that represent combinations of land use/land cover, slope, and soils.

5.6 Routing Geometry

Channel measurements were taken by the USGS at several locations in the watershed. In addition, DEQ's field team observed the channel width and depth in a few locations. These values were used to define the channel geometry, when available. Literature values were used if no measurements were taken (Chase 2015). If no data or literature values were available for a particular location, a USGS channel geometry-drainage area regression for western Montana (Lawlor 2004) was used, along with aerial photo interpretation. Manning's *n* values were in the range typical of natural stream systems (0.025 to 0.045). Routing coefficients used in the model can be found in **Appendix C**.

5.7 CLIMATE

Climate information is critical for model calibration. Solar radiation, dewpoint, relative humidity, and wind speed were obtained from the Miles City Airport and the Sheridan Airport, while daily temperature was acquired from nearby National Climatic Data Center (NCDC) and Western Regional Climate Center (WRCC) Remote Automated Weather stations (RAWS) (**Table 5-3**). Several of the climate stations were slightly outside the watershed. However, these stations had a relatively complete data set for the modeling time frame, and thus were used in the analysis. The model is configured to run at a daily time-step from 1/1/2000 to 12/31/2013, with 2000 to 2004 used for model "warm-up". This time frame (2000 through 2013) corresponds to a period when the greatest amount of climatic, hydrologic, and water-quality data were available. There are no SNOTEL stations in the model calibration area that could be used to calibrate snowpack results in SWAT.

Evapotranspiration (ET) is the combined loss of water from surface evaporation and by transpiration from plants. The potential evapotranspiration (PET) is the ET in a densely vegetated plant-soil system if soil water content was continuously maintained at an optimal level. 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. (EPA, 2007a). There are no PET stations located in or near the watershed. Since detailed observed PET data was not available, the PET was PET calculated internally by the model during run-time using the Penman-Monteith method. Calculated PET is potentially a source of model uncertainty and error (**Section 8.1**).

Table 5-3. Location of weather stations used in Tongue River model development.

Location	Station Type	Avg Annual Precip. (in)	Avg Annual Max Temp (F)	Avg Annual Min Temp (F)	Elevation (ft AMSL)	Parameter for Model
Badger Peak	RAWS	-	56.4	38.5	4,341	Temperature
Wolf Mountain	RAWS	15.1	54.6	35.8	5,217	Precipitation, Temperature
Fort Howes	RAWS	12.3	60.8	31.8	3,380	Precipitation, Temperature
Volborg	NCDC	15.7	-	-	2,979	Precipitation
Brandenberg	NCDC	14.7	61.7	32.4	2,769	Precipitation, Temperature
Busby	NCDC	14.7	60.2	30	3,432	Precipitation, Temperature
Decker	NCDC	12.8	-	-	3,520	Precipitation
Miles City AP	NCDC	12.7	59.2	34.7	2,625	Temperature, Precipitation, Solar Radiation, Dewpoint, Wind Speed
Sheridan AP	NCDC	-	60.1	29.4	3,967	Solar Radiation, Dewpoint, Wind Speed

5.8 Agricultural Management Practices

5.8.1 Auto-irrigation model

The SWAT auto-irrigation model used in the management scenario (see **Section 5.8.2**) was based on the water plant demand by setting the water stress threshold (AUTO-WSTRS) to 0.9. AUTO-WSTRS is defined as the fraction of potential growth. AUTO-WSTRS varies between 0.00 and 1.00, with 0 indicating no growth of the plant due to water stress and 1.0 indicating no reduction of plant growth due to water stress. It is usually set between 0.90 and 0.95 (Arnold et al. 2012b). For the Tongue River Model, anytime the water demand exceeds 0.9, or 90% of the field capacity, the model automatically withdraws a set amount of water from the river to satisfy it. The excess water is then returned to the river flow via overland flow, interflow (subsurface unsaturated flow), and groundwater.

5.8.2 Management schedules

Select agricultural and water management practices were simulated in SWAT by adjusting the scheduled management operations as described in the following section.

Schedule type

SWAT can represent agricultural management practices with several different schedules. Date-based schedules identify operations that are implemented strictly on the month and day specified by the user. Actual management operations on the field, however, may vary by year and are dictated by local variables such as weather and soil conditions. The heat-unit based scheduling in SWAT adjusts the timing of management operations based on fraction of heat units accumulated and may better represent the year-to-year variability in the timing of management practices than date-based scheduling. However, date-based scheduling allows for a more precise control on grazing practices which appear to alternate between hay/alfalfa/grassland and shrubland areas during the fall-winter and spring-summer seasons, respectively. Date-based scheduling was used in the SWATSalt model (see **Table 5-4)** .

Harvest schedule

Most alfalfa and hay rotations typically span several years before re-planting or re-seeding. Therefore, harvest only operation was simulated instead of harvest and kill, except that an end of growing season date was added to prevent inadvertent automatic crop irrigation during warm days in the winter before actual irrigation begins. Management schedules specified for hay and alfalfa in the model are summarized in **Table 5-4**.

Irrigation efficiency

Irrigation efficiency refers to the ratio between irrigation water used by growing crops and the amount diverted. Irrigation along the mainstem Tongue River consists of center pivot or flood irrigation of fields near the Tongue River. Both types of irrigation pull river water directly from the Tongue River, starting in the spring and finishing by October. The Tongue River has high quality irrigation water – though the SC occasionally rises above 1,000 µS/cm during the spring months and can often be above 1,000 µS/cm in the lower portion of the river below the T&Y Diversion. Based on discussions with landowners and DNRC staff, DEQ estimates that of the approximately 20,000 acres of irrigated land along the SWAT-modeled Montana portion of the Tongue River, approximately 65% is flood irrigated, and 35% is center pivot.

A multi-year study conducted by the Tongue River Agronomic Monitoring and Protection Program (AMPP) for the Montana Board of Oil & Gas Conservation (MBOGC) applied 1 inch of water every 3 to 4 days on sprinkler irrigated and 3 inches of water every 9 to 12 days on flood irrigated experimental plots

(MBOGC 2011a). The study reports a 100% efficiency for flood irrigation while noting that under normal conditions the maximum efficiency is about 50%. An efficiency for sprinkler irrigation is not reported although based on the configuration of sprinkler heads a 100% efficiency may be assumed. However, Gilley and Watts (1977) reports an efficiency of 60-90% for sprinkler (center pivot irrigation) irrigation. For the purposes of this model a value of conservative value of 70% was used for the following parameterization:

- Sprinkler Irrigation - 25.4 mm (1 inch) of water per application with an efficiency of 70%.
- Flood Irrigation - 76.2 mm (3 inches) of water per application with an efficiency of 50%.

The surface runoff ratio specified during an irrigation operation is the proportion of the applied irrigation water that is directly lost as surface runoff. The remaining amount percolates to the soil and is subject to the SWAT model's soil water routing algorithms including uptake by plants, evaporation, lateral flow, and percolation to lower soil layers. Based on discussions with local experts, the surface runoff ratio was set to 0 for sprinkler irrigation and 0.01 for flood irrigation (personal communication, Custer County Extension Agent Mike Schuldt, 9/29/21).

Grazing
The total number of cattle grazing within the SWAT-modeled portion of the Tongue River watershed was determined based on the total number of cattle reported by the US Department of Agriculture (USDA) National Agricultural Statistics Service (NASS) for Big Horn, Custer, Powder River and Rosebud counties, and the fractions of the county areas within the watershed (the USDA NRCS reports 174,000 cattle for the above four counties). This resulted in approximately 16,800 cattle available for grazing within the watershed. The cattle count was multiplied by a factor of 1.2 (to account for horses, sheep and hogs) raising the total number of grazers to 20,000. Grazing, trampling and manure deposition rates of 40, 36 and 15 lbs of dry matter per day per animal, respectively, were assumed.

Winter grazing is simulated on hay, alfalfa and grassland areas from October 15 through April 14. The as confirmed with local experts (personal communication with Art Hayes, Tongue River Water Users Association, December 2020 and May 2021). Grazing is evenly distributed over those land uses. The biomass consumption, trampling and manure deposition rates were revised to ensure that the same number of animals were grazing from October 15-April 14 on hay, alfalfa and grassland, and from April 15-October 14 on shrubland.

Table 5-4. Agricultural management schedules in the SWATSALT model

Crop	Date	Operation
Alfalfa	3/1	Tillage (Rototiller)
	3/2	Plant Alfalfa/Begin Growing Season
	4/1	• Begin auto-fertilization with 25-05-00 (N-P-K) • Auto-fertilization triggered when N-stress is above 0.9 (within the suggested range of 0.9-0.95 (Arnold et. Al.) • Maximum annual application limited to 10 lbs-N/ac (Jacobsen et. Al, 2005)
	5/1	• Begin auto-irrigation as a function of "Plant Water Demand" • Maximum 25.4 mm (sprinkler irrigation) of water per application

Table 5-4. Agricultural management schedules in the SWATSALT model

Crop	Date	Operation
		• Auto-irrigation triggered when water stress falls below 0.9 • Irrigation efficiency specified as 0.7 (sprinkler irrigation) • Surface runoff ratio = 0
	7/20	Harvest
	10/15	Harvest
	10/15	Begin grazing by beef cattle • Minimum biomass for grazing to occur = 200 kg/ha • Continuously grazed for 182 days • Biomass removal rate = 1.60 kg/ha/day • Biomass trampling rate = 1.44 kg/ha/day • Manure deposition rate = 0.60 kg/ha/day
	11/30	Kill or End Growing Season
Hay	3/1	Plant Hay/Begin Growing Season
	3/2	• Begin auto-fertilization with 25-05-00 (N-P-K) • Auto-fertilization triggered when N-stress is above 0.9 • Maximum annual application limited to 35 lbs-N/ac (Jacobsen et. Al., 2005)
	5/1	• Begin auto-irrigation as a function of “Plant Water Demand” • Maximum 76.2 mm (flood irrigation) of water per application • Auto-irrigation triggered when water stress falls below 0.9 • Irrigation efficiency specified as 0.5 (flood irrigation) • Surface runoff ratio = 0.01
	6/15	Harvest
	9/15	Harvest
	10/15	Begin grazing by beef cattle • Minimum biomass for grazing to occur = 200 kg/ha • Continuously grazed for 182 days • Biomass removal rate = 1.60 kg/ha/day • Biomass trampling rate = 1.44 kg/ha/day • Manure deposition rate = 0.60 kg/ha/day
	11/30	Kill or End Growing Season
Shrubland	4/15	Begin grazing by beef cattle • Minimum biomass for grazing to occur = 500 kg/ha • Continuously grazed for 182 days • Biomass removal rate = 2.66 kg/ha/day • Biomass trampling rate = 2.40 kg/ha/day • Manure deposition rate = 1.00 kg/ha/day
Grassland	10/15	Begin grazing by beef cattle • Minimum biomass for grazing to occur = 500 kg/ha

Table 5-4. Agricultural management schedules in the SWATSALT model

Crop	Date	Operation
		• Continuously grazed for 182 days • Biomass removal rate = 1.60 kg/ha/day • Biomass trampling rate = 1.44 kg/ha/day • Manure deposition rate = 0.60 kg/ha/day

Table 5-4. Agricultural management Schedules the SWATSalt Model

Wyoming management
Irrigation in Wyoming is also combination of flood and sprinkler irrigation, and flow from the Big Horn Mountains provides low EC water that in places travels several miles via ditches to irrigated fields. Irrigation practices in Wyoming were not explicitly captured in the Tongue River Reservoir inlet file. However, for the natural conditions scenario, the load of salt cations from Wyoming was adjusted to reflect an estimated amount from agricultural activities. This per cent was based on the influence of agricultural activities on the landscape on the load in Montana (**Section 7.4.1**).

5.8.3 T&Y Dam Diversion

Water diverted at the T&Y Diversion Dam (Twelve Mile Dam) was simulated as a negative point source boundary condition that removes flow, calcium, magnesium, and sodium from the mainstem of the Tongue River. The time series was compiled using observed flow data from the Montana DNRC stage measurement program at the T&Y diversion dam that covered seven years of the 14-year simulation period. The seven years of missing data were filled using the corresponding average daily value from the seven years of available data. The following two assumptions were made to correct for uncertainties in the aforementioned daily averages.

1. In cases when this calculated daily average diversion was greater than the observed streamflow at the nearest upstream USGS gaging location (06307990 - Tongue R ab T & Y Div Dam is approximately 6.9 miles upstream from the T&Y Diversion Dam), a diverted flow equal to 70% of this observed streamflow upstream was assumed. 70% was used based on dates where both streamflow at USGS gage and the DNRC gage were available – on those dates the DNRC diversion gage did not exceed 70% of the USGS streamflow.
2. The start date that the diversion first removes water from the Tongue River mainstem in the years where diversion data was not available was assumed to be the average start date of the observed seven years, May 26.

The water diverted at the T&Y Diversion Dam in subbasin 6 is then used for irrigation in all downstream subbasins. A portion of the water removed from the model to simulate the T&Y diversion is later added back into the model as irrigation water in subbasins 1 through 6. The remaining portion of the diverted water that is not used for irrigation is not returned to the model. Irrigation in all other model subbasins is sourced from the adjacent reach of the Tongue River mainstem.

5.8.4 Tributaries

While the Tongue River is classified as B-2 and B-3 (ARM 17.30.624(1) and 17.30.625(1)) and has water suitable for agriculture, the Tongue River tributaries are classified as C-3 streams, meaning their waters are "naturally marginal for agriculture" (ARM 17.30.629(1)). Salinity in the tributaries is high enough that much of the year the water is unsuitable for sustained irrigation. Accordingly, agricultural use in the tributaries is a passive type of flood irrigation. Dikes, check dams, and berms passively control runoff from large precipitation or snowmelt events and spread water across fields during high flow events when the water salinity levels are reduced and acceptable for irrigation. In this regard, producers are entirely dependent upon the snowpack and rainfall events each year. If no large runoff events occur, then there is almost no irrigation, although some sub-irrigation occurs due to the many check dams. Thus, crop yields vary greatly from year to year, with some years producing no harvest.

The three major tributaries (Hanging Woman, Otter, and Pumpkin) were not part of the model calibration area, and changes to tributary irrigation practices were not included in modeling scenarios. This decision was partly based on a modeling exercise for the Otter Creek watershed (**Appendix D**) which concluded that the tributary irrigation had a small impact on salinity loads and concentrations. A similar low impact was attributed to Hanging Woman and Pumpkin Creeks. Irrigation in the remaining minor tributaries, such as Foster Creek and Beaver Creek (within the calibration area) was assumed to happen similarly to that along the mainstem. This represents a small and insignificant source of modeling error since the amount of irrigated land along the tributaries is minor compared to the total irrigated acreage along the Tongue River.

5.9 Inlets and Point Sources

5.9.1 Inlets

An inlet source in SWATSalt is an outlet of a draining watershed, in which flow and water quality data is provided and not directly modeled by SWAT. The portion of the watershed above the outlet of Tongue River Reservoir, which was the largest salinity source, was included in the model as an inlet. Major tributaries entering the watershed downstream of this point, were also included as inlet files. These tributaries include Pumpkin Creek, Otter Creek, and Hanging Woman Creek watersheds (**Figure 1-1**).

Daily loads for Ca, Mg and Na inflows were estimated for each inlet location using the USGS Load Estimator (LOADEST) program (Runkel et al. 2004) using regression relationships between paired grab sampling of streamflow and cation concentrations, and continuous streamflow data (**Table 5-5**). These loads were added to the model beginning on 1/1/2005 because 2005 was the first year of the modeling period where flow and load data was available for all four inlets.

The LOADEST regression statistics for the Tongue River Reservoir dam boundary indicate that Na has the lowest r-squared value compared to Ca and Mg. This finding suggests the timeseries of the Na loading at the Tongue River Reservoir dam boundary condition may be the source of some of the downstream SC and SAR errors and contribute to model uncertainty (**Section 8.1**).

Table 5-5. R-squared Values for Loadest Regressions at Four Inlets Models for Ca, Mg, and Na

Location	Ca	Mg	Na
Tongue River Dam Boundary	0.96	0.88	0.8
Hanging Woman Creek	0.97	0.93	0.98
Pumpkin Creek	0.97	0.85	0.96
Otter Creek	0.98	0.96	0.98

5.9.2 Point Sources: Coalbed Methane Development

Salinity loads from CBM development were primarily based on data from the Montana Pollutant Discharge Elimination System (MPDES) and the Wyoming Pollutant Discharge Elimination System (WYPDES) programs. Water produced and discharged for CBM production is monitored as part of the MPDES and WYPDES permits and reported to each agency via discharge monitoring reports (DMRs). Where data was not available or sporadic, averages of existing data or extrapolation of data was used as described in this section. Off-channel ponds in Montana were not required to obtain an MPDES permit, for those sources produced water data from the MBOGC was used. The source of data used to calculate and estimate salinity loading from all the CBM sources in the watershed in summarized in **Appendix E.**

Most of the CBM discharges in the watershed are located above the Tongue River Reservoir outlet and in the Hanging Woman watershed. Therefore, the salinity loads from those sources are included in the model as a component of the measured and estimated discharge and salt concentrations from the Tongue River Reservoir and Hanging Woman Creek inlets (see **Section 5.9.1**). The only subbasin where CBM impacts were added directly as a point source to the model was subbasin 67. CBM loads in subbasin 67 included direct discharges with an active MPDES permit and off-channel ponds that were not required to have a MPDES permit. This subbasin is located directly downstream of the Tongue River Reservoir and includes Anderson Creek. The location of each pond with CBM water in the subbasin was based on the latitude/longitude location in the discharge permit.

The criteria for determining whether other ponds are on-channel or off-channel was partially based on a Wyoming DEQ potential risk to aquatic life in receiving surface waters. On-channel ponds are located adjacent to a channel (within 500 feet) and have a greater potential to discharge salts to surface water than off-channel ponds. Based on impacts to flows on Hanging Woman Creek from estimated CBM discharges during model development, a trend analysis of SC and SAR on three USGS gages on the Tongue River (HydroSolutions, 2022), and review of the literature (Wheaton et al 2007, National Research Council 2010), the estimated percent of the total salinity load discharged to each type of outfall that eventually would reach the Tongue River are:

- Off-channel ponds - 5% ;
- On-channel ponds - 50% ; and
- Direct discharge – 100%

Using the above percentages the salinity loads used in the model are summarized in **Figure 5-4**.

Many of the CBM discharges were located above where inlets discharged into the Tongue River. These include CBM discharges for the inlet above Tongue River Reservoir and Hanging Woman Creek and were not in subbasin 67. For the calibrated model, no changes were made to those two inlet files with upstream CBM discharges since CBM loads are already included in the loads measured and estimated for these inlets. The CBM discharges above the inlets was accounted for in CBM model reduction scenarios as discussed further in **Section 7.2**.

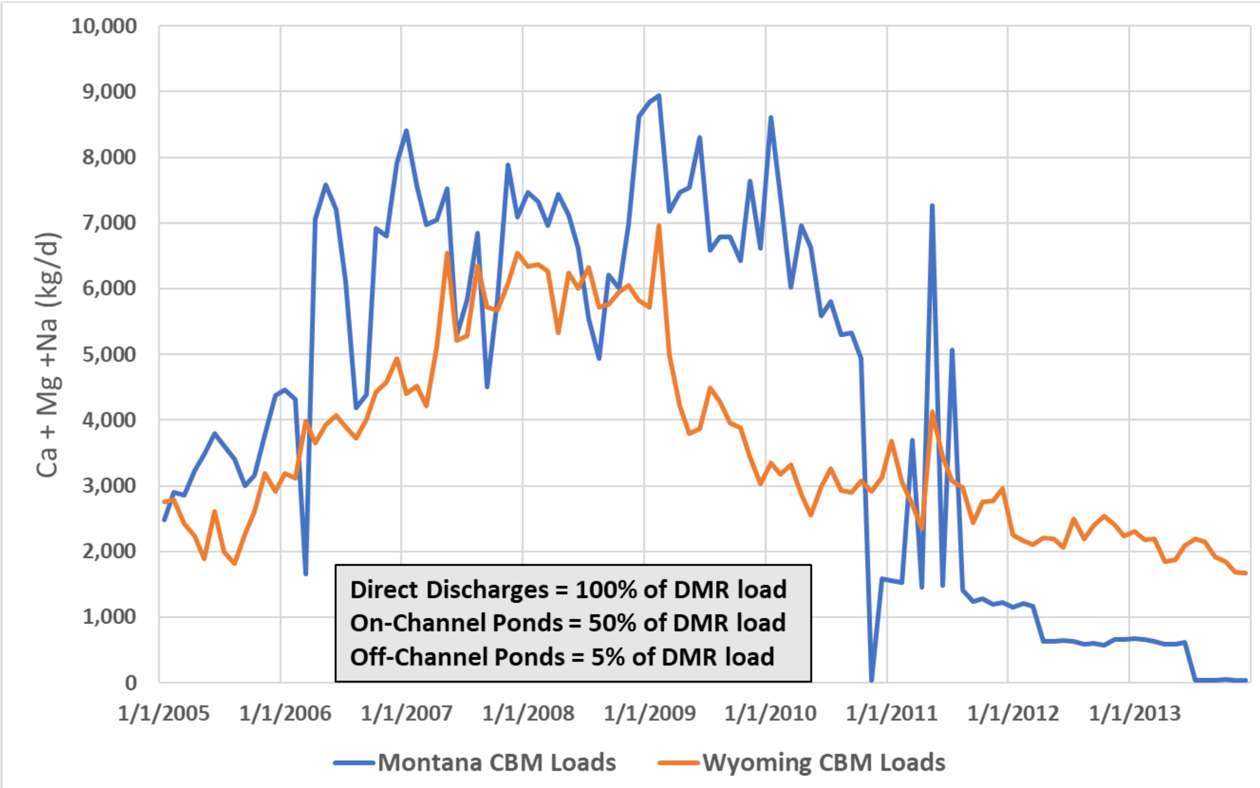


Figure 5-4. Total CBM salinity loads used in SWATSalt model

5.9.3 Point Sources: Coal Mines

For the model period of 2000-2013, there were three coal mines in the Tongue River watershed: Decker West, Decker East, and Spring Creek (**Figure 2-7**). All three of these mines are located upstream of the Tongue Reservoir outlet and therefore discharges from these mines were not included as a point source for the baseline scenario because their loads are part of the Tongue Reservoir inlet load. In addition to these mining operations, Wolf Mountain (MT0031411) is also located upstream of the reservoir and is part of the inlet load; it buys coal and sells it to residential users and also has an MDPES permit. However, no discharges have been reported. The combined salinity loads from the active coal mines used in the model are show in **Figure 5-5**.

Given that these point sources were already included in the inlet load for the baseline scenario, for the other scenarios the individual loads of Ca, Mg, and Na were subtracted from the inlet using water chemistry and flow data from the MPDES permits DMR data. The method depended on the scenario and whether coal discharges were removed or decreased as described in **Section 7.3**

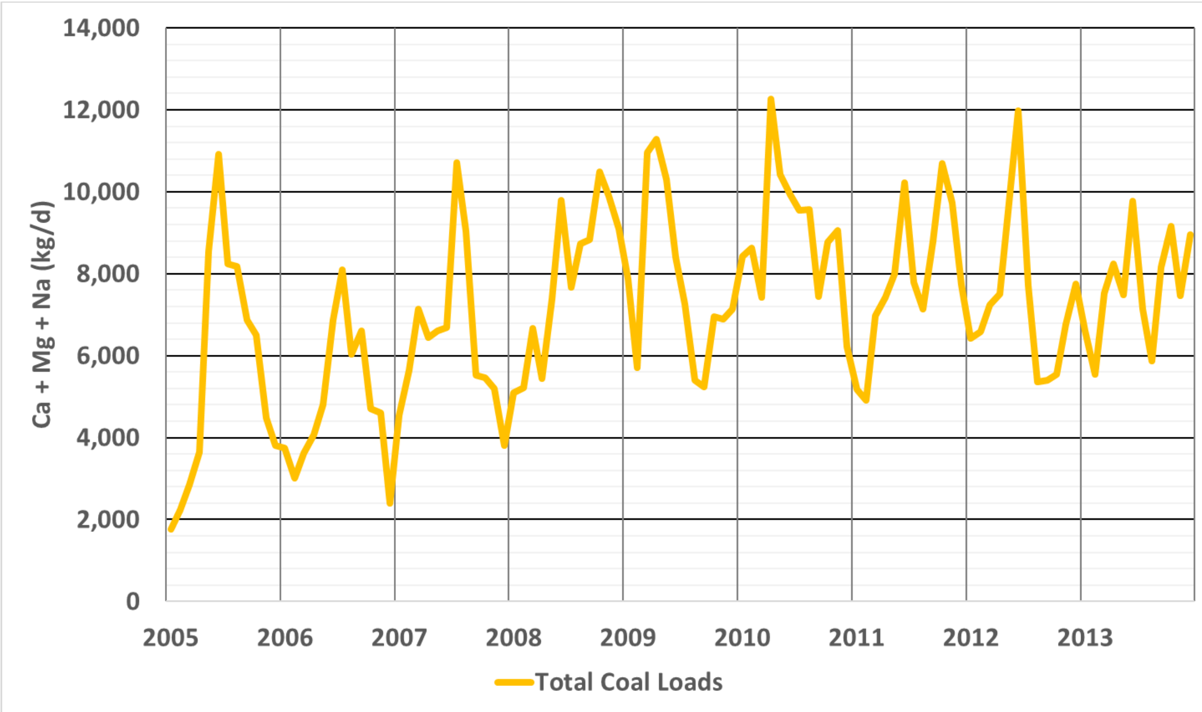


Figure 5-5 Total Coal salinity loads used in SWATSalt model

5.9.4 Point Sources: Wastewater Treatment Facilities

There are several wastewater treatment facilities in the watershed. All the permitted surface water discharges from wastewater treatment facilities are in Wyoming and were summarized by the USEPA (EPA 2007a). These Wyoming discharges are implicitly included in the model as a component of the measured discharge and salt concentrations from the Tongue River Reservoir and therefore are not included as separate point sources in the model. The relatively insignificant nature of salinity loading from these Wyoming facilities did not warrant their incorporation into SWATSalt modeling scenarios.

In the Montana portion of the watershed and within the calibration area, there are three wastewater treatment facilities in the calibration area of the watershed. Two are located within the Northern Cheyenne Tribal boundary: the Birney Wastewater Lagoon and the Northern Cheyenne Utilities Ashland lagoons. The third is the combined St. Labre/City of Ashland wastewater treatment facility. None of these has a permitted MPDES surface water discharge. All three are summarized below.

Birney Wastewater Lagoon

The following information is based on the most recent National Pollutant Discharge Elimination System (NPDES) inspection report (EPA, 2016). Birney wastewater lagoon is a two cell, unlined facility designed as a facultative lagoon. It is greatly over-sized for the community served, which is a portion of the approximate total Birney population of about 100. The lagoon has never filled up and the water is infiltrating into the ground. Based on size, lack of water quality information, and overall insignificant nature of salinity loading, this facility was not incorporated separately for model calibration or scenario purposes.

Northern Cheyenne Utilities Ashland Wastewater Lagoon

The Northern Cheyenne Utilities Ashland wastewater lagoon is a two cell, unlined facility designed as a facultative lagoon (EPA, 2016). It appears to be designed with the ability to discharge treated effluent from a small portion of the Ashland community consisting of approximately 30 households. Based on size, lack of water quality information, and overall insignificant nature of salinity loading, this facility was not incorporated into the model calibration or scenario purposes.

St. Labre/City of Ashland Wastewater Facility

The St. Labre/City of Ashland wastewater facility was originally a total retention facility that relied on evaporation to reduce volume. About 15 years ago it switched to a land application design where the wastewater was applied on land to grow a crop of alfalfa. The field is directly adjacent to the Tongue River, in some cases less than 20 feet from the river bank. However, the wastewater is relatively saline and has resulted in a sodic field. The field is no longer as capable of growing crops, and therefore a potentially significant portion of the irrigation water (with salts) now enters the Tongue River either via subsurface flow or surface runoff, particularly in early spring when snowmelt or stormwater further saturates the field and can facilitate runoff and associated transport of elevated salinity in the water. Current plans are to provide soil treatment to the spray irrigation land to improve the crop yield (1/3/23 email communication: Josh Jabalera, Midwest Assistance Program).

Because of increasing concern about the sodic field conditions, the loading from this facility was estimated by DEQ for understanding the potential contribution to salinity in the Tongue River. The water quality of this effluent was measured in May 2018 with values of 3,090 µS/cm for SC, and 16.7 for SAR. The flows were estimated from records at the treatment plant, but are generally very low – in the neighborhood of 0.1 cfs. Based on these values, it is estimated that even in the months of lowest flow of the Tongue River, the facility increases SC and SAR in the Tongue River by < 1% even if all of this effluent from the field enters the Tongue River. Given the lack of a complete dataset about this facility and the low impact, it was not included as a source of salinity in the model.

6.0 SIMULATION AND CALIBRATION

6.1 STREAM FLOW AND WATER QUALITY DATA

Streamflow has been monitored by the USGS at a number of locations along the Tongue River (**Figure 2-3; Table 6-1)**. Many of these gage locations have been used for the collection of continuous EC data and/or discrete EC data throughout the model period. Streamflow and salinity regression was conducted at inlets (see **Section 5.9.1**) and was used to estimate daily water quality values for the four inlet files. Continuous streamflow data from three gages with more complete data records were used as calibration gages to refine parameters that affected simulated flow (**Table 6-1**). Discrete data was also used to estimate Ca, Mg, and Na using LOADEST, and these LOADEST estimates were used to refine parameters affecting simulated loads of these ions (**Appendix F**). Finally, Continuous SC and estimated SAR data were also compared to model predictions for these water quality parameters to evaluate model performance (**Section 6.5**). The SC data was often missing the winter timeframe, because water quality meters were removed and then re-installed in mid to late March.

Table 6-1. USGS stations used in the Tongue River watershed model.

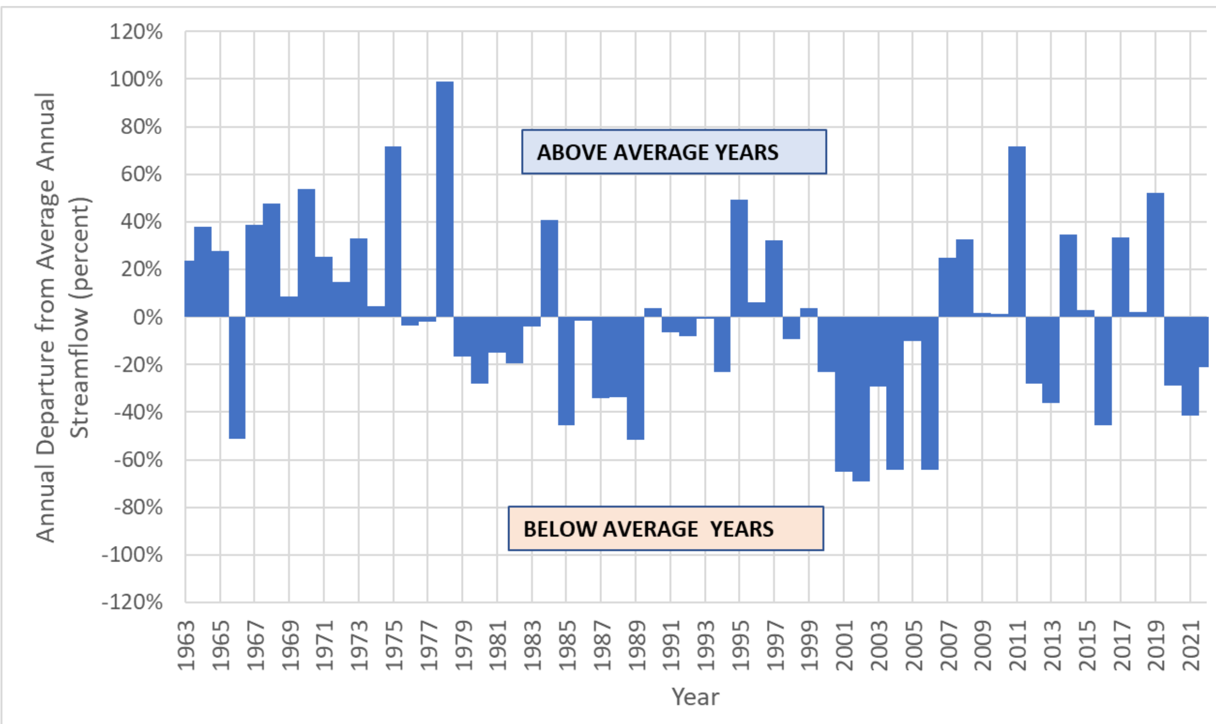
USGS Gage	Name	Drainage Area (square miles)	Period of Record*	Used in SWAT Salt Model	Data Type used in SWAT Salt Model
06306300	Tongue River at State Line	1,451	1960-current	No	N/A
06307500	Tongue River at Tongue River Dam	1,783	1939-current	Yes (inlet file only)	Flow; Ca, Mg, Na via LOADEST
06307616	Tongue River at Birney Day School	2,663	1979-current	Yes (calibration)	Flow, SC, SAR; Ca, Mg, Na via LOADEST
06307830	Tongue River at Brandenberg	3,879	1973-current	No	N/A
06307990	Tongue River ab T&Y Diversion Dam	4,505	2004-2011	Yes (calibration)	Flow, SC, SAR; Ca, Mg, Na via LOADEST
06308500	Tongue River at Miles City	5,404	1938-current	Yes (calibration)	Flow, SC, SAR; Ca, Mg, Na via LOADEST
06307600	Hanging Woman Creek near Birney	467	1973-2017	Yes (inlet file only)	Flow; Ca, Mg, Na via LOADEST
06307740	Otter Creek at Ashland	710	1972-2016	Yes (inlet file only)	Flow; Ca, Mg, Na via LOADEST
06308400	Pumpkin Creek near Miles City	696	1972-2018	Yes (inlet file only)	Flow; Ca, Mg, Na via LOADEST

*The period of record is often not continuous throughout the dates. All parameters may not be measured during the period of record.

6.2 Simulation Time Frame

The model simulation period was chosen to coincide with the availability of continuous instream data for flow and salinity, and climatic data sets with few or no missing values. Additionally, the model period was chosen to capture any effects of the CBM development in the watershed. The 14-year period from 2000 to 2013 was chosen to best meet the project goals. A model "warm-up" period from 2000 to 2004 was used to minimize initial condition effects and reach a dynamic steady-state.

The warm-up period lowers the effect of initial conditions, since state-variables have many years in which to equilibrate to model forcing functions. The model was then calibrated for the period 2005-2013. The period was originally split into a calibration period and a validation period, but due to the need to capture the significant year-to-year variability in watershed flows as part of the model, this was later combined to consist of only a calibration period. The overall period represents a typical range of Tongue River flows over the last 50 years (**Figure 6-1**). For example, within the modeling timeframe of 2000-2013, several years had well below average flows (2004, 2006, 2012, and 2013), several years had well above average flows (2007, 2008, and 2011), and several years were within 20% of normal flows (2005, 2009, and 2010). The modeling period also included the tail end of the worst drought in Tongue River recorded history, which happened between 2000 and 2006.



*

Figure 6-1. Annual streamflows compared to annual average at the Tongue River Dam, 1963-2022 (average annual streamflow = 438.8 cfs).

6.3 Simulation Water Balance

The overall water balance as simulated by the Tongue River SWATSalt model from 2005 to 2013 is shown in **Figure 6-2**. Approximately 97.4% of the precipitation is lost to evapotranspiration, which is consistent with the range of 90 to 99% reported for this region of the US by Sanford and Selnick (2013).

The portion that is not lost to evapotranspiration (2.6%) is the simulated water yield. Approximately 47% of the simulated water yield is surface runoff, 47% is lateral flow (or interflow) and 6% is groundwater outflow.

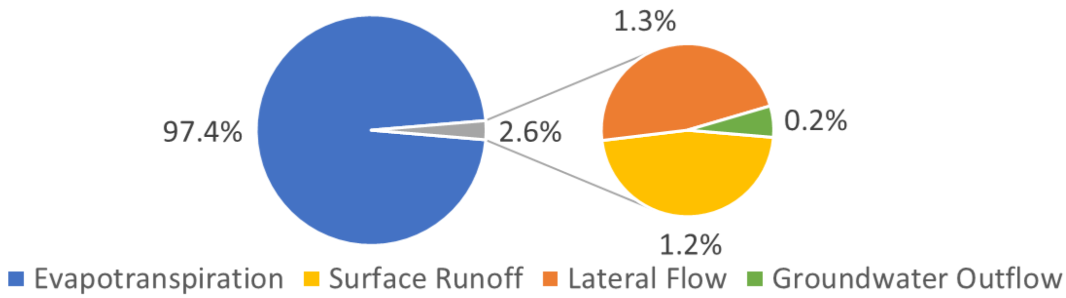


Figure 6-2. Tongue River SWATSalt model water balance (2005 to 2013).

Snowfall and snowmelt are significant aspects of the hydrological cycle in this watershed. Snow Water Equivalent (SWE) impacts the hydrology of the model through the timing and total magnitude of streamflow in the spring months when snow is melting. SWE is derived from many different aspects of the model including elevation data, meteorological data, user-specified snow melt factors, and user-specified snow pack temperature lag factors.

Daily satellite-based estimates of snow water equivalent (SWE) data at an approximate spatial resolution of 1 km^2 were acquired from the National Snow and Ice Data Center (NSIDC). Simulated SWE were compared against daily and monthly NSIDC SWE data, as shown in **Figure 6-3**. While the simulated SWE follows the trends estimated by NSIDC, the simulated magnitudes are generally lower than NSIDC estimates for some peak snowfall months.

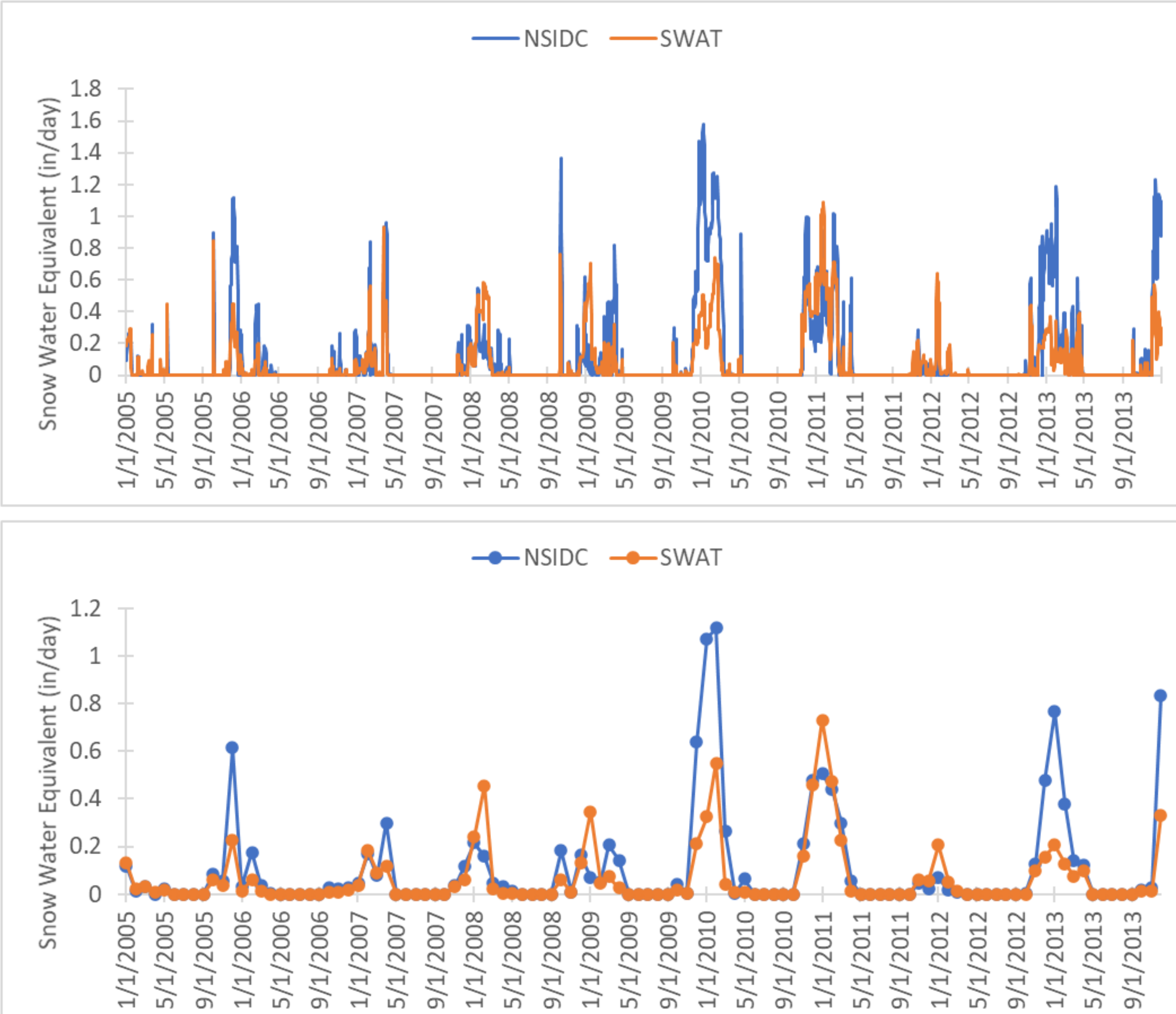


Figure 6-3. Timeseries of daily (top) and monthly (bottom) NSIDC and simulated SWE averaged over the Tongue River watershed

Flow pathways vary significantly by land use type, as shown in **Figure 6-4**. The majority of the outflow from urban areas is via surface runoff. Lateral flow and surface runoff outflow are the dominant outflow pathways in non-urban areas besides wetlands where groundwater flow is dominant. Representation of the relative importance of flow pathways is critical to the salt simulation as much lower salt concentrations are specified for surface runoff than for lateral flow. For instance, if most irrigation water is converted to surface runoff that will result in a lower total salt load to the Tongue River.

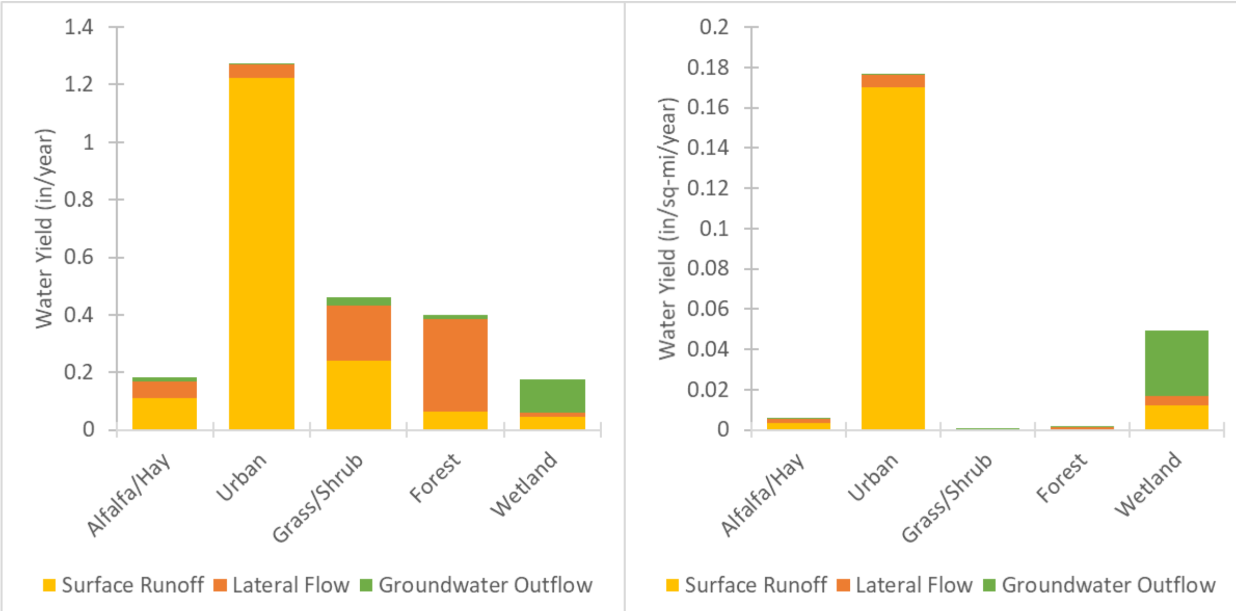


Figure 6-4. Simulated magnitudes and proportions of runoff, interflow and groundwater flow by land use

The timing of flow and magnitude of water yield from cultivated lands in alfalfa production, which is the dominant crop, is shown in **Figure 6-5** and **Figure 6-6**. A very small fraction of the irrigation water is converted to water yield, with most being converted to evapotranspiration. The bulk of this water yield is lateral flow. When there are large spikes in yield, they are in the form of surface runoff associated with large precipitation events.

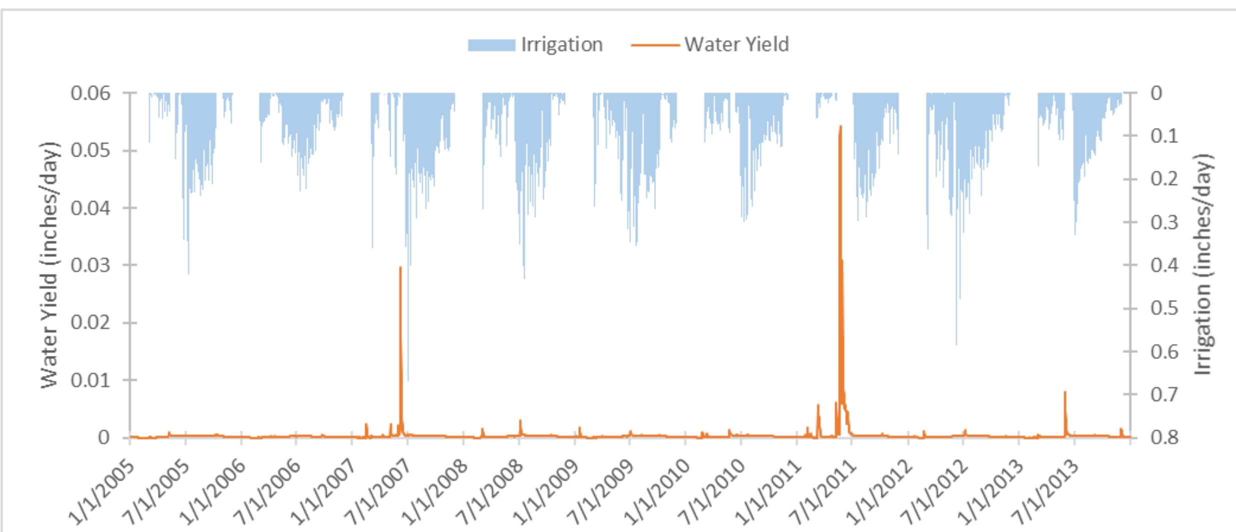


Figure 6-5. Simulated daily timeseries of irrigation and water yield for alfalfa (averaged over all alfalfa HRUs)

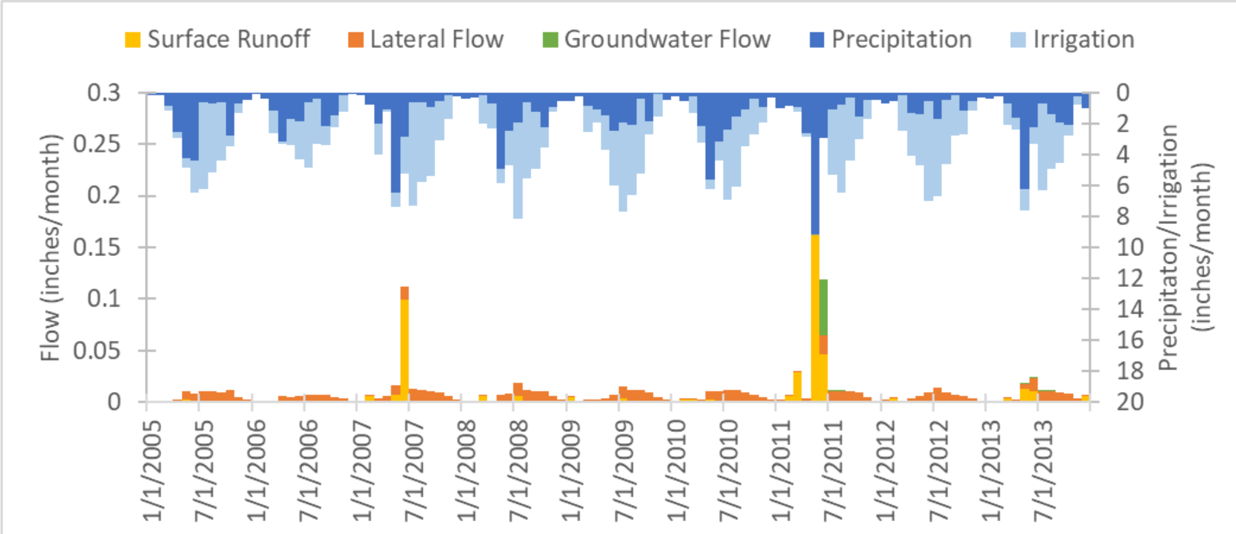


Figure 6-6. Simulated monthly timeseries of precipitation, irrigation, surface runoff, lateral flow and groundwater flow for alfalfa (averaged over all alfalfa HRUs)

The magnitudes of flows associated with the boundary conditions (3 tributaries and the Tongue River Dam) and those generated within Tongue River watershed are summarized in **Table 6-2**. Approximately 11% of the total flow at the mouth of the Tongue River is from the SWAT-modeled watershed area, the remainder (89%) is from the four boundary conditions (**Figure 6-7**).

Table 6-2. Magnitude of Flows from Boundary Conditions and the Local Watershed Area

Year	Flow (acre-ft)				
	Tongue River below Dam	Hanging Woman Creek	Otter Creek	Pumpkin Creek	Tongue River Watershed (SWAT-Modeled)
2005	285,414	95	1,355	10,389	30,591
2006	113,123	43	885	9,899	18,374
2007	396,258	2,430	3,288	14,281	66,652
2008	422,466	221	1,278	4,122	23,846
2009	322,445	912	2,416	4,717	19,554
2010	321,912	473	2,918	19,587	28,906
2011	544,858	3,960	11,622	83,641	135,322
2012	229,507	7,999	5,839	1,886	13,707
2013	202,828	823	4,852	9,941	37,093
Average	**315,423**	**1,884**	**3,828**	**17,607**	**41,561**

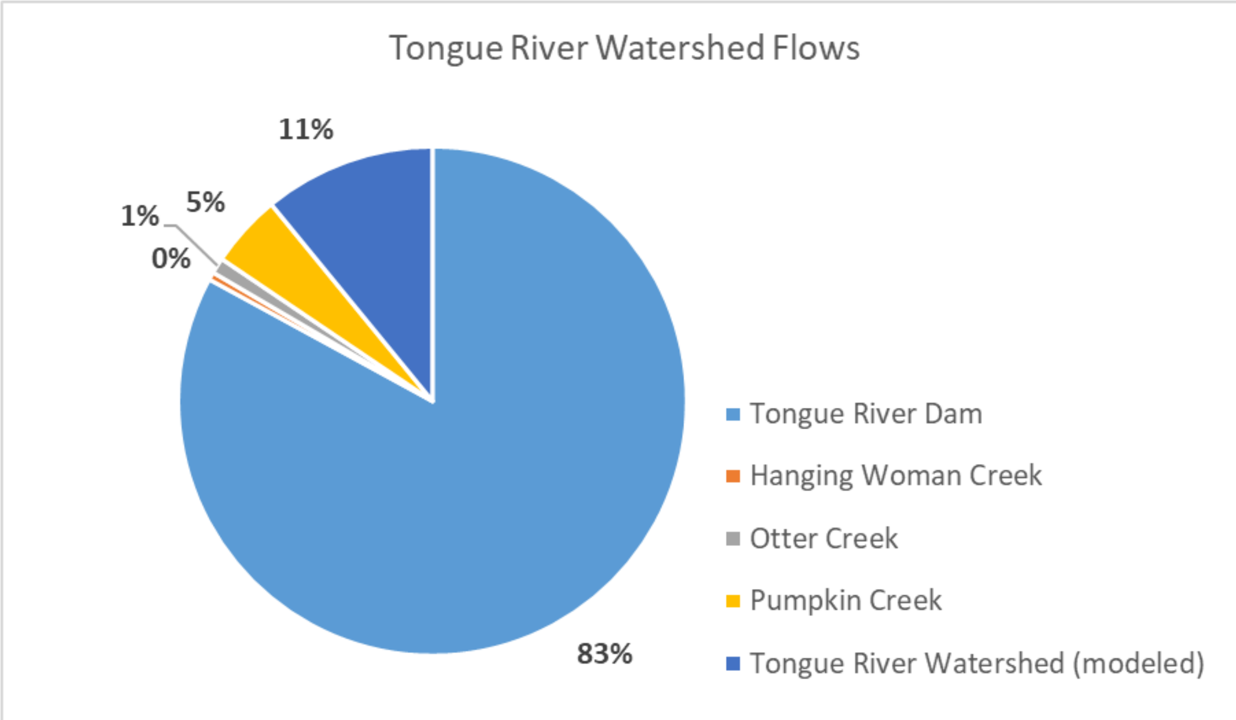


Figure 6-7. Proportions of flow from different sources in the Tongue River watershed

6.4 Simulated Irrigation Compared to Regional Studies

The MBOGC Tongue River AMPP 2011 Progress Report (MBOGC 2011a) reports crop yields and soil properties for sixteen (16) fields in the Tongue River watershed. Five (5) of the sixteen fields (situated along the length of the Tongue River) are irrigated with Tongue River water and are within the extent of the SWATSalt model. The average annual irrigation application on fields growing alfalfa or alfalfa/grass mixture reported in the AMPP report (**Table 3-3** to **Table 3-6** in MBOGC 2011a) from 2005 to 2010 varied between approximately 2.7 and 3.8 inches, regardless of irrigation type. In contrast, for the same time-period the average annual irrigation simulated by the SWATSalt model for alfalfa and hay were 21.2 and 17.3 inches, respectively. The latter values are consistent with irrigation volumes for this watershed reported by USGS (Cannon and Johnson 2000). Additionally, the 2011 Tier III Irrigated Crop and Soil Test Report produced under the Tongue River AMPP (MBOGC 2011b) reports irrigation amounts for alfalfa experimental plots from 2004 to 2010 that are similar to those generated by SWATSalt; the average application was 15.0 inches/year for sprinkler and 17.4 inches/year for flood irrigation. The reasons for the discrepancy in irrigation amounts between the two AMPP reports is unknown, but crop yields from the SWATSalt model are consistent with values reported by USDA (NASS 2017) therefore are believed to be representative and support the irrigation rates estimated in the model (**Figure 6-8**).

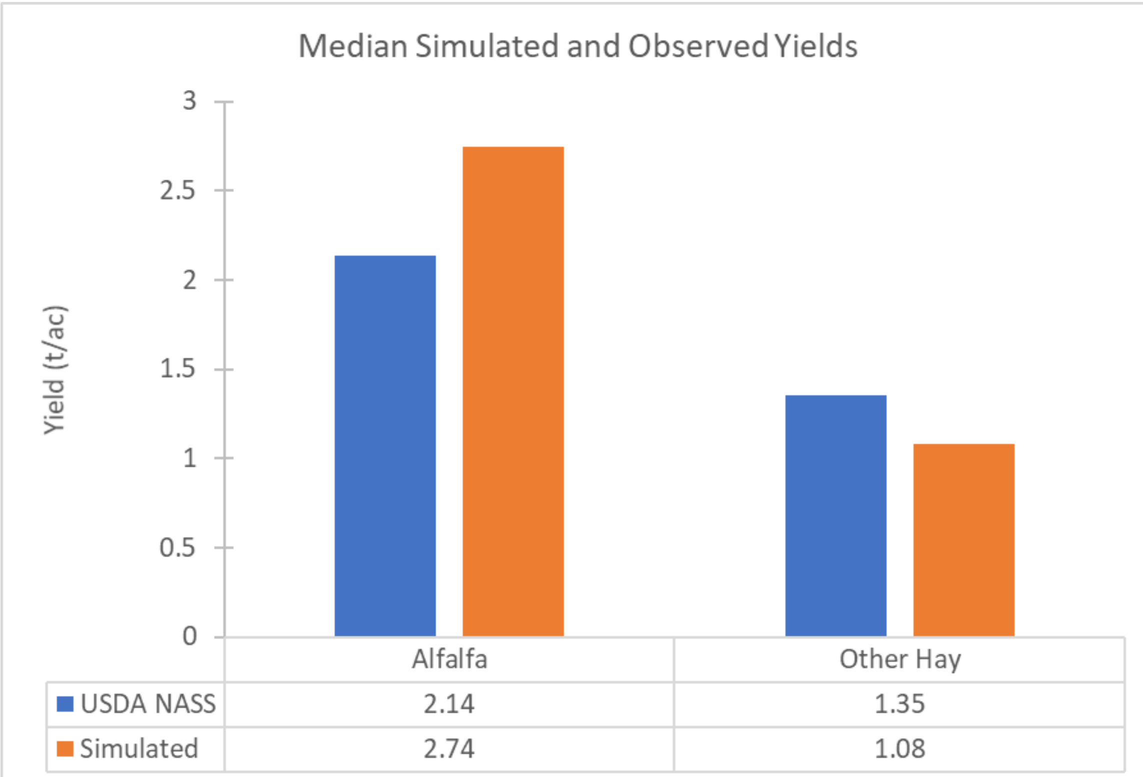


Figure 6-8. Median reported and simulated yields for alfalfa and other hay in tons per acre.

6.5 CALIBRATION

6.5.1 Calibration Evaluation criteria

The model was not validated through comparison to separate data not used in the calibration. Instead, calibration was completed over the entire model period in order to capture the variability occurring during the model period and to obtain the best model fit possible (Well 2005).

Two model performance statistics were used to assess monthly predictions of streamflow in the SWATSalt model. The first is relative error (RE), which is a measure of the average tendency of simulations to be larger or smaller than an observed value. RE is defined as the deviation between observed ($X_{i,obs}$) and simulated ($Y_{i,sim}$) values. An optimal RE is 0.0, and positive and negative values reflect bias toward over- or under-estimation. RE is calculated as:

$$\text{RE\%} = \frac{\sum_{i=1}^{n}(Y_{i,sim} - X_{i,obs})}{\sum_{i=1}^{n}(X_{i,obs})} \times 100$$

(EQ-2)

Van Liew et al. (2005) suggested RE values <±20% are “good”, while more strict guidelines have been suggested elsewhere. For this project, the acceptable RE depended on the parameter of interest. For total water balance, RE< ±10% was considered to be sufficient for model calibration, while for less important components such as seasonal volumes or storm volumes, higher REs were considered acceptable.

The second evaluation criterion was the Nash-Sutcliffe coefficient of efficiency (NSE) (Nash and Sutcliffe, 1970). NSE expresses the fraction of the measured variance reproduced by the model and is defined as:

$$\mathrm{NSE} = 1 - \frac{\sum_{i=1}^{n} (X_{i,obs} - Y_{i,sim})^2}{\sum_{i=1}^{n} (X_{i,obs} - \overline{X}_{i,obs})^2}$$

(**EQ-3**)

The NSE can range from $-\infty$ to 1.0. By increasing NSE, error in the model is inherently decreased. An NSE of 0 would indicate that the model is no better at predicting flows than using the long-term mean, whereas values above or below zero would mean that it does a better or worse job than the mean, respectively (Motovilov et al. 1999). Simulation results are considered to be good when NSE > 0.65, while NSE values above 0.5 are considered satisfactory (Moriasi et al. 2007).

The performance targets recommended by Moriasi et al. (2007) are summarized in **Table 6-3** and were used to evaluate the performance of monthly incremental and total streamflow totals. In addition, graphical comparisons of modeled vs. observed data were used to visually identify patterns and agreement between the simulated and observed values. Incremental flow is the flow modeled from the landscape (the portion modeled by SWAT), while total streamflow refers to the estimate of flow including that modeled from the landscape as well as point sources and inlets.

Table 6-3. Performance targets for SWAT streamflow simulation (evaluated monthly)

Statistic	Very Good	Good	Fair	Poor
Relative Error (RE)	≤ |10|%	≤ |15|%	≤ |25|%	> |25|%
Nash-Sutcliffe Efficiency (NSE)	≥ 0.75	≥ 0.65	≥ 0.50	< 0.50

Moriasi et al. (2007) does not recommend performance targets for salts. The performance targets recommended for sediment were therefore adopted for assessment of the model's performance for monthly salt loads (**Table 6-4**). The observed loads used in the evaluation were the total monthly loads of Na, Ca, and Mg estimated using LOADEST. To evaluate performance, these were compared to the simulated loads from the SWATSALT output.

A comparison was also done between daily estimates of salt loads, SAR, and SC from available grab sample data and daily simulated loads. Performance evaluation targets were based on the error tolerances for water quality and nutrients recommended for daily comparisons by Duda et al. (2012).

Table 6-4. Performance targets adopted for monthly SWAT salt loads and daily paired salt loads, SAR and SC

Constituent	Statistic	Very Good	Good	Fair	Poor
Monthly Salt Loads	Relative Error (RE)	≤ 15%	≤ 30%	≤ 55%	> 55%

	Nash-Sutcliffe Efficiency (NSE)	≥ 0.75	≥ 0.65	≥ 0.50	< 0.50
Paired Ca, Mg and NA loads; Paired SAR and SC	Relative Error (RE)	≤ 15%	≤ 25%	≤ 35%	> 35%

6.5.2 Streamflow Calibration

Total streamflow simulated by the SWAT model at Birney, the T&Y Diversion Dam, and Miles City, MT were compared against USGS timeseries data from 2005 to 2013 for calibration. The USGS gage at Brandenberg had data for only two years during the simulation period and therefore was deemed not sufficient for model calibration. Streamflow calibration generally focused on comparing incremental and total simulated streamflow against observed streamflow at the USGS gages.

Calibration of streamflow in the model was completed using a manual approach. First, a sensitivity analysis was performed on coefficients to identify those that have a strong effect on the model. Default parameters were used as the starting point for calibration and values were then manually adjusted based on desired system response and watershed knowledge. The parameters that govern precipitation runoff, evapotranspiration, soil water storage, stream channel routing, and subsurface flow were calibrated and final values are shown in **Table 6-5** along with the recommended minimum and maximum values for SWAT.

Table 6-5. Parameters used in the runoff calibration in the Tongue River SWATSalt model

Category	Parameter	Description	Calibrated Value	Min	Max	Units
Snow	SFTMP	Snowfall Temperature	1	-5	5	Celsius
Snow	SMTMP	Snowmelt Base Temperature	1	-5	5	Celsius
Snow	SMFMX	Melt Factor for snow on June 21	6.5	0	10	mm/C* day
Snow	SMFMN	Melt Factor for snow on June 21	1.5	0	10	mm/C* day
Snow	SNOCOVMX	Minimum water that corresponds to 100% snow cover	50	0	500	mm
Snow	SNO50COV	Fraction of snow volume that corresponds to 50% cover	1	0	1	-
Snow	TIMP	Snowpack lag factor	0	0	1	-
Water	SURLAG	Surface runoff lag time	4.0	1	24	days
Water	SPCON	Linear parameter for sediment re-entrainment	0.0001	0.0001	0.01	-
Water	SPEXP	Exponent parameter for sediment re-entrainment	1	1	2	-
Water	ESCO	Soil evaporation compensation factor	0.3	0	1	-
Water	EPCO	Plant water uptake compensation factor	1	0	1	-

Category	Parameter	Description	Calibrated Value	Min	Max	Units
Water	HRU SLP	Average slope steepness	0.0004-0.4269	0	1	m/m
Water	SLSUBBSN	Average slope length	100-150	0	90	m
Water	GW_DELAY	Delay time for aquifer recharge	10	0	500	days
Water	ALPHA_BF	Baseflow recession constant	0.9	0	1	days
Water	GW_REVAP	Revap coefficient	0.2	0.02	0.2	-
Irrigation	REVAPMN	Threshold depth for "revap" to occur	0	0	1000	mm
Irrigation	GWQMN	Threshold depth for return flow to occur	100	0	1000	mm
Water	RCHRG_DP	Deep aquifer percolation fraction	0	0	1	-
Water	CH_K2	Effective hydraulic conductivity of main channel	15-30	0	1000	mm/hr
Water	CH_EROD	Channel erodibility factor	0	0	1	-
Water	CH_COV2	Channel cover factor	1	0	1	-

The error statistics for incremental streamflow, which comprises a small portion of total streamflow compared to that from inlets and point sources, is summarized in **Table 6-6** and **Table 6-7**. The Birney station had poor performance of NSE for incremental streamflow, and the Miles City station had poor performance for RE for incremental streamflow. However, the performance for all other statistics was good or very good, including both statistics for T & Y diversion dam. The negative value for RE for Miles City for incremental stream flow indicates that the streamflow from the landscape was underestimated, while the low NSE for Birney's incremental streamflow indicates that model did not do well at estimating the variability in streamflow from the landscape at this site. The performance for total streamflow, which includes inlets and point sources as well as landscape sources, was very good for all three sites.

Monthly simulated and observed incremental and total streamflow at the T&Y Diversion Dam is shown in **Figure 6-9 and Figure 6-10**. Flow hydrographs for Birney and Miles City are presented separately in **Appendix G**.

Overall, the hydrology simulation results appear to produce reasonable results over a wide range of flow conditions. Simulated and observed data for total streamflow are comparable for most flow levels and total flow was predicted well. The streamflow calibration shows the model performs well for streamflow magnitude and timing, and that the underestimation of SWE (**Section 6.3**) minimally impacted the overall estimation of flow. The accuracy of the modeled flows was determined by DEQ to be sufficient for the purpose of conducting the scenario analyses that are described later in this document (**Section 7.0**).

Table 6-6. Model Error Statistics for Incremental Streamflow Comparison at Birney, T&Y Diversion Dam and Miles City

Location	RE	Monthly NSE	Performance (RE / NSE)
Birney	-2.1	0.36	Very Good / Poor

T&Y Diversion Dam	-4.8	0.67	Very Good / Good
Miles City	-29.3	0.80	Poor / Very Good

Note - Errors are reported as simulated minus observed.
*RE and NSE comparison to performance targets in **Table 6-3**.

Table 6-7. Model Error Statistics for Total Streamflow Comparison at Birney, T&Y Diversion Dam and Miles City

Location	RE	Monthly NSE	Performance (RE / NSE)
Birney	2.4	0.99	Very Good / Very Good
T&Y Diversion Dam	5.9	0.98	Very Good / Very Good
Miles City	4.4	0.99	Very Good / Very Good

Note - Errors are reported as simulated minus observed.
*RE and NSE comparison to performance targets in **Table 6-3**.

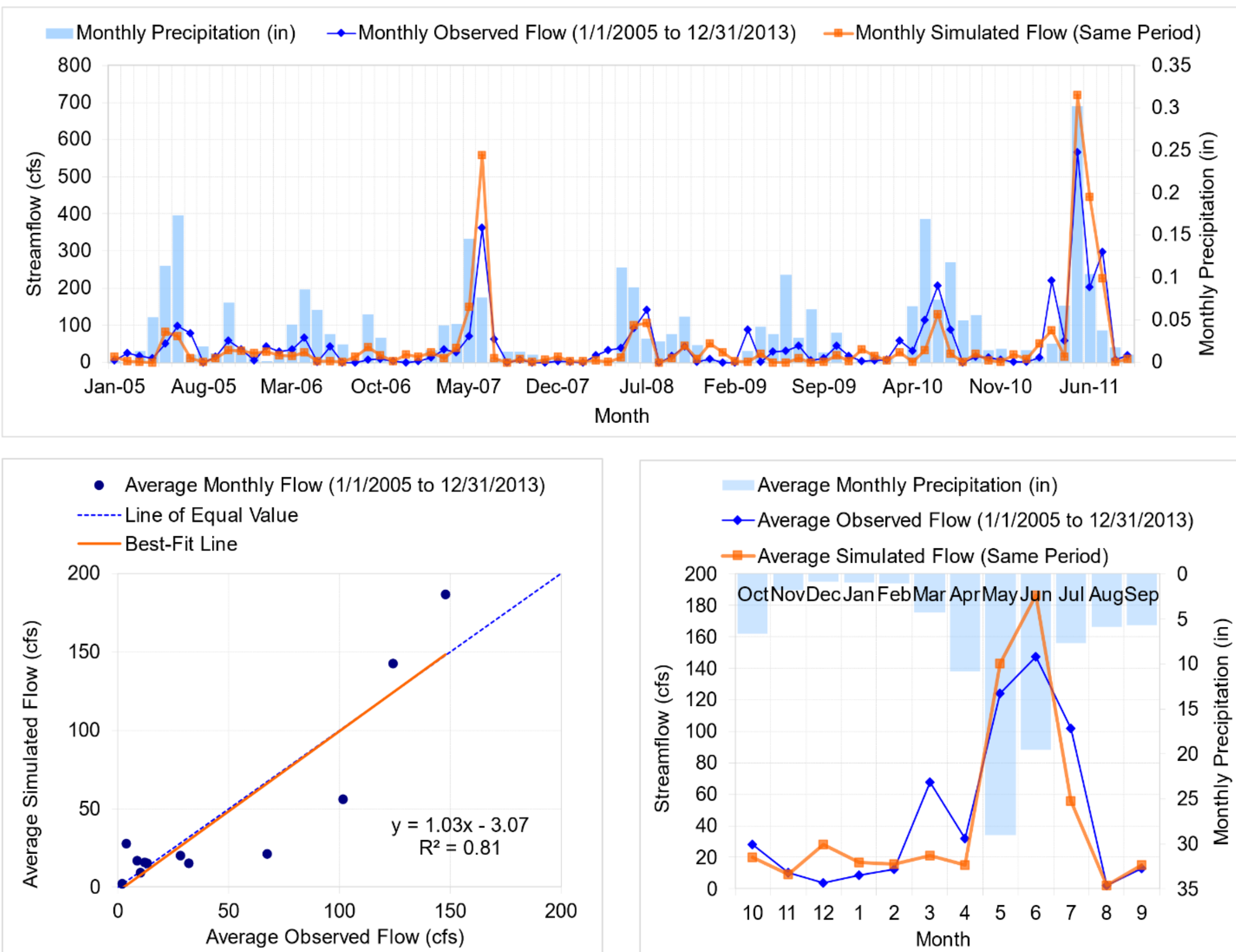


Figure 6-9 Simulated and observed monthly incremental streamflow for USGS gage above T&Y Diversion Dam

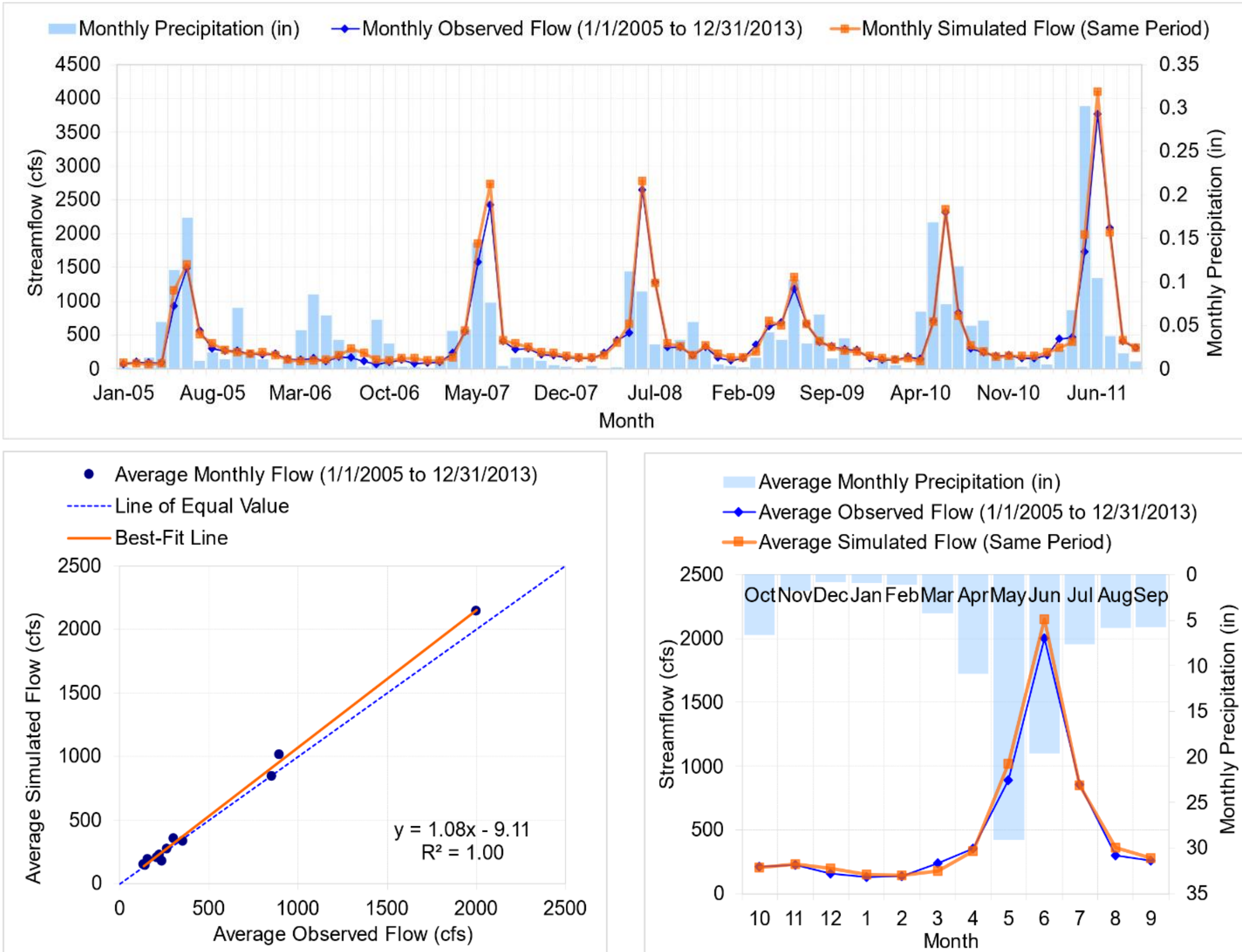


Figure 6-10. Simulated and observed monthly total streamflow for USGS gage above T&Y Diversion Dam

6.5.3 Salinity (SC/SAR) Calibration

As water moves across and through the landscape, salts are added from interactions with soil and rock. In surface runoff, readily dissolved salts are carried into the stream. Water flowing through pores in soil or rock (groundwater and other sub-surface flows) is directly in contact and undergoes a similar process via solubility. Thus, salts are in the soil; eroded out of rock, deposited by rain and the atmosphere (Nilles, 2000), and also added by humans in the form of fertilizer, wastewater, industrial discharges, livestock manure, etc. Some of these salts are eventually transported to surface water through hydrologic processes. The following sections describe how these salts are simulated in the model and the results of the calibration.

Salt loads simulated in the model are determined by a combination of tributary boundary conditions and user-specified salt concentrations in local surface and subsurface flow pathways. EMCs of calcium (Ca), magnesium (Mg), and sodium (Na) in surface runoff, lateral flow (interflow), and shallow groundwater outflow by land use categories in the calibrated model are shown in **Table 6-8**. The concentrations were initially based on the Tongue River LSPC model and subsequently refined during model calibration of the SWATSalt model. Specifically, concentrations in surface runoff were increased to match the observed loads during peak flows and monthly regression loads. The salt concentrations for alfalfa and hay are generally within the range reported by the Tongue River AMPP under irrigated fields, shown in **Table 6-8**.

Table 6-8. Concentrations of Ca, Mg, and Na in Flow Pathways in the SWATSalt Model

Landuse	Surface Runoff (mg/L)			Lateral Flow (mg/L)			Shallow Groundwater Flow (mg/L)		
	Ca	Mg	Na	Ca	Mg	Na	Ca	Mg	Na
Alfalfa/Hay	113	225	225	206	413	413	450	900	900
Urban	5	20	20	10	40	40	35	140	140
Grass/Shrub	10	20	20	20	40	40	70	140	140
Forest	10	20	20	20	40	40	70	140	140
Wetland	10	20	20	20	40	40	70	140	140
Landuse	Surface Runoff (meq/L)			Lateral Flow (meq/L)			Shallow Groundwater Flow (meq/L)		
	Ca	Mg	Na	Ca	Mg	Na	Ca	Mg	Na
Alfalfa/Hay	5.6	18.5	9.8	10.3	34.0	18.0	22.5	74.1	39.2
Urban	0.2	1.6	0.9	0.5	3.3	1.7	1.7	11.5	6.1
Grass/Shrub	0.5	1.6	0.9	1.0	3.3	1.7	3.5	11.5	6.1
Forest	0.5	1.6	0.9	1.0	3.3	1.7	3.5	11.5	6.1
Wetland	0.5	1.6	0.9	1.0	3.3	1.7	3.5	11.5	6.1

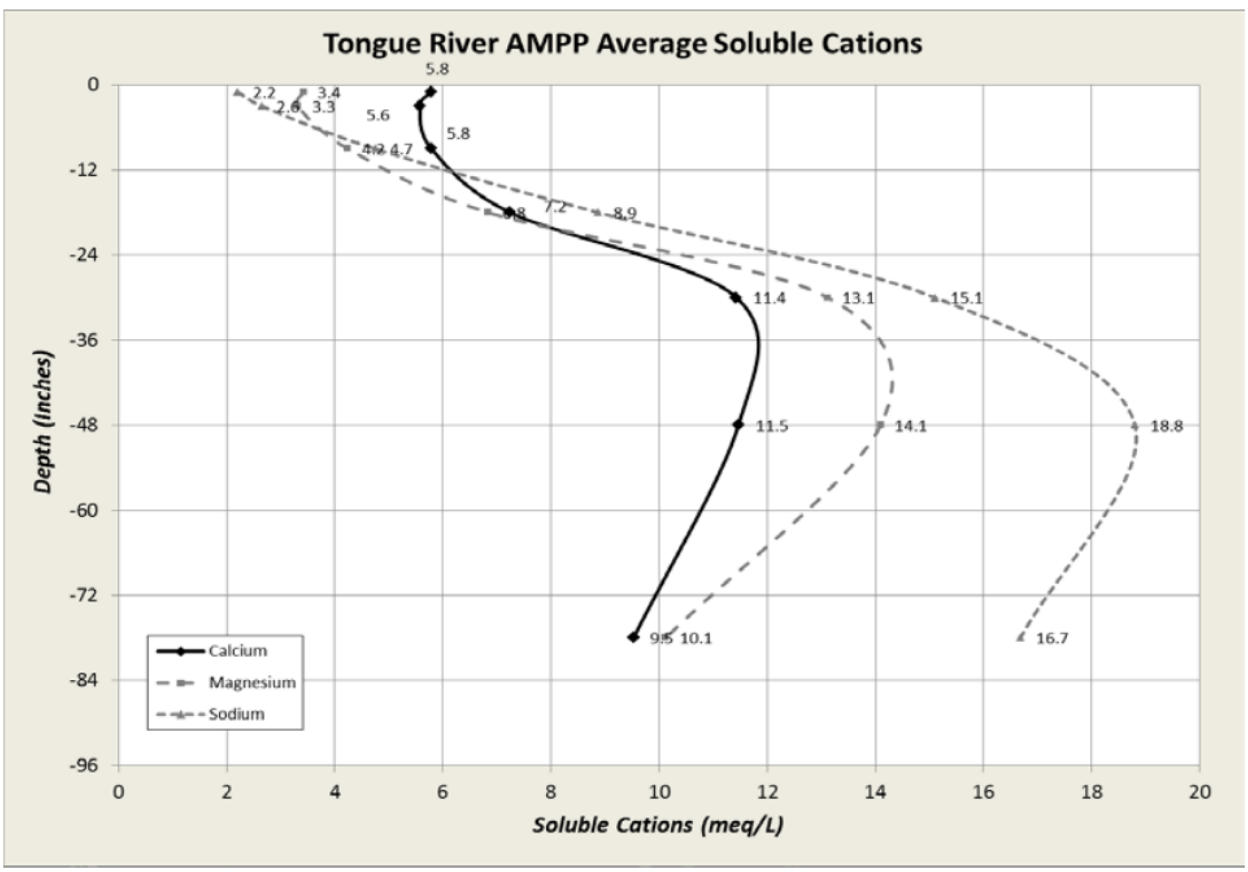


Figure 6-11. Ca, Mg, and Na concentrations with depth for AMPP fields irrigated with Tongue River water (MBOGC, 2011b)

There are no observed data at the Tongue River above T&Y Diversion Dam USGS gage in 2012 or 2013. However, simulated concentrations of Ca, Mg, and Na match well with daily grab sample data in years that do have data from 2005 to 2011 (**Figure 6-12 – Figure 6-15**). A visual analysis of the daily simulated and observed cation concentrations indicates simulated Ca and Mg concentrations are within reasonable ranges during both high and low flow periods throughout the model period. However, the model has more difficulty matching the observed Na concentrations, particularly during the low flow periods of early spring from 2009 to 2011. Timeseries for the Tongue River at Birney and Miles City are presented separately in **Appendix H.** Simulated daily values at Miles City for Na show the biggest discrepancy from actual values. This discrepancy occurred during low flow periods and indicated that during low flows the model was poorly capturing sources of Na from soils or other sources for this reach.

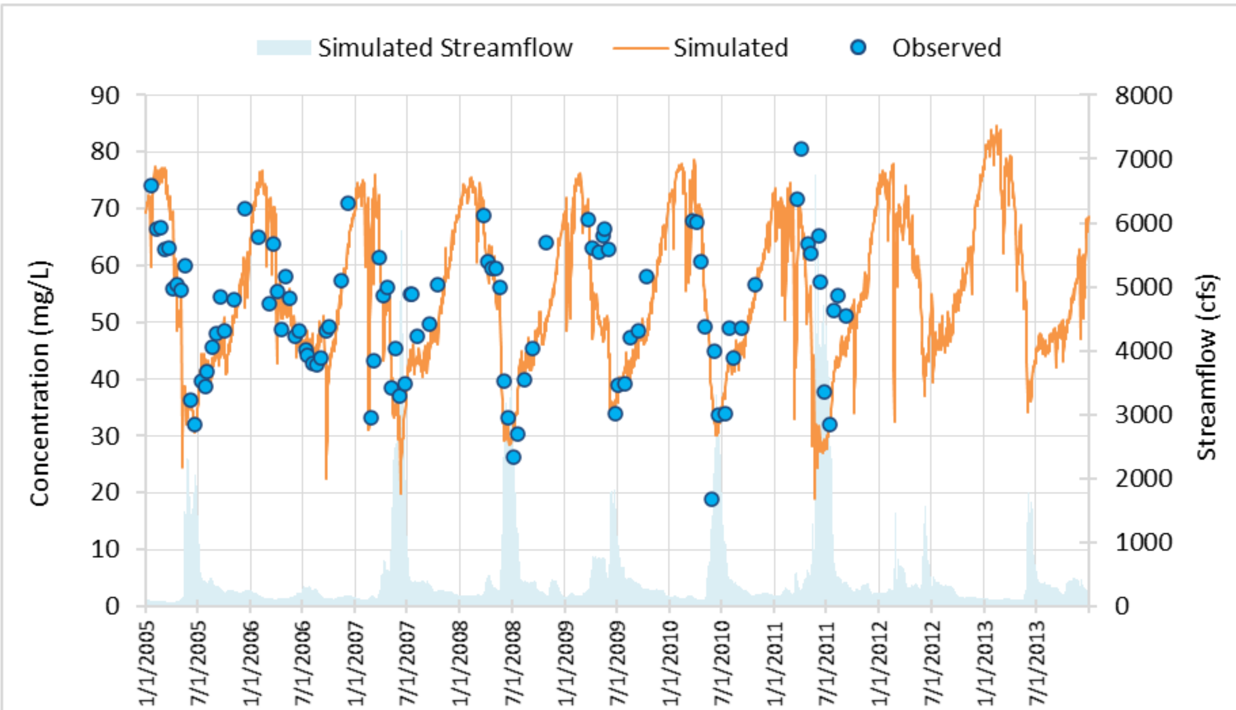


Figure 6-12. Daily simulated and discrete observed Ca concentrations at T&Y Diversion Dam

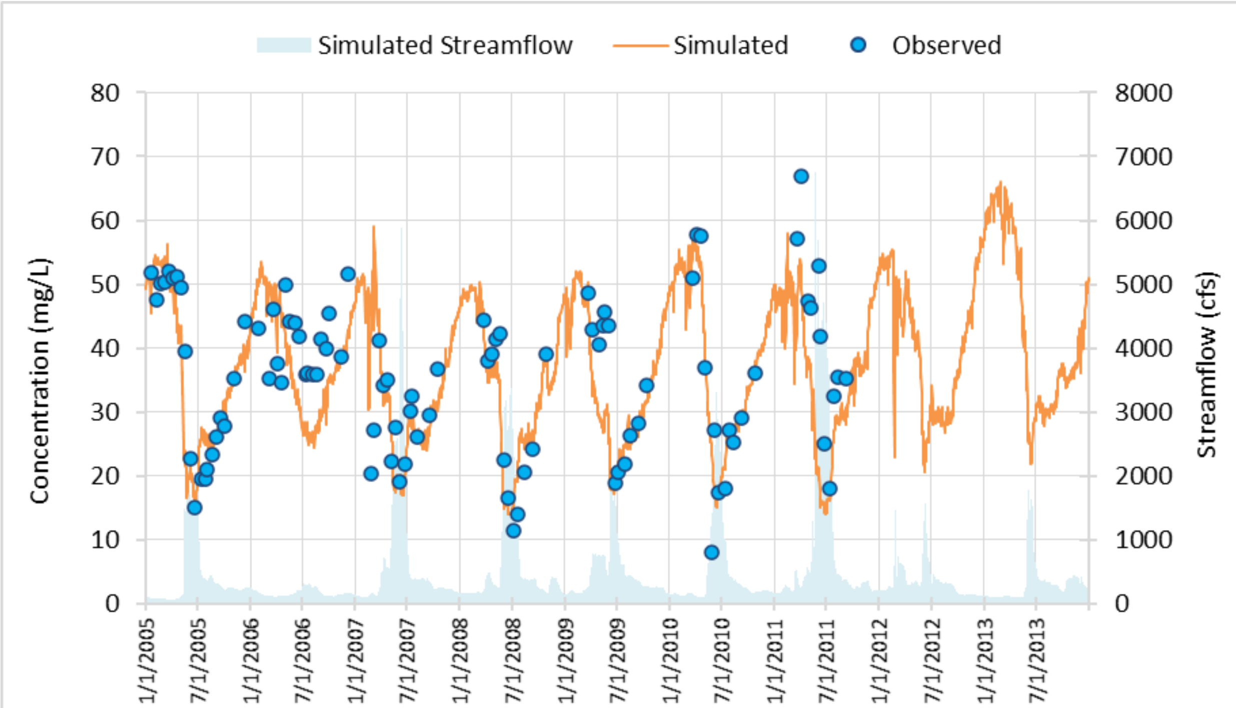


Figure 6-13. Daily simulated and discrete observed Mg concentrations at T&Y Diversion Dam

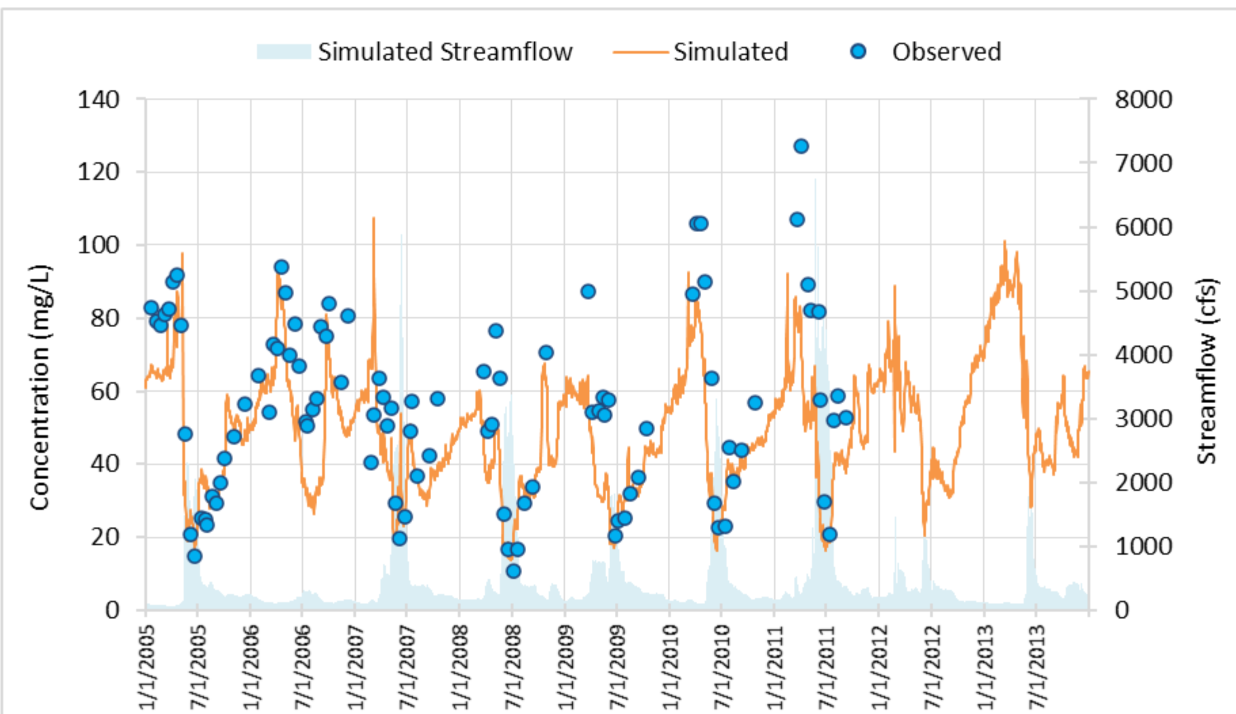


Figure 6-14. Daily simulated and discrete observed Na concentrations at T&Y Diversion Dam

The performance of the model for monthly Ca, Mg and Na loads at T & Y Diversion Dam are good to very good based on comparison of simulated loads against regression estimates generated using LOADEST (as summarized in **Table 6-9**). Visual comparisons of monthly loads are presented for the T&Y Diversion Dam for all three cations in **Figure 6-15** through **6-17** and in **Appendix H** for Birney and Miles City.

The simulated monthly loads of Ca, Mg, and Na match well with the LOADEST regressions in years that do have data from 2005 to 2011. Similar to the concentration time series, Na loads are underestimated by the model particularly during 2007, 2009, and 2010. **Table 6-9** and **Appendix H** show that the Na performance is not as good as the Ca and Mg results. The negative values for RE indicates that the simulated Na was underestimated compared to actual Na loads. Whether that is due to inaccuracies in the estimates of observed cations based on LOADEST or the estimates of cations in the model simulation is unknown. These uncertainties are further discussed in **Section 8.0**.

Table 6-9. Performance Assessment for Simulated versus LOADEST Monthly Salt Loads on the Tongue River at Birney, T&Y Diversion Dam, and Miles City.

Salt (Cation)	Birney			T&Y Diversion Dam			Miles City		
	RE (%)	NSE	Performance*	RE (%)	NSE	Performance*	RE (%)	NSE	Performance*
Ca	-4.2	0.96	Very Good / Very Good	-7.4	0.94	Very Good / Very Good	-7.3	0.93	Very Good / Very Good
Mg	-8.3	0.89	Very Good / Very Good	-7.2	0.92	Very Good / Very Good	-8.7	0.93	Very Good / Very Good
Na	-6.4	0.89	Very Good / Very Good	-16.7	0.78	Good/ Very Good	-21.6	0.72	Good / Good

Note - Errors are reported as simulated minus LOADEST.
*RE and NSE comparison to performance targets in **Table 6-4**

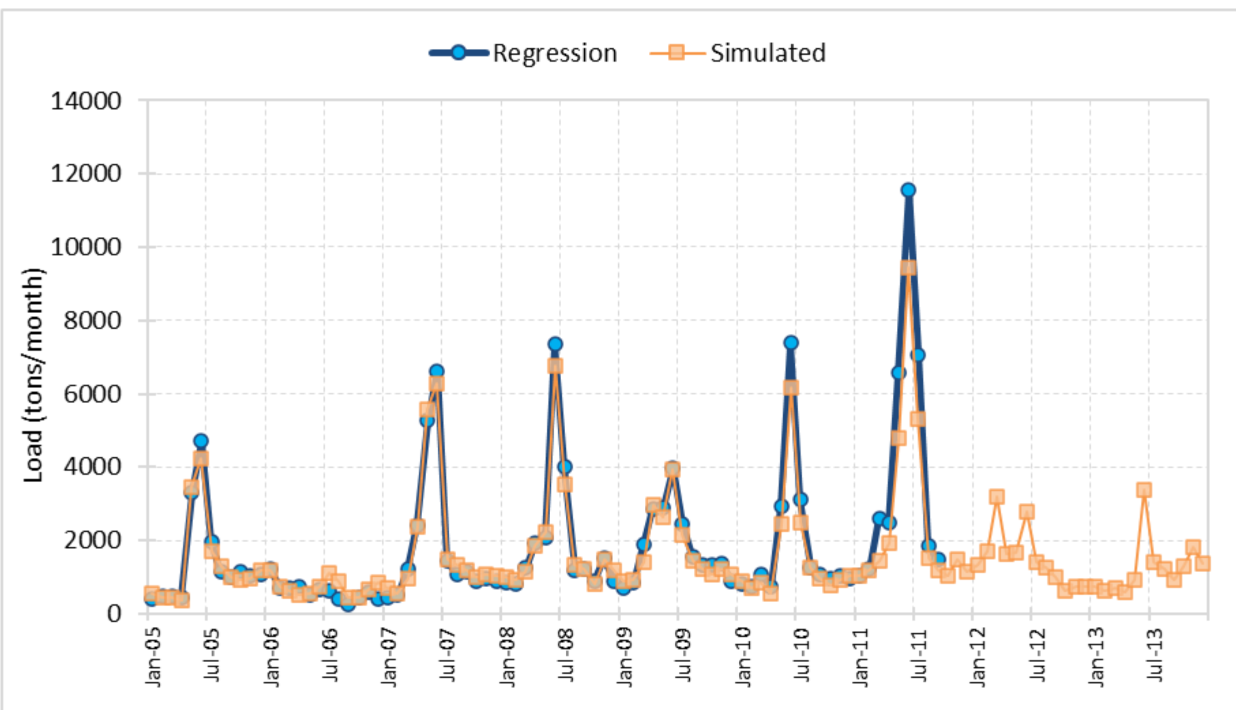


Figure 6-15. Monthly simulated and LOADEST regression loads for Ca at T&Y Diversion Dam

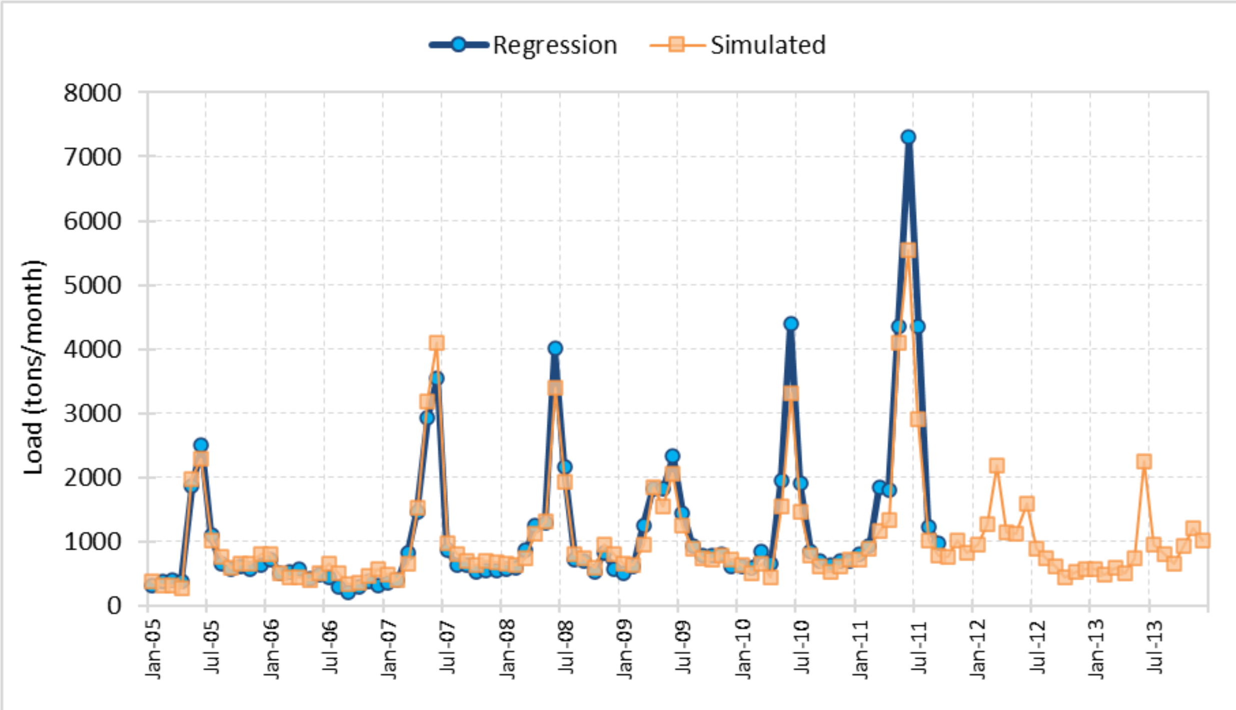


Figure 6-16. Monthly simulated and LOADEST regression loads for Mg at T&Y Diversion Dam

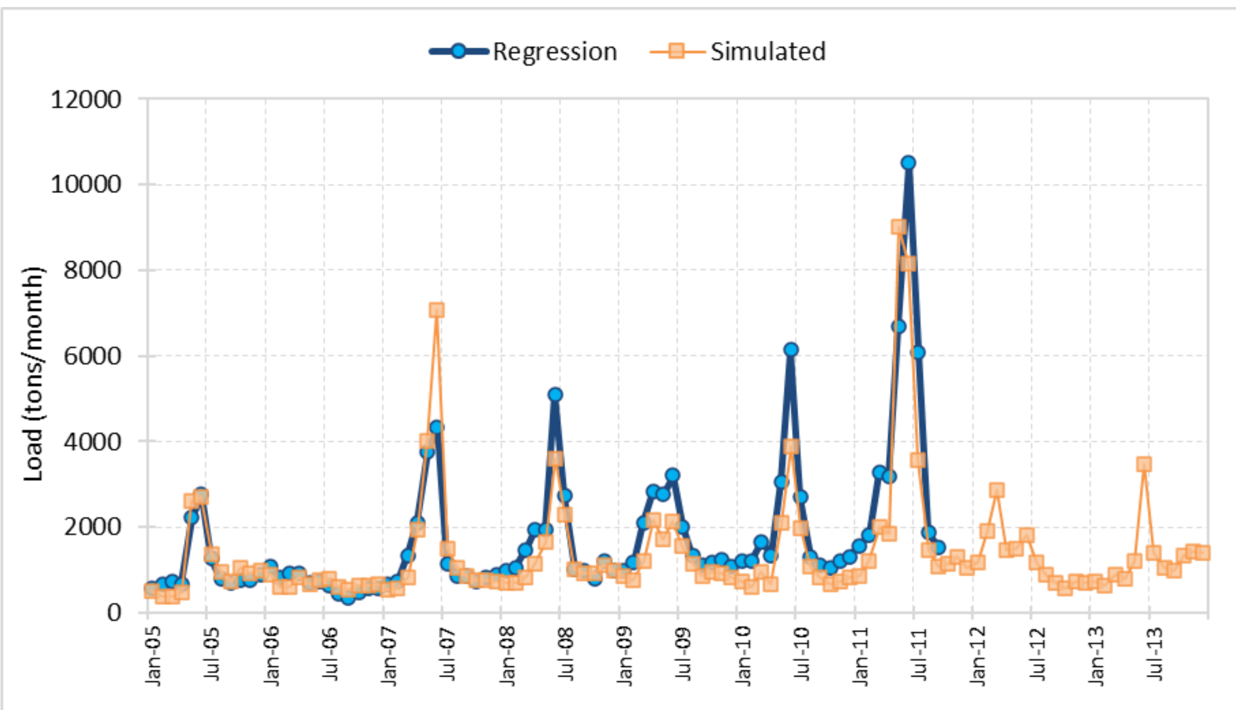


Figure 6-17. Monthly simulated and LOADEST regression loads for Na at T&Y Diversion Dam

In addition to monthly loads, simulated Ca, Mg, and Na paired daily loads in the Tongue River were compared against loads based on data from these cations estimated from USGS NWIS grab samples at the Birney, T&Y Diversion Dam, and Miles City USGS gages. The paired load RE and normalized root mean square error (NRMSE) for Ca, Mg, and Na are summarized in **Table 6-10**. The paired load errors suggest good or very good agreement between estimates of daily salt loads from grab samples compared to that estimated by the model. There are no criteria for model performance assessment based on NRMSE of paired simulated and observed loads; therefore, they are provided for informational purposes.

Table 6-10. Daily Paired Salt Load Errors at Birney, T&Y Diversion Dam, and Miles City

Salt (Cation)	Birney				T&Y Diversion Dam				Miles City			
	#	RE (%)	NRMSE (%)	Rating*	#	RE (%)	NRMSE (%)	Rating*	#	RE (%)	NRMSE (%)	Rating*
Ca	122	-8.9	48.1	Very Good	99	-12.2	52.4	Very Good	99	-8.1	42.7	Very Good
Mg	122	-16.3	73.4	Good	99	-16.1	75.8	Good	99	-10.5	57.9	Very good
Na	122	-14.3	83.6	Very Good	99	-23.6	85.8	Good	99	-24.9	70.0	Good

*RE comparison to performance targets in **Table 6-4**

6.5.4 Calibration of Specific Conductance

The SWATSalt model calculates SC using a user-defined regression relationship based on the concentration of one salt. The regression relationship does not consider other salts being modeled. The default approach is therefore limited since the simulated and observed SC could match very well even if there are large errors in the simulation of other salts not used to drive the regression equation. Therefore, a new regression relationship was developed for the Tongue River watershed using the sum of cation (Ca, Mg, Na) grab sample concentrations and observed instantaneous SC at USGS calibration locations. The different regression relationships developed for the Tongue River Birney, T&Y Diversion Dam and Miles City gages are shown in **Figure 6-18** through **Figure 6-20**. The predicted concentrations of Ca, Mg, and Na from SWATSalt were input to these regression relationships to calculate the model's estimate of SC. For subbasins between the three locations in which regressions are available, SC is calculated using the regression of the next available downstream location. For example, SC at subbasin 7 (the downstream end of the impaired segment) is calculated using the regression developed for Miles City which is in subbasin 2.

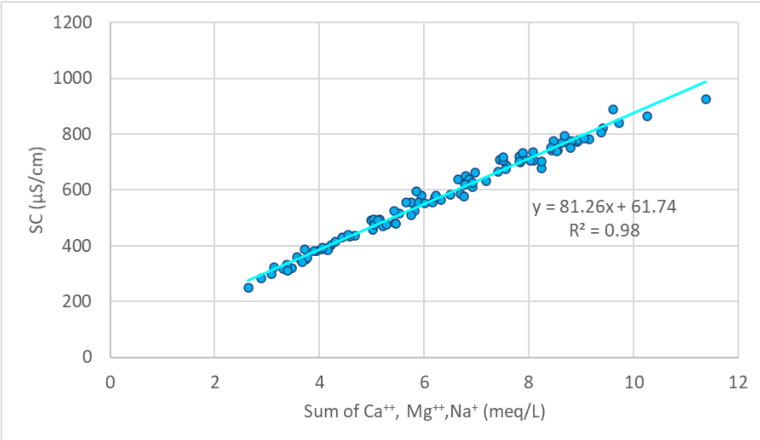


Figure 6-18. Linear relationship between observed SC and sum of cations at Birney (subbasin 54)

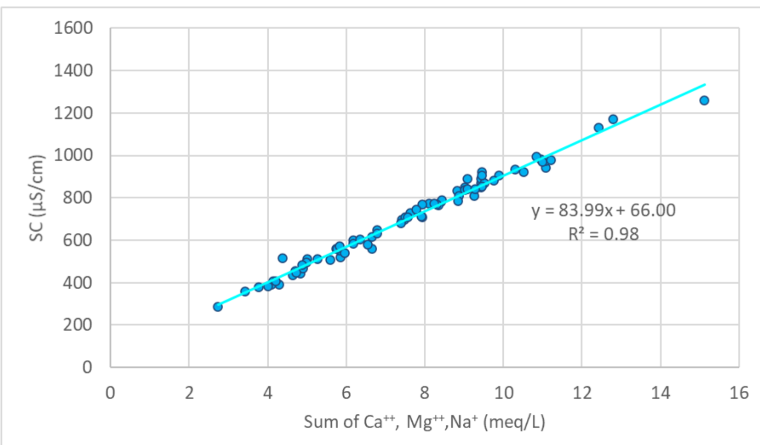


Figure 6-19. Linear relationship between observed SC and sum of cations at T&Y Diversion Dam (subbasin 10)

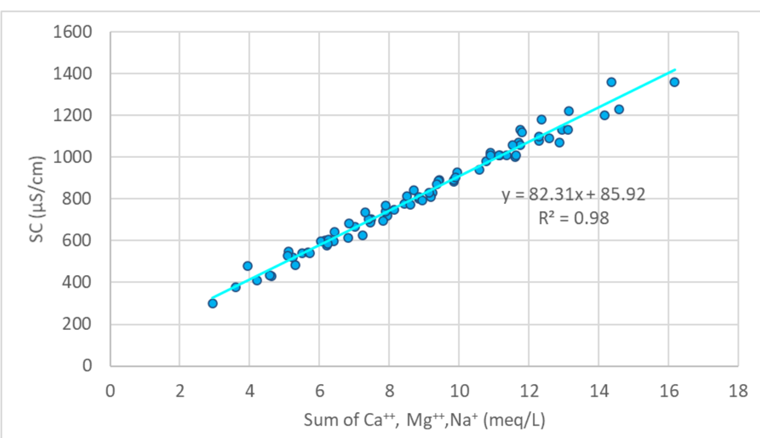


Figure 6-20. Linear relationship between observed SC and sum of cations at Miles City (subbasin 2)

Daily and monthly timeseries of simulated and observed concentrations for SC at the T&Y Diversion Dam are shown in **Figure 6-21.** Paired errors were estimated comparing SC from grab samples to average daily SC estimated in the model. The performance of the model for SC based on RE is very good at the T&Y Diversion Dam, very good at Birney, and good at Miles City).

Although the model generally reproduces SC values well, the largest discrepancies occur in the spring of 2011 where SC is underestimated compared to observed values. One potential explanation for this is that all of the salts in an HRU are delivered to the stream at the same time regardless of where the pixels in the HRU are located spatially in a subwatershed. It should also be noted that some of the observed monthly averages are not based on a full month of data due to data logger deployment dates or equipment malfunctions; those data gaps may contribute to errors in the estimates of monthly average SC.

Simulated SC is highest in the spring of 2013 likely due to relatively lower flows during the previous winter. Although the T&Y Diversion Dam does not have observed data during this time of high SC in 2013, observed SC at the Miles City and Birney monitoring locations confirm that SC is in fact higher than most years during this time (**Appendix H**). Data collected at the T&Y Diversion Dam in the spring of 2011 indicate that SC values simulated for 2013 are within the range of possible values (**Figure 6-21**).

Table 6-11. Paired Errors for SC at Birney, T&Y Diversion Dam, and Miles City.

Constituent	Birney				T&Y Diversion Dam				Miles City			
	#	RE (%)	NRMSE (%)	Rating*	#	RE (%)	NRMSE (%)	Rating*	#	RE (%)	NRMSE (%)	Rating*
SC	1897	3.5	17.1	Very Good	1462	-13.7	43.9	Very good	1833	-19.0	47.6	Good

*RE is comparison to performance targets in **Table 6-4**. “#” refers to number of observations used in the analysis.

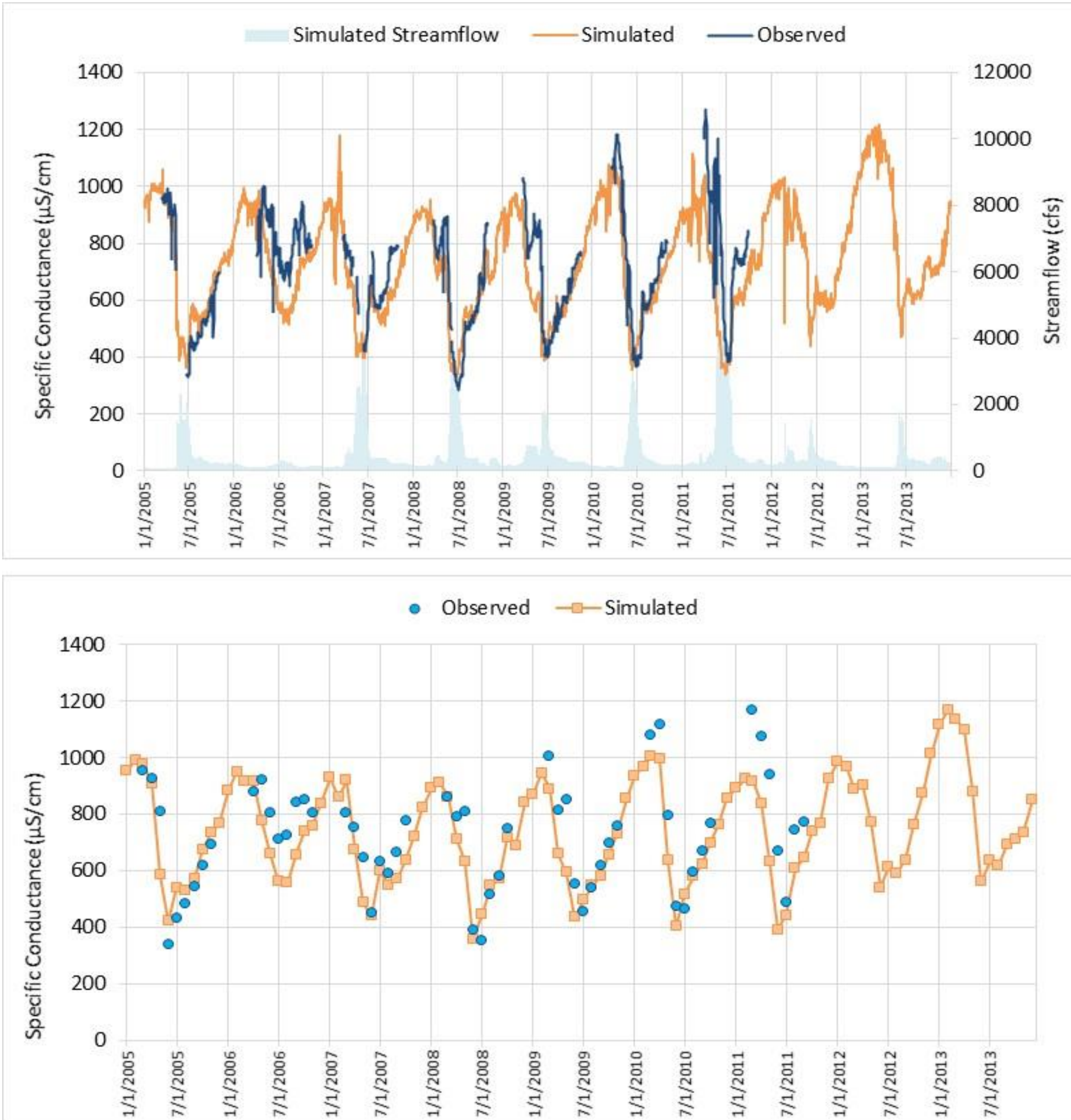


Figure 6-21. Average daily (top) and monthly (bottom) simulated and continuous observed SC concentrations at T&Y Diversion Dam

6.5.5 Calibration of SAR

The SWATSalt model also internally calculates SAR using EQ-1 in **Section 3.2**. The simulated SAR values were compared against observed SAR at the Tongue River Birney, T&Y Diversion Dam, and Miles City gages (**Table 6-12**). Daily and monthly timeseries of simulated and observed concentrations for SAR at the T&Y Diversion is shown in **Figure 6-22** while graphs for the other sites are found in **Appendix H**. The simulated daily SAR generally matches the observed data well with the exception of high spikes in SAR between 2005 and 2007. Note that some of the monthly averages are not based on a full month of data due to data logger deployment dates or equipment malfunctions; those data gaps may contribute to some of the observed errors in the figures.

Table 6-12. Paired Errors for SAR at Birney, T&Y Diversion Dam, and Miles City.

Constituent	Birney				T&Y Diversion Dam				Miles City			
	#	RE (%)	NRMSE (%)	Rating*	#	RE (%)	NRMSE (%)	Rating*	#	RE (%)	NRMSE (%)	Rating*
SAR	1853	-3.6	21.6	Very Good	1437	11.0	26.7	Very good	1635	27.2	41.1	Fair

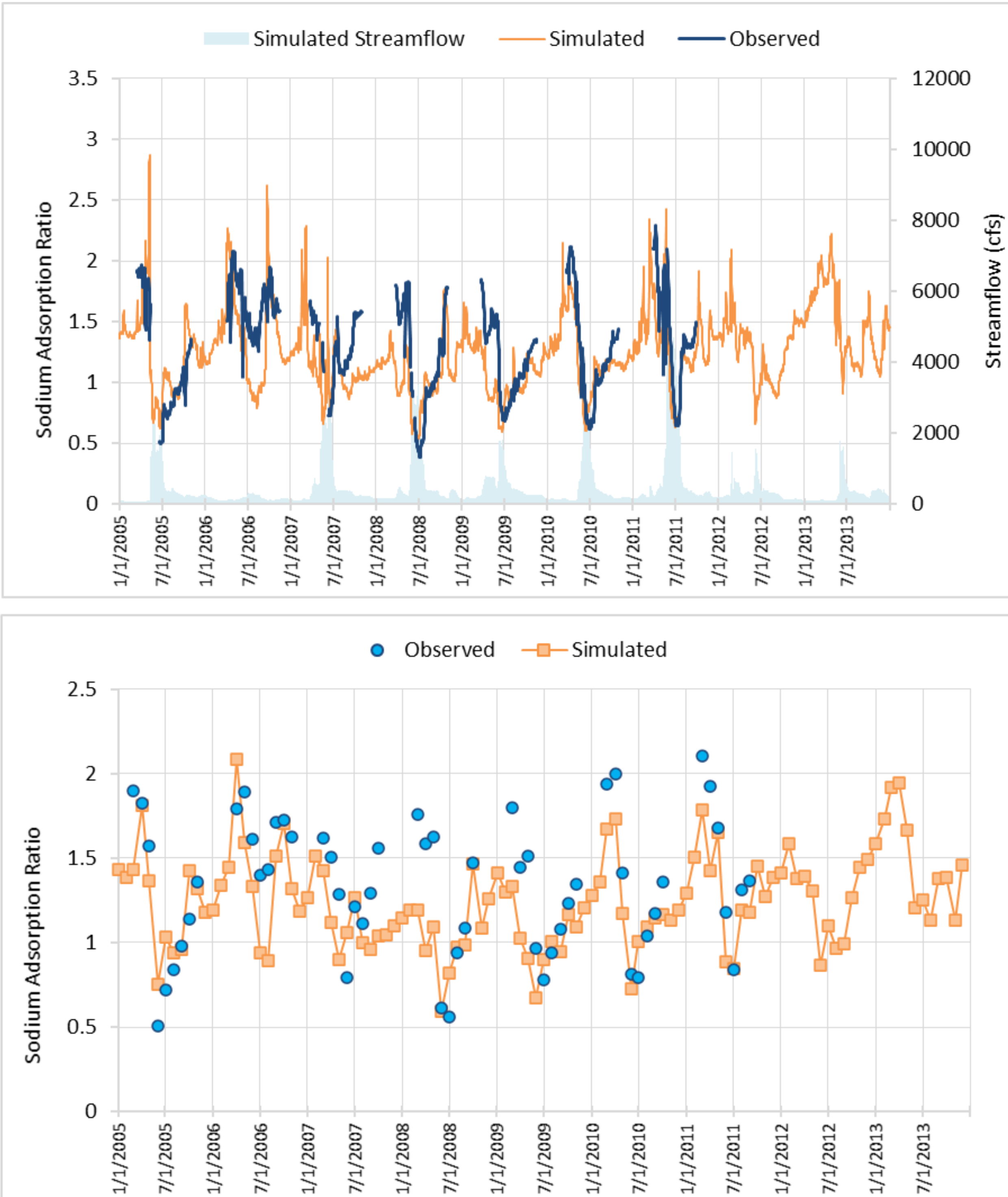
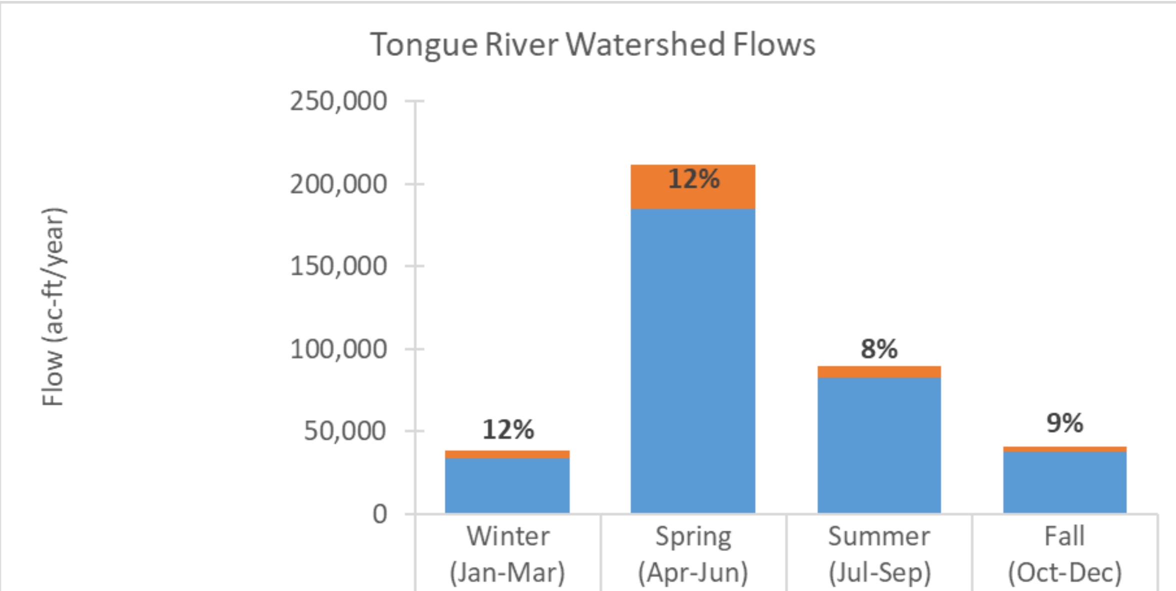


Figure 6-22. Average daily (top) and monthly (bottom) simulated and continuous observed SAR at T&Y Diversion Dam

6.6 POST-CALIBRATION MODEL OUTCOMES

Only 11% of the average annual flow volume is generated within the SWAT-modeled watershed area while the rest is attributed to the boundary conditions determined for four inlets (Hanging Woman Creek, Otter Creek, Pumpkin Creek, and the Tongue River Dam). However, there is seasonal variability in the proportion of flow volume from the SWAT modeled watershed (**Figure 6-23).** Approximately 66% of the annual flow from the SWAT modeled portion of the Tongue River watershed is during the winter/spring months and is likely associated with snowmelt.



	Winter (Jan-Mar)	Spring (Apr-Jun)	Summer (Jul-Sep)	Fall (Oct-Dec)
Tongue River Watershed (modeled)	4,528	26,306	6,976	3,750
Tributary and Tongue River Dam	33,778	185,235	82,315	37,415

Figure 6-23. Seasonal tributaries and Tongue River Dam and SWAT-modeled watershed flow volumes in the SWATSalt model

The land use based total salt loads and loading rates (expressed as the sum of Ca, Mg and Na) as simulated by the SWATSalt model from 2005 to 2013 are summarized in **Table 6-13**. The simulated unit area salt loading rate is highest for cultivated areas (alfalfa/hay) followed by forested and urban areas. Other than wetlands, the lowest loading unit area rate is associated with the grass/shrub areas. It should be noted that geology and existing soil characteristics have a large influence on salt loading. As such, some of the patterns in the unit area loading rates are due to these natural conditions rather than the type of anthropogenic land use/activity (i.e., alfalfa/hay) occurring there.

Table 6-13. Simulated Average Annual Salt Loads and Loading Rates by Landuse*.

Landuse	SWAT Landuse Code *	Load (tons/year)	Rate (lbs/ac/year)
Alfalfa/Hay	AGRR, HAY	211.0	21.4
Urban	URLD, URHD	41.5	18.0
Grass/Shrub	RNGB, RNGE	7,602.7	17.4
Forest	FRSE	1,987.4	18.7

Table 6-13. Simulated Average Annual Salt Loads and Loading Rates by Landuse*.

Landuse	SWAT Landuse Code *	Load (tons/year)	Rate (lbs/ac/year)
Wetlands	WETF	9.0	7.9

Refer to **Table 5-2** for Land Use Distribution

Except for wetlands the unit area loading of the other four major land uses are similar and within 20% of each other, which contribute to the natural salinity conditions described in the previous paragraph. Overall, the grass/shrub and forest are the predominant total salt sources in the watershed because they are the land uses comprising the largest percentage of watershed area.

The average annual seasonal surface runoff and lateral flow volumes and salt loads simulated by the SWATSalt model for alfalfa are depicted in **Figure 6-24.** The bulk of the simulated salt load is associated with lateral flow (approximately 65%). In comparison, for the hay category which uses flood irrigation as compared to sprinkler irrigation for alfalfa, the proportion of lateral flow is lower (by approximately 14%). **Appendix I** contains simulated seasonal and annual average surface runoff, lateral flow and groundwater flow volumes and salt loads for the non-alfalfa simulated land uses.

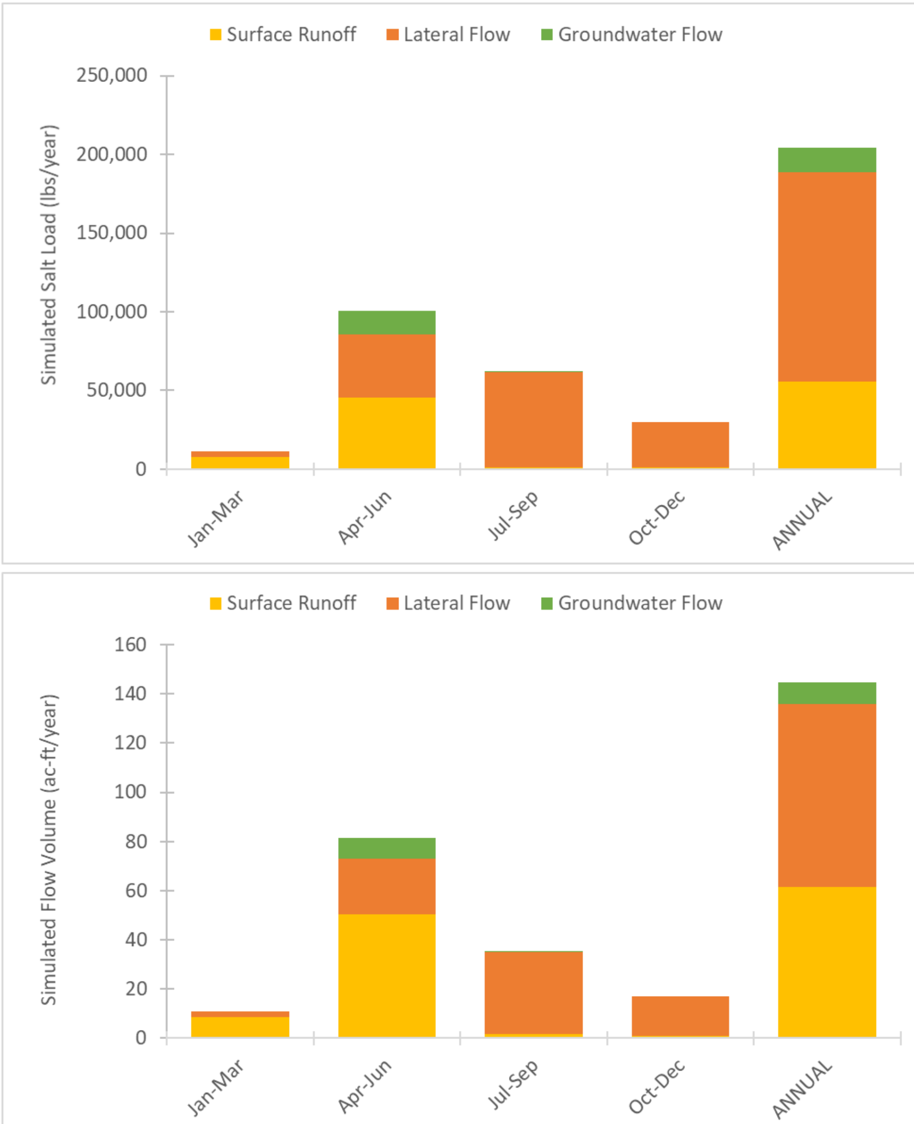


Figure 6-24. Simulated seasonal salt load and flow volume for alfalfa by type.

The average annual Ca, Mg and Na loads generated from the SWAT-modeled watershed, the Tongue River Dam and the tributaries are shown in **Figure 6-25.** The SWAT-modeled watershed generates approximately 28% of the total salt load measured at the mouth of the Tongue River. The greatest proportion of the salt load is attributable to the discharges from the Tongue River Dam. Even though a large proportion is generated by the Tongue River Dam, results of a trend analysis and reservoir investigation for the Tongue River indicate that SC has not changed significantly over time. (HydroSolutions 2022, **Appendix D**). Seasonal loading summary suggests that a higher proportion of the total salt load from the SWAT modeled portion of the watershed is during the spring months (**Figure 6-26**).

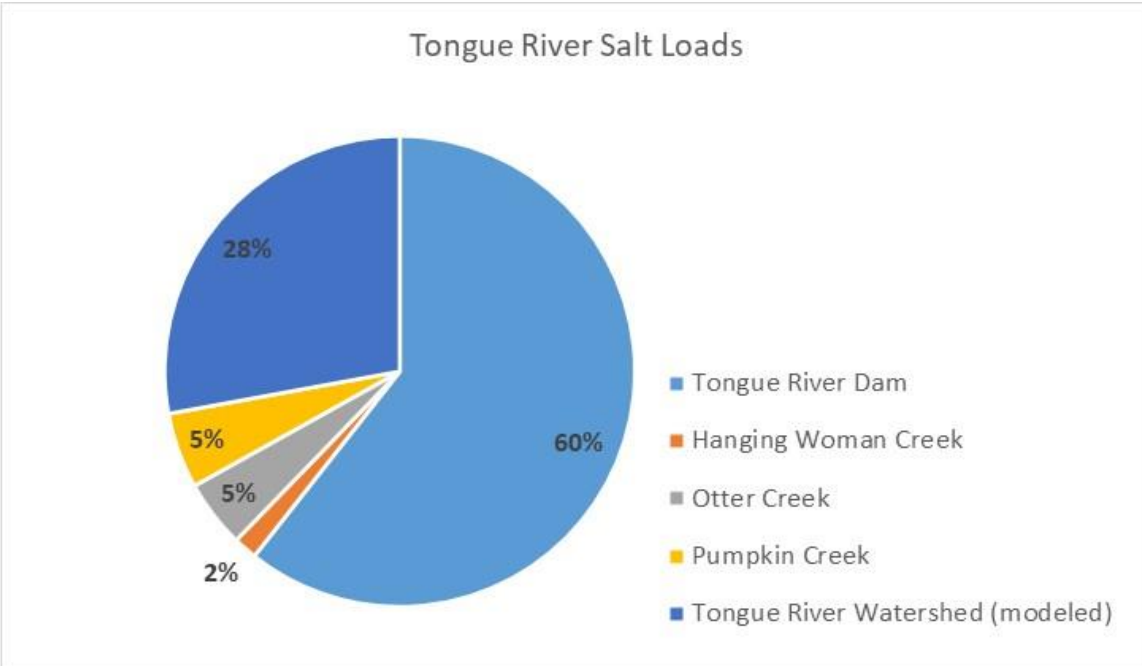


Figure 6-25. Proportions of annual salt loads from tributary watersheds, Tongue River Dam, and SWAT modeled portion of the Tongue River watershed

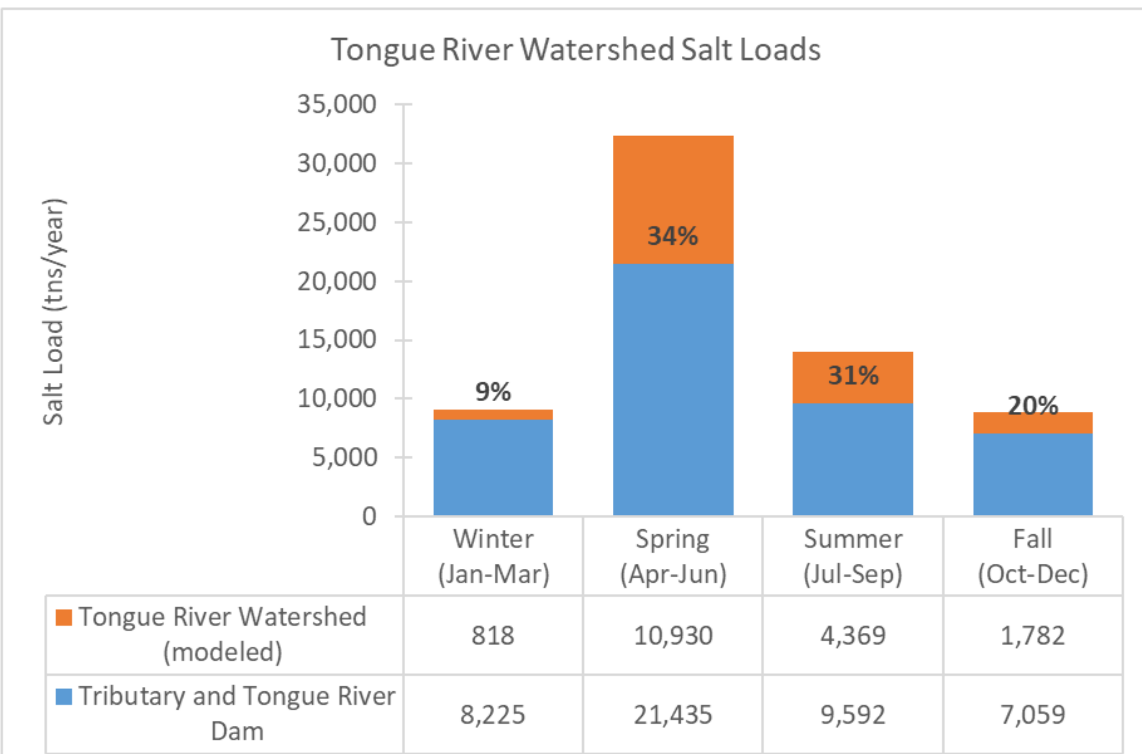


Figure 6-26. Seasonal tributary and modeled watershed salt loads in the SWATSalt model

7.0 SCENARIOS

The calibrated SWAT-Salt Tongue River model was used to evaluate the relative amount that activities including CBM extraction, coal mining, and agriculture contribute to the overall salinity load as well as how changes to hydrology might affect the load. This involved calibrating the model to a baseline condition using historical water quality data and source information about sources of salinity (**Section 6**), and modifying the model to determine how measures of salinity change under different management scenarios (**Table 7-1**) . The DEQ is not endorsing any of these scenarios, and does not even consider all of the scenarios realistic. For instance, removing agriculture or the Tongue River Dam is not feasible. However, these scenarios help inform our understanding of the sources contributing to SAR and salinity in the watershed and may inform future management recommendations.

Scenarios results are presented for monthly average SC which had multiple exceedances of the monthly average irrigation standard for SC in subbasins 30, 10, 7 and 2.. Daily exceedances of SC are not presented. The model had a poor ability to estimate salts at a daily time step, which is typical of watershed models. (Baily et al. 2019). However, the modeled daily SC values for all subbasins met water quality standards. This is consistent with measured water quality data for the Tongue River, in which exceedances are generally at the monthly time frame.

Results for SAR are not presented given that zero daily or monthly water quality standard exceedances occurred in any model subbasin for SAR. This is consistent with measured SAR data at USGS gages in the watershed that have no monthly exceedances and one daily exceedance (Miles City gage) during the model period.

Model scenario results are provided for the following locations:

- subbasin 54 corresponding to the Tongue River near Birney USGS calibration gage;
- subbasin 30 corresponding to the Tongue River near Brandenberg USGS gage and the upstream end of the upper impaired segment;
- subbasin 10 corresponding to the Tongue River above the T&Y diversion USGS calibration gage;
- subbasin 7 located at the downstream end of the upper impaired segment and represents conditions immediately upstream of the T & Y diversion;
- subbasin 2 located near the downstream end of the lower impaired segment (mouth of Tongue River) and corresponding to the Tongue River at Miles City USGS calibration gage.

The model results for each subbasin represent conditions in the Tongue River at the downstream end of each subbasin.

Figures regarding scenarios are presented in the model report only for subbasin 7, but tables are provided for all subbasins of interest. Most of the irrigation that occurs in the Montana portion of the watershed is upstream of subbasin 7, or uses water from the T & Y diversion that is diverted in the model from the upstream end of subbasin 6 (adjacent to subbasin 7). The relative effects of scenarios tended to be similar across subbasins.

Table 7-1. Scenarios used to evaluate effects of human activities on salt loads.

Scenario	Description
Baseline	Simulates actual conditions between 2005 and 2013 based on initial model calibration and parameterization
CBM Scenario 1: Remove All CBM Discharges in Watershed	Simulates removing all CBM discharges from the watershed for the modeling period.
CBM Scenario 2: Limit All CBM Discharges to the WQ standard	Simulates reducing daily salt loading for any CBM discharge that is above the water quality standard to what it would be at the monthly irrigation season standard, which is 1,000 µS/cm SC and 3.0 SAR units. CBM discharges in the baseline run that already meet the water quality standards remained unchanged.
CBM Scenario 3: Limit Only CBM Direct Discharges to the WQ Standard	Simulates setting only directly discharging CBM wells to the monthly irrigation season water quality standard of 1,000 µS/cm SC and 3.0 SAR. CBM discharges to on and off channel ponds remained unchanged. This is a more likely scenario if CBM activities were to resume to levels that occurred during the model period.
CBM Scenario 4: Change all CBM Discharges to be Direct Discharges	Simulates the effects of having all CBM discharges diverted directly to streams, and not treated or going to on or off channel ponds. It shows the maximum potential impact from CBM development (i.e., more than the baseline conditions) at the production rates during the model period.
Coal Mine Scenario 1: Remove all discharges from Decker coal mines	Simulates removing all East and West Decker discharges as estimated from MPDES permit DMRS.
Coal Mine Scenario 2: Limit Decker discharges to WQ standards	Simulates reducing daily salt loading for all Coal discharge that is above the water quality standard to what it would be at the monthly irrigation season standard, which is 1,000 µS/cm SC and 3.0 SAR units.
Agricultural Scenario 1: Remove All Agricultural Uses in Montana	Simulates converting agricultural land uses to range land and range brush, and removes cattle grazing and irrigation from the management scenario; the T & Y diversion was also removed.
Agricultural Scenario 2: Increase Irrigated Agriculture on Northern Cheyenne Lands	Simulates converting grasslands within the lowest slope category of the Northern Cheyenne Tribal lands to irrigated agriculture, and removes grazing-related management in those lands
Additional Scenario 1: Natural Conditions Remove All Point Discharges and Agriculture	Simulates removing all human activities by removing point discharges for CBM and coal, all discharges related to CBM, and all agricultural activities including removing the T&Y diversion; however the Tongue River Dam remains
Additional Scenario 2: Natural conditions without Tongue River Dam	Simulates removal of all human sources according to additional scenario 1, but also simulates removing the Tongue River Dam.

Table 7-1. Scenarios used to evaluate effects of human activities on salt loads.

Scenario	Description
Additional Scenario 3: Flow Augmentation Increase Flow from the Reservoir	Simulates added flow by increasing the flow from the Tongue River Dam from March through May for a total of 10,000 acre-feet annually added.
Combined scenario 1	Combines multiple scenarios including: removal of CBM s(CBM Scenario 1); , coal discharges at standard (Coal mine Scenario 2); and flow augmentation (additional Scenario 3).
Combined scenario 2	Combines multiple scenarios including: setting CBM direct discharges at standard (CBM scenario 3) ; coal discharges at standard (Coal Mine scenario 2); and flow augmentation (additional Scenario 3).

7.1 Baseline Scenario

The calibrated model was used to develop the baseline scenario. The baseline scenario represents the conditions that existed in the watershed in the 2005-2013 period. The calibration for the baseline results have been discussed already in **Section 6.0**

The baseline scenario resulted in zero monthly exceedances for subbasin 54 near Birney (which is upstream of the impaired sections of the Tongue River) and three to four exceedances of the monthly water quality standard for all other subbasins in the impaired sections. All exceedances occurred during the March to April time period.

Table 7-1. Daily and monthly SC standard exceedances for Baseline scenario

Subbasin	No. Daily Standard Exceedances	No. of Monthly Standard Exceedances	Maximum SC (µS/cm)	Day of Maximum SC
54	0	0	1,072	3/6/2007
30	0	4	1,256	3/15/2013
10	0	3	1,217	3/15/2013
7	0	4	1,215	3/15/2003
2	0	3	1,347	4/16/2013

*Subbasins 2,7,10,and 30 are located in the impaired sections while subbasin 54 is upstream of the impaired sections.

7.2 Coalbed Methane (CBM) Scenario Results

CBM development began in 1999, peaked in 2008, and continued through the end of the modeling period in 2013 (**Section 2.5**). Characterizing CBM impacts in the model enables TMDL allocations to be developed through assessing results of various model scenarios. The following four scenarios were run:

1. *Remove CBM development from the watershed:* This scenario simulates removing all CBM discharges from the watershed for the modeling period.
2. *Limit CBM discharges to the water quality standards:* This scenario reduces daily salt loading for any CBM discharge that is above the monthly average irrigation standard to 1,000 µS/cm SC and 3.0 SAR. CBM discharges in the baseline run that already meet the water quality standards remained unchanged.
3. *Limit Only Direct Discharges to Water Quality Standard:* This scenario simulates CBM discharges that could occur in the future if CBM production increases back to rates that existed during the model period by setting only directly discharging CBM wells to the monthly average irrigation standard of 1,000 µS/cm SC and 3.0 SAR. CBMs that discharge to on and off channel ponds remained unchanged.
4. *All CBM development discharges directly to streams:* This scenario simulates the effects of having all CBM discharges diverted directly to streams. It shows the maximum potential impact from CBM development at the production rates that existed during the model period. (i.e., more than the baseline conditions).

7.2.1 Removal of all CBM Discharges in Watershed

This scenario is designed to estimate the amount of salinity in the Tongue River impaired segment due to CBM discharges.

The few CBM discharges that are within the simulation area (see **Figure 5-1**) are in the most upstream reach and discharge to the Tongue River below the Tongue River Reservoir dam. They are represented as a single point source in the model (file 67p.dat) which was removed in this scenario. Because most CBM discharges in the Tongue River watershed occur outside of the simulation area, development of this scenario also involved removing all CBM flow and salt loads from their respective inlet files including the Tongue River Reservoir in subbasin 67 (file 67i.dat) and Hanging Woman Creek in subbasin 56 (file 56i.dat).

As discussed in **Section 2.5**, the high salinity produced water from CBM gas harvesting is typically discharged directly into a stream or held in a constructed pond that may be considered either “on-channel” or “off-channel”. Based on exploratory scenarios and best professional judgement, it was assumed that 100%, 50%, and 5% of the flow and loads in the discharge monitoring reports are delivered to the stream from direct stream discharges, on-channel ponds, and off-channel ponds, respectively.

Removing CBM flow from this scenario initially caused Hanging Woman Creek to dry up 21% more often compared to the calibration model. However, about half of these newly dry days occur when Hanging Woman Creek flow is already lower than 0.2 cfs. This indicates that that in Hanging Woman Creek CBM discharge contributed to the baseflow during the period when discharges occurred. Additionally, a significant portion of those dry days can be attributed to a lack of knowledge of the exact dates that on-channel ponds overflow (as they are designed to do) and the lag time from both on-channel and off-channel leakage to the ground until it reaches the stream network. For these reasons, removing CBM discharges from the calibrated Hanging Woman timeseries at a daily time step resulted in days with counterintuitive or unexpected scenario concentrations. Therefore, the following assumptions were required to correct these issues. First, when CBM flows were greater than the observed flows in Hanging Woman Creek, the Hanging Woman Creek timeseries was set to zero rather than a negative value because negative values would cause flow and loads to be removed from the Tongue mainstem. Second, when CBM removal caused Hanging Woman flow to be less than 200 m^3/day (0.08 cfs), salt concentrations were artificially high. For example, certain days with low flows and high loads yielded concentrations as high as 11,000 mg/L. Therefore, when flows were less than 200 m^3/day (0.08 cfs) after removing CBM discharges, the salt concentration from the calibrated model on that day was used in this scenario.

A discrepancy that remained after making the two changes just described were instances when CBM discharge was at lower salt concentrations than what was observed in the calibrated model (which includes natural streamflow and CBM flows). No changes were made to the model to account for these periods because the flow from Hanging Woman Creek is relatively small compared to that from the Tongue River Reservoir, and these infrequent time periods had little impact on overall SC/SAR values in the mainstem of the Tongue River downstream.

Removal of all CBM discharges in the watershed reduced daily SC by an average of 4.2% in the example subbasin (subbasin 7) when averaged over the 2005 to 2013 model period. This represents approximately a 31 µS/cm reduction of SC and 0.31 units of SAR (25%). Larger reductions are observed between 2005 and 2010 when CBM discharges were at their peak. This scenario also resulted in eliminating the two exceedances of the SC monthly irrigation season standard that occur under baseline conditions in 2010 in subbasin 7; however, the exceedance of the monthly SC standard in 2013 remains (**Table 7-2; Figure 7-1**).

7.2.2 Limit CBM Discharges to the Water Quality Standard

This scenario simulates full CBM production in both Wyoming and Montana to discharge limits that equal the monthly average irrigation season standard (1,000 µS/cm SC and 3.0 SAR). When past CBM discharge permits issued by Montana had limits of 1,000 µS/cm SC and 3.0 SAR, permittees would reduce Na only until SAR came down to the permit limit of 3.0. By reducing the Na to meet the SAR standard, SC was also reduced to well below 1,000 µS/cm, as low as 265 µS/cm due to high SAR values in the discharge. Therefore, this scenario was developed to match past practices by CBM producers rather than arbitrarily set discharges exactly equal to 1,000 SC and 3.0 SAR. The DMR data was adjusted by similarly reducing Na loading from all CBM discharges until a SAR of 3.0 was achieved, this resulted in SC concentrations below 1,000 µS/cm for many of the CBM sources.

This scenario is designed to estimate the effects of Montana and Wyoming CBM discharges at the highest level of treatment that can be required in Montana. Although the Montana standards are not necessarily applicable to discharges in Wyoming, they were used in this scenario for Wyoming discharges for best case comparative purposes.

This scenario results in the largest reductions in SC among CBM-related scenarios compared to baseline conditions (for example subbasin 7 had a daily average reduction of 5.6% = 42 µS/cm). The reductions in this scenario were greater than the removal of CBM scenario (see **Section 7.2.1**) because it has the benefit of a diluting effect with the CBM flow volumes that had reduced Na loads. SAR was also reduced in this scenario by 0.30 units or 24%. However, this scenario has the same number of monthly irrigation season SC standard exceedances (two in 2013) compared to removing all CBM discharges (**Table 7-2; Figure 7-1**).

7.2.3 Limit Only CBM Direct Discharges to the WQ Standard (Potential Future Scenario)

This scenario involves reducing CBM facilities that directly discharge to the stream network to instream the monthly average irrigation season standard (1,000 µS/cm SC and 3.0 SAR) as was done in the "Limit CBM Discharges to the Water Quality Standard" scenario. However, CBM facilities that discharge to on-channel and off-channel ponds were not reduced to the standard but rather simulated unchanged from the baseline conditions where the baseline model assumed 50% for on-channel and 5% for off-channel delivery of flow and loads to the main channel, respectively.

This scenario treated direct discharges differently than on-channel and off-channel ponds, which is supported based on SC and SAR trend analysis completed for this project. The trend analysis (HydroSolutions 2022) suggested that direct discharges of CBM produced water to the Tongue River had a more immediate and significant impact to SC concentrations in the Tongue River than discharges from on-channel and off-channel ponds. The scenario of only limiting direct discharges is also a scenario that could occur if large-scale CBM activities returned to the Tongue River watershed, because it is similar to the conditions that did occur starting in 2010.

Results of this scenario are similar to those of the previous two scenarios; average daily SC in example subbasin 7 decreases by 21 µS/cm (2.8%) and average daily SAR decreases by 0.15 units (12%) throughout the 2005 to 2013 model period. Similarly, the two exceedances of the monthly irrigation season SC standard that occur in 2013 remain (**Table 7-2; Figure 7-1**).

7.2.4 Convert All CBM to Direct Discharges

This scenario is designed to show the impacts CBM production would have if all permittees discharged directly to the stream, rather than to on-channel or off-channel ponds at the same concentrations and loads used in the baseline model. It should be noted that some CBM discharges remained unchanged in this scenario because they are already discharging directly to the stream under conditions in the baseline scenario.

For example subbasin 7, the results indicate that daily SC increases by an average of 24 µS/cm (3.2%) and daily SAR increases by an average of 0.26 units (21%) . The number of monthly irrigation season SC standard exceedances increases by one compared to baseline conditions (**Table 7-2; Figure 7-1**).

7.2.5 CBM Scenarios Summary

The biggest decreases in monthly exceedances of SC occurred for the scenario that limits CBM to the monthly average irrigation season standard (**Table 7-1**). For this scenario the flow volumes remain from CBM sources, while the average cation concentrations contributing to SC are reduced. The effect of this is a greater reduction in SC for the Tongue River compared to actually removing CBM entirely, which reduces both the amount of salt cations and the volume of water. Not surprisingly, limiting only direct discharges to the standard results in more exceedances than limiting all discharges (including off and on channel ponds) to the standard. And, finally, setting all CBM discharges directly to streams in the watershed instead of off channel or on channel ponds significantly increases the amount of produced water discharged to streams , and illustrates that direct discharges have a much greater impact on the river as compared to off channel and on channel ponds.

Results of the four CBM scenarios indicate that CBM produced water has some effect on salinity concentrations on the impaired section of the Tongue River. However, the effects are not sufficient to remove all the monthly SC exceedances in the Tongue River. As shown in **Figure 7-1** for subbasin 7, the best- and worst-case scenarios of CBM discharges produce noticeable SC changes in the Tongue River, particularly during spring low flow periods when SC concentrations are highest. The CBM discharges do not exhibit seasonal fluctuations and thus have the greatest impact to instream SC concentrations during the Tongue River low flow periods when the percentage of CBM-related flow in the Tongue River is highest.

Although the CBM scenarios (except for the direct discharge of all CBM produced water to streams) reduce the number of exceedances of the monthly average irrigation season SC standard, none of them eliminate all the standard exceedances. Therefore, additional reductions from other sources are needed to meet the monthly SC standards.

Table 7-2. Daily and monthly SC standard exceedances at key subbasins for CBM scenarios .

Subbasin	Scenario	No. of Monthly Standard Exceedances*	Maximum SC (µS/cm)	Day of Maximum SC	% Change in Daily SC
54	Baseline	0	1072	3/6/2007	--
	Removal of CBM	0	1039	2/2/2013	-5.1
	Limit CBM to the Standard	0	1013	1/26/2013	-6.7
	Limit Only Direct CBM to Standard	0	1060	2/2/2013	-3.3
	All CBM As Direct Discharge	0	1103	3/6/2007	+3.9
30	Baseline	4	1256	3/15/2013	--
	Removal of CBM	2	1255	3/15/2013	-4.4
	Limit CBM to the Standard	2	1232	3/15/2013	-5.9
	Limit Only Direct CBM to Standard	3	1260	3/15/2013	-3.0
	All CBM As Direct Discharge	6	1283	3/15/2013	+3.4
10	Baseline	3	1217	3/15/2013	--
	Removal of CBM	2	1215	3/15/2013	-4.3
	Limit CBM to the Standard	2	1194	3/15/2013	-5.8
	Limit Only Direct CBM to Standard	2	1221	3/15/2013	-2.9
	All CBM As Direct Discharge	5	1243	3/15/2013	+3.3
7	Baseline	4	1,215	3/15/2013	--
	Removal of CBM	2	1,213	3/15/2013	-4.2
	Limit CBM to the Standard	2	1,194	3/15/2013	-5.6
	Limit Only Direct CBM to Standard	2	1,219	3/15/2013	-2.8
	All CBM As Direct Discharge	5	1,241	3/15/2013	+3.2
2	Baseline	3	1,347	4/16/2013	--
	Removal of CBM	2	1,350	4/16/2013	-4
	Limit CBM to the Standard	2	1,327	4/16/2013	-5.4

Table 7-2. Daily and monthly SC standard exceedances at key subbasins for CBM scenarios .

Subbasin	Scenario	No. of Monthly Standard Exceedances*	Maximum SC (µS/cm)	Day of Maximum SC	% Change in Daily SC
	Limit Only Direct CBM to Standard	2	1,348	4/16/2013	-2.7
	All CBM As Direct Discharge	6	1,241	4/16/2013	+3.1

*Note: Standard exceedances occurred during the irrigation season (March 2 – October 31) that has a monthly average SC standard of 1,000 (µS/cm) and 1,500 (µS/cm), respectively. No daily exceedances occurred during the model period.

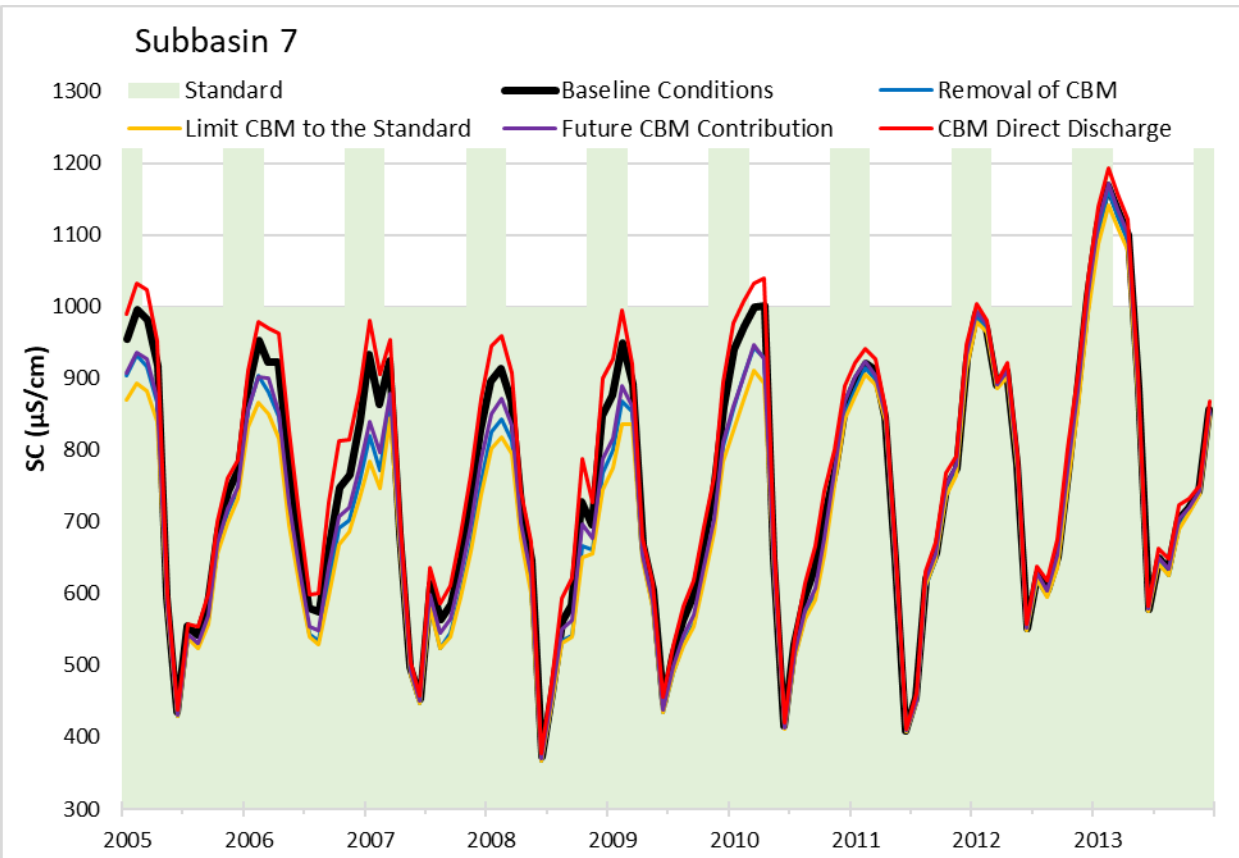


Figure 7-1. Monthly average SC results for CBM scenarios (downstream point of impaired segment – subbasin 7)

The results of the CBM scenarios can be evaluated in relation to a water quality trend analysis study completed for this project (HydroSolutions, 2022; **Appendix D**). The trend analysis was flow-adjusted to remove any trends related to climate fluctuations and resulting changes in salinity concentrations. The study examined SC and SAR trends at three USGS gage locations (Tongue River at State Line nr Decker MT (State Line), Tongue River at Tongue R Dam nr Decker MT (Tongue River dam), and Tongue River at Birney Day School Br nr Birney MT (Birney) from 2000 through 2020.

At the state line gage there was a statistically significant decreasing trend in SAR from 2000 through 2016, but a shorter term statistically significant increasing trend in SC from 2016-2020. CBM discharge water in the watershed is typically very high in SAR (an average SAR of 35.9 was used for Wyoming discharged CBM water in the CBM scenarios based on WDEQ DMR data). However the decreasing trend in SAR was opposite to the trend in CBM activity. This finding suggests that CBM did not have a measurable influence on water quality in the Wyoming portion of the watershed, otherwise a corresponding increasing SAR trend would be expected.

In contrast to the State line gage, the two gages in Montana at the Tongue River dam and Birney showed a statistically significant increasing SAR trend starting in 2004 and ending in 2010 for the Tongue River dam gage and ending in 2012 for the Birney gage. The increasing and decreasing trends correspond well to rise and fall of CBM activity in Montana. The Birney gage also showed a statistically significant increasing SC trend from 2006 through 2016, but the reason for this trend is unclear because it does not correspond to the trend in CBM activity, and a similar SC trend did not occur at the upstream Tongue River Dam gage. It is possible that CBM activity did affect trends in SC during this time; however, these trends were masked by other factors affecting SC. Statistically significant trends can be more difficult to define for water quality data exhibiting small change but high variability. Although CBM discharges in Wyoming were greater than those in Montana, the Montana discharges were primarily via direct discharges to the Tongue River while the Wyoming discharges were primarily from on-channel and off-channel ponds. The different types of discharges may be causing some of the trend variations measured at the State Line gage compared to the two Montana gages.

7.3. Coal Mine Scenario Results

There are four coal mines in the watershed upstream of the Tongue River Reservoir. However, only two of these mines, East Decker and West Decker, actively discharged during the model period. The Decker coal mine has DMR records for the modeling period (**Figure 7-2 to Figure 7-5**), these records were used to modify the baseline boundary conditions of the Tongue River Reservoir inlet file to simulate the following two scenarios:

1. *Remove Decker's discharges from the model:* This scenario simulates removing all Decker discharges from the watershed for the modeling period.
2. *Limit Decker's discharges to the monthly average irrigation season standard:* This scenario reduces all daily salt loading from the coal mine discharge that is above the water quality standard of 1,000 µS/cm SC and 3.0 SAR. Coal mine discharges meeting the water quality standards remained unchanged.

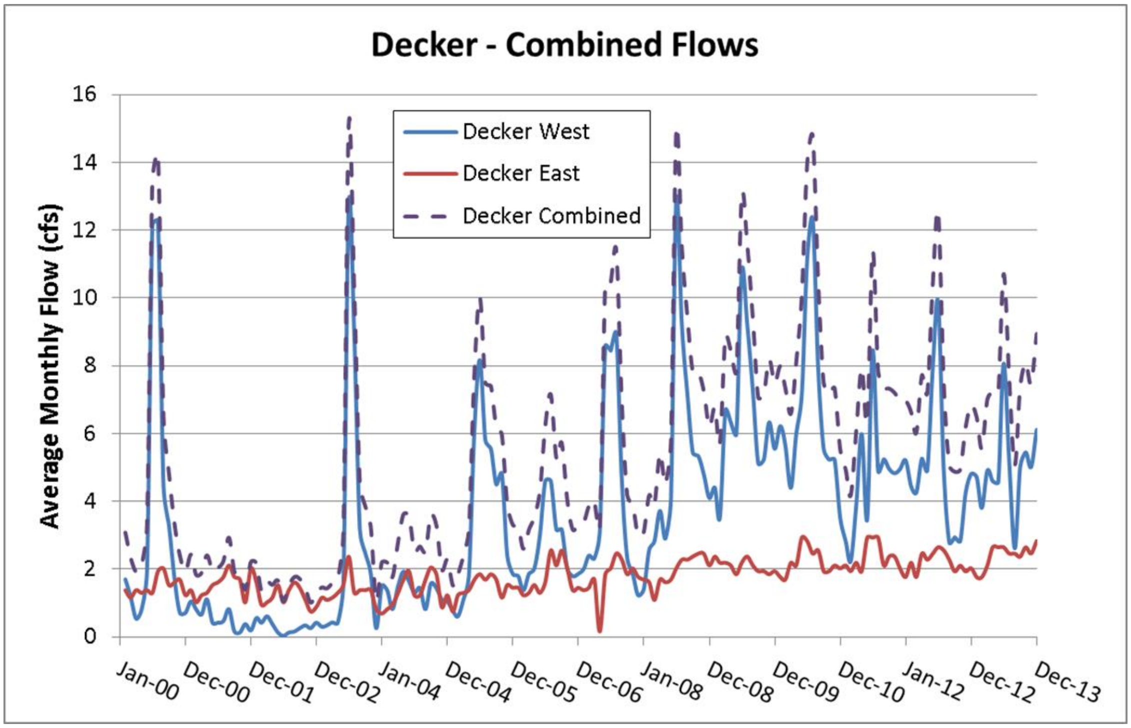


Figure 7-2. Combined Flows for Discharges at Decker West and Decker East before and during the model period.

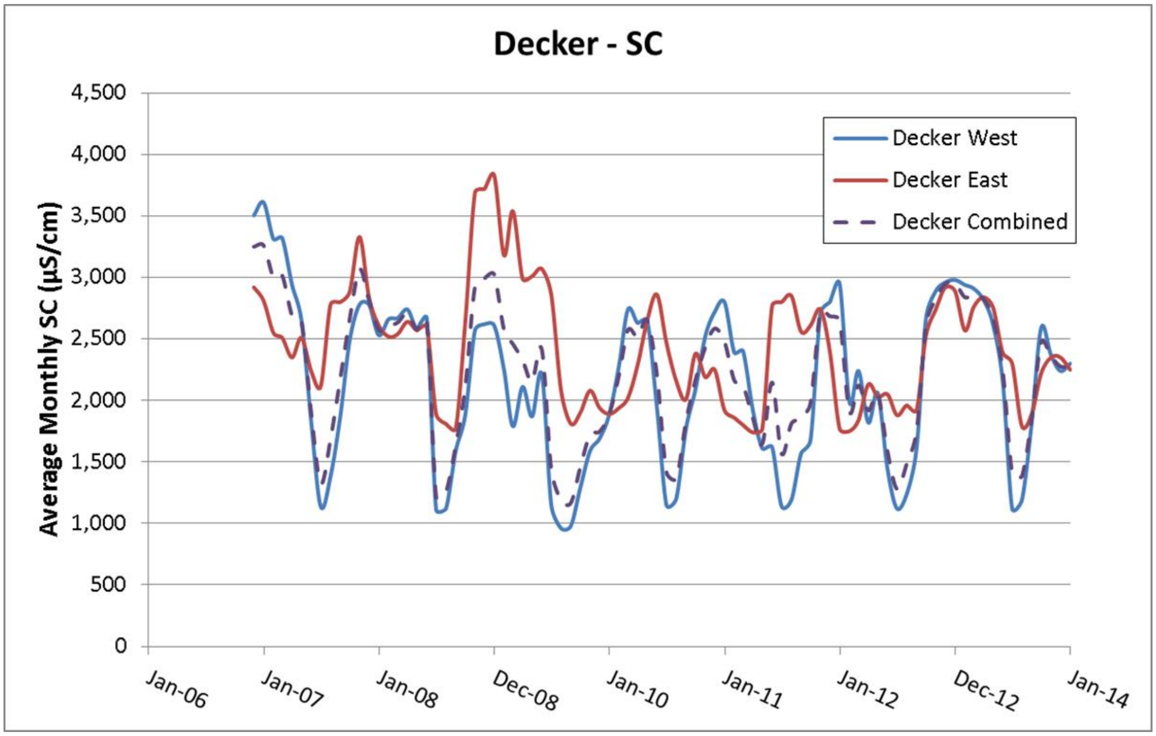


Figure 7-3. SC of Decker West and Decker East discharges during the model period.

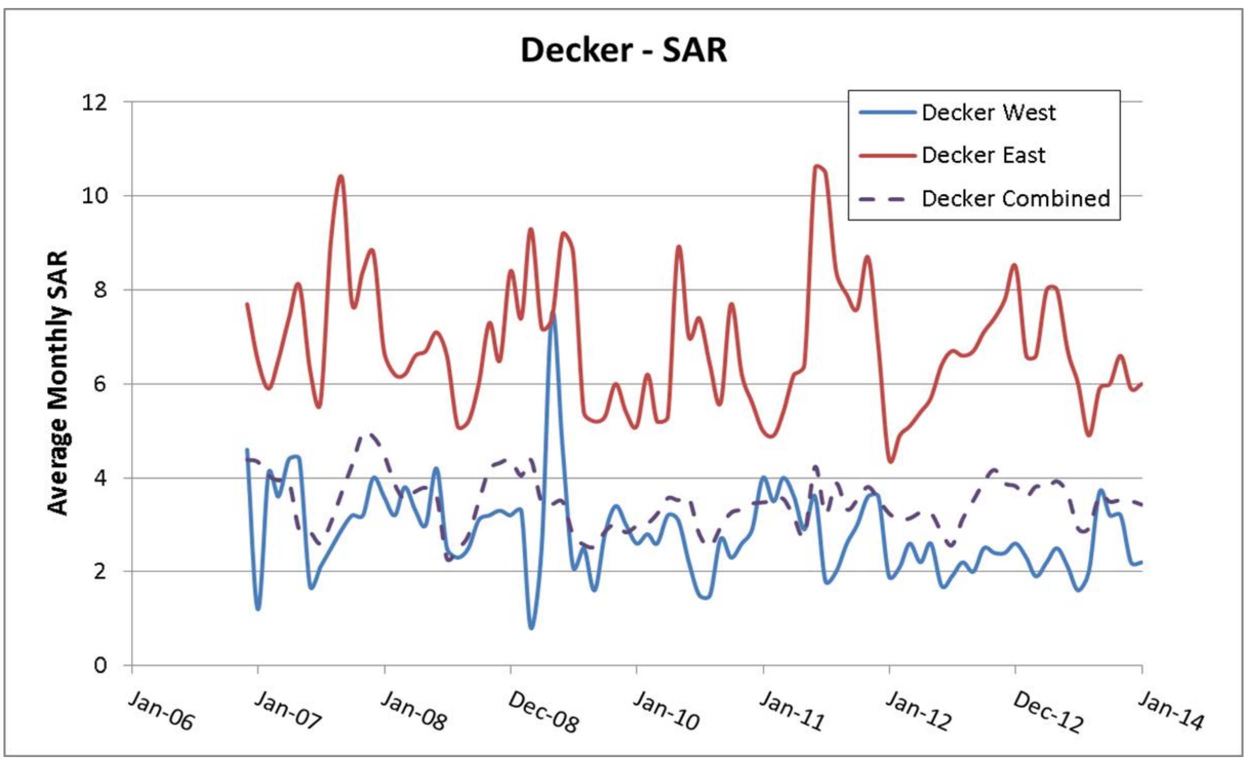


Figure 7-4. Combined SAR of Decker West and Decker East discharges during the model period.

7.3.1 Removal of Decker Coal Mine

This scenario is designed to simulate the amount of salinity in the Tongue River impaired segment due to coal mine discharges.

Development of this scenario involved removing all coal mine flow and salt loads for Decker East and Decker West from the DMR records from the Tongue River Reservoir boundary condition point inlet file in subbasin 67.

Removal of all coal mine discharges in the watershed reduced daily SC by an average of 4.7% in subbasin 7 throughout the 2005 to 2013 model period. This represents approximately a 35 µS/cm reduction of SC and 0.10 units of SAR (8.2%). The largest reductions occur in winter of 2009 and spring of 2010 (**Figure 7-6**). This scenario also resulted in eliminating the two 2010 average irrigation season monthly standard exceedances compared to baseline conditions in subbasin 7; however, the 2013 average irrigation season monthly standard exceedances remain (**Table 7-3**).

7.3.2 Limit Decker Coal Mine Discharges to the Water Quality Standard

The coal mine discharges had significantly lower SAR values than the CBM discharges which affected how the discharge concentrations were altered for this scenario as compared to the similar CBM scenario (**Section 7.2)** Similar to the CBM scenario where discharges were set to the monthly average irrigation season standard, this scenario was developed by reducing Na from some of the coal mine discharges until a SAR of 3.0 was achieved, which resulted in SC concentrations slightly lower than 1,000 µS/cm. As described in the CBM scenarios, this is the treatment practice that permittees would likely employ for discharges with higher SAR values to achieve discharges below their permit limits. For other coal mine discharges where the SAR was near or below the SAR standard of 3.0, reducing the SC to 1,000 was the controlling factor. In those cases, reducing the Na concentration was used to lower the SC to 1,000 which resulted in SAR values below 3.0. However, for those low SAR discharges there is no comparable treatment process that has been implemented by coal mine permittees to copy in the simulation, therefore the process used in this scenario to adjust the SAR and SC values is an approximation of actual treatment methods.

This scenario results in similar reductions in SC (**Figure 7-6**) compared to the "Removal of Decker Coal Mine" scenario with a daily average SC reduction of 3.8% (28 µS/cm). SAR was also reduced in this scenario by 0.08 units (6.7%). This scenario also has the same number of standard exceedances, two, compared to removing all coal mine discharges (Error! Reference source not found. **7-3**).

7.3.3 Coal Mine Scenarios Summary

Results of the two coal mine scenarios indicate that the discharge from coal mines has some effect on salinity concentrations on the impaired section of the Tongue River. Similar to the CBM scenarios, the largest changes in SC seen in the coal mine scenarios occur during spring low flow periods (**Figure 7-6**) when the Tongue River SC concentrations are at their annual high levels. However as shown by the scenario that removed all coal mine discharges, the effects are not sufficient to remove all the monthly SC exceedances in the Tongue River (**Table 7-3**). The scenarios indicate additional reductions from other sources are needed to meet the monthly SC standards.

Table 7-3. Daily and monthly SC standard exceedances at key subbasins for coal scenarios.

Subbasin	Scenario	No. of Monthly Standard Exceedances*	Maximum SC (µS/cm)	Day of Maximum SC	% Change in Avg. Daily SC
54	**Baseline**	0	1072	3/6/2007	--
	Removal of Coal Mines	0	1011	3/6/2007	-5.8
	Limit Coal Mines to Standard	0	1010	3/6/2007	-4.6
30	**Baseline**	4	1256	3/15/2013	--
	Removal of Coal Mines	2	1205	3/15/2007	-5.0
	Limit Coal Mines to Standard	2	1205	3/15/2013	-4.0
10	**Baseline**	3	1217	3/15/2013	--
	Removal of Coal Mines	2	1169	2/26/2013	-4.9
	Limit Coal Mines to Standard	2	1168	3/15/2013	-3.9
7	**Baseline**	4	1194	3/15/2013	--
	Removal of Coal Mines	2	1169	2/26/2013	-4.7
	Limit Coal Mines to Standard	2	1167	3/15/2013	-3.8
2	**Baseline**	3	1347	4/16/2013	--
	Removal of Coal Mines	2	1,98	2/26/2013	-4.5
	Limit Coal Mines to Standard	2	1295	4/16/2013	-3.6

*Note: Standard exceedances occurred during the irrigation season (March 2 – October 31) that has a monthly average SC standard of 1,000 (µS/cm) and 1,500 (µS/cm), respectively. No daily exceedances occurred during the model period.

Error! Reference source not found.**Figure 7-6.** The scenario results are shown at subbasin 7 which is downstream of all coal discharges to the Tongue River and the downstream end of the impaired river segment.

7.4 Agricultural Scenario Results

Agriculture can have a major impact on salinity; in other watersheds with salinity studies, agricultural land uses have had a large anthropogenic impact (Wurbs 2002; Miller et al. 2017) Agriculture increases salinity in two main ways – plants tend to uptake water (but not salt), resulting in higher concentrations of salt when irrigation runoff returns to the river, leaching of salts from the soil as water flows across and through soils, and also by absorption of salts in the soil as the water flows across and through soils.

Two scenarios were developed to explore the impacts that changes in agriculture would have on water quality in the Tongue River watershed:

1. *Removal of all agriculture in the SWAT modeled portion of the watershed:* This scenario converts all agricultural land to rangeland in appropriate HRUs and also removes both grazing and irrigation in those HRUs.

2. *Northern Cheyenne Tribe – Additional Agriculture Scenario:* This scenario converts rangeland to agricultural land with center pivot irrigation within the Northern Cheyenne Tribe land.

Land use in the model was modified in two primary ways to characterize both scenarios. First, the curve number which determines runoff/infiltration ratios from precipitation is unique for each land use. As such, modifying the land use type will therefore change the hydrology of the impacted area. Second, each land use has different concentrations of salts that vary by flow pathway type as described in **Section 6.6**. For example, the Alfalfa/Hay land use has much higher salt concentrations than the Grass/Shrub land use in the surface runoff, lateral flow, and shallow groundwater flow pathways.

7.4.1 Removal of Montana Agricultural

To determine the effects of agriculture, a scenario was run with all agricultural land uses and livestock management removed from the SWAT-modeled portion in Montana. This was achieved by converting agricultural land uses (AGRR and HAY) to range grasses and range brush (RNGE and RNGB) land uses by setting the agricultural HRU fraction (HRU_FR in .mgt1 table) to zero and applying that area to the rangeland HRU fractions consistent with their existing proportions within each subbasin. In total, 19,679 acres were converted to RNGE and RNGB. This scenario also removed all irrigation water withdrawals from the model. Irrigation activities were also eliminated from the model by turning off irrigation for all HRUs (IRRSC = 0) and by removing the T&Y diversion (6p.dat) negative point source from the model. Finally, all cattle related parameters (BIO_MIN, GRZ_DAYS, MANURE_ID, BIO_EAT, BIO_TRMP, and MANURE_KG) were adjusted so that no cattle or grazing impacts were simulated in the watershed. This removal of agriculture and livestock was only done in the modeled portion of the Tongue River watershed. The impacts of agriculture and livestock in Wyoming remain simulated in the model through the Tongue River Dam point inlet file because this contains flow and loading information for the upstream/Wyoming portion of the watershed.

This scenario results in little reduction in SC with monthly average values nearly identical to the baseline conditions (**Figure 7-7**). The daily average SC was reduced by 1 µS/cm (0.1%) and daily average SAR remained unchanged. Despite minimal monthly average reductions overall, this scenario does reduce the number of irrigation season standard exceedances by one compared to the baseline conditions model (**Table 7-4**). This is because in March 2010 under baseline conditions, the monthly average standard is exceeded only by 0.3 µS/cm; which is then reduced to under the standard by removing agriculture/livestock from the model.

SC was minimally impacted by removal of agriculture largely because less than two percent of the SWAT modeled area is cultivated agricultural land (**Table 5-2**).

7.4.2 Northern Cheyenne Tribe Uses Additional Water Rights for Agricultural Activities

The Northern Cheyenne Tribe (NCT) has unused water rights on the Tongue River that entitles them to 20,000 acre-feet of stored water from the Tongue River Reservoir each season. The NCT has never used this water right for irrigated agriculture. Currently, the NCT is leasing out a portion of this water right, but these leases are temporary, and in the future the entire or a portion of the 20,000 acre-feet may be available for agricultural use. Increasing the acreage of irrigated agriculture in the watershed would have an impact on salinity; this scenario was developed to determine the impacts if the NCT used the water right for developing agriculture along the Tongue River.

Simulations such as this with hypothetical anthropogenic land use changes are inherently difficult because there are multiple model inputs that need to be modified based on limited information. For example, the location of the new agricultural land is unknown and the rate and timing of new water releases from the dam to supply new agriculture is unknown. These decisions also depend on climatic patterns during the irrigation season (precipitation and potential evapotranspiration), as well as climatic patterns the previous winter and spring (snowpack). In addition, some dry years may not have enough stored water to accommodate all the new agriculture. For these reasons, this simulation should be viewed as an educated estimate of the magnitude of the potential effects of this scenario.

Based on conversations with NCT staff that approximately 5,000 acres of irrigated land may someday be developed, the following modeling assumptions were made:

- Approximately 5,200 acres were changed from grass rangeland (RNGE) to agricultural land (AGGR and HAY) (**Table 7-4; Figure 7-7**). Sub-basins within the NCT reservation were chosen by converting the grass rangeland with the lowest slopes that was available along the Tongue River. Similar to the “Removal of all Agriculture/Livestock in SWAT Modeled Portion of Watershed” scenario land uses were changed by setting the rangeland HRU fraction (HRU_FR in .mgt1 table) to zero and applying that area to the agricultural HRU fractions consistent with their existing proportions within each subbasin.
- All new agricultural land on the NCT reservation was irrigated with center pivot irrigation (no flood irrigation). Because irrigation is applied when plant water stress exceeds a set threshold, it is impossible to tell in advance how the Tongue River Reservoir releases need to be modified as far as timing and amount goes. Irrigation in the new agricultural HRUs in the NCT reservation was therefore set to be from an "unlimited outside source", which means the model supplies the needed water without removing it from any water source within the model boundaries. This can be done because it is assumed the Tongue River Reservoir will always have sufficient water to irrigate these HRUs and that in practice, the additional amount released will be the same as the amount removed from the adjacent reach for irrigation (therefore under both the model scenario and actual management conditions there would be no impact to streamflow and salinity in the downstream impaired river segments). It was confirmed that the irrigation for these new agricultural HRUs did not exceed the NCT water rights of 20,000 acre-ft/year. From 2005 to 2013, annual irrigation on these HRUs ranged from 8,771 acre-ft to 15,676 acre-ft with an annual average of 11,912 acre-ft.

Table 7-4. Changes from Grass Rangeland Land Use (RNGE) to Agricultural Land Use (AGRR and HAY) within subbasins located on the NCT reservation.

Sub-basin	Slopes (%)	Acres
40	2-5	364
44	2-5	1,211
46	0-2	2,083
48	0-2	310
49	0-2	206
54	0-2	1,007
Total		*5,182*

All of the added agricultural land (5,200 acres) was added between the Tongue River Reservoir dam and the Brandenberg USGS gage (**Figure 5-1**). The added agricultural land nearly doubles the existing agricultural land in this portion of the watershed.

The scenario results are nearly identical to the baseline conditions model in both monthly average SC (Error! Reference source not found. **7-8**) and the number of standard exceedances (**Table 7-5**). This is expected given that a relatively small area (approximately 5,200 acres) was changed to agriculture compared to the previous scenario where 19,679 acres of agriculture was removed from the watershed with minimal impacts on SC.

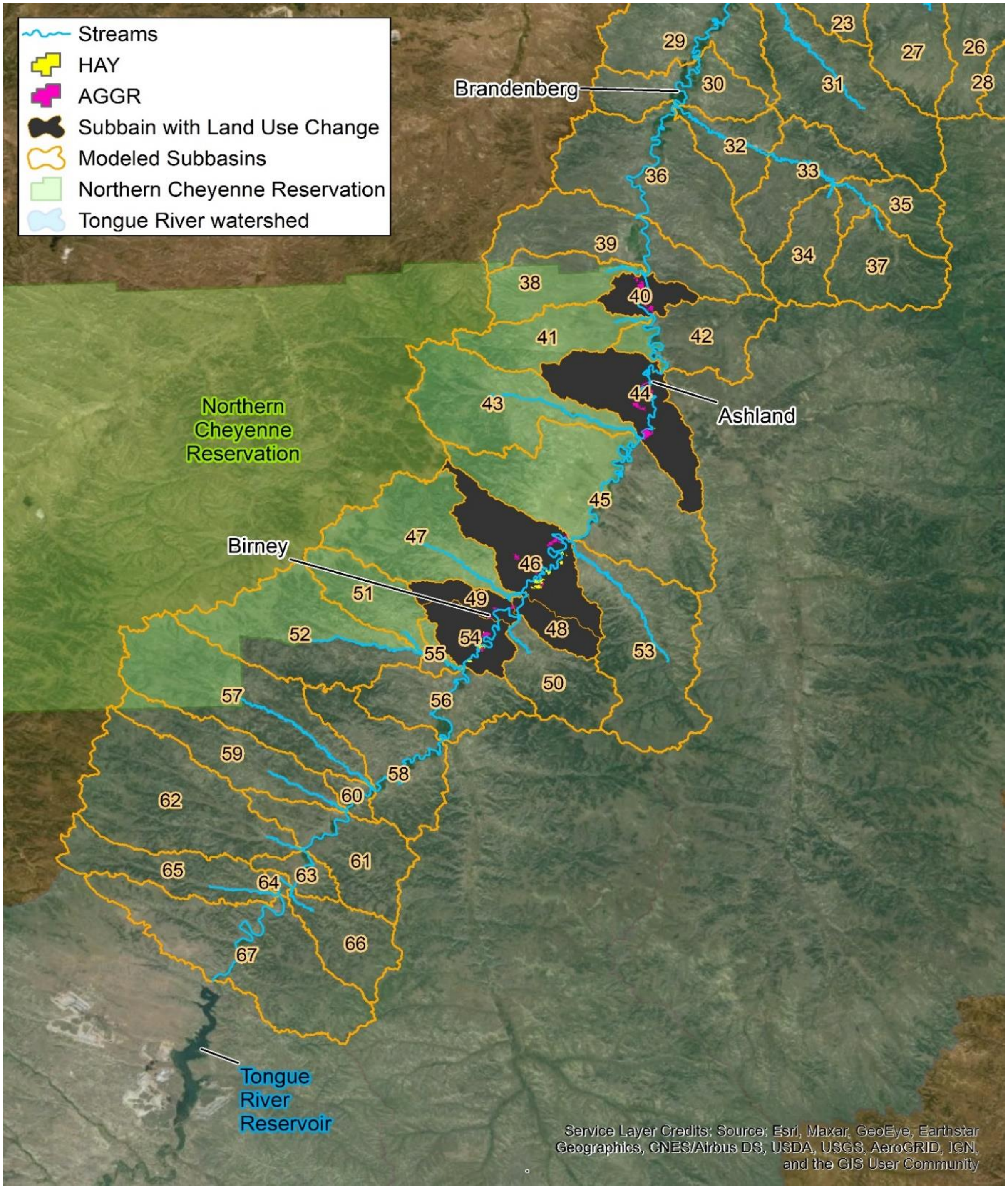


Figure 7-7. Sub-basin locations where agricultural land was added to the model.

7.4.3 Agriculture/Livestock Scenarios Summary

The two scenarios for agriculture/livestock indicate the agriculture and livestock management practices in the watershed do not have a significant impact on salinity concentrations in the Tongue River. These results are different than seen for some other studies (Wurb et al. 2002; Miller et al. 2017), and is primarily due to the limited aerial extent of agriculture/livestock, and the naturally elevated salinity concentrations in this watershed.

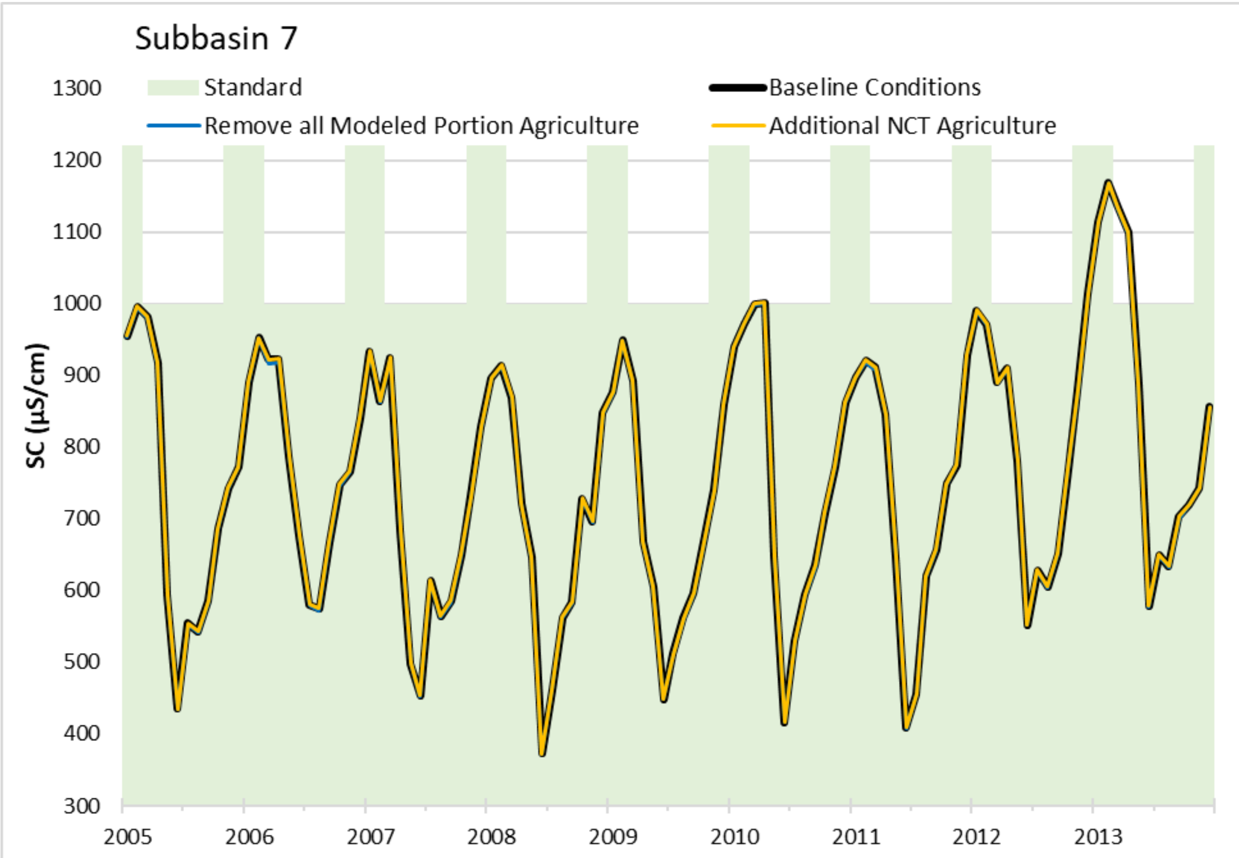


Figure 7-8. Monthly average SC results for agricultural Scenarios (bottom of impaired segment – subbasin 7)

Table 7-5. Daily and monthly SC standard exceedances at key subbasins for agriculture scenarios.

Subbasin	**Scenario**	**No. of Monthly Standard Exceedances***	**Maximum SC (µS/cm)**	**Day of Maximum SC**	**% Change Avg. in Daily SC**
54	**Baseline**	0	1072	3/6/2007	--
	Remove Agriculture	0	1071	3/6/3007	-0.04
	Additional NCT Agriculture	0	1072	3/6/3007	+.007
30	**Baseline**	4	1256	3/15/2013	--
	Remove Agriculture	4	1255	3/15/2013	-0.12
	Additional NCT Agriculture	4	1256	3/15/2013	+.046
10	**Baseline**	3	1217	3/15/2013	--
	Remove Agriculture	3	1214	3/15/2013	-0.14

Table 7-5. Daily and monthly SC standard exceedances at key subbasins for agriculture scenarios.

Subbasin	Scenario	No. of Monthly Standard Exceedances*	Maximum SC (µS/cm)	Day of Maximum SC	% Change Avg. in Daily SC
	Additional NCT Agriculture	3	1217	3/15/2013	+.045
7	**Baseline**	4	1194	3/15/2013	--
	Remove Agriculture	3	1,213	3/15/2013	-0.22
	Additional NCT Agriculture	4	1,216	3/15/2013	+.044
2	**Baseline**	3	1347	4/16/2013	--
	Remove Agriculture	3	1,346	4/16/2013	-0.29
	Additional NCT Agriculture	3	1,347	4/16/2013	+.042

*Note: Standard exceedances occurred during the irrigation season (March 2 – October 31) that has a monthly average SC standard of 1,000 (µS/cm) and 1,500 (µS/cm), respectively. No daily exceedances occurred during the model period.

7.5 ADDITIONAL SCENARIO RESULTS

Two more exploratory scenarios were run to assess SC concentrations under natural watershed conditions, and SC concentrations by augmenting flow from the Tongue River Reservoir.

1. *Natural Conditions:* This scenario removes sources from the model that are associated with anthropogenic influences. This includes removal of all CBM discharges, coal mine discharges, agricultural land uses, irrigation, and grazing. Salt loads from the Tongue River Reservoir were also reduced based on an approximation of how much the Wyoming portion of the watershed is affected by anthropogenic activity.
2. *Natural Conditions with Tongue River Reservoir Dam removed*
3. *Tongue River Reservoir Flow Augmentation:* This scenario increases flow from the Tongue River Reservoir during months in which most SC standard exceedances occurred in the baseline conditions model (March and April).

7.5.1 Natural Conditions with Dam

This scenario removes all sources from the model that are associated with anthropogenic influences while leaving the Tongue River Reservoir Dam. This scenario includes elements of the “Removal of CBM in the Watershed”, “Removal of Decker Coal Mine”, and “Removal of all Agriculture in the SWAT Modeled Portion of the Watershed” scenarios . Withdrawals of water through the T & Y Canal were removed since they were no longer needed for agriculture. Data processing and model set up for these elements are described in **Sections 0, 0, and 0** respectively.

This scenario was conducted to estimate how much of the Tongue River salinity is naturally occurring in the watershed without removing the Tongue River dam. The scenario can be used to evaluate if the SC concentration in the impaired river segment can realistically be reduced to below the SC standard through allocation reductions to point source and non-point source salinity sources.

Three modifications were used to simulate natural conditions. First, CBM and coal mine discharges were removed as was done in CBM Scenario 1 and Coal Mine Scenario 1 (**Table 7-1**). Second, all agriculture from the SWAT modeled portion of the watershed was removed as was done in Agricultural Scenario 1 (**Table 7-1**). Finally, the average percent load reductions from Agricultural Scenario 1 were applied to agricultural land in the watershed upstream of the Tongue River Reservoir to extrapolate these agricultural reductions to the Wyoming portion of the watershed. The Wyoming load reductions were applied to the Tongue River Reservoir boundary condition point inlet file (67i.dat).

This scenario reduced daily SC by an average of 7.8% in example subbasin 7 throughout the 2005 to 2013 model period. This represents approximately a 58 µS/cm reduction of SC and 0.41 units of SAR (33%). Larger reductions are observed between 2005 and 2010 when CBMs and coal mines were discharging greater volumes (**Figure 7-9**). This scenario also resulted in eliminating the two 2010 monthly average irrigation season standard exceedances compared to baseline conditions; however, the 2013 monthly standard exceedances remained (Error! Reference source not found. **7-6**).

The scenario results suggest that salinity levels in the impaired river segment could exceed the SC standards even with all anthropogenic sources removed.

7.5.2 Natural Conditions with Dam Removal

This scenario combines the natural conditions (7.5.1) with removal of the Tongue River Reservoir dam for an estimate of natural conditions before the dam was constructed. Even though Montana law considers longstanding dams to be "Natural", the hydrologic manipulation does affect timing of the hydrograph as well water quality, and this scenario was intended to investigate these impacts. However, DEQ is not recommending removal of the dam nor is that feasible.

The State line gage water quality and flow data was used in place of the Tongue River Reservoir outlet data to complete this simulation. The estimated residence time between the state line gage and the Tongue River dam gage would be less than a day if the dam was not present. Therefore, the state line gage flow and cation loading data was used on same date to replace the existing flow and load data from the Tongue River dam gage. The cation loading data for both gages was estimated using the same LOADEST program. All other inputs to the model were kept the same as the baseline scenario, which includes all sources actually present during the model period.

Removal of the dam changed the hydrology of the Tongue River by creating a more natural hydrograph with lower flows in the later summer rather than in the spring. That change affected the water quality such that all of the SC monthly standard exceedances occurred in August and September, instead of primarily in the spring. A slight decrease in maximum SC was observed and occurred across all subbasins, however, the average SC increased slightly. For instance, subbasin 7 had an 8 uS/cm increase in average SC (1.1%). Whereas SC increased, a 0.3 decrease in average SAR (20%) was observed. This difference in response between SC and SAR is likely due to the higher SAR levels at the Tongue River Dam gage than at the state line gage. The trend analysis results (see **Section 7.2.5**) showed an increasing SAR trend at the Tongue River Dam gage during the modeling period (likely due to Montana CBM discharges) and a decreasing SAR trend at the state line gage.

7.5.2 Tongue River Reservoir Flow Augmentation

The Tongue River Reservoir Flow Augmentation scenario was run to assess the degree that SC can be reduced by diluting stream flow with additional volume in months when the monthly SC standard was exceeded (March and April). This scenario was set up by dividing 10,000 acre-ft/year of flow available evenly across all days of these two months (61 days) resulting in an increase in flow of 202,213 cubic meters per day (82.7 cfs) in the Tongue River Reservoir point inlet file (67i.dat). The concentrations of Ca, Mg, and Na remained the same.

This scenario is dependent on the availability of water rights or modification of dam management that would allow the flexibility to release additional water from the Tongue River Reservoir. DEQ has explored leasing 10,000 acre-ft/year of water from the Northern Cheyenne Tribe (NCT) water right for this purpose, but that lease is no longer a feasible option for DEQ. Modification of dam management with DNRC or other water right holders has not been explored. Despite that, this scenario does provide insight into water management options regardless of the legal source of the additional water.

As expected, results indicate that SC is only decreased in the months of March and April when the Tongue River Reservoir outflow is augmented. In the months of March and April, daily SC was reduced by an average of 2.9%% in subbasin 7 throughout the 2005 to 2013 model period. This represents approximately a 26 µS/cm reduction of SC and a reduction of 0.15 units of SAR (10%). When considered over the entire annual time period, however, this represents a < 1% change in average daily SC (Table 7-4)The largest reductions occur in the spring of 2010 (**Figure 7-9**). This scenario also resulted in eliminating the two 2010 average irrigation monthly SC standard exceedances compared to baseline conditions; however, the 2013 monthly SC standard exceedances remain (**Table 7-6**).

7.5.3 Additional Scenarios Summary

Both the flow augmentation scenario and the natural conditions with the dam scenario reduced SC concentrations and eliminated the 2010 exceedances (**Table 7-6; Figure 7-9**). However, the 2013 exceedances still remain. These results indicate that the water quality standard can not be met in the impaired sections even if all human sources are removed. When the Tongue River dam was removed, the number of SC exceedances increased in some subbasins and shifted to the late summer, and average SC increased. This indicates that SC standards would be exceeded even if the dam was not present. Further, the dam has the primary effect of improving conditions during late summer because flows are higher than they would be if the dam was not present.

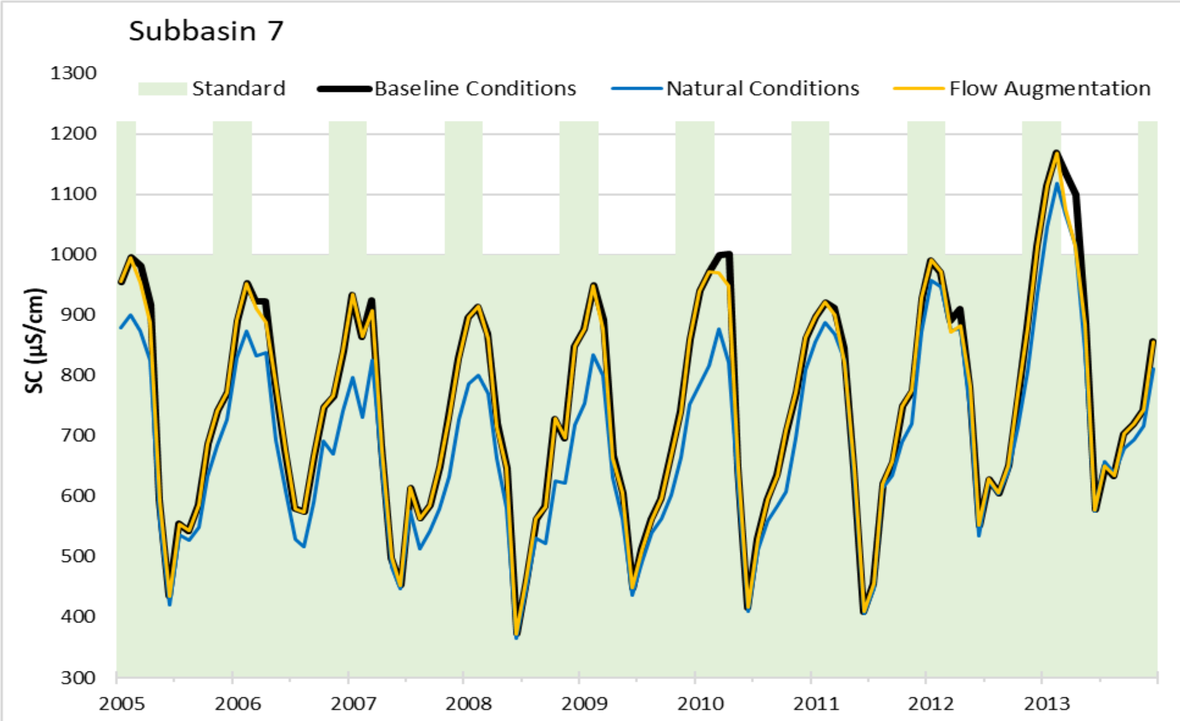


Figure 7-9. Monthly average SC results for additional scenarios (bottom of impaired segment – subbasin 7)

Table 7-6. Monthly SC standard exceedances at key subbasins for combined scenarios.

Subbasin	Scenario	No. of Monthly Standard Exceedances*	Maximum SC (µS/cm)	Day of Maximum SC	% Change Avg. in Daily SC
54	**Baseline**	0	1,072	3/6/2007	--
	Natural Conditions	0	986	3/6/2007	-9.5
	Natural + Remove Dam	0	1,051	9/6/2013	+1.45
	Flow Augmentation	0	1,051	2/2/2013	-1.6
30	**Baseline**	4	1,256	3/15/2013	--
	Natural Conditions	2	1,199	3/15/2013	-8.0
	Natural + Remove Dam	2	1,216	9/8/2013	+0.79
	Flow Augmentation	1	1,205	2/26/2013	-0.78
10	**Baseline**	3	1,217	3/15/2013	--
	Natural Conditions	2	1,163	2/26/2013	-7.8
	Natural + Remove Dam	2	1,158	9/6/2013	+1.07
	Flow Augmentation	2	1,208	2/26/2013	-0.63
7	**Baseline**	4	1,194	3/15/2013	--

Table 7-6. Monthly SC standard exceedances at key subbasins for combined scenarios.

Subbasin	Scenario	No. of Monthly Standard Exceedances*	Maximum SC (µS/cm)	Day of Maximum SC	% Change Avg. in Daily SC
	Natural Conditions	2	1,164	2/26/2013	-7.6
	Natural + Remove Dam	3	1,163	9/6/2013	+1.1
	Flow Augmentation	2	1,208	2/26/2013	-0.6
2	Baseline	3	1,347	4/16/2013	--
	Natural Conditions	2	1,295	4/16/2013	-7.4
	Natural + Remove Dam	3	1,218	8/7/2013	+1.22
	Flow Augmentation	2	1,241	2/26/2013	-0.71

*Note: Standard exceedances occurred during the irrigation season (March 2 – October 31) that has a monthly average SC standard of 1,000 (µS/cm) and 1,500 (µS/cm), respectively. No daily exceedances occurred during the model period.

7.5 Combined Scenario Results

The individual scenarios described in **Section 7.2** through **Section 7.4** demonstrated that salinity reductions from any single industry or land use would not be sufficient to reduce the SC concentrations to below the standard in the impaired river segments. The combined scenarios described in this section were developed to determine if salinity reductions from multiple sources and dam management practices could be combined to reduce the SC concentrations to below the standard in the impaired river segment. The two scenarios are described below. The references to CBM and Coal in these scenarios apply to all sources within the Tongue watershed as was done in the individual scenarios previously described, not just the SWAT-modeled portion of the watershed.

1. *Combined Scenario 1:* This scenario removes all CBM discharges, limits coal discharges to monthly average irrigation standard of 1,000 µS/cm SC and 3.0 SAR, and augments the Tongue River Reservoir flow in the months of March and April.
2. *Combined Scenario 2:* This scenario simulates CBM direct discharges at the monthly average irrigation season standard of 1,000 µS/cm SC and 3.0 SAR and all on-channel and off-channel CBM ponds at baseline condition assumptions. All coal mine discharges are also simulated at instream standards. Finally, the Tongue River Reservoir flow is augmented in the months of March and April.

7.5.1 Combined Scenario 1

This scenario is intended to combine the logistically attainable aspects of the coal and CBM reduction scenarios, but also includes flow augmentation. The scenario assumes that there is no CBM production, which is a possibility considering that discharges are now greatly reduced compared to the peak of CBM development (see **Figure 2-6**). Therefore, components of the “Removal of CBM in the Watershed”, “Limit Decker Coal Mine Discharges to the Standard”, and “Tongue River Reservoir Flow Augmentation” scenarios are combined here. Data processing and model set up for these elements are described in **Sections 0, 7.3.2,** and **7.5.2** respectively.

As expected, compared to previous scenarios, this scenario resulted in the greatest decreases in daily average SC and SAR during the 2005-2013 model period. For example, for subbasin 7, this was a decrease of 64 µS/cm for maximum SC observed (8.4%) and 0.42 units for maximum SAR observed (34%). The greatest decreases occur in winter of 2009 and spring 2010 (**Figure**). Most notably however, the monthly SC standard exceedances at the top of subbasin 7 that occurred in the spring of 2013 were also eliminated resulting in a total of zero standard exceedances for this subbasin (**Table 7-7**). Subbasin 7 is at the most downstream end of the upper impaired segment and generally has the most exceedances of subbasins within the upper impaired segment. However, for this scenario, the monthly SC exceedances in subbasin 30 (which is upstream of subbasin 7) were not eliminated as in subbasin 7, but were reduced from 4 to 1. This scenario also reduces the monthly exceedances in subbasin 2 from 3 to 1.

7.5.2 Combined Scenario 2

This scenario is the same as the Combined Scenario 1 with the exception of CBM discharges being simulated with their potential future contributions at the same production rates used in Scenario 7.2.3; this is a feasible scenario if CBM were to increase again in the watershed. CBM discharges that directly discharge to the stream are simulated at of the monthly average irrigation season standard of 1,000 µS/cm SC and 3.0 SAR and all on-channel and off-channel CBM ponds are simulated at baseline condition assumptions. This scenario still reduces all coal mine discharges to the standard and augments the Tongue River Reservoir flow during March through May. Data processing and model set up for these elements are described in **Sections 7.2.3, 7.3.2,** and **7.5.2** respectively.

This scenario explores the potential SC concentrations under future re-expansion of CBM production. Without any feasible method to estimate future CBM production rates, the measured production rates during the model period were used as a surrogate.

Results of this scenario are similar to those of the Combined Scenario 1 for the example subbasin 7, with decreases in monthly average SC during the 2005-2013 model period of 55 µS/cm SC (7.3%) (**Figure 7-10**) and decreases in monthly average SAR of 0.27 units (22%). The one monthly average irrigation season SC standard exceedance in subbasin 7 occurs in March of 2013 with an average SC of 1,014 µS/cm (**Table 7-7**).

7.5.3 Combined Scenarios Summary

Combined scenario 1, which removes both CBM and coal and adds flow augmentation, does not bring the number of exceedances of the monthly standard down to zero. However, only two exceedances remain (**Table 7-7**). One exceedance remains for subbasin 30 in the upper impaired section, and one exceedance remains for subbasin 2 in the lower impaired section. This scenario greatly reduces SC concentrations and reduces the number of monthly exceedances more than any other scenario in the upper and lower impaired sections.

Combined scenario 2, which is similar to combined scenario 2 but limits CBM direct discharges to standards instead of removing them, results in more exceedances than combined scenario 1. The subbasins within impaired reaches that had zero exceedances in combined scenario 1 now have one exceedance, and exceedances in subbasin 2 increased to two.

If flow augmentation were removed from both these scenarios the SC reductions would be less. For instance, without flow augmentation, the average decrease in SC would be 6.7% as compared to 7.3%

with flow augmentation (**Table 7-7**). The two combined scenarios, in conjunction with the natural condition scenario (see Section 7.5.1), indicate that the monthly SC water quality irrigation season standard cannot be met in the impaired river segments solely through reducing or eliminating anthropogenic sources.

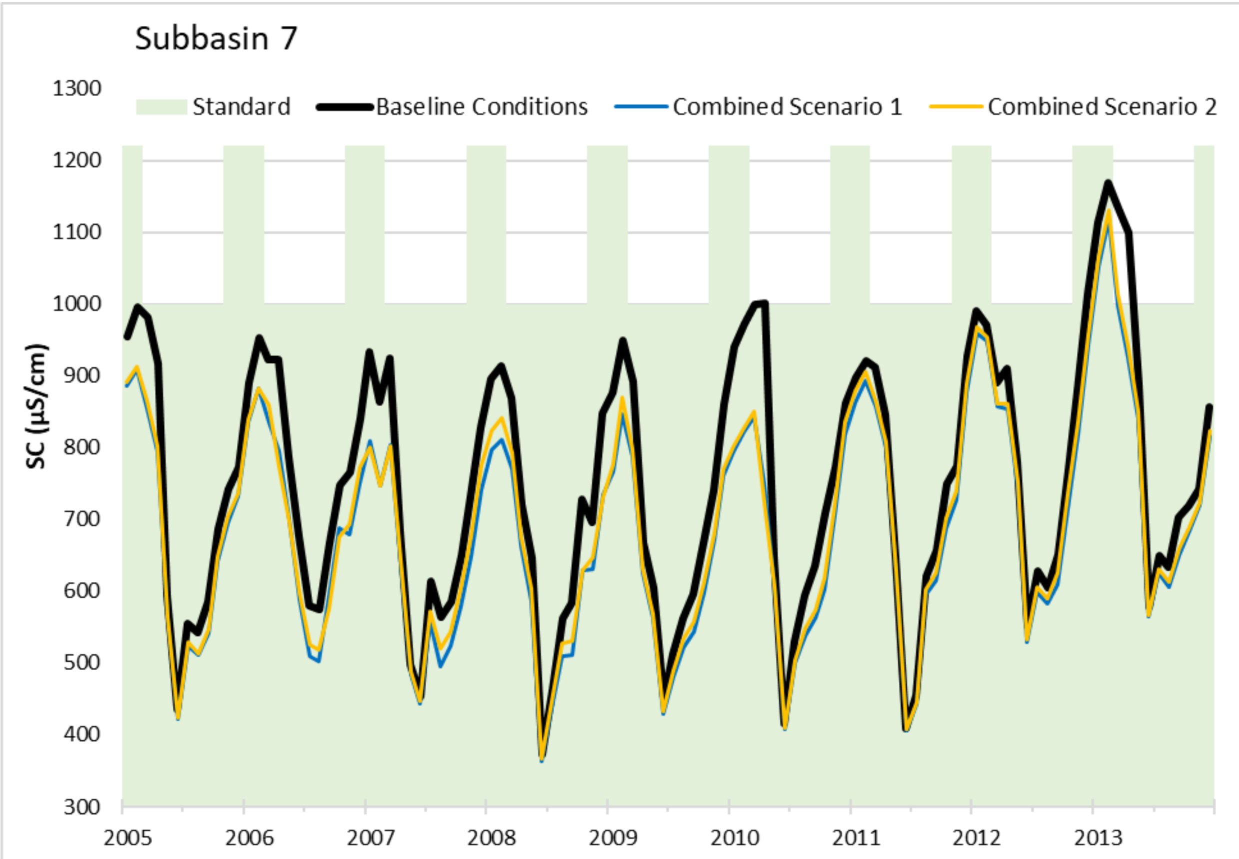


Figure 7-10. Monthly average SC results for Combined Scenarios (bottom of impaired segment – subbasin 7)

Table 7-7. Monthly SC standard exceedances at key subbasins for combined scenarios.

Subbasin	Scenario	No. of Monthly Standard Exceedances*	Maximum SC (µS/cm)	Day of Maximum SC	% Change Avg. in Daily SC
54	**Baseline**	0	1,072	3/6/2007	--
	Combined Scenario 1	0	970	1/26/2013	-9.7
	Combined Scenario 2	0	988	2/2/2013	-8.2
30	**Baseline**	4	1,256	3/15/2013	--
	Combined Scenario 1	1	1,153	2/26/2013	-9.1

Table 7-7. Monthly SC standard exceedances at key subbasins for combined scenarios.

Subbasin	Scenario	No. of Monthly Standard Exceedances*	Maximum SC (µS/cm)	Day of Maximum SC	% Change Avg. in Daily SC
	Combined Scenario 2	1	1,164	2/26/2013	-7.9
10	**Baseline**	3	1,217	3/15/2013	--
	Combined Scenario 1	0	1,156	2/26/2013	-8.7
	Combined Scenario 2	1	1,167	2/26/2013	-7.6
7	**Baseline**	4	1,194	3/15/2013	--
	Combined Scenario 1	0	1,156	2/26/2013	-8.5
	Combined Scenario 2	1	1,167	2/26/2013	-7.3
2	**Baseline**	3	1,347	4/16/2013	--
	Combined Scenario 1	1	1,192	2/26/2013	-8.3
	Combined Scenario 2	2	1,202	2/26/2013	-7.1

*Note: Standard exceedances occurred during the irrigation season (March 2 – October 31) that has a monthly average SC standard of 1,000 (µS/cm) and 1,500 (µS/cm), respectively. No daily exceedances occurred during the model period.

8.0 UNCERTAINTY, STRENGTHS, AND LIMITATIONS

8.1 UNCERTAINTY

Simulation models are approximations of reality. Uncertainty is an inherent component of every modeling process and can never be fully eliminated. The relevant question is not whether a model is uncertain but whether it is sufficiently reliable to address decision questions. This in turn requires an understanding of the sources and magnitude of uncertainty in model outputs relevant to those decision questions (Council for Regulatory Environmental Modeling 2009). Model performance depends on the input data, assumptions, and parameterization used to develop the model. EPA's Council for Regulatory Environmental Modeling divides the sources of model uncertainty into three broad categories, all of which are present in the Tongue River SWATSALT modeling effort (Council for Regulatory Environmental Modeling 2009):

- **Mathematical Formulation** (model framework uncertainty). Real world systems are generally too complex for all aspects to be represented in a mathematical formulation, thus simplified representations are used. The simplifications ideally omit processes that have an insignificant effect on the decision questions; however, uncertainty arises when those neglected factors start to play some detectable roles.
- **Data Uncertainty**. Site-specific data are the basis for developing a water quality model for a specific water body. A water quality model requires data from different sources and for a large number of parameters. Many of these data are subjected to either systematic or random errors. Also, data are always limited in both time and space, thus an interpolation method has to be used to represent continuous inputs. In most cases, monitoring data are not available for all the water quality parameters; thus, they have to be derived based on some empirical method. All these can contribute to uncertainty in the model.
- **Parameter Specification** (model application uncertainty). In a water quality model, parameters quantify the relationships in the major dynamic processes. The values of parameters are generally obtained through the model calibration process while constrained by a range of reasonable values documented in literature. Due to the sparseness and uncertainty in data used to configure and calibrate a water quality model, the model parameter selection is also subjected to uncertainty.

The following describes some of these sources of uncertainty pertaining to the Tongue River SWATSALT modeling effort; however, uncertainty is not limited to these sources.

8.1.1 Mathematical Formulation

- Salt Storage
    - Salt storage in soil is represented in a simplified manner. As irrigation water is applied to a field, salt in the applied water can wash off, build up in the soil, or be flushed through the soil column to re-emerge with interflow and groundwater discharge to the receiving water. SWATSalt does not represent these processes on a mass balance basis. Instead, concentrations of salt in surface and subsurface discharges are user-assigned based on monitoring studies and can be adjusted within reasonable limits during the calibration process. In addition to the uncertainty inherent in applying limited, field-scale studies to

entire classes of land use, cumulative changes over time cannot be represented in this approach.
    - Salt storage also occurs within stream channel sediment, represented in the model through the process of bank storage. Tetra Tech modified the SWATSalt code to account for the effects of bank storage on the salt mass balance, but there will be some uncertainty in simulating the rate of salt storage in the bank soils and the release back into the river over time.
    - SWATSalt includes a simplifying assumption that salts are conserved in the water column, meaning that they do not precipitate out of the water column (e.g., salts lining the sides of a pond after the water dries up). Salts are only removed from the SWATSalt modeled reaches when water is also removed due to irrigation diversions or temporary bank storage. This approach likely over-estimates salt loads during dry times of the year, but averages out over longer time periods.
- Flow paths and hydrology
    - Generation of cations in the SWATSalt model is performed for HRUs using a simple event mean concentration (EMC), which is the average concentration in runoff from various land uses multiplied by runoff volume (with appropriate conversions) to create a mass loading to the water column. One of the simplifications used in SWATSalt is that water does not retain its mass loading of salt when moving between water pathways within a sub-basin. For example, if surface runoff pools in a small depression and slowly infiltrates to groundwater, it would lose its EMCs and mass loading attributed to surface water, and instantly assume the EMCs and mass loading associated with groundwater (usually much higher). This primarily affects the flow from surface to interflow to groundwater. Due to the long travel times and large volumes associated with groundwater, it is unlikely this assumption introduces significant errors into the salinity modeling.
    - The model performance for hydrology and salts is generally within the acceptable range of errors for watershed models. The model in its current state is well-suited for evaluation of salt load reduction scenarios. However, as with many models, there are uncertainties associated with the model's simulation of watershed hydrology and salt loads, and these uncertainties may propagate to the load reduction scenarios.

8.1.2 Data Uncertainty

- Snow Water Equivalent (SWE)
    - SWE is not a direct input to the model but is calculated based on available data related to elevation, precipitation, and temperature. Less-detailed spatial resolution of these inputs affects estimates of accumulation and estimates of streamflow. However, the calibration indicated that estimates of streamflow for the Tongue model were highly accurate. The lack of SNOTEL sites within the modeled portion of the watershed limited calibration of the SWE. However, the snowpack in the modeled portion of the watershed is generally low which limits the level of uncertainty.
- CBM Discharges
    - The method for modeling CBM discharges is also coarse due to the uncertainty on how the volume and quality of water discharged to on-channel and off-channel ponds changes as it migrates to the river network. The water quality of these ponds was also estimated because data was not available. The storage of salt in ponds and the subsequent delivery of salt to the receiving water via seepage and runoff during large

runoff events is also estimated in the model. Additional data on pond discharges and how the volume and quality change as discharges migrate towards the river network would help to better parameterize actual discharge loads to the river network. However the model results are consistent with the water quality trend analysis which showed a low contribution of CBM to SC concentrations, but a higher contribution to SAR (HydroSolutions 2022; **Appendix D**). The model results are also consistent with a previous model regarding the impacts of CBM discharges (EPA, 2007a).

  - Many of the CBM discharges in the watershed are outside the SWAT modeled area and are therefore included within the boundary conditions using other methods. As described in **Section 7.2**, the portion of the boundary condition loads associated with CBM was estimated to facilitate several scenarios. As a result, there is some uncertainty associated with the exact impact of CBM.
  - Direct discharges of produced water to the Tongue River have only minor uncertainty associated with the monthly monitoring schedule that is used to inform daily loading values.
- LOADEST estimates for tributaries and Tongue River Dam
  - The major tributaries downstream of the dam are specified as boundary conditions where flow is based on observed data and salt loads are based on LOADEST regressions, which provided better results for Ca and Mg than for Na. Visually, the model performs well for Ca and Mg but has more difficulty matching the observed Na concentrations, particularly during the low flow periods of early spring from 2009 to 2011. The higher Na errors may be a relic of errors in the LOADEST results used to inform observed flows from the Tongue River Reservoir and three tributaries or it may be due to model parameterization.
- Irrigation for tributaries
  - For the SWAT model, the major tributaries (Hanging Woman, Otter, and Pumpkin) were not explicitly part of the calibration area, and changes to tributary irrigation practices did not play a significant role in modeling scenarios. Previous salinity modeling that focused on the Otter Creek watershed (DEQ, 2015) concluded that the tributary irrigation had a small impact on salinity loads and concentrations within Otter Creek. Irrigation in the remaining minor tributaries, such as Foster Creek and Beaver Creek, within the calibration area was assumed to happen similar to that along the mainstem. This represents a small and insignificant source of modeling error since the amount of irrigated land along the minor tributaries is minor compared to the total irrigated acreage along the Tongue River.
- SC approximation
  - A regression relationship between measured cation concentrations and SC from grab samples (**Section 6.5.4**) was first established for three location in the watershed. Next, this regression relationship was applied to the daily estimated cation concentrations from the model to calculate simulated SC. Because the regression approximates this relationship and the model estimates cation concentrations, these two components of calculating SC may lead to compounding uncertainty in the simulation of SC.
- Data gaps
  - Calibration data at USGS gages was not available for all time periods of the model.

8.1.3 Parameter Specification

- PET
    - Because there are no PET stations located in or near the watershed. PET was estimated using observed climate data at Miles City and Sheridan. PET was calculated internally by the model using the Penman-Monteith method. Calculated PET was consistent with PET estimates from Miles City and Sheridan, but is still a potential source of model uncertainty and error.

- Management Scenarios
    - The parameterization of management scenarios was based on county level and interviews from stakeholders. However, assumptions were made that may affect model outcomes regarding inputs from agriculture.

8.2 STRENGTHS

As previously introduced in **Section 1.0**, the two principal study questions to be addressed by the Tongue River SWATSalt modeling effort are the following:

1) What are the baseline flow and salinity conditions in the watershed, including the relative contributions of nonpoint and point sources?
2) What sources can be reduced to achieve reductions in in-stream salinity, and what are the best methods to achieve those reductions?

The combination of simulating both flow and concentrations resulted in an accurate simulation of loads and the ability to determine the primary sources of salts within the watershed as a function of the model configuration (e.g., boundary conditions and the land uses within the SWAT modeled portion of the watershed).

The model simulates the hydrology of the watershed well (**Section 6.5.2**), both for total streamflow (much of which is based on observed flows from the Tongue River Reservoir and three tributaries) and for incremental flow (which is based on model output). The model therefore provides useful information about the sources and pathways of flow within the watershed, which are directly linked to the sources of pollutants. Simulating streamflow also benefits the simulation of salt concentrations since dilution is the major instream process affecting salt loading.

Simulated concentrations for most calibration stations (**Sections 6.5.3 and 6.5.4**) had high performance compared to actual concentrations during both high and low flow periods throughout the model period, which helps have confidence that the model adequately captures the relative effects of CBM and mining on salt loads.

8.3 LIMITATIONS

The performance of a simulation model and its associated uncertainty can be evaluated in two general ways: 1) by comparison of model output to observations and 2) by evaluating the propagation of uncertainty in model formulation and inputs. Comparison of model output to observations provide a direct measure of uncertainty; however, such comparisons are most applicable to the conditions under the range which the model was calibrated and may not apply to model scenarios where those conditions are changed. The evaluation criteria indicate that the model performed well when compared to observations (**Section 6.5**). However, the evaluation was only based on the calibration period because enough data was not available to do a separate, more rigorous evaluation using a separate validation dataset.

The model performs better at the reaches located father upstream. For instance, the simulation of SC (which is based on individual ion concentrations) at the T&Y Diversion Dam (located near the downstream end of the impaired river segment) is "very good" based on the model performance criteria, but the simulation for Miles City SC is only "good". Similarly, the simulation for SAR is very good for T & Y Dam but only "Fair" for Miles City section. The figures in **Appendix H** illustrate the inability of the simulation to capture some of the peaks in SC and SAR, particularly for the Miles City section. The high performance of the model for the more upstream sections including Birney and T & Y indicate that the model is adequately capturing the impacts of coal and CBM activity, which is upstream of these sections. The uncertainty farther downstream may be due to the model not capturing the more complex hydrology and soils, as well as impacts of water withdrawals and irrigation. Due to the poorer performance in the Miles City reach, the model results for this section may not be as suitable to be used in management decisions without further re-examination or re-calibration.

Although not a limitation of the model itself, several of the scenarios result in estimated SC values that are extremely close to the numeric criteria. For example, there are instances when the monthly average baseline SC value is only 1 to 2 percent higher than 1,000 µS/cm (the criterion) and the Combined Scenario 1 and Combined Scenario 2 results are 1 to 2 percent less than 1,000 µS/cm. The uncertainty of the model results are outside that narrow of a range. This places an extra burden on decision makers compared to a situation where the results are more clearly above or below the thresholds, particularly considering the Margin of Safety that is required by law if a TMDL is developed (U. S. EPA 1991). This is why any decisions made using model outcomes should be made using a weight-of-evidence approach. To minimize the uncertainties associated with the reported load reductions from management scenarios it is recommended that output is evaluated and reported as relative change in addition to the absolute change in salt loads. Furthermore, the model is more likely to be reliable when evaluating output at the monthly rather than the daily scale given the inability of this and other watershed models to resolve hydrology and salt loading at the daily time step (Baily 2019).

Finally, another limitation of the model is that it was developed for years, 2006-2013, and does not extend into present day. Missing flow data and/or water quality data for more recent years would make it difficult to extend the model with an adequate calibration dataset to evaluate model performance. However, measured data available for more recent time periods supports the outcome of the model that current water quality standards cannot be met. The model can still be used to describe relative contribution of human caused sources if a TMDL were to be developed, or to inform any revision of standards.

The current application of the model meets DEQ requirements for assessing the impact of difference sources on salinity concentrations in the watershed and as a *relative gage of system response to various management practices*, rather than an absolute loading model. The model should be used in combination with other information (e.g., results of the trend analysis study) in a weight-of-evidence approach to support decision making and potential TMDL development. Additionally, continued management of the watershed should be based on an adaptive management approach where ongoing monitoring informs decisions about how best to maintain and improve water quality.

9.0 CONCLUSIONS

A SWAT modeling approach "SWATSalt" was developed for the Montana portion of the Tongue River to identify the contribution of different source categories to salt loading, and to assess potential management scenarios that could be implemented to meet water quality standards for agricultural beneficial uses. Most exceedances occur during the irrigation season from March 2 – October 31, when monthly average standards for SC (specific conductivity) and SAR (sodium absorption ratio) are 1,000 µS/cm and 3 units. The SWATsalt model used topography, climate, soil, land cover, land use, and management data to determine a wide range of hydrologic and water quality outputs through physical equations and laws. The model simulated individual magnesium, calcium, and sodium cations for reaches within 67 subbasins extending from the Tongue River Reservoir to the confluence with the Yellowstone River at Miles City. Regression equations were used to predict SC and SAR from these modeled ions for the reaches of interest, which spanned two impaired segments of the river. Model simulations were completed on a daily time step and average SC and SAR and loads were calculated for both a daily and monthly time step. Other methods, including LOADEST.

The calibrated watershed model met nearly all of the pre-determined error analysis requirements. Performance of the model was highest for more upstream sections, including the upper impaired section near T & Y dam. Performance decreased for the downstream impaired section near Miles City, likely due to the more complex soils and hydrology not being accounted for in the model. During the model period, neither daily SC or SAR standards were exceeded and only one monthly exceedance of SAR occurred for one reach. In addition, because the model is not designed to accurately model salts at a daily time step, the model report focused primarily on the results for monthly SC. Results indicate that scenarios to reduce or completely eliminate human sources including Coalbed Methane, coal, and agriculture decreased the number of monthly standard exceedances but did not completely eliminate them. Augmenting the flow of the Tongue River by increasing the flow from the dam during the irrigation season further decreased the number of exceedances, but there was always at least one exceedance of the monthly water quality standard for SC. The overall conclusion is that while human sources contribute significantly to salinity, much of the salinity on the Tongue River is natural and water quality standards for salinity cannot be met even if all of these sources are removed. Additional watershed management changes are likely needed to either reduce the salinity levels below water quality standards or to reduce the effect of existing salinity levels on land uses within the watershed. These findings should be considered in any future TMDL or other planning efforts.

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