Model Documentation Report for the Lake Hennessey and Milliken Reservoir Watershed Study

A Deliverable

to

Napa County and the City of Napa

Prepared by

Joel Herr and Scott Sheeder
Systech Water Resources, Inc.
Walnut Creek, CA 94596

March 2019

TABLE OF CONTENTS

List of Figures

List of Tables

1 MODEL DOCUMENTATION

INTRODUCTION

Background

Lake Hennessey and Milliken Reservoirs in Napa County, California provide water supply for the city of Napa. Lake Hennessey stores 31,000 acre-feet of water in the hills 5 miles east of St. Helena near the northern end of the Napa Valley. Milliken Reservoir, located 6 miles northeast of the City of Napa, has a capacity of 1,390 acre-feet. The City of Napa operates water treatment plants which treat water from each of these reservoirs. Maintaining high source water quality is of vital concern to the City of Napa to provide its customers with high quality water while minimizing treatment cost.

The watersheds of Lake Hennessey and Milliken Reservoir are primarily rural, but include rural residential development, discharge from the town of Angwin's regulated wastewater treatment plant, and an increasing number of vineyard developments. From 2008-2016, the measured nitrogen concentration in Lake Hennessey trended higher. This is of concern because higher nutrient concentrations promote the growth of phytoplankton in the reservoirs which can lead to taste and odor problems in drinking water and higher treatment costs. The City of Napa needs to learn about the effects of land use change in the watersheds on water quality in the reservoirs. With this knowledge the city can better participate in land use decisions in the watersheds of its reservoirs.

Modeling Objective

The City of Napa and Napa County need a tool which can be used for many purposes going forward. Among these are analyzing the impact of land use change and climate change. The model must include inputs, processes, and outputs in order to achieve these objectives. The model should be transparent and have a graphical user interface (GUI) which facilitates the use of the model and the interpretation of its results.

The primary objective of modeling is to identify the sources of pollutant loading to Lake Hennessey and Milliken Reservoir. Although simulating the creeks entering the reservoirs is part of that process, water quality in the creeks themselves is not the primary interest. While concentrations of pollutants may be higher in the creeks and more impactful upon them under low flow conditions, this may contribute much less loading to the reservoirs than lower concentrations under high flow conditions. Thus, the modeling priority is to focus on higher flow conditions.

WARMF WATERSHED MODEL

About WARMF

The Watershed Analysis Risk Management Framework (WARMF) was selected to model the Lake Hennessey and Milliken Reservoir watersheds. WARMF is a comprehensive physically based model which simulates the hydrologic, chemical, and physical processes which occur on land and in surface water. It has a user-friendly (GUI) which allows users to access model inputs and outputs by point-and-click on a map. It has a complete and recently updated User's Guide (Sheeder & Herr, 2017), Technical Documentation (Systech Water Resources, 2017), and an online context-sensitive help system at www.warmf.com.

A watershed is divided into catchments, river segments, and reservoirs. Each catchment is divided into many land uses and up to 5 soil layers. The watershed is defined by characteristics such as river slope, reservoir bathymetry, catchment area, slope and aspect. Soils are defined by thickness of each horizon, field capacity, porosity, and hydraulic conductivity. All catchments, river segments and reservoirs are connected by flow paths into one seamless model.

The model is driven by meteorology, air & rain chemistry, point sources, and managed flows. Hydrologic processes simulated include rainfall, snowfall, snow melt, evaporation, transpiration, infiltration, subsurface flow, surface runoff, and kinematic wave routing in rivers. Chemical processes include atmospheric deposition, nutrient cycling through vegetation, adsorption/desorption, chemical reactions, sediment transport, and phytoplankton growth.

All of the model's input data, coefficients, and simulation results can be accessed through the WARMF GUI by point and click on a map. A scenario manager lets the user keep track of multiple input scenarios and the resulting model outputs. WARMF has several forms of model output including classic time series graphs, loading output tracking loading back to individual catchments and land uses, flux output, longitudinal output, and Gowdy Output identifying the loading sources at a location in the river on any day of the simulation.

Model Setup

WARMF catchments and rivers were delineated using the EPA BASINS software. Descriptions of the software and its capabilities are available through the EPA BASINS website (https://www.epa.gov/ceam/better-assessment-science-integrating-point-and-non-point-sources-basins), and a document describing the use of the software for preparation of WARMF catchments and river segments is provided along with the WARMF models (WARMFSetupWithBASINS4_v6_2.pdf). BASINS 4.1 is the latest version of a comprehensive framework for obtaining datasets for watershed analysis, analyzing the data with several tools and preparing the datasets for use in different water quality models.

A digital elevation dataset provides the foundation for delineation of watersheds and river networks within the BASINS software environment. For the Lake Hennessey and Milliken Reservoir WARMF models, the threshold for stream network delineation was set so that the resulting stream network depicted all perennial streams within the watershed, and the resulting level of detail was sufficient to capture the spatial variability of land use within the watershed. The catchment delineation was further modified so that catchment pour points (point on the land surface at which water flows out of the catchment) exist at all historical hydrologic and water quality monitoring locations. Co-locating hydrologic and water quality measurement sites with model catchment pour points facilitates model calibration because model output is reported at each of the catchment pour points.

The WARMF catchment and river delineations for the Lake Hennessey and Milliken reservoir watersheds are illustrated in Figure 1.1 and Figure 1.2. The Lake Hennessey watershed delineation resulted in creation of 63 catchments, ranging in area from 53 to 1870 acres. The river network is comprised of 66 river segments. The Milliken Reservoir watershed delineation resulted in creation of 30 catchments, ranging in area from 14 to 750 acres. The river network is comprised of 26 river segments.

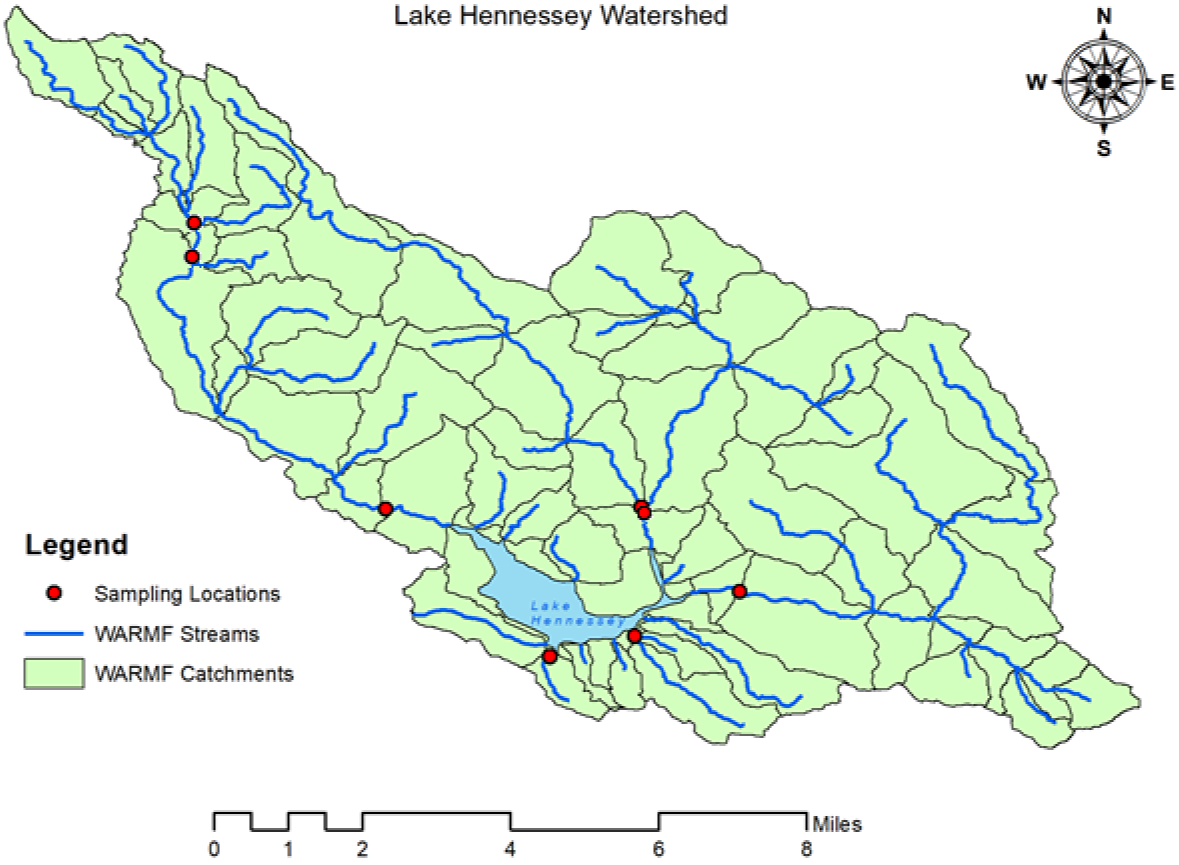


Figure 1.1 WARMF catchment and river delineations for the Lake Hennessey watershed

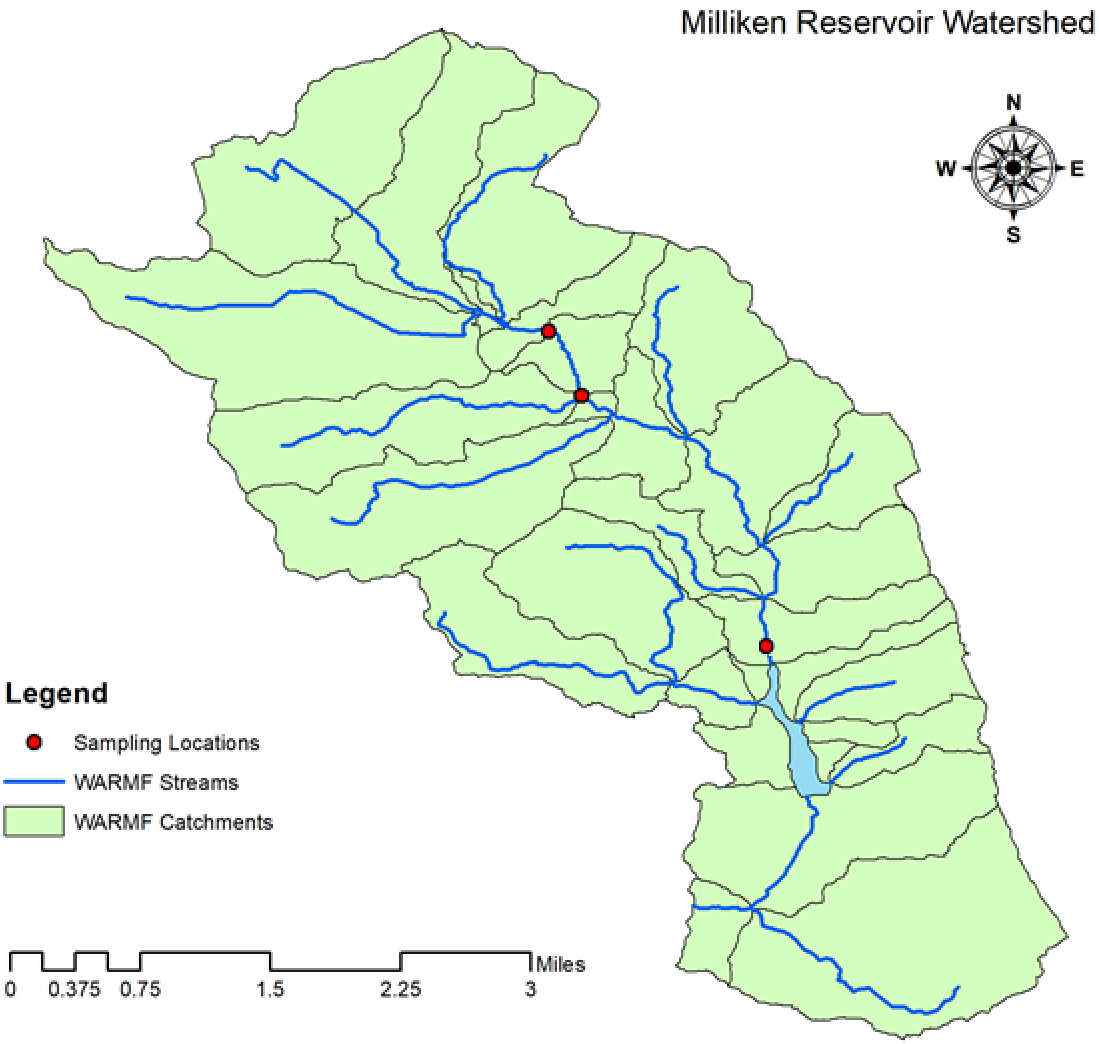


Figure 1.2 WARMF catchment and river delineations for the Milliken Reservoir watershed

Hydrologic Simulation

WARMF simulates hydrology based on water balance and physics of flow. It begins with precipitation on the land surface. Precipitation and irrigation water can percolate into the soil. Within the soil, water first goes to increase the moisture in each soil layer up to field capacity. Above field capacity, water percolates down to the water table, where it flows laterally out of the land catchment according to Darcy's Law. Water on the soil or within the soil is subject to evapotranspiration, which is calculated based on temperature, humidity, and season. The amount of water entering and leaving each soil layer is tracked. If more water enters the soil than leaves it, the water table rises. If the water table reaches the surface, the soil is saturated and overland flow occurs. Manning's equation is used to calculate the overland flow.

Rivers accept the subsurface and overland flow from catchments linked to them. They also receive point source discharges and flow from upstream river segments. Diversion flows are removed from river segments. The remaining water in the river is routed downstream using the kinematic wave algorithm. The channel geometry, Manning's roughness coefficient, and bed slope are used to calculate depth, velocity, and flow. The velocity is a measure of the travel time down the river, which in turn affects the water quality simulation. A thorough description of the processes simulated by WARMF is in the WARMF Technical Documentation (Systech Water Resources, 2017)

Water Quality Simulation

The fundamental principle which guides WARMF simulation of water quality is heat and mass balance. Heat enters the soil in water from precipitation and irrigation. Heat is exchanged between catchments and the atmosphere based on the thermal conductivity of the soil. Heat in water leaving the catchments enters river segments, which combine the heat from multiple sources. Within river segments, there is thermal exchange with the atmosphere based on the difference in temperature between the water and the air, incoming short-wave radiation and long-wave back radiation. Temperature is then calculated by heat balance throughout the model.

Chemical constituents enter the model domain from atmospheric deposition and from point source discharges. They can also enter the model domain in irrigation water and fertilizer application. Chemical species move with water by percolation between soil layers, groundwater lateral flow to rivers, and surface runoff. Each soil layer is considered to be a completely mixed reactor, as is the land surface within each land use. Within the soil, cations are adsorbed to soil particles through the competitive exchange process. Anions are adsorbed to the soil using an adsorption isotherm. A dynamic equilibrium is maintained between dissolved and adsorbed phases of each ion. Reactions transform the dissolved chemical constituents within the soil. The dissolved oxygen (DO) concentration is tracked, and as DO goes to zero, anoxic reactions take place. When overland flow takes place, sediment is eroded from the catchment surface according to the modified universal soil loss equation. The sediment carries adsorbed ions (e.g. phosphate) with it to the river.

Rivers accept the water quality which comes with each source of flow. Each river segment is considered a completely mixed reactor. Ions form an equilibrium between dissolved and adsorbed to suspended sediment. Sediment deposition and re-suspension are simulated according to simulated hydraulic conditions. Chemical reactions are based on first order kinetics, and the rate at which reactions proceed is controlled by temperature. Algae are represented by three types: greens, blue-greens, and diatoms. Each has their own optimum growth rate, nutrient half-saturation concentrations, light saturation, optimum temperature, and temperature range for growth. At each time step, algal growth is a function of nutrient limitation, light limitation, and temperature limitation. Light penetration is a function of the algae, detritus, and total suspended sediment concentrations. Light intensity is integrated over the depth of the river segment.

Simulated Parameters

WARMF comes with a default set of simulated hydrologic, water quality, and composite parameters which can be expanded for individual watersheds. Hydrologic parameters are those that only reflect the quantity of water. Composite parameters are not directly simulated but rather are calculated from simulated water quality parameters. Table 1.1 shows the parameters used in the Hennessey and

Milliken WARMF watershed models. The only parameters which are not included in WARMF by default are simazine, copper, and the various forms of iron.

Table 1.1: Parameters Simulated by WARMF in the Hennessey & Milliken Watersheds

Hydrologic Parameters	Flow, Elevation, Volume, Depth, Velocity, Spill, Flow Adjust, Snow Water Depth, Precipitation, Irrigation, Evapotranspiration, Evaporation
Water Quality Parameters	Temperature, SO_X, NO_X, pH, Ammonia, Aluminum, Calcium, Magnesium, Potassium, Sodium, Sulfate, Nitrate, Chloride, Phosphate, Alkalinity, Organic Carbon, Inorganic Carbon, Silica, Ferrous Iron, Ferric Ion, Copper, Simazine, Fecal Coliform, BOD, Dissolved Oxygen, Carbon Dioxide, Blue-green Algae, Diatoms, Green Algae, Periphyton, Detritus, Settled Detritus, Clay, Silt, Sand, Sediment Deposition
Composite Parameters	Total Phosphorus, Total Kjeldahl Nitrogen, Total Nitrogen, Total Organic Carbon, Total Iron, Total Phytoplankton, Total Dissolved Solids, Electrical Conductivity, Total Suspended Sediment, Total Sediment, Turbidity, Sediment Depth

Three types of algae are simulated by WARMF. For the Hennessey and Milliken watersheds, they represent blue-green algae, diatoms, and green algae. The biomass concentrations of algae species were converted to chlorophyll-a by a chlorophyll-a to carbon ratio which can be set in WARMF. Sediment is represented by sand, silt, and clay fractions. Sand is considered bed load, while silt and clay are suspended load. Total Suspended Sediment is the sum of silt and clay. Total Sediment is the sum of total suspended sediment and sand. Table 1.2 describes how each of the composite parameters is calculated.

Electrical conductivity was used as an analog for total dissolved solids because it is much easier to measure and often well correlated with TDS. The ratio between them depends on the proportions of the various ions in the water. The San Joaquin River has high TDS which is strongly correlated to EC when measured concurrently with an EC/TDS ratio of 1.67. The Sacramento River has low TDS which is not as well correlated to EC at an EC/TDS ratio of 1.50. A ratio of 1.11 for EC/TDS was used because that is the ratio calculated from measured data collected in the Lake Hennessey and Milliken Reservoir watersheds.

Turbidity is a direct measure of light scattering in water. It is higher when there is particulate matter in the water. There can be several contributors to turbidity including suspended sediment, detritus, and phytoplankton. There is no concurrent turbidity and suspended sediment data with which a ratio between the two could be calculated. A turbidity / total suspended sediment ratio of 0.5902, calculated from Sacramento River data, was used in the Hennessey and Milliken watersheds.

Table 1.2: Components of Composite Parameters

Total Phosphorus	Dissolved PO_4, Adsorbed PO_4, P portions of Detritus, Blue-green Algae, Green Algae, and Diatoms
Total Kjeldahl Nitrogen	Dissolved NH_4, Adsorbed NH_4, N portions of Total Organic Carbon, Detritus, Blue-green Algae, Green Algae, and Diatoms
Total Nitrogen	Total Kjeldahl Nitrogen + Nitrate
Total Organic Carbon	Dissolved Organic Carbon, Adsorbed Organic Carbon, N portions of Total Organic Carbon, Blue-green Algae, Green Algae, and Diatoms
Total Iron	Dissolved and Adsorbed Ferrous Iron and Ferric Iron
Total Phytoplankton	Blue-green Algae, Diatoms, and Green Algae
Total Dissolved Solids	Dissolved NH4, Al, Ca, Mg, K, Na, SO4, NO3, Cl, PO4, inorganic carbon, SiO2, Ferrous Iron, Ferric Iron, Cu
Electrical Conductivity	Total Dissolved Solids x 1.11
Total Suspended Sediment	Clay + Silt
Total Sediment	Clay + Silt + Sand
Turbidity	Total Suspended Sediment x 0.5902
Sediment Depth	Cumulative Sediment Deposition

Model Inputs

WARMF model inputs include coefficients which describe the properties of the watershed, initial conditions, and time series inputs which drive the simulation. The model coefficients include a wide variety of parameters which describe processes that occur in the watershed: soil and vegetation characteristics, reaction rates and products, adsorption parameters, and hydrologic routing coefficients. Initial conditions are the water depth and concentrations of each constituent in each catchment's soil layers and in each river segment at the beginning of the simulation. The water volume and concentrations then change at every time step using volume and mass balance calculations. Many of the initial conditions specified for river segments wash out in the first few days or weeks of the simulation.Initial soil concentrations are of greater importance because a large amount of mass is adsorbed to soil particles, and it may take several years for soil chemistry to reach equilibrium with model inputs if the initial conditions are not appropriately assigned.

Land management is defined by model coefficients such as monthly fertilizer and pesticide application rates, applied irrigation water rates, and implementation of best management practices like buffer zones and detention ponds. Time series data of meteorology, air & rain chemistry, point sources, and managed flows drive the simulation. Meteorology includes precipitation, minimum and maximum temperature, dewpoint temperature, cloud cover, air pressure, and wind speed on a daily or hourly interval. Air and rain chemistry has atmospheric particulate, gaseous, and rain concentrations of each chemical constituent. The last two types of time series inputs are anthropogenic inputs: point source discharges and managed flow (reservoir releases and diversions). Time series data is stored in the WARMF Data Module, from which it is automatically fed into the simulation.

The following sections described the site specific input data for the Hennessey and Milliken watersheds.

Land Use / Land Cover

Land use for the Milliken and Hennessey watersheds was developed using a geographic information system (GIS), and is based on a combination of two shapefiles that were provided to Systech by the Napa County GIS office or downloaded from the Napa County GIS data catalog (http://gis.napa.ca.gov/giscatalog/catalog_xml.asp?srch_opt=all&db_name=x&theme=x&sort_order=layer&meta_style=fgdc&submit=Submit, *accessed 11/3/2017*). The GIS shapefiles used include:

- agriculture_county.shp
  - Napa County Agriculture: including Vineyard, Grazing and Orchard. Historically, Napa County staff have calculated vineyard acreage by adding together planted vineyard acres and fallow acres. Fallow acreage is included in this calculation in order to account for vineyard removals/replants that occurred during the time when the reference orthophoto was taken.
  - Original layer created by Lynsey Kelley, GIS Specialist; 2011 Update Team: M. Chavez, A. Davis, M. Lamborn; 2014 updates: M. Lamborn
- Veg_BDR_10.shp
  - Vegetation community dataset developed by the Information Center for the Environment at UC Davis. For the Napa County Baseline Data Report the dataset is the primary dataset for identification of potential special status species habitat, sensitive communities and is the GIS portion of the Biological Resource Database.

The process for creating the land use shapefiles that were imported into each of the WARMF watershed models is the same. The steps are briefly described here:

1. Agriculture_county.shp and veg_BDR_10.shp were combined using a spatial union. A union operation combines features (shapes) from multiple independent shapefiles into a new shapefile. The operation preserves the spatial delineation and data attributes from each of the input shapefiles.
2. Each shape in the resulting shapefile (Ag_Veg_BDR_Union.shp) was assigned a WARMF land use. All shapes classified as an agricultural use in the Agrigulture_County.shp shapefile were assigned to a WARMF agricultural land use. All areas within the watersheds not classified as agricultural in the Agriculture_County.shp shapefile were assigned to a WARMF land use class based on the land use classification provided in the Veg_BDR_10.shp shapefile.

The land use classification scheme is provided in Table 1.3 and Table 1.4.

Table 1.3 Veg_BDR_10.shp shapefile land use classes, and the WARMF land use equivalents

WARMF Land Use	Corresponding map unit names from Veg_BDR_10.shp shapefile
Barren	Serpentine Barren
Broadleaf Evergreen Forest	California Bay - Leather Oak - (Rhamnus spp.); Mesic Serpentine NFD Super Alliance; California Bay - Madrone - Coast Live Oak - (Black Oak Big - Leaf Maple) NFD Super Alliance; Canyon Live Oak Alliance; Coast Live Oak Alliance, Eucalyptus Alliance; Interior Live Oak Alliance; Tanbark Oak Alliance; Winter-Rain Sclerophyll Forests & Woodlands Formation
Coniferous Forest	California Juniper Alliance; Coast Redwood - Douglas-fir / California Bay NFD Association; Coast Redwood Alliance; Douglas-fir - Ponderosa Pine Alliance; Douglas-fir Alliance; Foothill Pine / Mesic Non-serpentine Chaparral NFD Association; Foothill Pine Alliance; Knobcone Pine Alliance; McNab Cypress Alliance; Ponderosa Pine Alliance; Sargent Cypress Alliance; Sugar Pine - Canyon Oak NFD Association
Deciduous Forest	Black Oak Alliance; Blue Oak Alliance; Brewer Willow Alliance; Mixed Willow Super Alliance; Oregon White Oak Alliance; Valley Oak - Fremont Cottonwood - (Coast Live Oak) Riparian Forest NFD Association; Valley Oak Alliance; White Alder (Mixed Willow - California Bay - Big Leaf Maple) Riparian Forest NFD Association
Developed	Urban or Built-up
Grassland	California Annual Grasslands Alliance; Perennial Bunchgrass Restoration Sites; Serpentine Grasslands NFD Super Alliance; Upland Annual Grasslands & Forbs Formation
Marsh	(Bulrush - Cattail) Fresh Water Marsh NFD Super Alliance; (Carex spp. - Juncus spp - Wet Meadow Grasses) NFD Super Alliance; Riverine, Lacustrine and Tidal Mudflats; Saltgrass - Pickleweed NFD Super Alliance
Mixed Forest	Coast Live Oak - Blue Oak - (Foothill Pine) NFD Association; Interior Live Oak - Blue Oak - (Foothill Pine) NFD Association; Mixed Oak Alliance; Valley Oak - (California Bay - Coast Live Oak - Walnut - Ash) Riparian Forest NFD Association
Rock Outcrop	Rock Outcrop; Sparse Bush Lupine / Annual Grasses / Rock Outcrop NFD Alliance; Sparse California Juniper-Canyon Live Oak-California Bay-California Buckeye / Steep Rock Outcrop NFD Alliance
Scrub / Brush	Chamise - Wedgeleaf Ceanothus Alliance; Chamise Alliance; Coyote Brush - California Sagebrush - (Lupine spp.) NFD Super Alliance; Leather Oak - California Bay - Rhamnus spp. Mesic Serpentine NFD Alliance; Leather Oak - White Leaf Manzanita - Chamise Xeric Serpentine NFD Super Alliance; Lotus scoparius Alliance (post-burn); Mixed Manzanita - (Interior Live Oak -California Bay - Chamise) West County NFD Alliance; Sclerophyllous Shrubland Formation; Scrub Interior Live Oak - Scrub Oak - (California Bay - Flowering Ash - Birch Leaf Mountain Mahogany - Toyon - California Buckeye) Mesic East County NFD Super Alliance; White Leaf Manzanita - Leather Oak - (Chamise - Ceanothus spp.) Xeric Serpentine NFD Super Alliance
Not imported[1]	Other; Unknown; Vacant
Water	Water

[1] Land classified as Other, Unknown, or vacant was not imported into WARMF. It was an extremely small contribution to the overall acreage (0.2% and 1.2% for Hennessey and Milliken, respectively), and, if

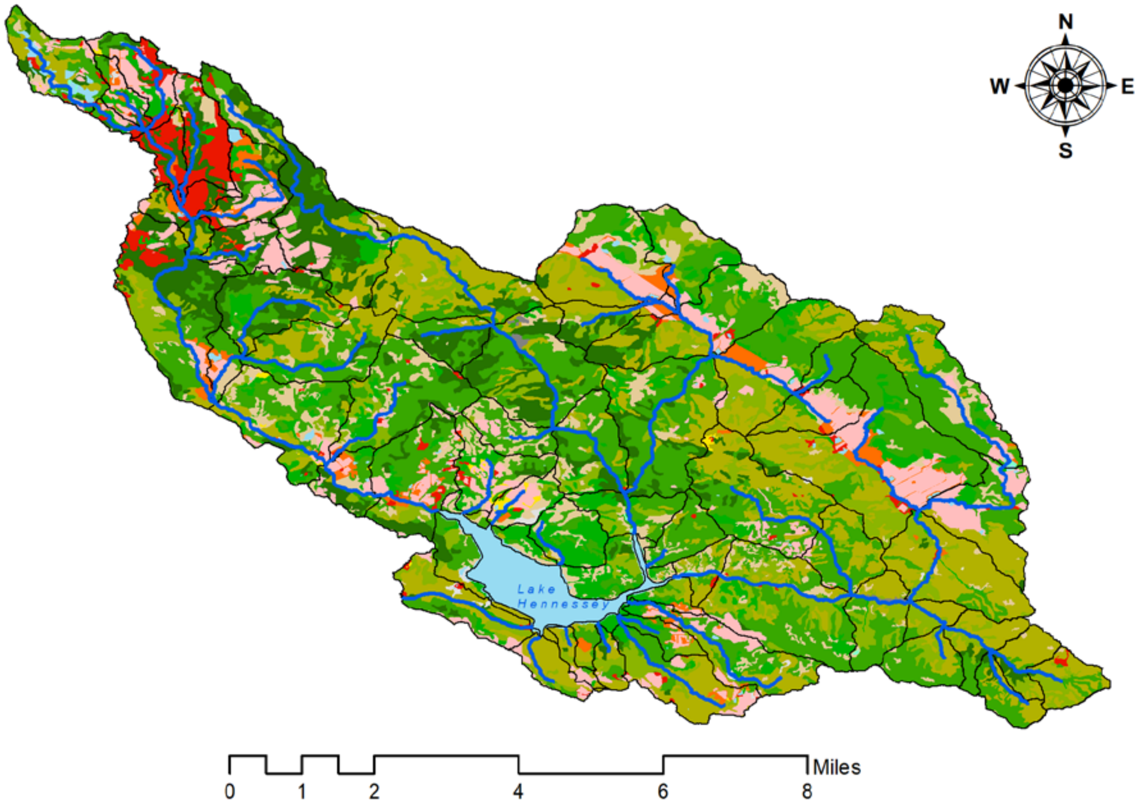
used, would add additional complication and uncertainty to the model without providing useful information. The land use in these areas was assumed to be the same as in the rest of the catchment in which they occurred.

Table 1.4 Agriculture_County.shp shapefile land use classes, and the WARMF land use equivalents

WARMF Land Use	Corresponding map unit names from agriculture_county.shp shapefile
Pasture/hay	Fallow
Vineyard	Vineyard
Orchard	Orchard
Not used – revert to Veg_BDR_10 classification[1]	Grazing/Pasture
Pasture/hay	Other
Pasture/hay	Non-Agriculture
Pasture/hay	Flagged for Follow-up

[1] Grazing/pasture designation in this coverage is incorrect, according to Napa County personnel. Information from the veg_BDR_10.shp file was used for areas classified as grazing/pasture in the agriculture_county.shp shapefile

Figure 1.3 and Figure 1.4 illustrate the land use that was imported into the Lake Hennessey and Milliken Reservoir WARMF models respectively. The figures also include a tabulation of the land use composition within the watershed. Dominant land uses in the Hennessey watershed include vineyards (8%), forests (59%), and scrub/brush (20%). Dominant land uses in the Milliken watershed include vineyards (8%), forests (38%), grassland (10%), and scrub/brush (41%).



Legend

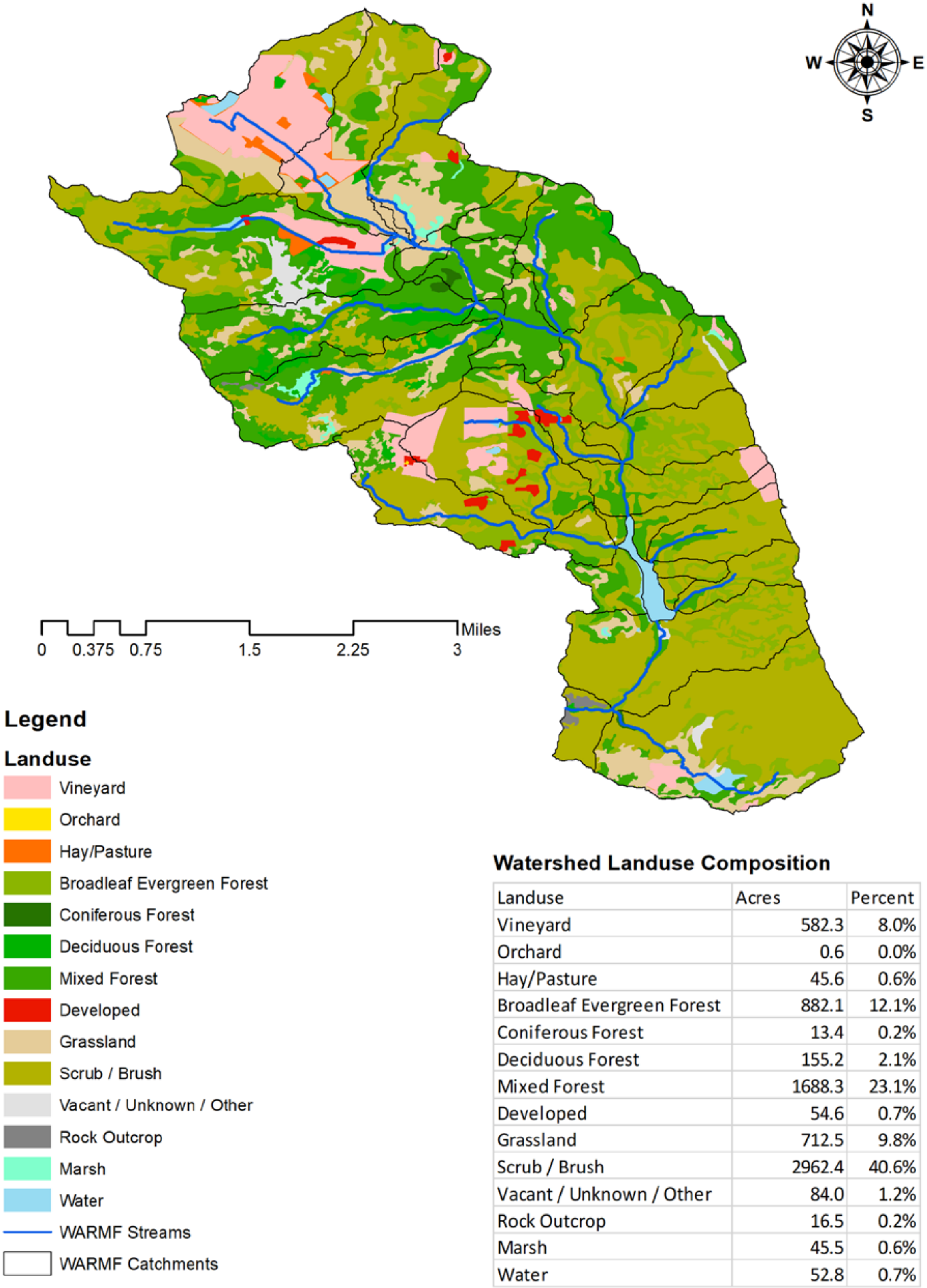
Landuse

- Vineyard
- Orchard
- Hay/Pasture
- Broadleaf Evergreen Forest
- Coniferous Forest
- Deciduous Forest
- Mixed Forest
- Developed
- Grassland
- Scrub / Brush
- Vacant / Unknown / Other
- Barren
- Rock Outcrop
- Marsh
- Water
- WARMF Streams
- ☐ WARMF Catchments

Watershed Landuse Composition

Landuse	Acres	Percent
Vineyard	2669.9	8.1%
Orchard	87.4	0.3%
Hay/Pasture	715.2	2.2%
Broadleaf Evergreen Forest	3215.4	9.8%
Coniferous Forest	3653.5	11.1%
Deciduous Forest	2391.8	7.3%
Mixed Forest	9995.5	30.3%
Developed	923.7	2.8%
Grassland	2353.4	7.1%
Scrub / Brush	6540.4	19.8%
Vacant / Unknown / Other	72.9	0.2%
Barren	0.8	0.0%
Rock Outcrop	38.4	0.1%
Marsh	30.4	0.1%
Water	276.8	0.8%

Figure 1.3 Lake Hennessey watershed land use



Watershed Landuse Composition

Landuse	Acres	Percent
Vineyard	582.3	8.0%
Orchard	0.6	0.0%
Hay/Pasture	45.6	0.6%
Broadleaf Evergreen Forest	882.1	12.1%
Coniferous Forest	13.4	0.2%
Deciduous Forest	155.2	2.1%
Mixed Forest	1688.3	23.1%
Developed	54.6	0.7%
Grassland	712.5	9.8%
Scrub / Brush	2962.4	40.6%
Vacant / Unknown / Other	84.0	1.2%
Rock Outcrop	16.5	0.2%
Marsh	45.5	0.6%
Water	52.8	0.7%

Figure 1.4 Milliken Reservoir watershed land use

Soils Data

Soil coefficients in WARMF are key parameters for simulating hydrology and constituent transport. Although soils are highly variable, data from soil surveys provides guidance for modeling. The Soil Survey Geographic database (SSURGO) produced by the Natural Resources Conservation Service has maps which divide the land into soil types and files which describe each soil type. The characteristics in the database include soil layer thickness and available water capacity. The shapes of the soil types in the SSURGO were overlaid with the WARMF catchment boundaries and the percentages of each soil type within each catchment were estimated. A weighted average was used to calculate representative soil layer thicknesses and available water capacities in each catchment based on the SSURGO data.

The California Soil Resource Lab SoilWeb (California Soil Resource Lab, 2018) expands on the SSURGO database and includes several parameters useful for WARMF modeling purposes. It has vertical profiles for different soil types showing clay fraction, sand fraction, soil erosivity, and cation exchange coefficient. These parameters were used to estimate the equivalent WARMF model inputs.

Meteorology Data

Meteorology data were compiled from several sources in order to have complete data for all 7 meteorology parameters and as much spatial and temporal resolution as possible. Model simulations are very sensitive to precipitation, so it is important to have the greatest possible spatial resolution in model inputs. Minimum temperature, maximum temperature, and dewpoint temperature are used to calculate evapotranspiration so these also play an important role in model simulations. Cloud cover, air pressure, and wind speed are used primarily for reservoir hydrology and heat balance calculations. Among these, the reservoir simulation is most sensitive to wind speed.

The Napa Valley Regional Rainfall and Stream Monitoring System (NVRRSMS) collects real-time precipitation data for Conn Dam Spillway, Lake Hennessey, and Milliken Reservoir on irregular intervals, generally multiple times per day. Sites located at Angwin, Atlas Peak, and St Helena have hourly precipitation and temperature data which are available for download from the California Data Exchange Center (CDEC). The California Irrigation Management Information System (CIMIS) has a site in Oakville which measures precipitation, temperature, dewpoint temperature, and wind speed. Daily precipitation, minimum daily temperature, and maximum daily temperature are available from the National Climatic Data Center (NCDC) for a site at Pacific Union College in Angwin. . The Napa Airport also provides data to the NCDC. Data available for this location include daily precipitation, minimum and maximum temperature, dewpoint temperature, air pressure, and wind speed. Table 1.5 summarizes the available raw meteorology data.

Table 1.5 Summary of Raw Meteorology Data

Station	Data Source	Frequency	Annual Average Values					
			Precipitation, inches	Temperature, °F	Cloud Cover	Dewpoint Temp., °F	Air Pressure, inches Hg	Wind Speed, mi/hr
Angwin	CDEC	Hourly	3.0	57.4				
Atlas Peak	CDEC	Hourly	43.9	57.7				
Conn Dam Spillway	NVRRSMS	Sub-daily	25.2					
Lake Hennessey	NVRRSMS	Sub-daily	22.2					
Milliken Reservoir	NVRRSMS	Sub-daily	24.0					
Napa County Airport	GSOD	Daily	19.2	57.6		47.1	29.94	6.5
Oakville	CIMIS	Hourly	32.6	57.6		46.9		3.6
Pacific Union College	NCDC	Daily	40.7	58.1				
St Helena	CDEC	Hourly	17.3	58.8				

There is little variation in temperature across the watersheds, but there are large differences in precipitation with Atlas Peak averaging 2.5 times the precipitation measured at St Helena. In general, sites at higher altitude have higher precipitation. The measured precipitation at the CDEC station in Angwin appears to be an outlier and is therefore not accurate and is not used in the WARMF simulations. Dewpoint temperature is similar between the two stations with data. Wind speed is highly spatially variable and is a key factor in reservoir evaporation, so it would have to be adjusted as part of reservoir hydrology calibration.

All of these data sources except the CDEC Angwin station were combined to fill data gaps. Missing parameters from one station were filled in with parameters from the nearest station whose data included those parameters. Missing data were filled in using data from nearby stations with a precipitation multiplier or temperature shift based on the average difference between two stations when they both reported data. Cloud cover was estimated from temperature, dewpoint temperature, and precipitation as shown below.

$$CC = 0.79e^{-0.11*(T_{ave}-T_{dew})} + 0.43 * P$$

T_{ave} is the average of the minimum and maximum temperature in °C, T_{dew} is the dewpoint temperature in °C, and P is the precipitation in cm. If the estimated cloud cover is greater than 1, it is set to 1.

The processed meteorology files were imported into the Hennessey and Milliken WARMF models. Each catchment and reservoir segment is assigned to a meteorology station with a precipitation multiplier and a temperature shift to adjust for different conditions between the meteorology station and the catchment/reservoir. WARMF has an automated process which assigns the closest meteorology station to each catchment and reservoir and calculates the precipitation multipliers and temperature shifts to have linear precipitation and temperature gradients between meteorology stations. The precipitation multiplier and temperature shift can then be adjusted from the default calculated values during model calibration. Figure 1.5 and Figure 1.6 show the locations of the meteorology stations used to drive simulations in the Lake Hennessey and Milliken Reservoir watersheds.

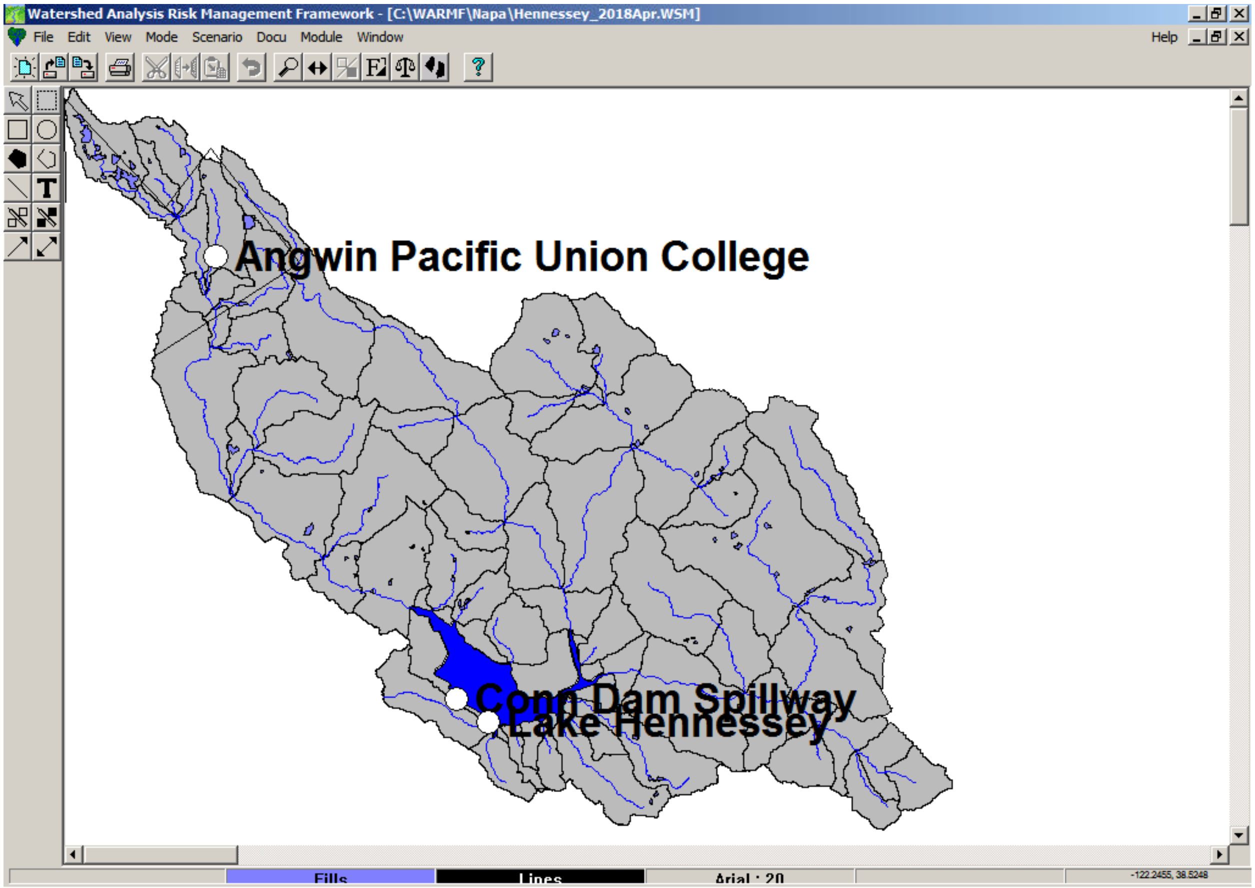


Figure 1.5 Meteorology Stations in the Lake Hennessey Watershed

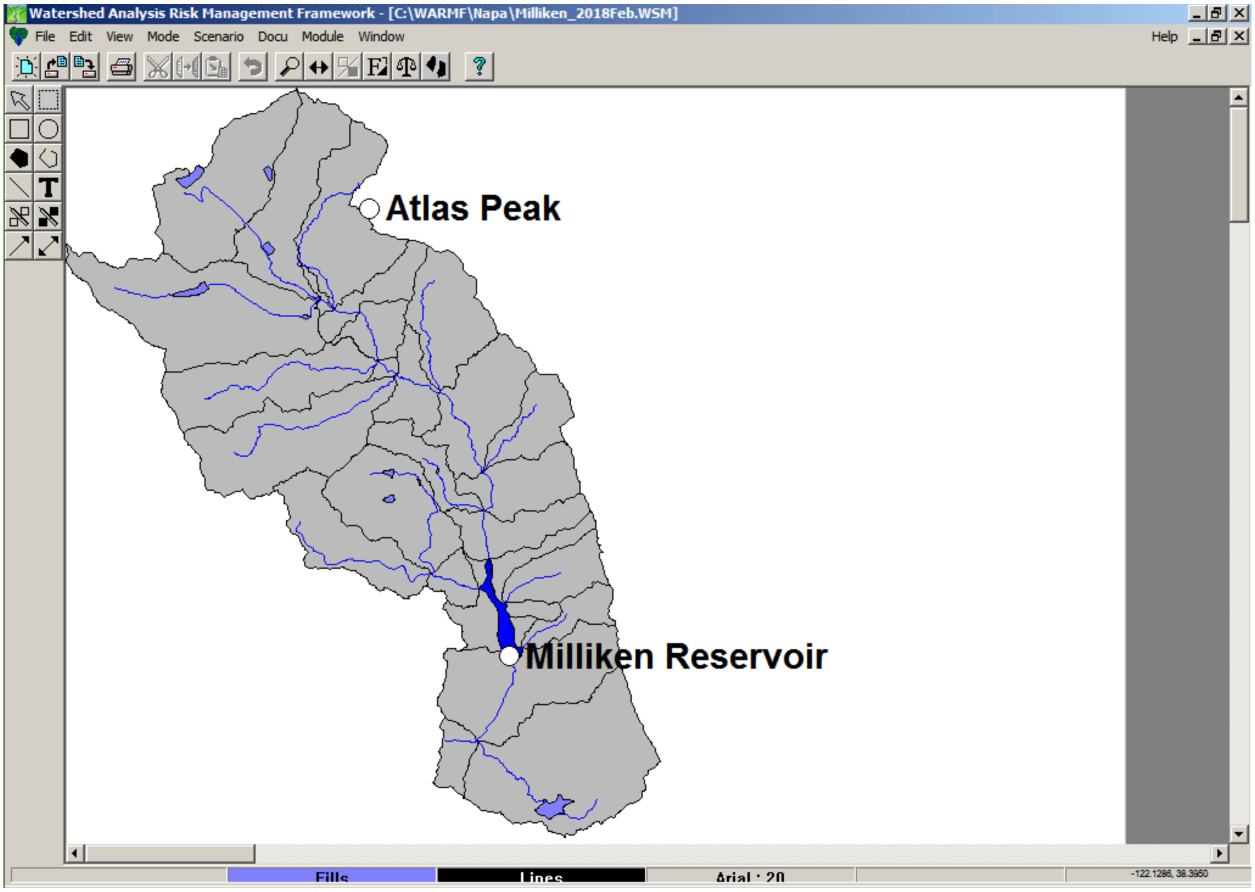


Figure 1.6 Meteorology Stations in the Milliken Reservoir Watershed

Air Quality and Rain Chemistry Data

In WARMF, atmospheric deposition is calculated from concentrations of each chemical constituent in precipitation and in the air. Those concentrations are stored as time series in WARMF input files. Three databases were used to develop these inputs for the Hennessey and Milliken watersheds. The nearest station of the National Atmospheric Deposition Program (NADP), which monitors precipitation concentrations, is in Hopland about 50 miles northwest of Lake Hennessey. The Clean Air Status and Trends Network (CASTNET) measures gaseous and particulate air concentrations. The nearest CASTNET stations are at Lassen National Park 150 miles north-northeast of Lake Hennessey and Pinnacles National Park 150 miles to the south-southeast. The Bay Area Air Quality Management District (BAAQMD) has a station in Napa which collects gaseous nitrogen oxides (NO_x) and sulfur oxides (SO_x) data but no other chemical constituents needed for input to WARMF. The three data sources for air quality are shown in Table 1.6.

Table 1.6 Average Air Concentrations (μg/m³)

	Gaseous		Particulate							
	SO_x	NO_x	NH_4	Ca	Mg	K	Na	SO_4	NO_3	Cl
Lassen N.P.	0.22	0.10	0.12	0.06	0.01	0.03	0.06	0.42	0.05	0.02
Pinnacles N.P.	0.33	0.58	0.17	0.14	0.09	0.07	0.56	0.95	0.27	0.45
Napa	1.81	33.5								

Although many of the air concentrations are similar between the Lassen and Pinnacles sites, Pinnacles has much higher Na and Cl concentrations since it is closer to the coast than Lassen. For that reason, Pinnacles was judged to be more representative of Napa because it closer to the coast, but the concentrations of Na and Cl could be scaled in calibration if necessary. The BAAQMD station in Napa has far higher SO_x and NO_x concentrations than the two CASTNET sites because it is in an urbanized area. The Hennessey and Milliken watersheds have very few atmospheric emission sources in the watersheds like the CASTNET sites, but are near the heavily urbanized Bay Area. This leaves a large amount of uncertainty about the NOx concentration in the Hennessey and Milliken watersheds which would have to be reduced through model calibration. After calibration, the NO_x concentration was reduced by multiplying it by a factor of 0.04 which still leaves the concentration 2.3 times what was measured at Pinnacles National Park.

Point Source Discharge Data

The Pacific Union College Wastewater Treatment Plant (WWTP) is the only point source discharger in the Hennessey and Milliken watersheds. It is located near Conn Creek on the south side of Angwin. Its treatment train includes a primary clarifier, trickling filter, secondary clarifier, and effluent oxidation ponds. Its capacity is 0.2 million gallons per day (MGD). Effluent is stored in ponds from November through March and is used to irrigate fields in April through October so there is no direct discharge to Conn Creek. (Brown & Caldwell, 2012)

There is no monitoring data available for the WWTP, so its effluent concentrations were estimated. Concentrations must be provided for the major cations and anions, nutrients, organic carbon, and dissolved oxygen. The source water for the Angwin area is the headwaters of Conn Creek, which has very low salinity, but wastewater has more sodium and chloride than the source water. The effluent concentrations of nutrients and organic carbon were estimated based on the treatment process used. Table 1.7 shows the effluent concentrations assumed. These were multiplied by an assumed annual WWTP discharge rate of 140,000 gallons per day to determine loading. The evaporation rate for the holding pond was assumed to be the same as the simulated evaporation rate for Lake Hennessey, which results in 25% of the discharged water to be evaporated. The net flow rate of applied water from April through October is 180,000 gallons per day or 0.279 cfs.

Table 1.7: Assumed Effluent Concentrations for Pacific Union College WWTP

NH_4 mg/l N	NO_3 mg/l N	PO_4 mg/l P	OC mg/l	BOD mg/l	DO mg/l	Ca mg/l	Mg mg/l	K mg/l	Na mg/l	SO_4 mg/l	Cl mg/l
15	15	4	20	43	6	4	2	.5	10	2	15

Reservoir Releases

Records of outflows from reservoirs and surface elevation/storage are vital to calibrating the inflows. These outflows include releases to the stream below the dam, diversions for water supply, and spill from the dam. Operations data were obtained from the City of Napa for Lake Hennessey and Milliken Reservoirs. The data for Lake Hennessey included daily reservoir surface elevation, storage, inflow from the three main tributary creeks, release to Conn Creek below the dam, spill to Conn Creek via the open spillway, and intake to the Hennessey Water Treatment Plant. The data for Milliken Reservoir included inflow, surface elevation, spill, and diversion dam flow. Milliken Reservoir has five pipes through the dam which are normally left open and serve as an open spillway, but there is no data for the amount of water spilled through the pipes.

While the Lake Hennessey data were complete and had self-consistent inflow, outflow, and storage records, the total outflow from Milliken Reservoir had to be calculated from inflows and surface elevation. Precipitation was calculated from precipitation data and reservoir surface area. Evaporation was calculated from the average monthly pan evaporation rate for Monticello Dam at Lake Berryessa (California Department of Water Resources, 1974). The outflow was then calculated as shown below:

$$Q_O = Q_I + (P - E)A - \frac{\Delta S}{\Delta t}$$

Where: Q_O is outflow (cfs), Q_I is inflow (cfs), P is precipitation rate (ft/s), E is evaporation rate (ft/s), ΔS is the change in storage (ft^3) and Δt is the time interval (1 day = 86,400 s). Q_O was not allowed to be less than zero.

Diversion Data

There are many diversions from the creeks upstream of Lake Hennessey and Milliken Reservoir, primarily for irrigation but also for domestic use (Table 1.8). The State of California Electronic Water Rights Management System (eWRIMS) database has a list of all water rights holders with annual reports including the amount of water diverted each month. The database was searched to identify all the active diversions in the Lake Hennessey and Milliken Reservoir watersheds and the diversion data were tabulated from the annual reports for each. The locations of the diversions are shown in Figure 1.7 and Figure 1.8. Many diversions put water in ponds during the winter for use during the dry season. These cases are simulated in WARMF by putting the diverted water in a creek with impoundment volume. A second diversion takes water from the impoundment during the dry season for application on vineyards.

Table 1.8 Surface Water Diversions in the Lake Hennessey Milliken Reservoir Watersheds

Diversion	Amount (ac-ft/year)	Use	Source Water
Gallo Vineyards 1	1.5	Irrigation	North Fork Sage Creek
Gallo Vineyards 2	1.5	Irrigation	North Fork Sage Creek
Gallo Vineyards 3	4.9	Irrigation	North Fork Sage Creek
Gallo Vineyards 4	0.7	Irrigation	North Fork Sage Creek
Patricia Boydston	13.3	Irrigation	North Fork Sage Creek
Hennessey WTP	7,759	Domestic	Lake Hennessey
Howell Mountain MWC	0	Domestic	Conn Creek
Glendale Ranch	0	Irrigation	Conn Creek
Elsie Asplund Hudak	0.1	Domestic	Conn Creek
Joel Gott Wines	0	Irrigation	Conn Creek
Bruce E. Neyers	4.6	Irrigation	Conn Creek
Seavey Ranch	4.6	Irrigation	Conn Creek
Barry J Cox	0.6	Domestic	Tributary to Chiles Creek
R Stanley Dollar	8.4	Irrigation	Tributary to Chiles Creek
Robert Dickson	87	Irrigation	Conn Creek
Sculatti Domestic	0	Domestic	Conn Creek
Trevor Foster	27	Irrigation	Conn Creek
Yellow Alpha II	51	Irrigation	Sage Creek
Antinori California 1	37	Irrigation	Milliken Creek
Antinori California 2	35	Irrigation	Milliken Creek
Antinori California 3	385	Irrigation	Milliken Creek

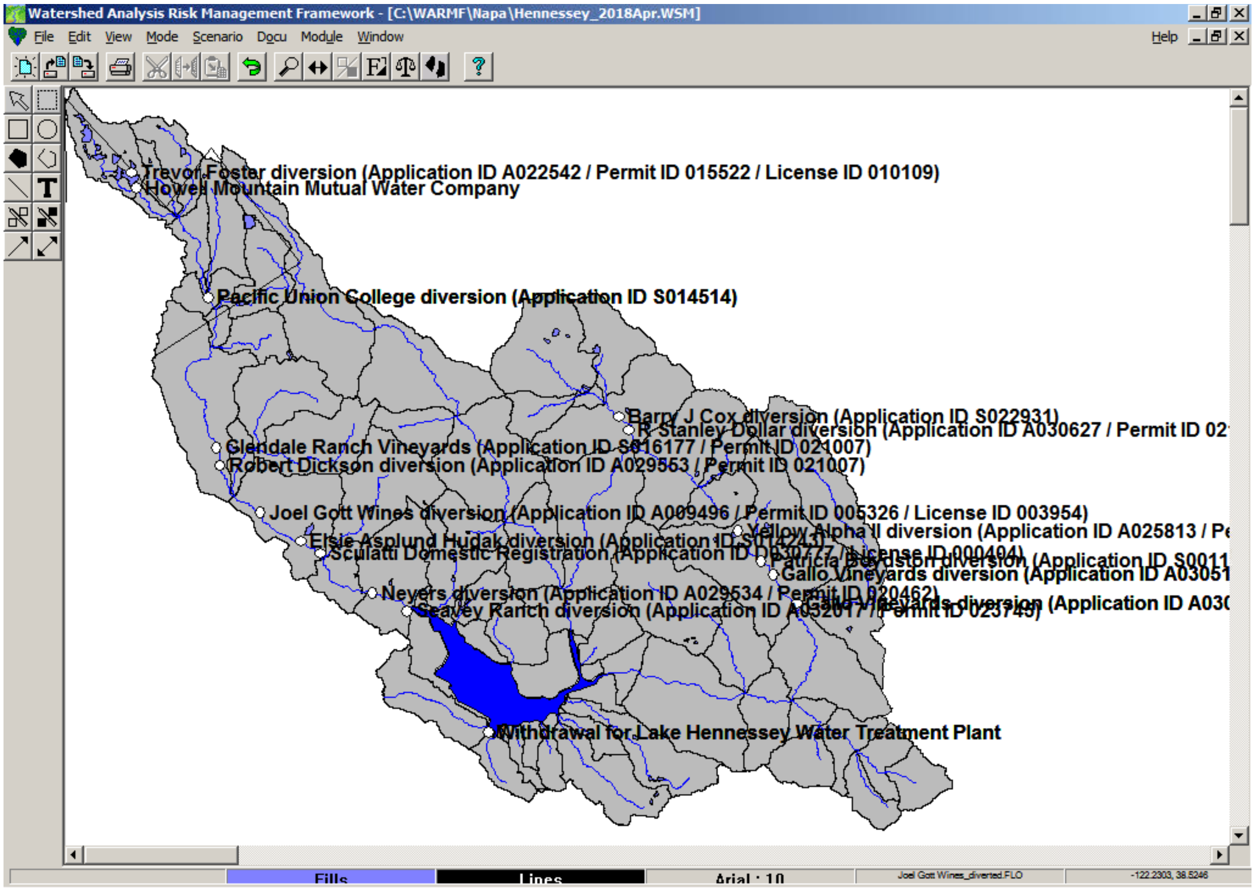


Figure 1.7 Locations of Diversions in the Lake Hennessey Watershed

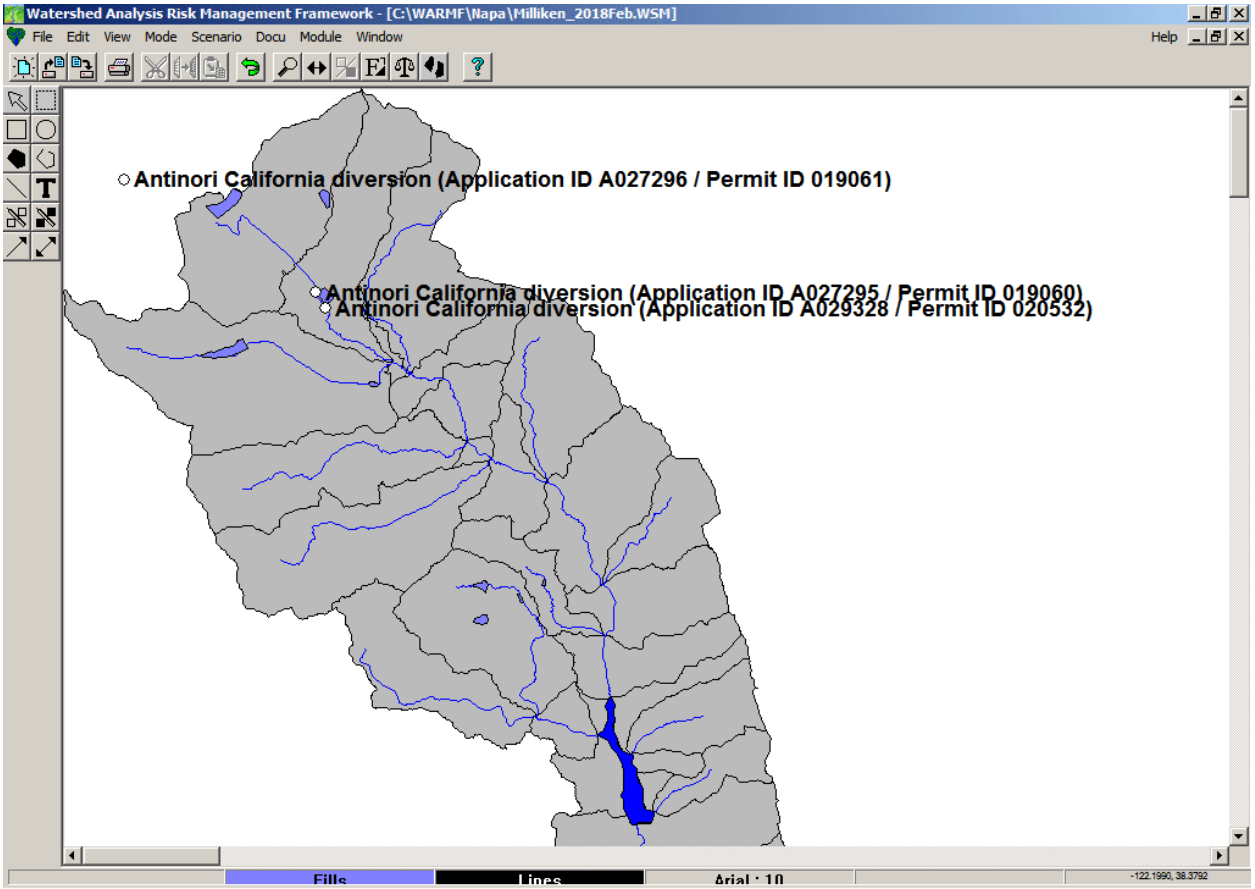


Figure 1.8 Locations of Diversions in the Milliken Reservoir Watershed

Fertilizer and Pesticide Application Rates

There are three agricultural uses in the Lake Hennessey and Milliken Reservoir which are delineated in the WARMF model: Vineyards, Orchards, and Pasture/Hay. Orchards are less than 0.3% of the watershed, so their fertilizer application was assumed to be equal to the WARMF default values for this land use class. Pasture/Hay was assumed to have no fertilizer or pesticide application. For vineyards, a literature search was done to determine the appropriate application rates for Napa County.

It is recommended that established wine grapes receive 51 lb/acre/year of NPK 8-8-8 fertilizer applied in May and October (Cooper, Klonsky, & De Moura, 2012). New plantings require 3 applications during the growing season but use the same amount of fertilizer as established vineyards. Since the fertilizer is 8% by weight of nitrogen, phosphorus, and potassium and is applied twice per year that is 2.04 pounds per acre each in May and again in October. The herbicide simazine is applied to the soil under established vines once per year after harvest at a rate of 0.5-1.0 pounds per acre (University of California Integrated Pest Management Program, 2016). In WARMF an application of 0.75 pounds per acre is applied once per year in November.

Irrigation

Irrigation is set up in WARMF to apply a percentage of each available water source to each irrigated land use in each catchment. Surface water sources are the diversions whose use is for irrigation (Table 1.8).

Irrigation is used primarily for vineyards. Some pasture/hay is irrigated by Pacific Union College with their surface water diversion and with effluent from their wastewater treatment plant. Vineyards receive 0.3 feet per year of irrigation. Where surface water supplies are insufficient for that irrigation rate, it is assumed that groundwater pumping makes up the difference. Pasture/hay, where irrigated, was assumed to only receive irrigation from surface water and point source effluent.

MODEL CALIBRATION

Calibration Procedure

Initially, some model coefficients, such as physical properties of the watershed, are known. One of the largest sources of error in modeling is from model coefficients whose value is not known and are assigned default values. To minimize this source of error, the model is calibrated by adjusting these coefficients within ranges of possible values so that the simulated flow and water quality match the observed flow and water quality at locations where measured data are available.

Model calibration follows a logical sequence between parameters, locations, and time scales. Hydrologic calibration was performed first, because an accurate flow simulation is a prerequisite for accurate water quality simulation. The calibrations for temperature, suspended sediment, and conservative substances are performed before the calibration of nutrients (phosphate, ammonia, and nitrate) and dissolved oxygen concentrations. Where there are monitoring sites upstream of one another, the calibration proceeds from upstream to downstream. The first time scale for calibration is the entire simulation period, so that there is little average bias between simulated and observed values. Next is seasonal calibration to capture the variation with different hydrologic conditions. Last is event-based calibration to correctly simulate storm events.

Model predictions are compared with observed data in several ways. The first is visual examination of the simulated time series overlaid with measured data. This type of comparison is particularly helpful for seasonal and event calibration. The model predictions and observed data were also compared statistically. The differences between the predicted and observed values are errors. The primary statistical measures of error used for calibration are relative error E_R and absolute error E_A as shown in the following equations.

$$E_R = \frac{\sum(x_s - x_o)}{n}$$

$$E_A = \frac{\sum|x_s - x_o|}{n}$$

Where: x_s and x_o are concurrent simulated and observed values, and n is the number of concurrent values. Since positive and negative errors cancel out with relative error, it is a measure of model accuracy or bias. A positive relative error means the simulated values are greater than measured. Absolute error is a measure of precision. Neither error takes into account the possibility of error in timing, which can be important for storm simulation. Although the square of the correlation coefficient (r^2) is a popular statistical measure of fit between two curves, it is not very well suited to hydrologic modeling. r^2 is inappropriate primarily because of errors in timing and magnitude. If the model predicts a flow peak one day early or late, the r^2 is low even if the shape of the hydrograph were matched well between simulated and measured. Conversely, if the simulated values were always twice the measured values, the r^2 would be very high but the calibration would be very poor.

Calibration is done systematically by making incremental changes to model coefficients. The WARMF scenario manager is used to create a duplicate of the current scenario. The duplicate is then modified and run. The output of the two scenarios are compared side by side to determine if the changes made improved the model calibration.

Hydrologic Calibration

The WARMF User's Guide (Sheeder & Herr, 2017) lists the hydrologic parameters to which model simulations are generally most sensitive. For the Hennessey and Milliken watersheds, where snowfall is minimal, the primary coefficients for hydrologic calibration relate to evapotranspiration, precipitation, and routing of flow through the soil. Two systemwide coefficients, evaporation magnitude and skewness, affect the overall amount of evapotranspiration and the amount of seasonal variation. In catchments, the precipitation weighting factor is an important coefficient because the wettest station in the Hennessey and Milliken watersheds receives almost twice as much precipitation as the driest station. Since the soil layer thickness and available water capacity in the soil were set based on SSURGO data, the hydraulic conductivity and root distribution in each soil layer were the key calibration parameters among the soil coefficients.

Simulated Years

To the extent available, time series input data were collected for the 2001 through 2017 water years. For model calibration, the 2010 through 2017 water years were used (10/1/2009 – 9/30/2017). Table 1.9 shows the average total net inflow (after evaporation) to Lake Hennessey and Milliken Reservoir. According to the California Department of Water Resources hydrologic classification index, two of the years were critically dry, 1 was dry, 3 were below normal, and 2 were wet years. This provides a broad variety of hydrologic conditions for model calibration.

Table 1.9 Average Net Annual Flows for Water Years 2010 to 2017

Water Year	Average Flow into Lake Hennessey, cfs	Average Inflow into Milliken Reservoir, cfs	Water Year Classification
2010	20.8	4.5	Below normal
2011	64.6	6.9	Wet
2012	20.3	2.1	Below normal
2013	32.7	3.1	Dry
2014	2.2	2.1	Critically dry
2015	17.3	3.4	Critically dry
2016	24.3	3.8	Below normal
2017	82.4	7.8	Wet

Hydrologic Calibration Results

There are three stream gages upstream of Lake Hennessey on each creek entering the reservoir. Another gage is on Milliken Creek just upstream of Milliken Reservoir. Water surface elevation, translated into storage volume, is available for each reservoir. The flow data from the stream gages and the operations data for the reservoirs were not consistent with each other. If the flow in the stream gages were matched with no relative error, there would be too little water in the reservoir for its operations data to be possible. The gages are designed to be most accurate at low flow and are not necessarily accurate under peak flow conditions. There may also be a small amount of flow passing through the stream bed substrate underneath the gages. For these reasons, the reservoir was the primary target of hydrologic calibration because the measurements of water surface elevation are accurate. Calibration of stream gages was done to match the shape of the hydrograph and have a relative error which was consistent between the gages.

Figure 1.9 through Figure 1.16 show the comparison of simulated and observed hydrology for Conn Creek, Chiles Creek, Sage Creek, Lake Hennessey, and Milliken Reservoir. In these plots, the simulated results are shown in blue lines and the observed data is in black circles. The simulated peak flow in the creeks is generally greater than the observed data, but this is intentional because of the inaccuracy of the stream gages at high flow and the need to balance the water volume in the reservoir. WARMF simulates more flow entering Lake Hennessey in 2014 than actually occurred, but otherwise follows the observed water surface elevation closely. WARMF simulates spill over the ungated spillways of the reservoirs using a weir relationship between water surface elevation and flow. If there were too much water entering the reservoir in the simulation, it would result in more storage in the reservoir than observed, or more spill. The simulated spill flow is only slightly greater than measured, indicating a good simulated water balance in the reservoir.

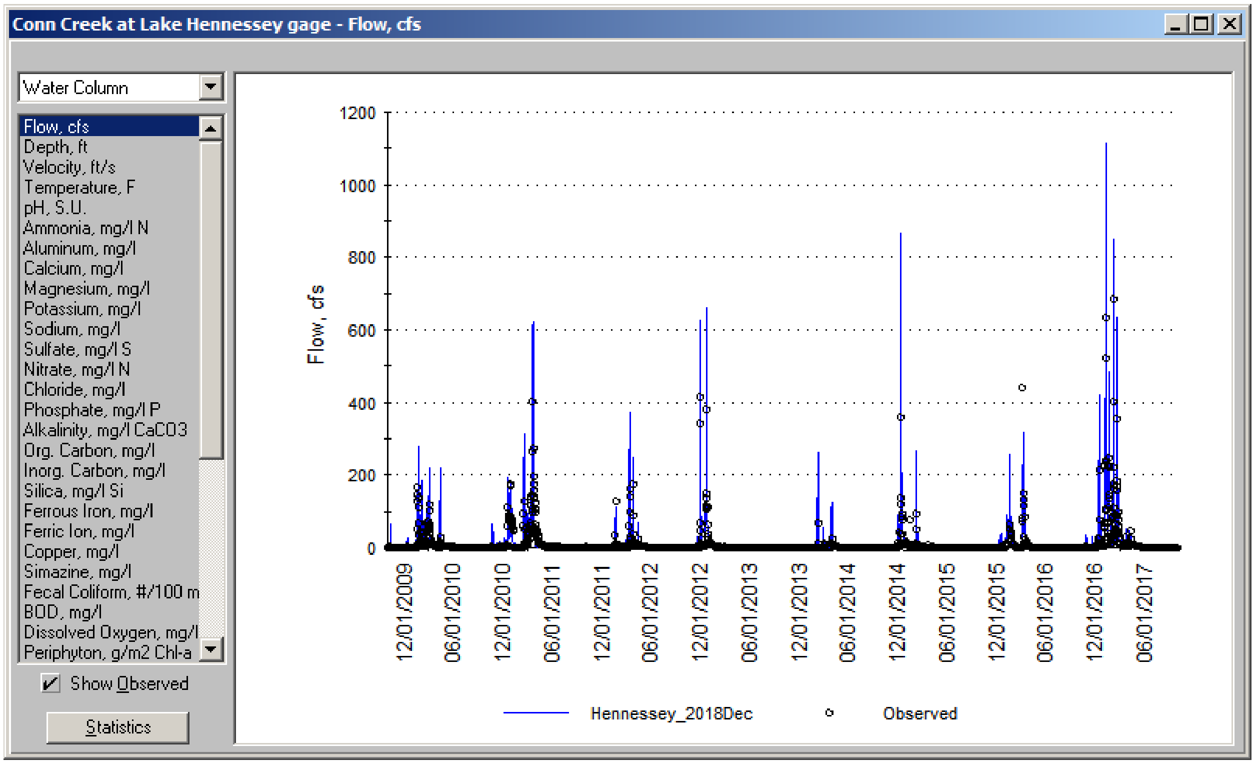


Figure 1.9 Simulated vs Observed Flow, Conn Creek at Lake Hennessey

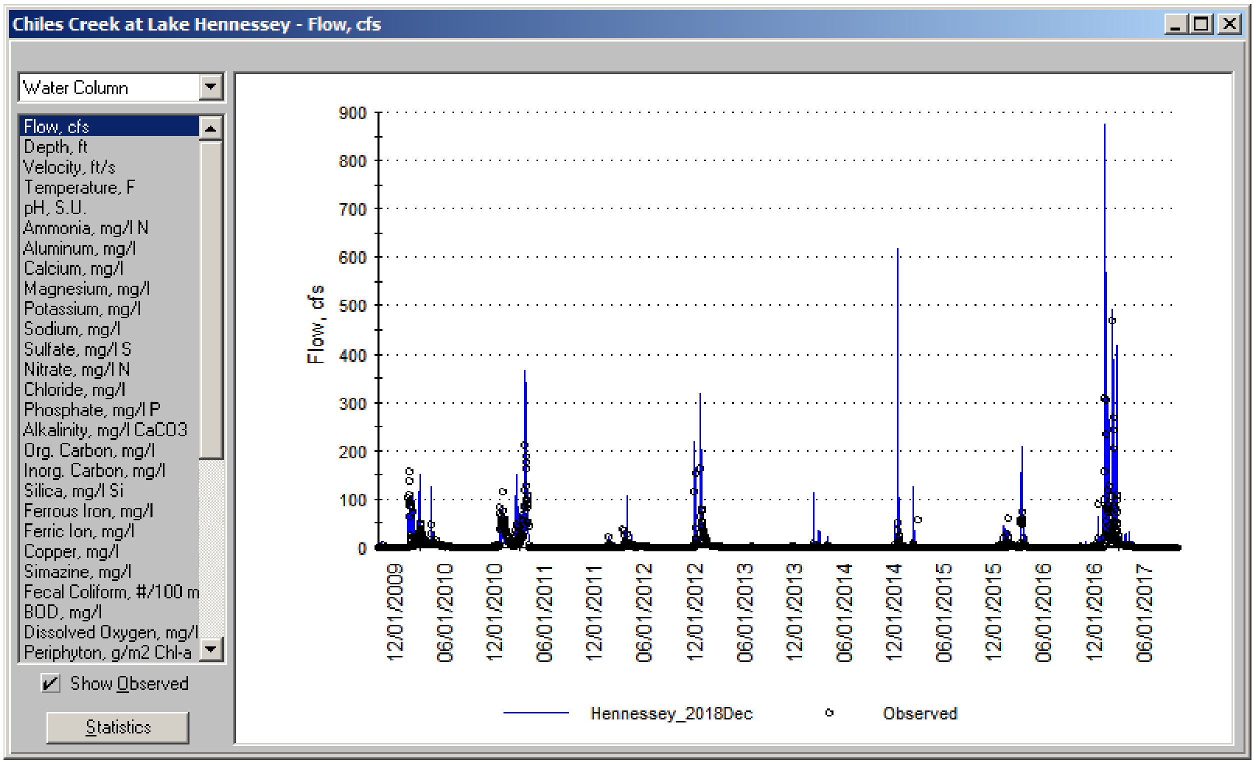


Figure 1.10 Simulated vs Observed Flow, Chiles Creek at Lake Hennessey

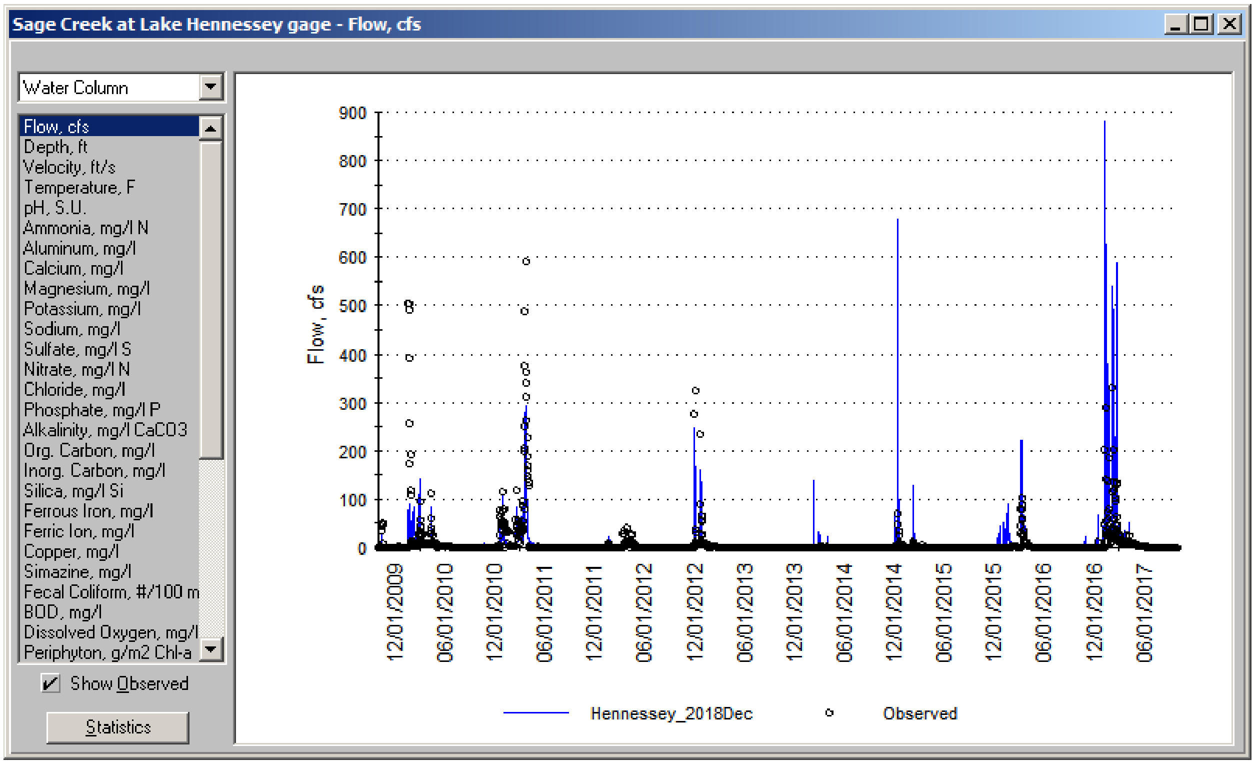


Figure 1.11 Simulated vs Observed Flow, Sage Creek at Lake Hennessey

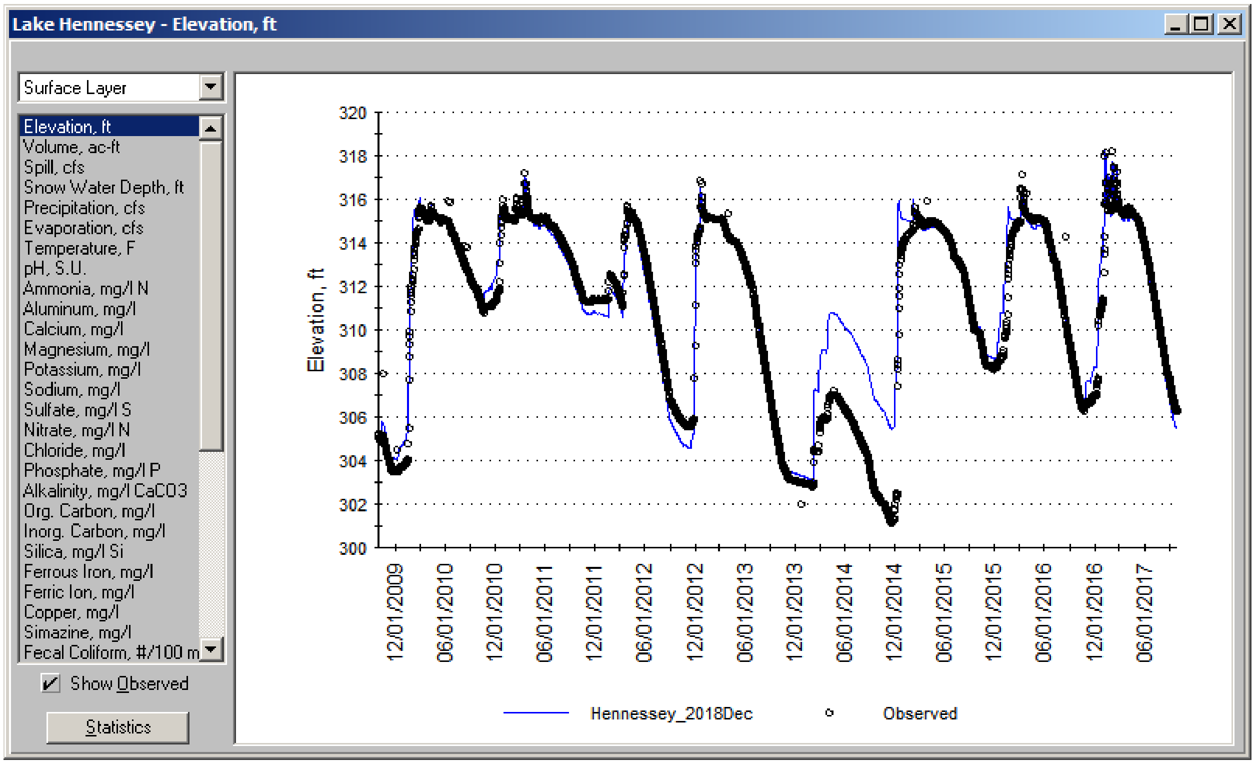


Figure 1.12 Simulated vs Observed Water Surface Elevation for Lake Hennessey

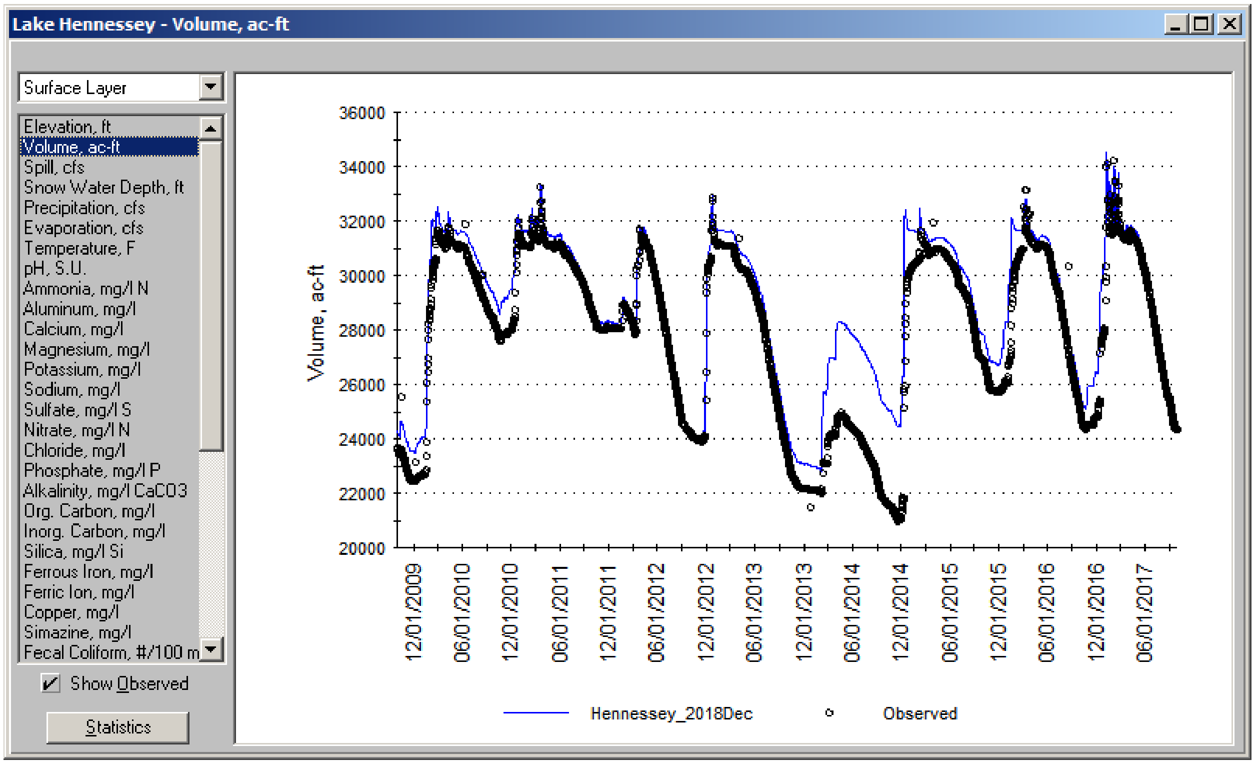


Figure 1.13 Simulated vs Observed Storage for Lake Hennessey

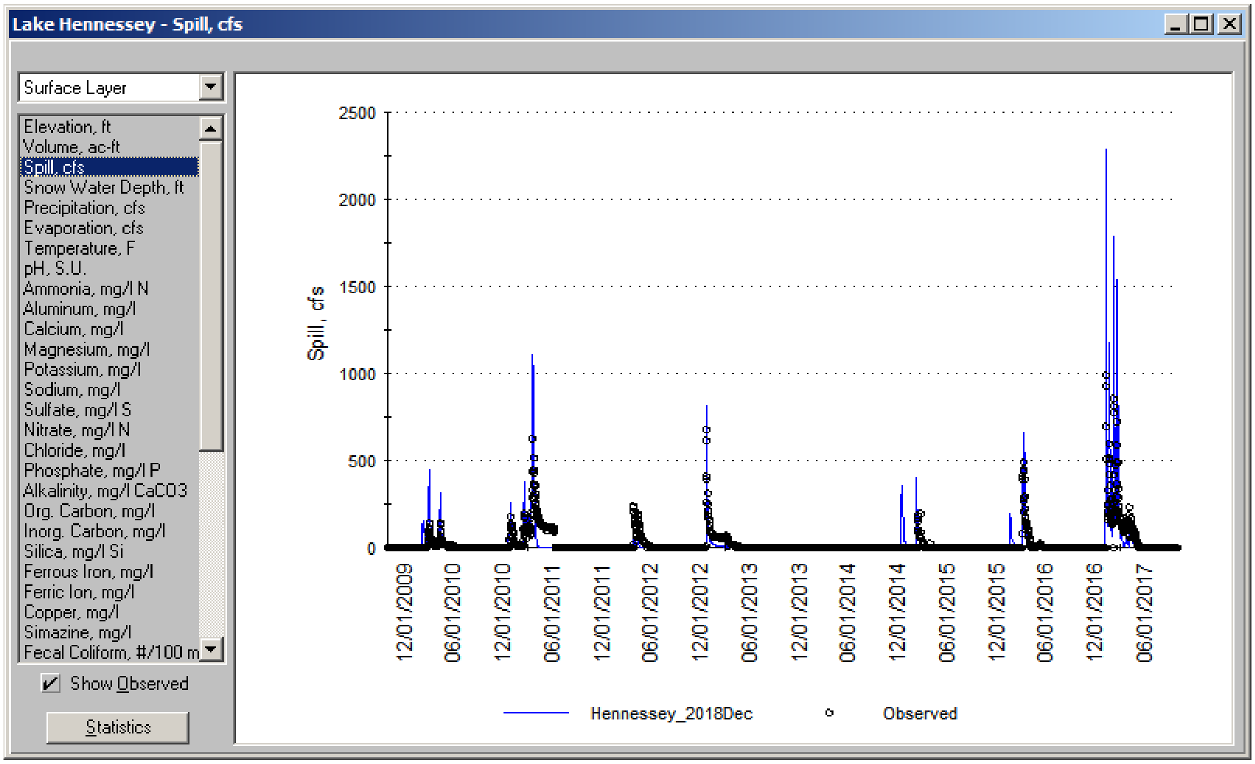


Figure 1.14 Simulated vs Observed Spill for Lake Hennessey

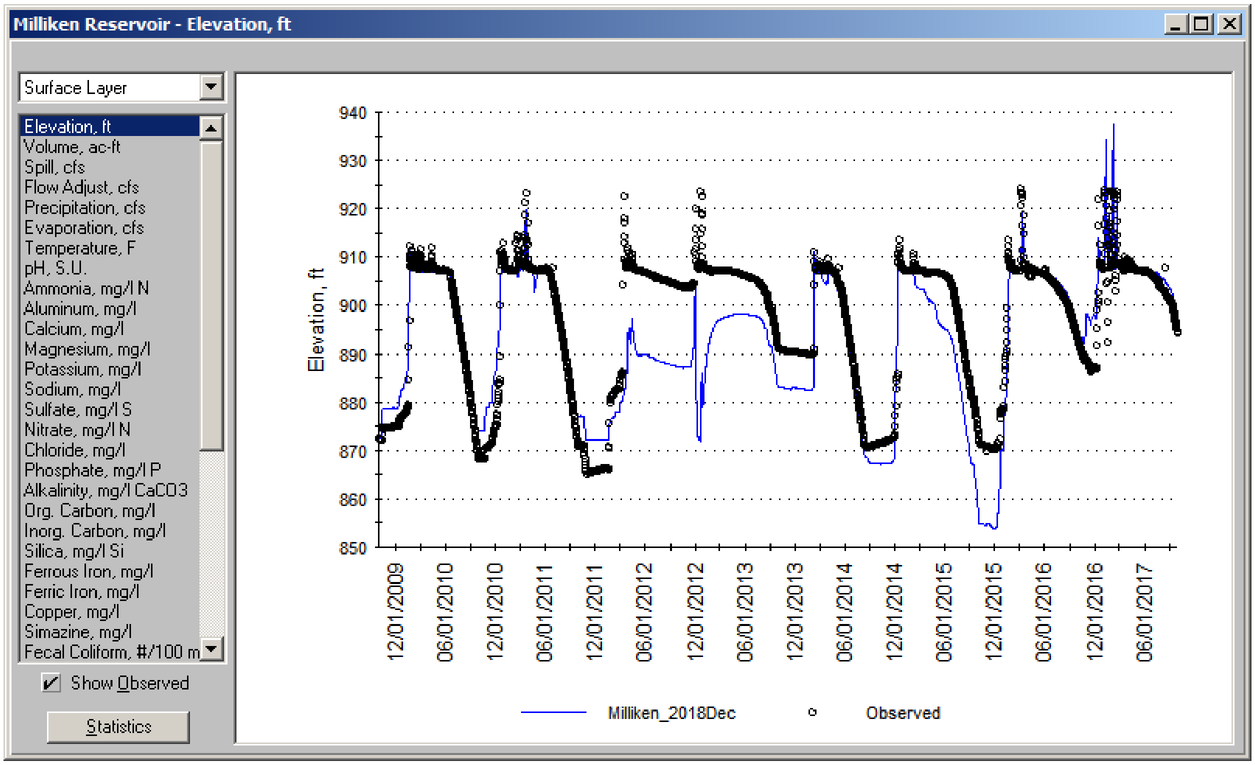


Figure 1.15 Simulated vs Observed Water Surface Elevation for Milliken Reservoir

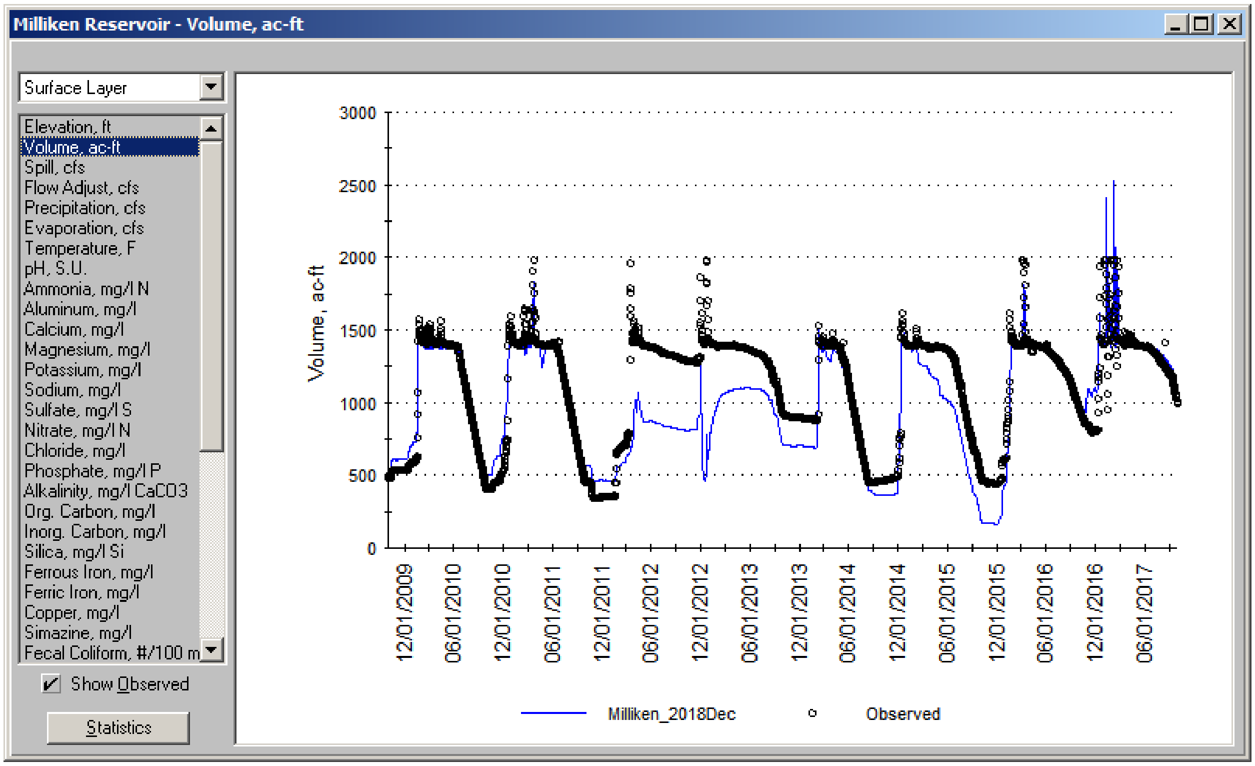


Figure 1.16 Simulated vs Observed Storage for Milliken Reservoir

Table 1.10 provides the summary statistics of model errors, which can be expressed as a percentage for all but water surface elevation. The predictions of surface elevation and storage are quite close to measured data for Lake Hennessey. While the model's prediction of the amount of spill from Lake Hennessey was accurate over the long term as seen by the low relative error, there is much more uncertainty around the model's prediction of spill on a given day as shown by the high absolute error. The simulated storage and surface elevation for Milliken Reservoir averaged less than measured because the surface elevation is often at the level of the pipes which function as the dam's spillway. While the model can predict too little storage below this level, it is difficult for the model to predict too much storage because it spills out of the reservoir in the model like at the actual dam. There is no data for spill from the pipes to compare against the WARMF simulated spill.

Table 1.10 Statistics of Model Errors for Hydrology Simulation

Gaging Station	Relative Error	Absolute Error
Lake Hennessey surface elevation	+0.4 feet	0.9 feet
Lake Hennessey storage	+3%	3%
Lake Hennessey spill	+4%	85%
Milliken Reservoir surface elevation	-3.6 feet	6.2 feet
Milliken Reservoir storage	-10%	15%

Water Quality Calibration

After the hydrologic calibration, water quality calibration was performed. As stated earlier, the water quality calibration followed a certain order, reflecting the dependence of each constituent on the others. Temperature was calibrated first, followed by turbidity, conservative substances, and nutrients. Data for water quality calibration is limited, especially for nutrients and the Milliken Reservoir watershed. The current model calibration should be considered preliminary until more data is collected and the calibration is refined.

The primary locations where water quality data were collected are Conn, Chiles, and Sage Creeks at Lake Hennessey. One to three samples were collected at various other locations in the Lake Hennessey and Millliken Reservoir watersheds as shown in Figure 1.17 and Figure 1.18. Catchments were calibrated in groups by soil type between water quality monitoring locations.

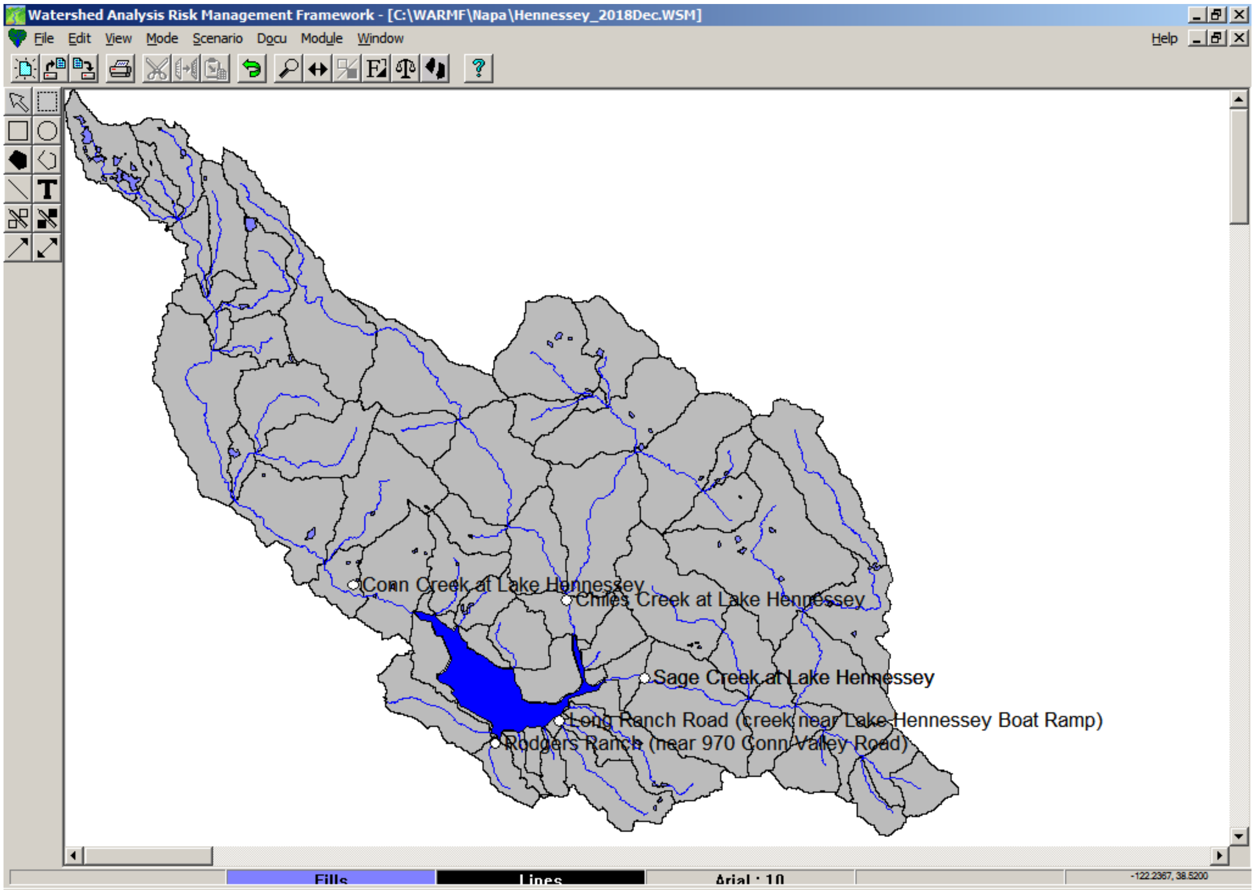


Figure 1.17 Locations with Water Quality Data in the Lake Hennessey Watershed

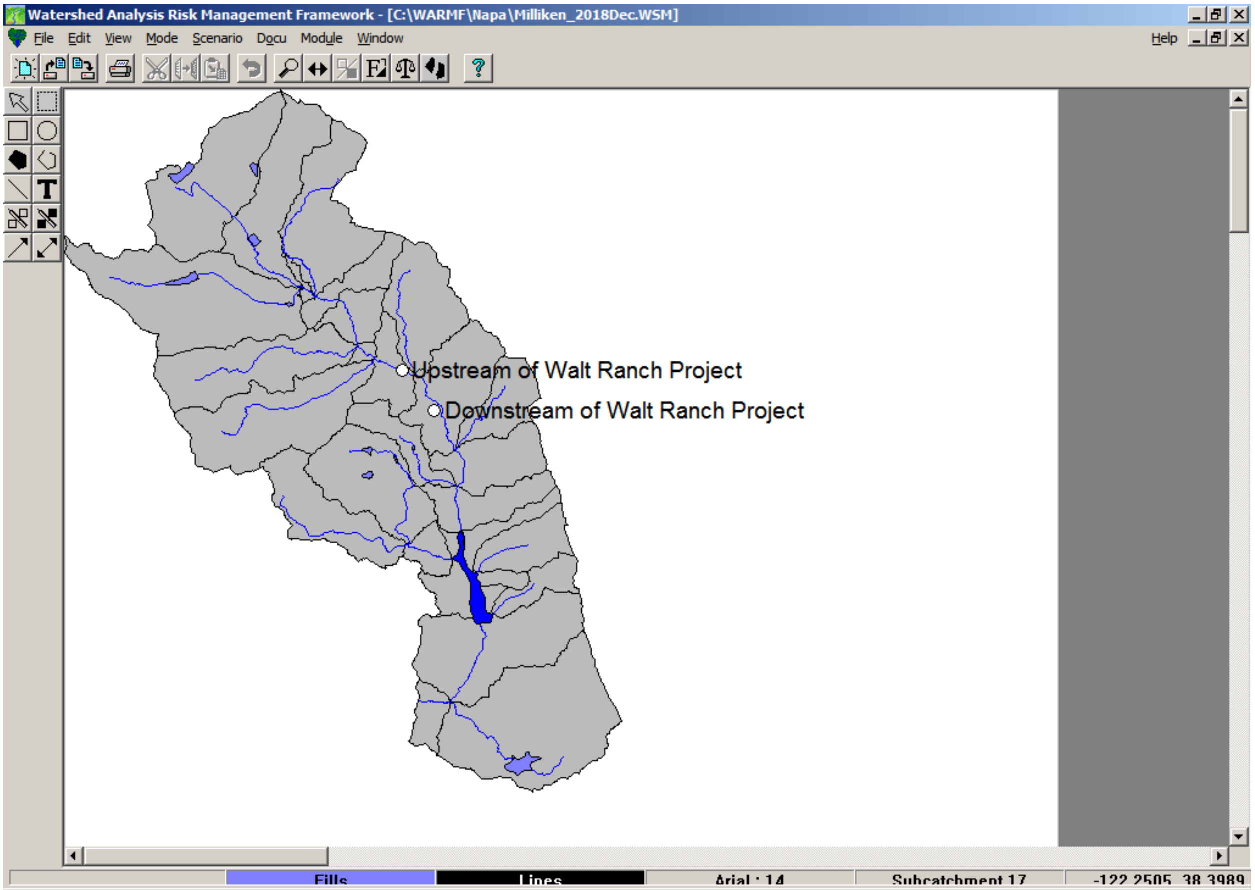


Figure 1.18 Locations with Water Quality Data in the Milliken Reservoir Watershed

The following sections describe the calibration results for Conn Creek, Chiles Creek, and Sage Creek at Lake Hennessey. For Milliken Creek, simulation results are compared with measured data at the sites above and below Walt Ranch since there is no site with a long-term data record. For each water quality parameter, the simulated results (blue lines) and observed data (black circles) are compared graphically. Breaks in the blue lines represent time periods when simulated flow is zero. In the graphs, red circles are used to highlight where there is observed data if there is too little measured data to see clearly.

Statistical measures of model performance (relative error, absolute error) are provided in tables. Statistics generated with limited data may or may not be an accurate assessment of model performance across a diverse range of hydrologic conditions. Confidence in statistical measures of model performance increases with greater numbers of observations.

Conn Creek at Lake Hennessey

The watershed of Conn Creek includes relatively wet headwaters around the town of Angwin and drier lower part of the watershed. The watershed is 60% forested, 9% scrubland, 8% grassland, 10% vineyards, and 8% developed. 90% of the flow in Conn Creek occurs from December through March, and the average flow is less than 0.1 cfs in August and September.

Figure 1.19 shows the simulated and measured temperature. The measured water temperatures higher than 60 °F in winter of 2010-2011 are likely outliers, and in general the simulated temperature in summer is somewhat higher than measured. This is likely because the heat balance performed by

WARMF assumes that incoming solar radiation heats the water, whereas Conn Creek is actually heavily shaded by riparian vegetation.

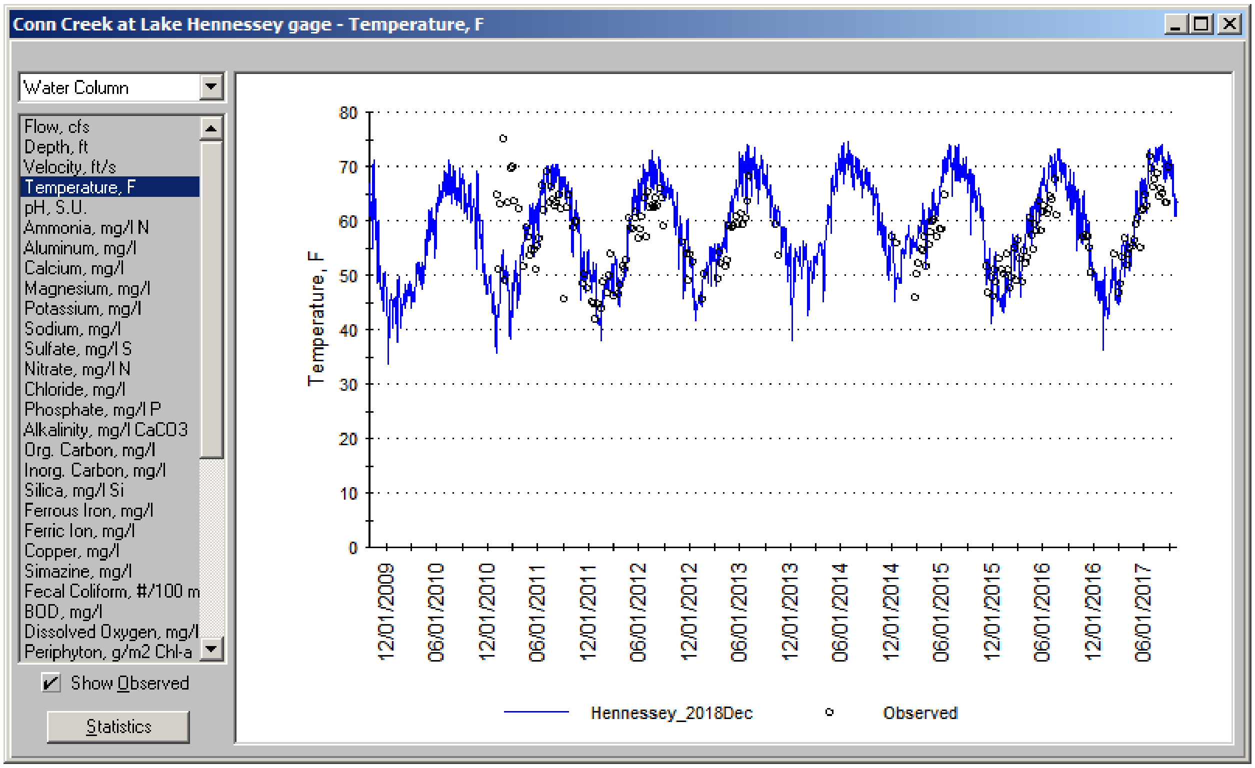


Figure 1.19 Simulated vs Observed Temperature, Conn Creek at Lake Hennessey

The comparison of turbidity calculated by WARMF and measured turbidity is shown in Figure 1.20. WARMF does not directly simulate turbidity, but instead simulates total suspended sediment and uses a linear relationship to estimate the turbidity. The relationship between turbidity and sediment is not known for this watershed, and the two parameters are only moderately correlated, so there are additional sources of error beyond the typical model error. The simulated and measured turbidity both show the expected pattern of high peaks during storms followed by rapid recession to near zero as shown in the expanded plot of winter 2015-2016 of Figure 1.21. The observed data doesn't necessarily capture the peak turbidity during storms. Without continuous monitoring data it is difficult to discern whether errors are in magnitude or timing of turbidity peaks.

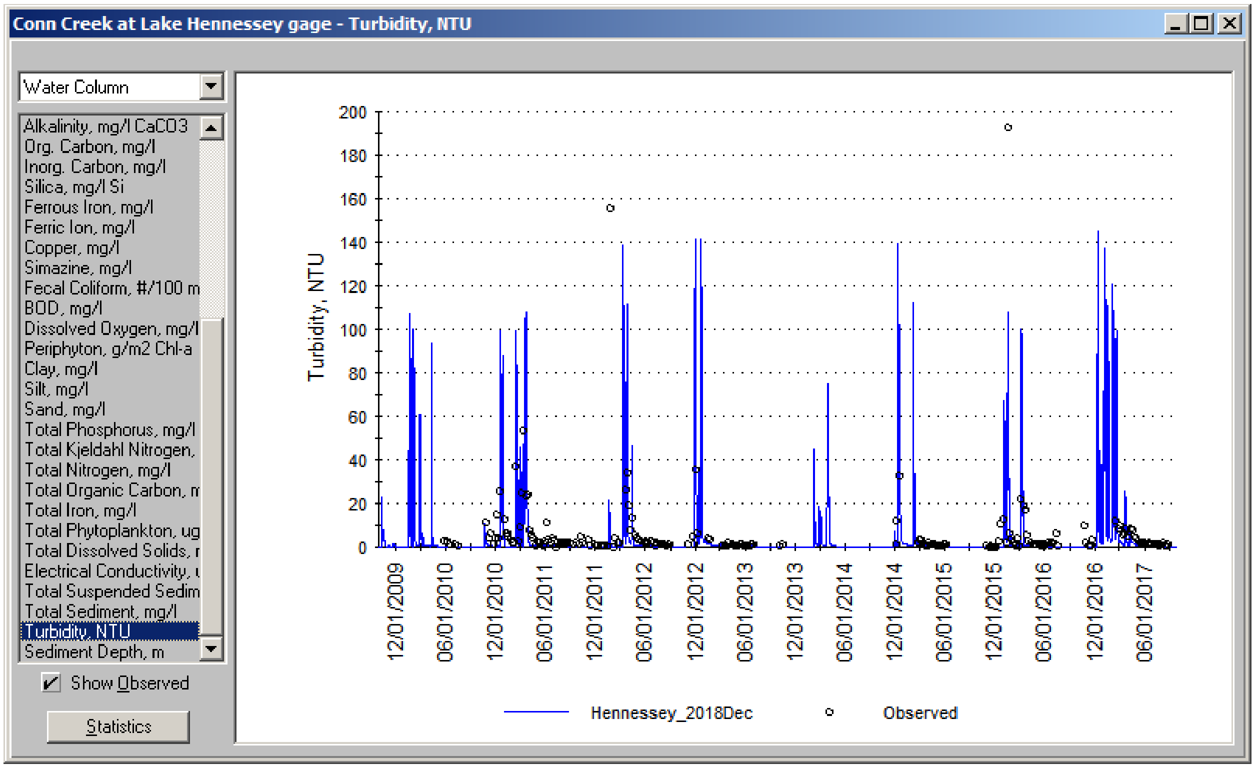


Figure 1.20 Simulated vs Observed Turbidity, Conn Creek at Lake Hennessey

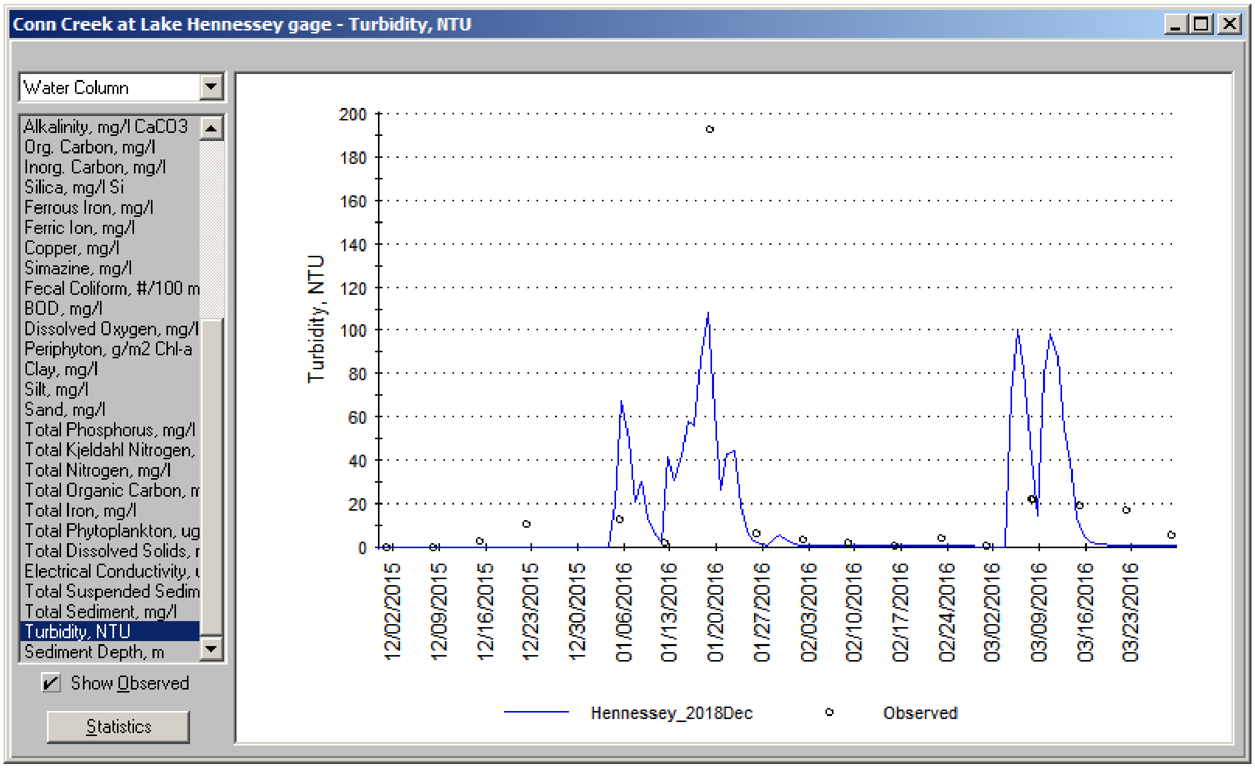


Figure 1.21 Simulated vs Observed Turbidity 12/15-3/16, Conn Creek at Lake Hennessey

Conservative substances have higher concentrations during low flow conditions, when the primary source of water is exfiltration of shallow groundwater, than during high flow conditions. The measured concentrations of conservative ions like calcium, magnesium, and chloride were far greater than precipitation concentrations during storm events, implying that either the precipitation concentrations in the watershed are far greater than those measured by the National Atmospheric Deposition Program in Hopland or a large amount of ions are leached from the soil during precipitation events. Figure 1.22 through Figure 1.26 show simulation results and observed data. WARMF simulations were not able to predict concentrations as high as measured during winter high flow, although the hydrology calibration was adjusted somewhat to route more precipitation through the soil and less through overland flow. Measured sulfate concentration ranged from 0.1 – 14 mg/l in samples taken under very low flow conditions in summer 2016, implying that some very localized conditions are influencing water quality. Isolated land use and/or soil characteristics are difficult to capture in the model without conducting significant field work to identify spatially- and temporally-isolated contributors to localized water quality. Calibration instead adjusted the simulated sulfate concentration to be close to the measured sulfate from March 2016 when flow was higher and loading to the reservoir would be much greater.

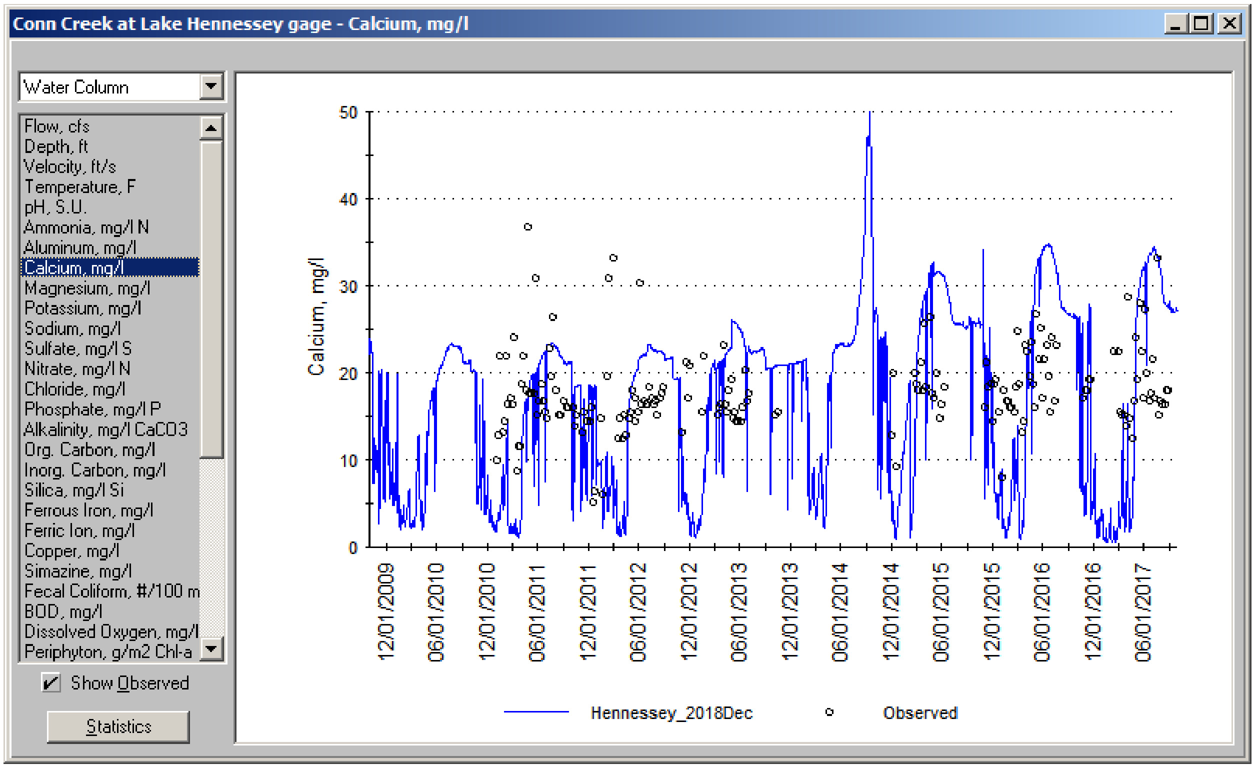


Figure 1.22 Simulated vs Observed Calcium, Conn Creek at Lake Hennessey

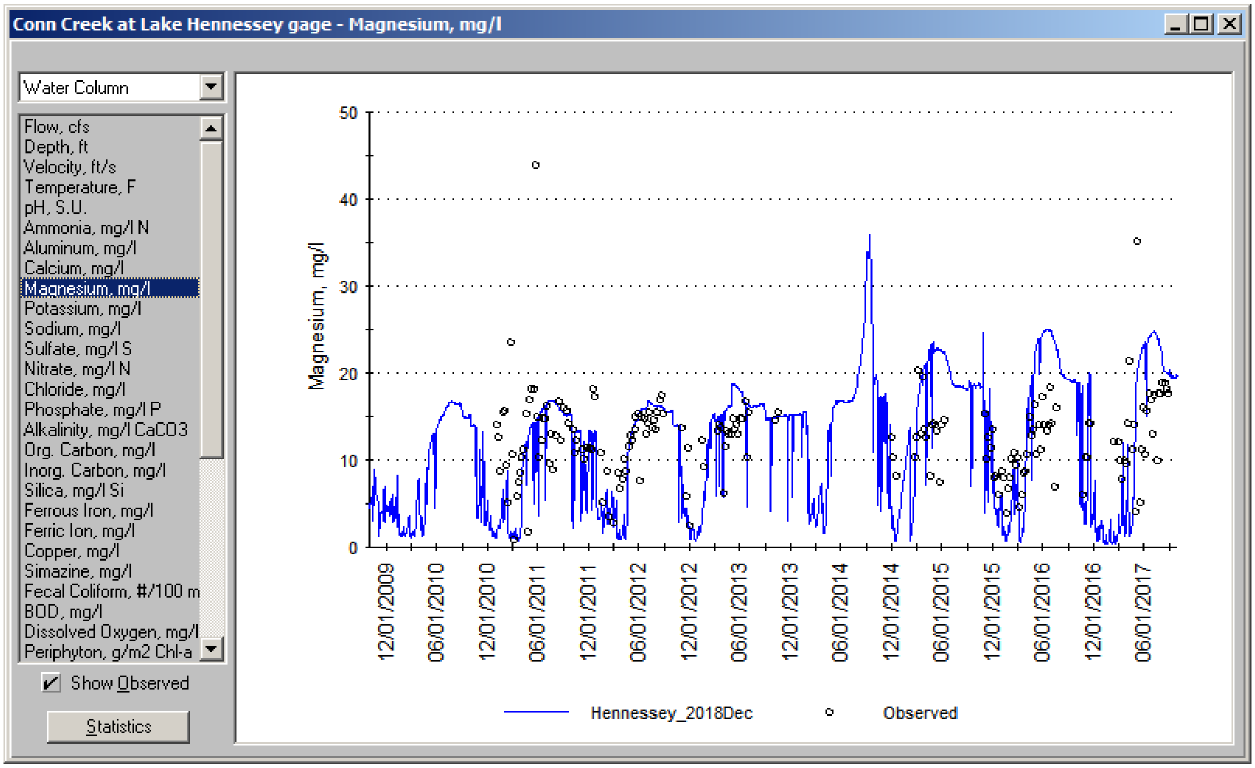


Figure 1.23 Simulated vs Observed Magnesium, Conn Creek at Lake Hennessey

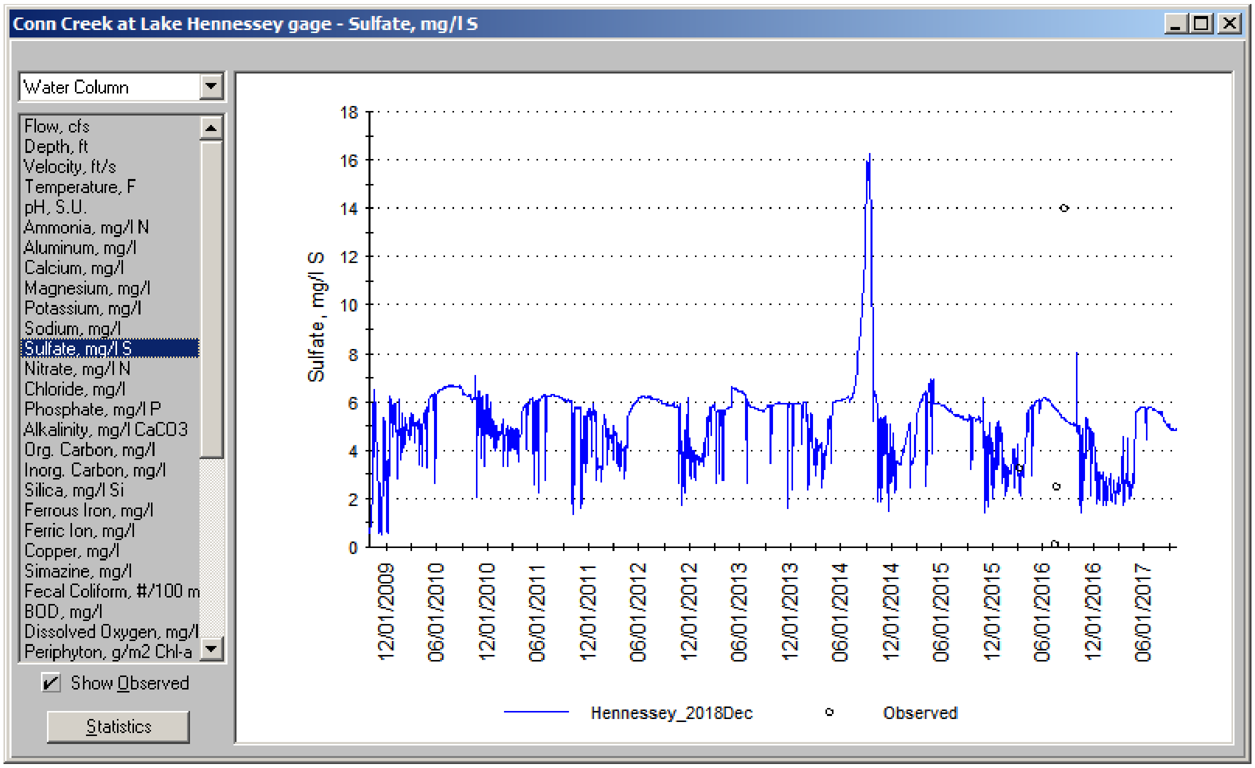


Figure 1.24 Simulated vs Observed Sulfate, Conn Creek at Lake Hennessey

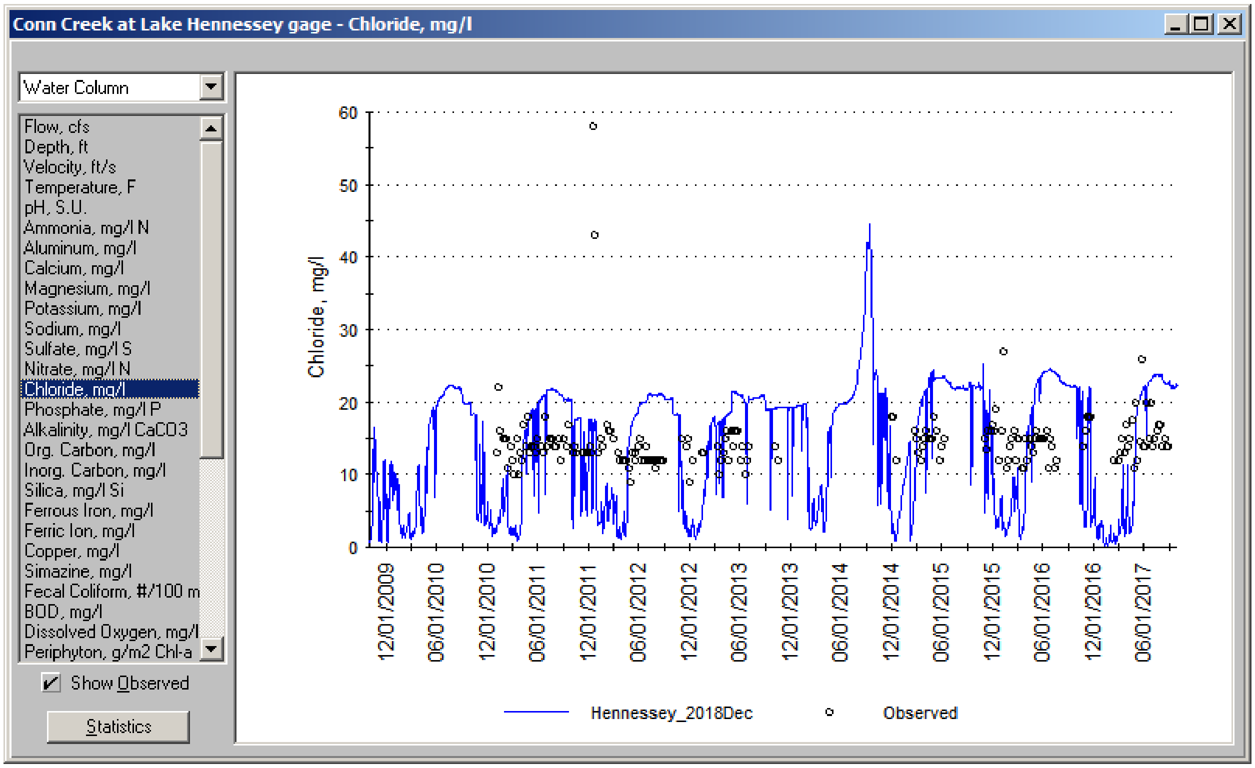


Figure 1.25 Simulated vs Observed Chloride, Conn Creek at Lake Hennessey

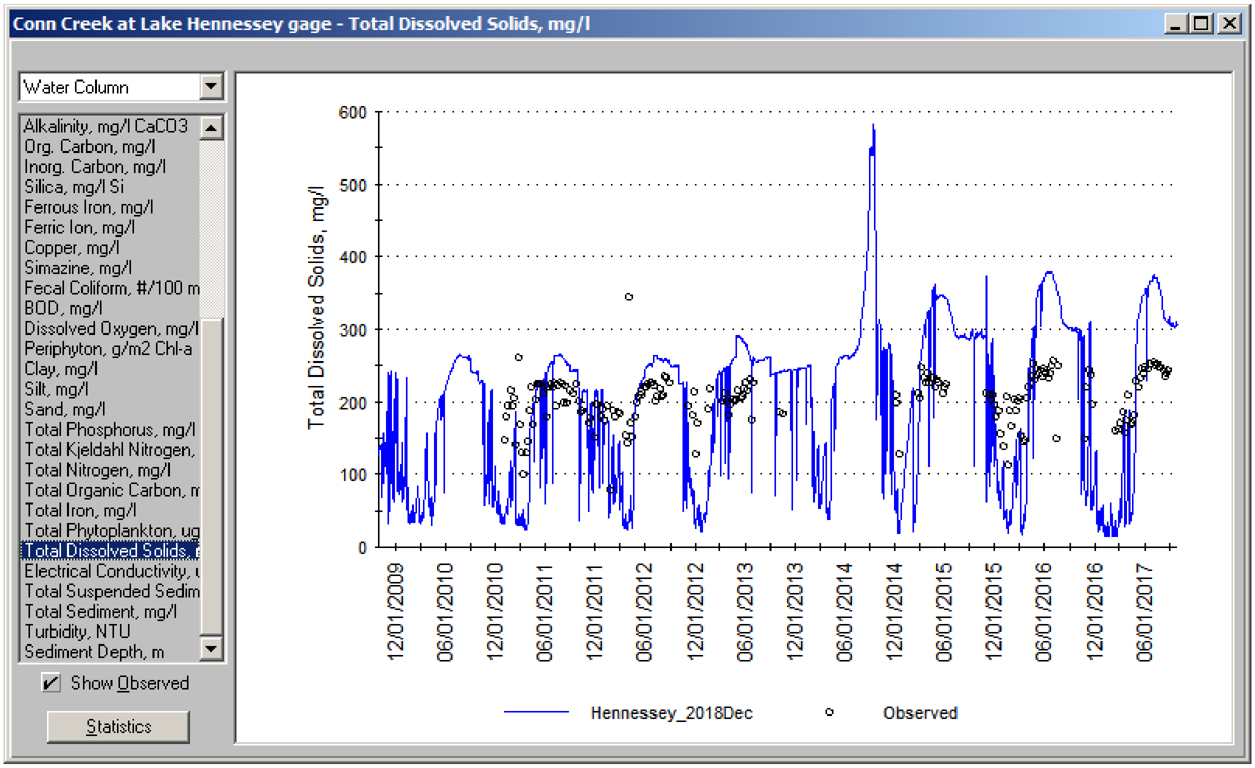


Figure 1.26 Simulated vs Observed Total Dissolved Solids, Conn Creek at Lake Hennessey

Nutrient data for Conn Creek is quite limited, especially for the wet season when the vast majority of nutrient loading to Lake Hennessey occurs. Calibration was performed on the available data, but the accuracy of WARMF simulations during the remainder of the simulation time period is not known. Simulated vs observed ammonia, nitrate, and total phosphorus are shown in Figure 1.27 through Figure 1.29. Note the observed data in 2016. The observed ammonia ranged from 0.008 to 0.093 mg/l N in July and August while on two of the three sampling dates there was zero flow recorded. While the model was calibrated to split the difference between these measurements in the mostly stagnant creek, it is not known how well the model can extrapolate from that data to the wet season when almost all of the loading to the reservoir occurs. There was one data point for measured nitrate in March 2016 which implied a pattern of higher concentration in winter and lower concentration in summer which was followed by the WARMF simulation. There was one measurement of phosphate concentration in March and two in July 2016. The WARMF model was calibrated to have little bias in the simulation of phosphate, but its concentration can change dramatically during storms so additional data collected in winter would help reduce uncertainty in the model's predictions of winter phosphorus loading to the reservoir.

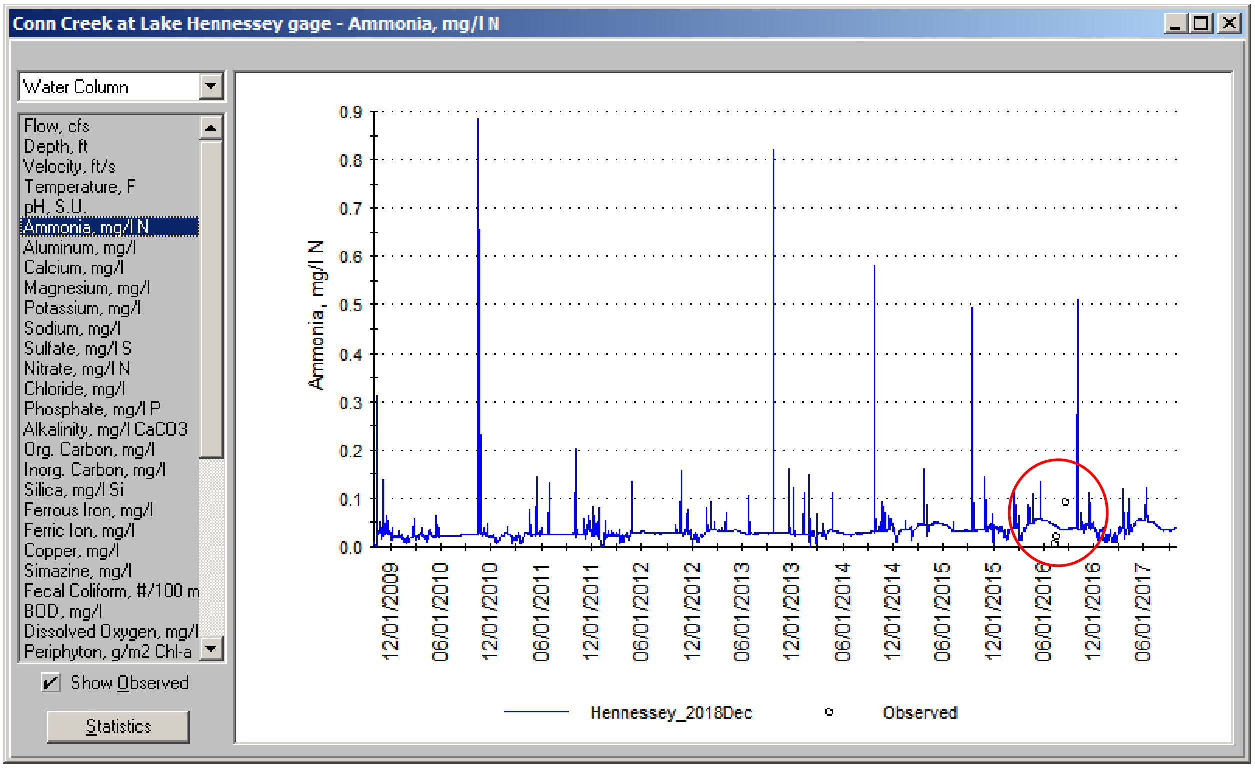


Figure 1.27 Simulated vs Observed Ammonia Nitrogen, Conn Creek at Lake Hennessey

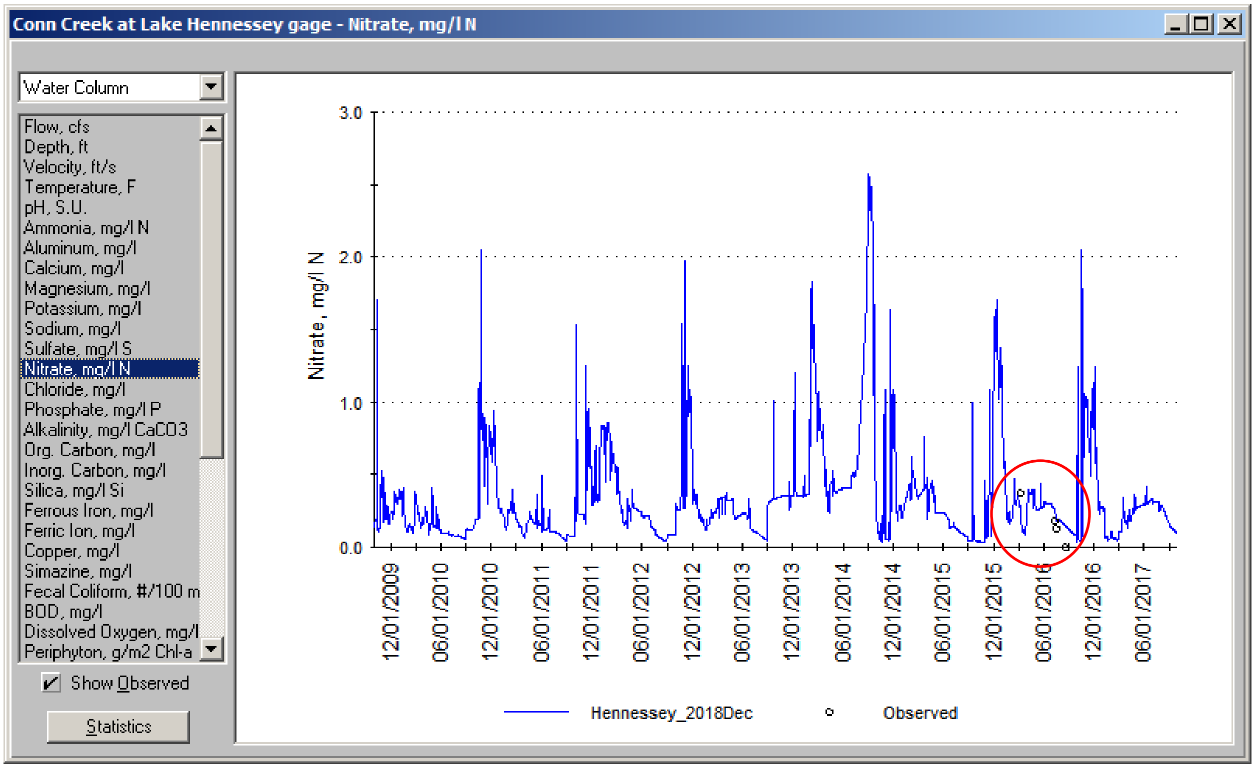


Figure 1.28 Simulated vs Observed Nitrate Nitrogen, Conn Creek at Lake Hennessey

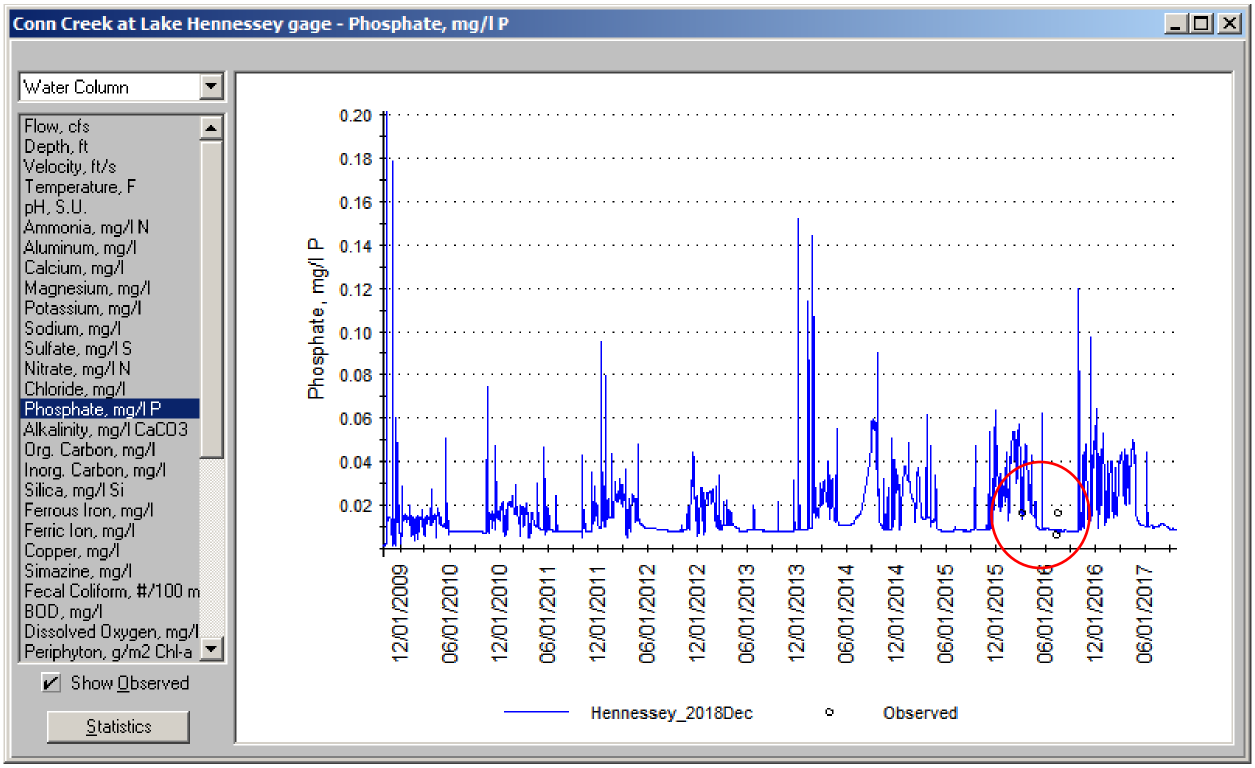


Figure 1.29 Simulated vs Observed Total Phosphorus, Conn Creek at Lake Hennessey

Table 1.11 provides a summary of model errors for each constituent at the Conn Creek at Lake Hennessey monitoring site. Relative errors are very low, but conservative substances have relatively high absolute error. Sulfate and nutrient statistics are provided for consistency, but readers should note that the statistics are based on very few observations. As discussed above, simulated temperature is higher than observed, likely because of the WARMF assumption that solar radiation reaches the creek.

Table 1.11
Summary of Model Errors for Conn Creek at Lake Hennessey

Water Quality Parameter	Relative Error	Absolute Error
Temperature[1]	+2.5 °F	3.7 °F
Turbidity	-3.4 NTU	4.7 NTU
Calcium	-0.2 mg/l	9.3 mg/l
Magnesium	+0.1 mg/l	5.7 mg/l
Sulfate[2]	+2.7 mg/l	5.0 mg/l
Chloride	-0.8 mg/l	8.0 mg/l
Total Dissolved Solids	1.0 mg/l-	82.6 mg/l
Ammonia	+0.00 mg/l N	0.04 mg/l N
Nitrate	+0.05 mg/l N	0.09 mg/l N
Phosphate	+0.00 mg/l P	0.01 mg/l P

1 Temperature statistics exclude data from January – April 2011 and 9/1/2011 which appear to be outliers

2 Sulfate calibration was focused on wet season data, but statistics reflect entire measured data set.

Chiles Creek at Lake Hennessey

The Chiles Creek monitoring station is immediately downstream of the confluence of Chiles Creek and Moore Creek. Moore Creek drains a watershed which is 68% forest, 20% scrubland, 8% grassland, 3% vineyard, and 0.4% developed. The Chiles Creek watershed upstream of Moore Creek is 60% forest, 19% scrubland, 8% grassland, 8.5% vineyards, 3.5% pasture/hay, and 0.9% developed. The soils between the two halves of the watershed are quite different: the Chiles Valley is dominated by thick soils where the surveys did not reach bedrock, while most of the Moore Creek watershed has about 2.5 feet of soil over bedrock.

Figure 1.30 shows the simulated and measured temperature. If the apparent outlier data from 2011 is excluded, there is little bias in the model simulation.

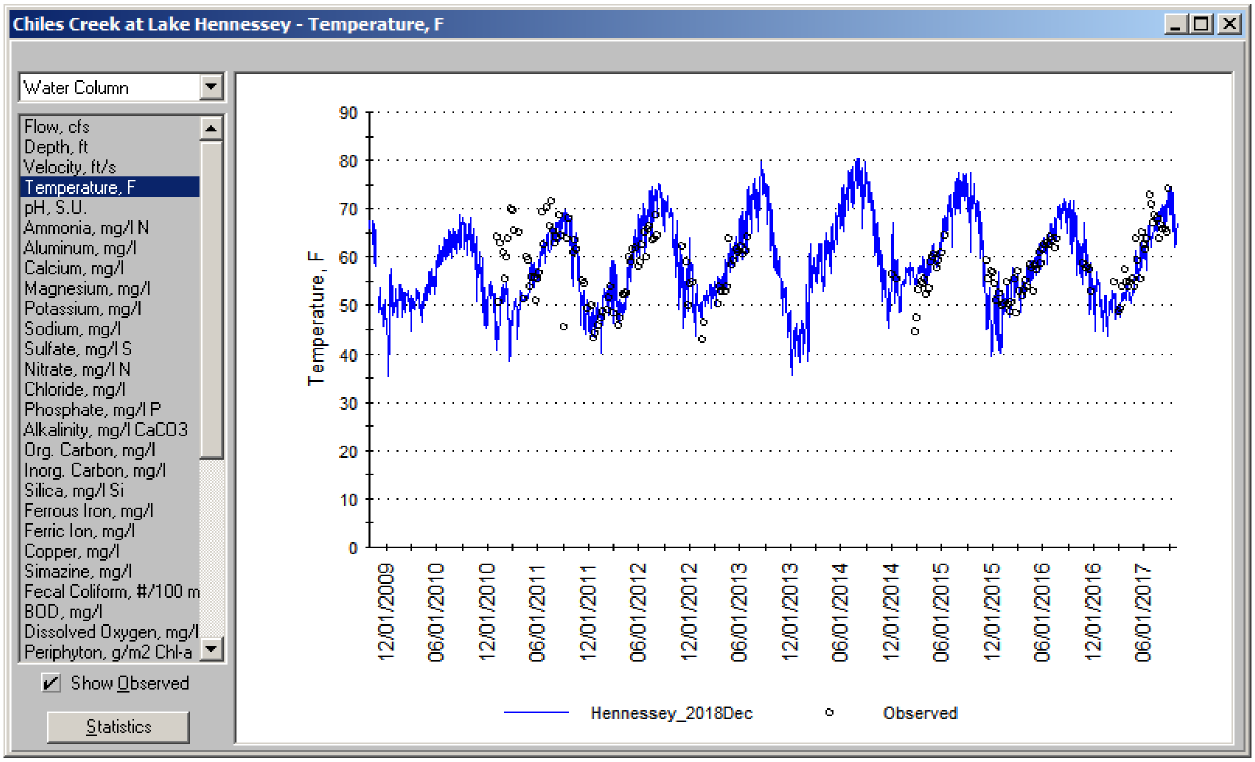


Figure 1.30 Simulated vs Observed Temperature, Chiles Creek at Lake Hennessey

The comparison of turbidity calculated by WARMF and measured turbidity is shown in Figure 1.31. The peak turbidity measurements in January 2016 and January 2012 came after storms which produced measured peak flows of 63 and 24 cfs, much less than the maximum measured flow of 469 cfs. The simulated peak flow for each of those storms was 37 and 23 cfs respectively. Since these storms came after an extended dry period, they may have flushed a large amount of debris into the creeks which was measured as turbidity but not simulated by WARMF. The graph of turbidity during the wet winter of November 2010 through May 2011 (Figure 1.32) shows that samples were not necessarily collected during peak storm flow but WARMF is fairly accurate for the days on which sampling occurred. Collection of continuous data through storms would reduce uncertainty about simulated turbidity (and therefore suspended sediment).

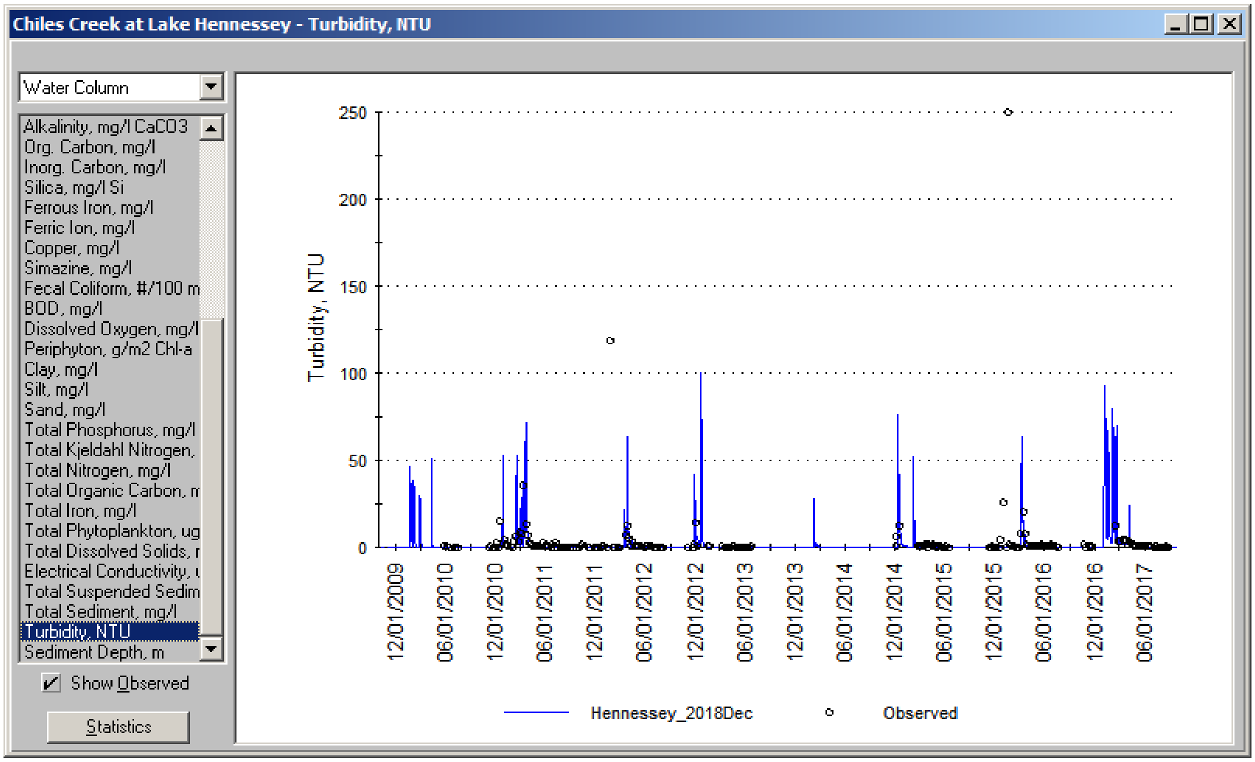


Figure 1.31 Simulated vs Observed Turbidity, Chiles Creek at Lake Hennessey

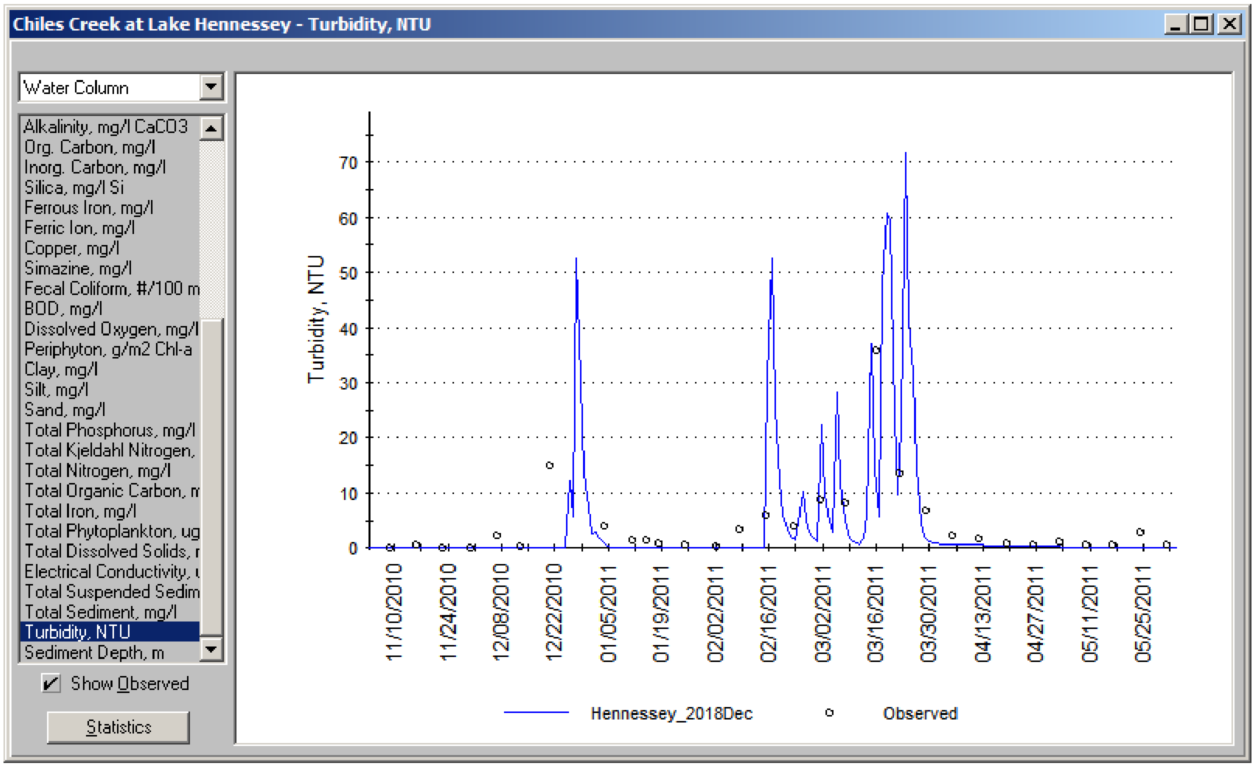


Figure 1.32 Simulated vs Observed Turbidity (11/2010-5/2011), Chiles Ck at Lake Hennessey

The measured data for Chiles Creek has a similar pattern to that observed for Conn Creek: the highest concentrations during low flow, but also relatively high concentrations at high flow. Figure 1.33 through Figure 1.37 compare the simulated concentrations with observed data. WARMF simulations were not able to predict concentrations as high as measured during high flow. Under low flow conditions, WARMF simulated concentrations were often higher than measured data.

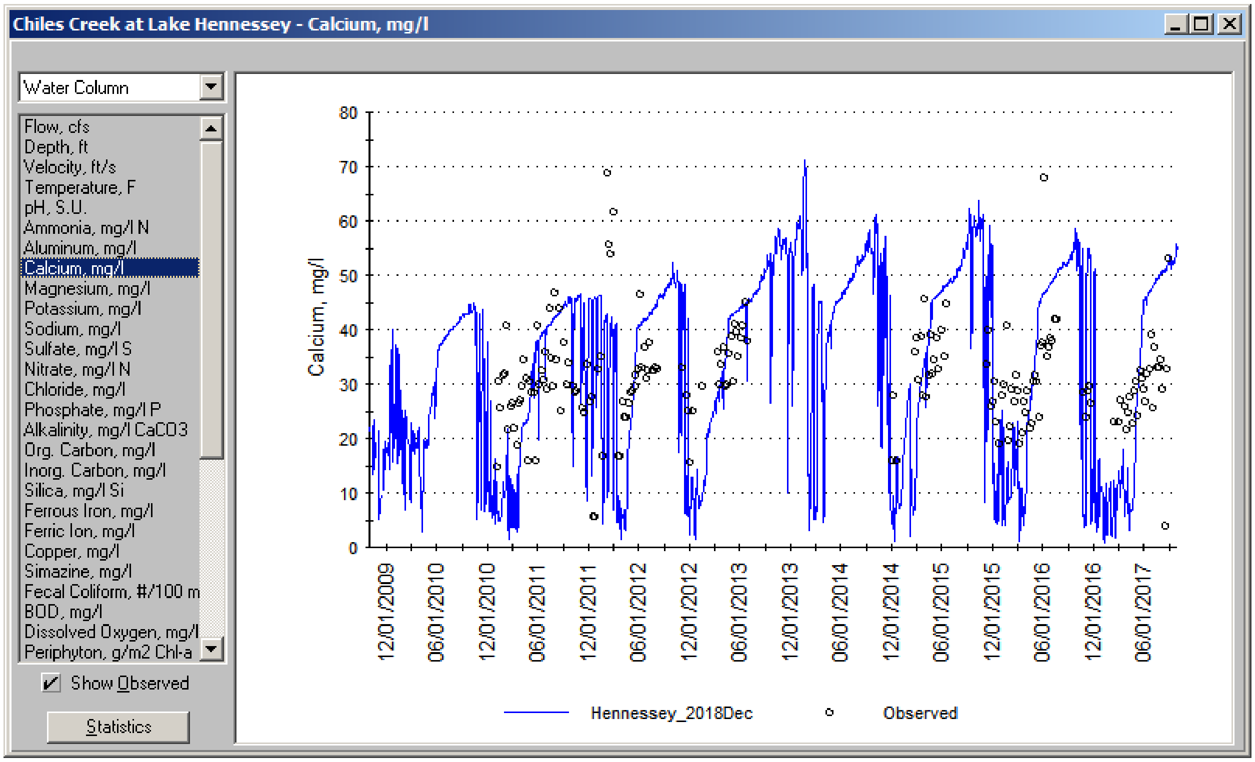


Figure 1.33 Simulated vs Observed Calcium, Chiles Creek at Lake Hennessey

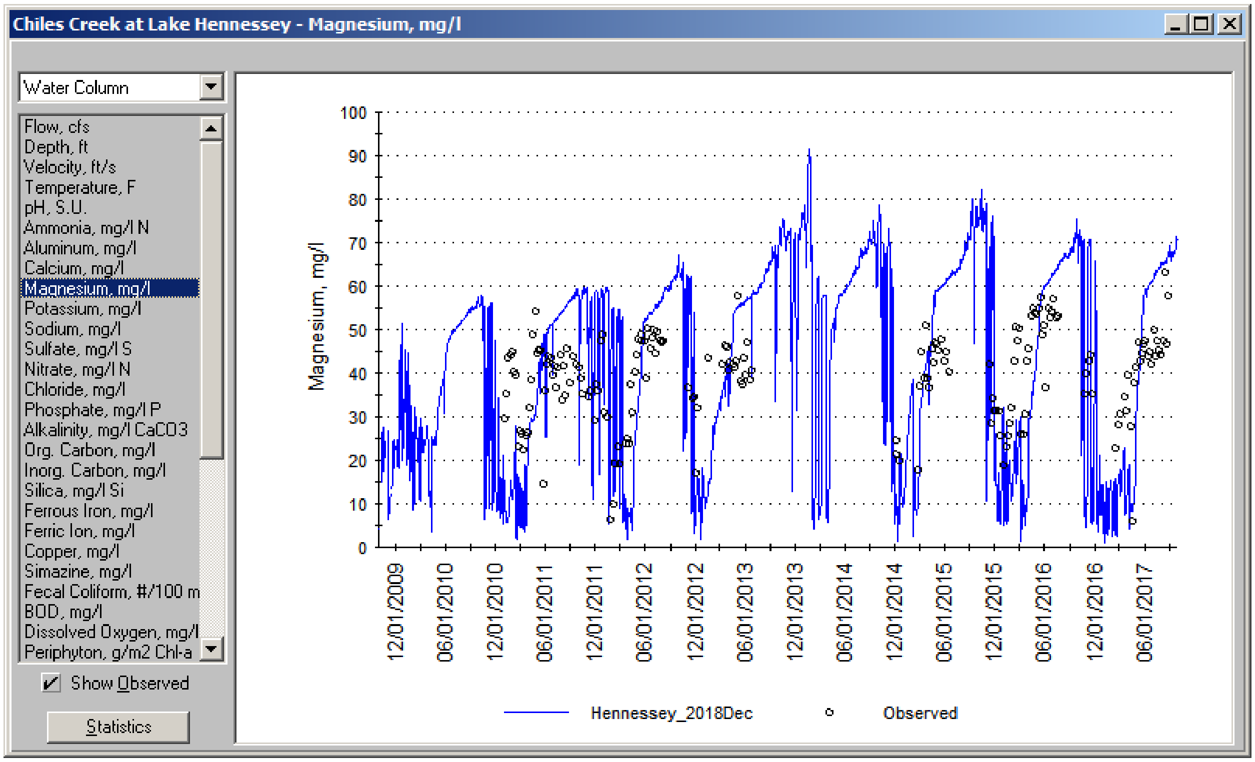


Figure 1.34 Simulated vs Observed Magnesium, Chiles Creek at Lake Hennessey

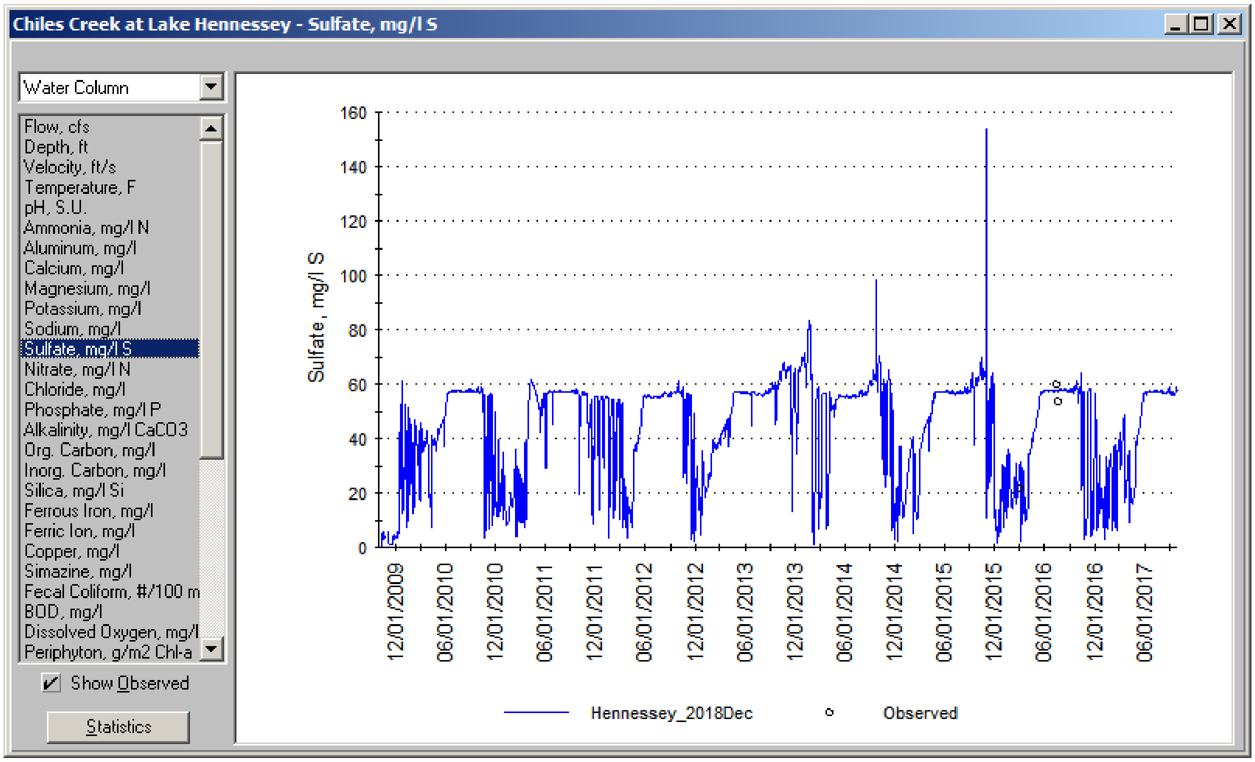


Figure 1.35 Simulated vs Observed Sulfate, Chiles Creek at Lake Hennessey

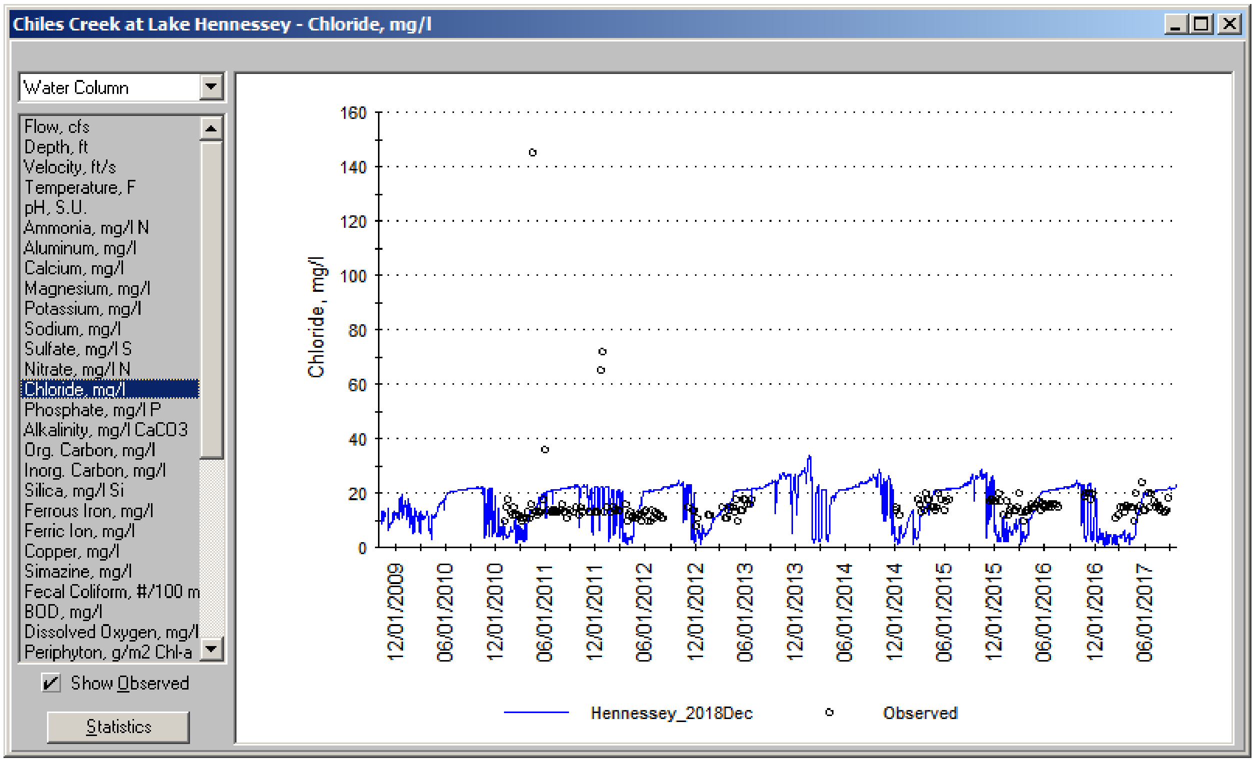


Figure 1.36 Simulated vs Observed Chloride, Chiles Creek at Lake Hennessey

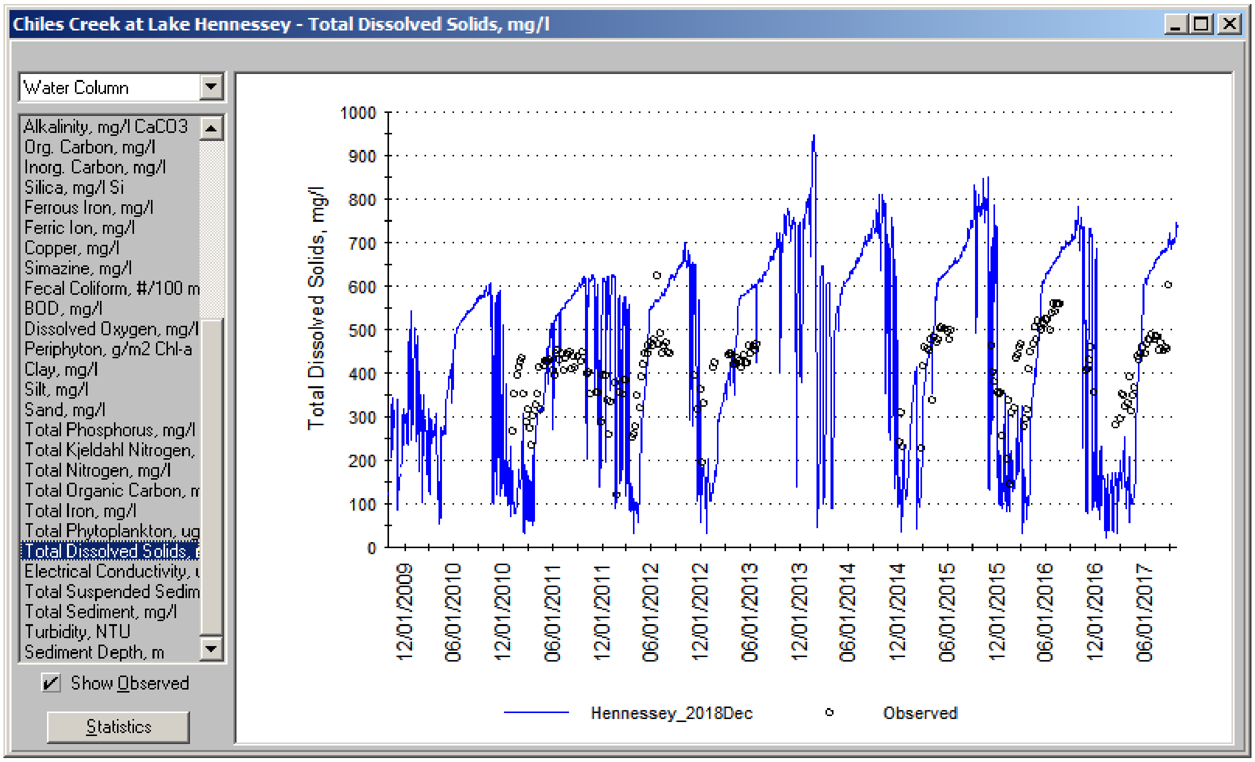


Figure 1.37 Simulated vs Observed Total Dissolved Solids, Chiles Creek at Lake Hennessey

Nutrient data for Chiles Creek is quite limited, especially for the wet season when the vast majority of nutrient loading to Lake Hennessey occurs. Calibration was performed on the available data, but the accuracy of WARMF simulations during the remainder of the simulation time period is not known. Simulated vs observed ammonia, nitrate, and phosphate are shown in Figure 1.38 through Figure 1.40. Note the observed data collected in 2016. The WARMF model calibration is quite accurate for the limited number of measured data points, but the number of observations limits evaluation of the WARMF simulation across seasons and throughout the simulation time period.

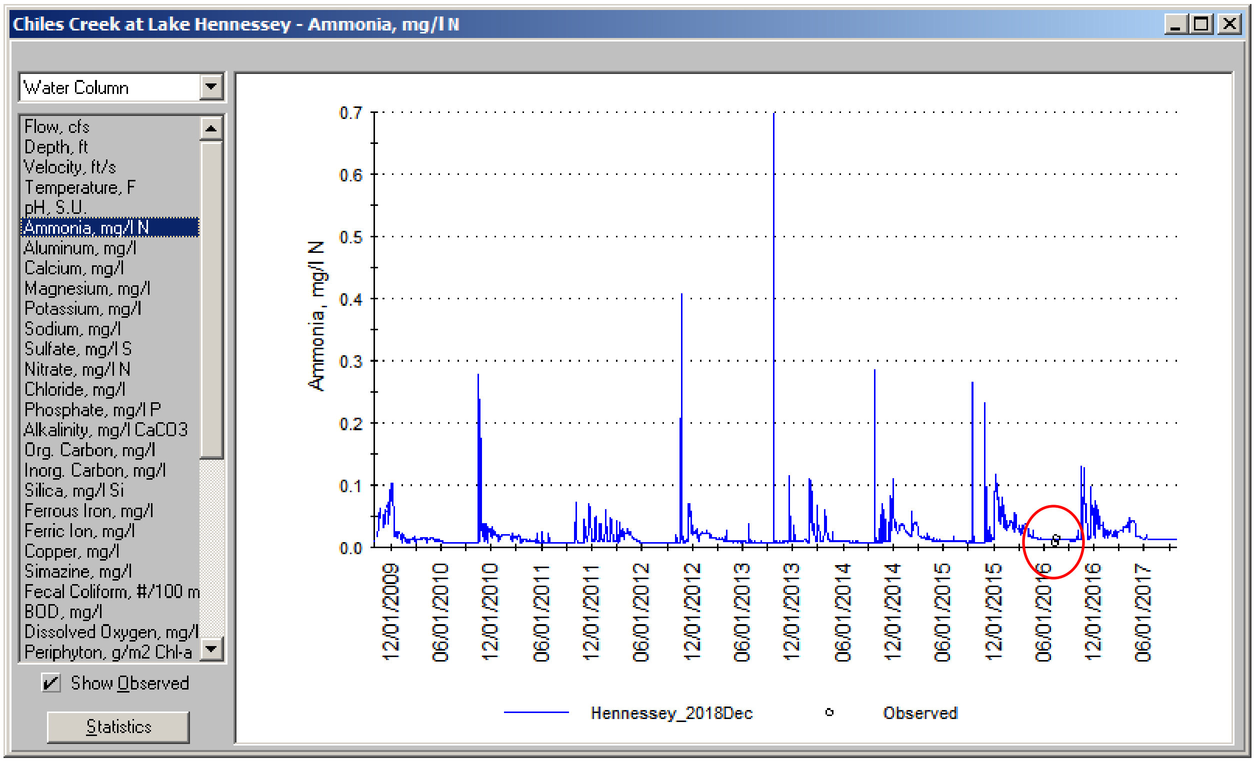


Figure 1.38 Simulated vs Observed Ammonia Nitrogen, Chiles Creek at Lake Hennessey

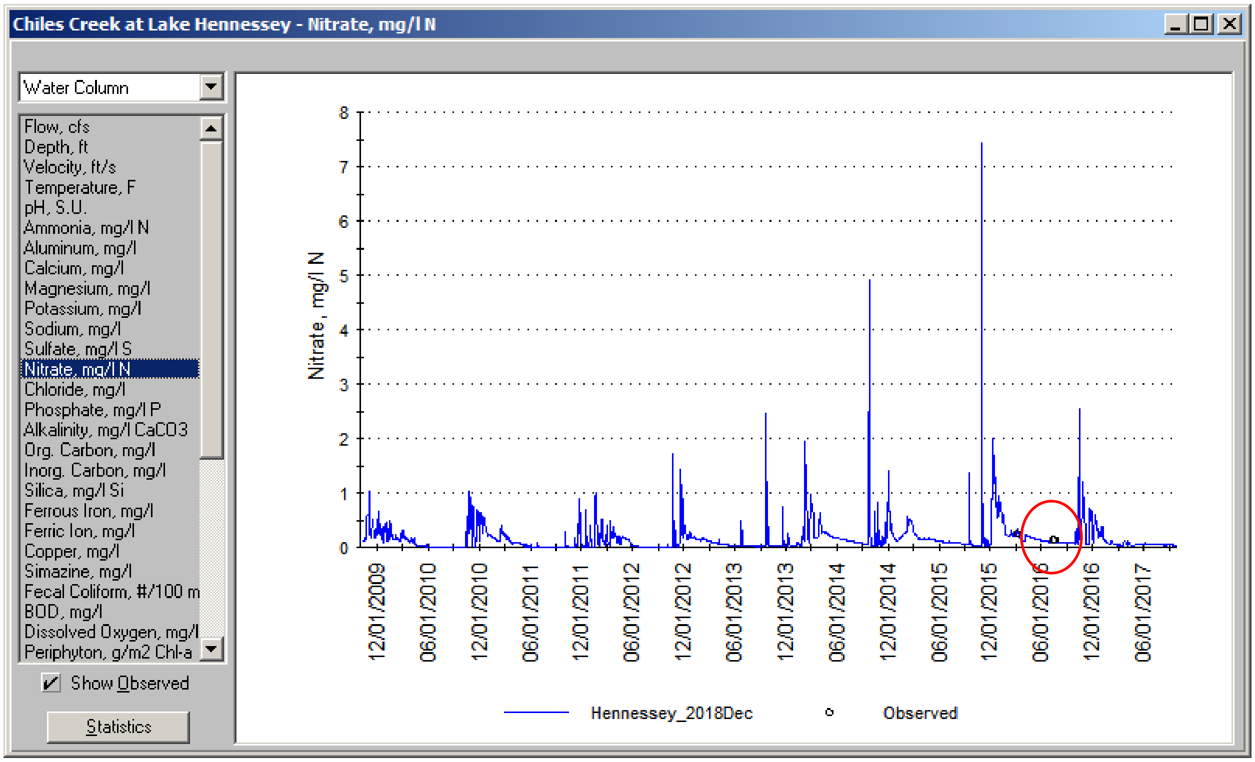


Figure 1.39 Simulated vs Observed Nitrate Nitrogen, Chiles Creek at Lake Hennessey

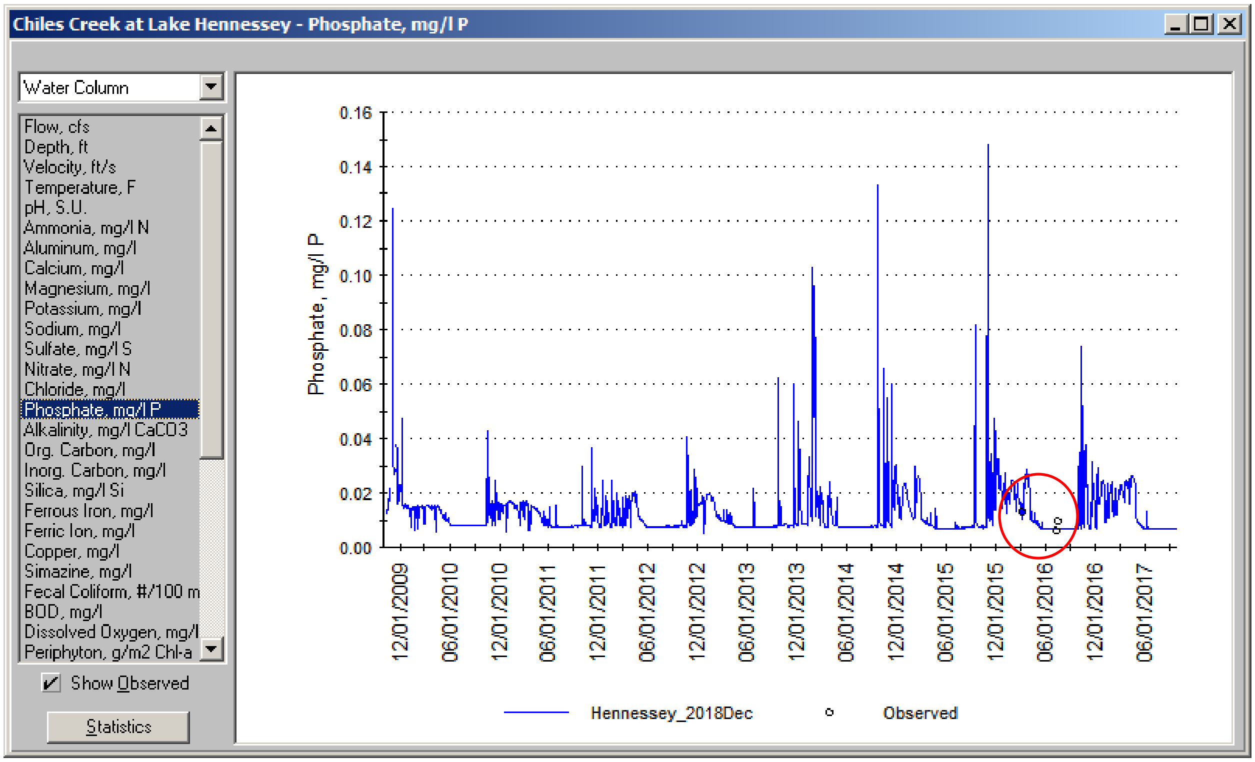


Figure 1.40 Simulated vs Observed Phosphate, Chiles Creek at Lake Hennessey

Table 1.12 provides a summary of model errors for each constituent at the Chiles Creek at Lake Hennessey monitoring site. Relative errors are generally quite low for all constituents, but the absolute error is high for conservative substances: calcium, magnesium, sulfate, chloride, and total dissolved solids. Sulfate and nutrient statistics are provided for consistency, but readers should note that the statistics are based on very few observations.

Table 1.12
Summary of Model Errors for Chiles Creek at Lake Hennessey

Water Quality Parameter	Relative Error	Absolute Error
Temperature[1]	+0.1 °F	3.0 °F
Turbidity	-2.9 NTU	3.3 NTU
Calcium	-0.9 mg/l	12.2 mg/l
Magnesium	-0.5 mg/l	14.4 mg/l
Sulfate	+3.2 mg/l	4.8 mg/l
Chloride	-1.5 mg/l	7.6 mg/l
Total Dissolved Solids	+3.8 mg/l	140 mg/l
Ammonia	+0.00 mg/l	0.00 mg/l
Nitrate	-0.02 mg/l	0.05 mg/l
Phosphate	+0.00 mg/l	0.02 mg/l

1 Temperature statistics exclude apparent outlier data collected January – April 2011 and 9/1/2011

Sage Creek at Lake Hennessey

The watershed of Sage Creek is 60% forested, 9% scrubland, 8% grassland, 10% vineyards, and 8% developed. 90% of the flow in Sage Creek occurs from December through March, and the average flow is less than 0.1 cfs in August and September.

Figure 1.41 shows the simulated and measured temperature. The measured water temperatures higher than 60 °F in winter of 2010-2011 are likely outliers, and in general the simulated temperature in summer is somewhat higher than measured. This is likely because the heat balance performed by WARMF assumes that incoming solar radiation heats the water, but Sage Creek is actually heavily shaded by topography and riparian vegetation.

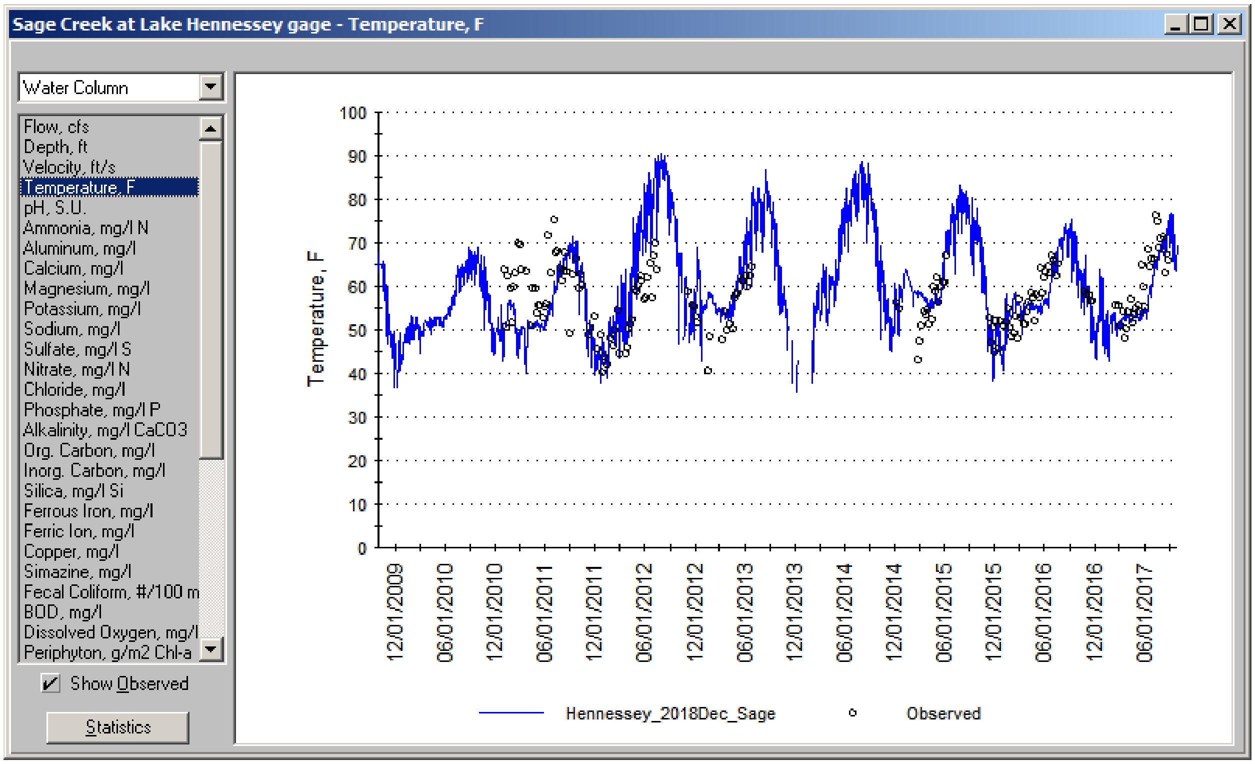


Figure 1.41 Simulated vs Observed Temperature, Sage Creek at Lake Hennessey

The comparison of turbidity calculated by WARMF and measured turbidity is shown in Figure 1.42 and in Figure 1.43. The WARMF simulated peak turbidity in January 2016 is much less than observed but the simulated peak in March is either higher than observed or does not recede as quickly in the simulation as it did in the actual creek. Although it appears from the graph that WARMF is simulating far more turbidity than was measured, this is because observed data were not generally collected during storms. The WARMF simulated turbidity averages somewhat less than measured.

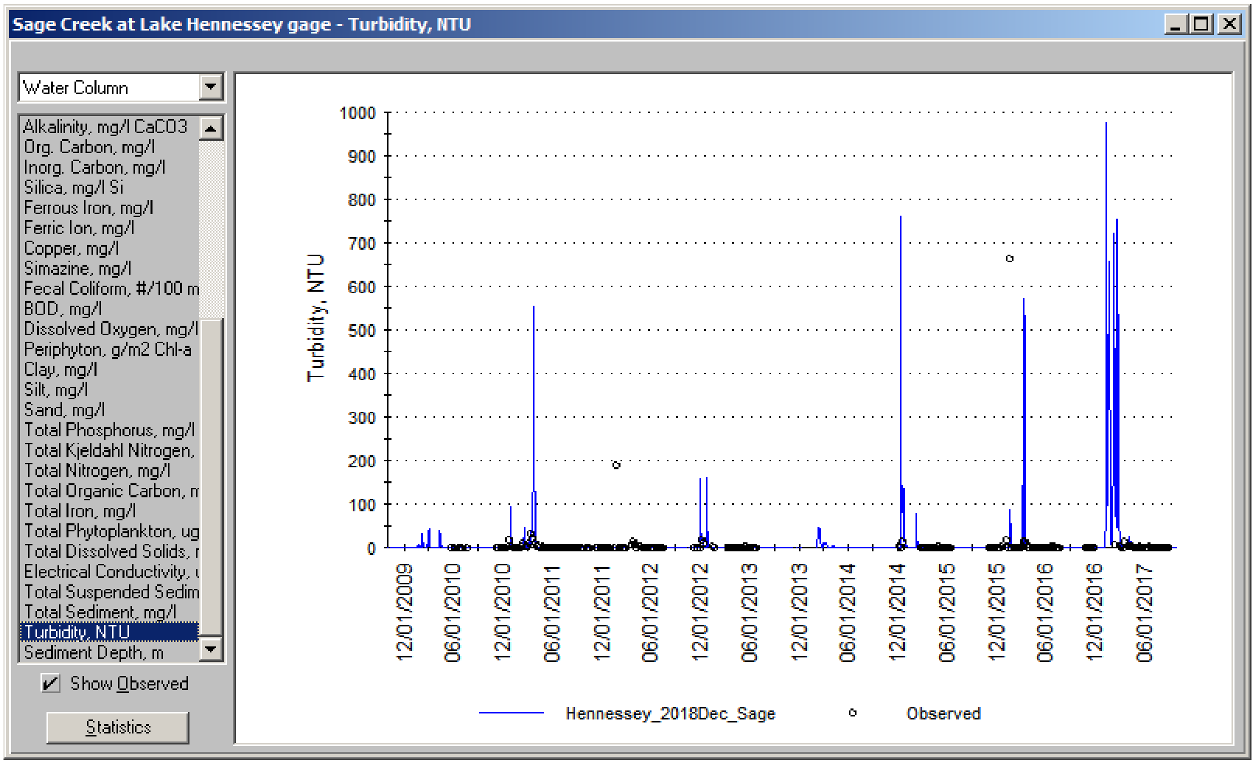


Figure 1.42 Simulated vs Observed Turbidity, Sage Creek at Lake Hennessey

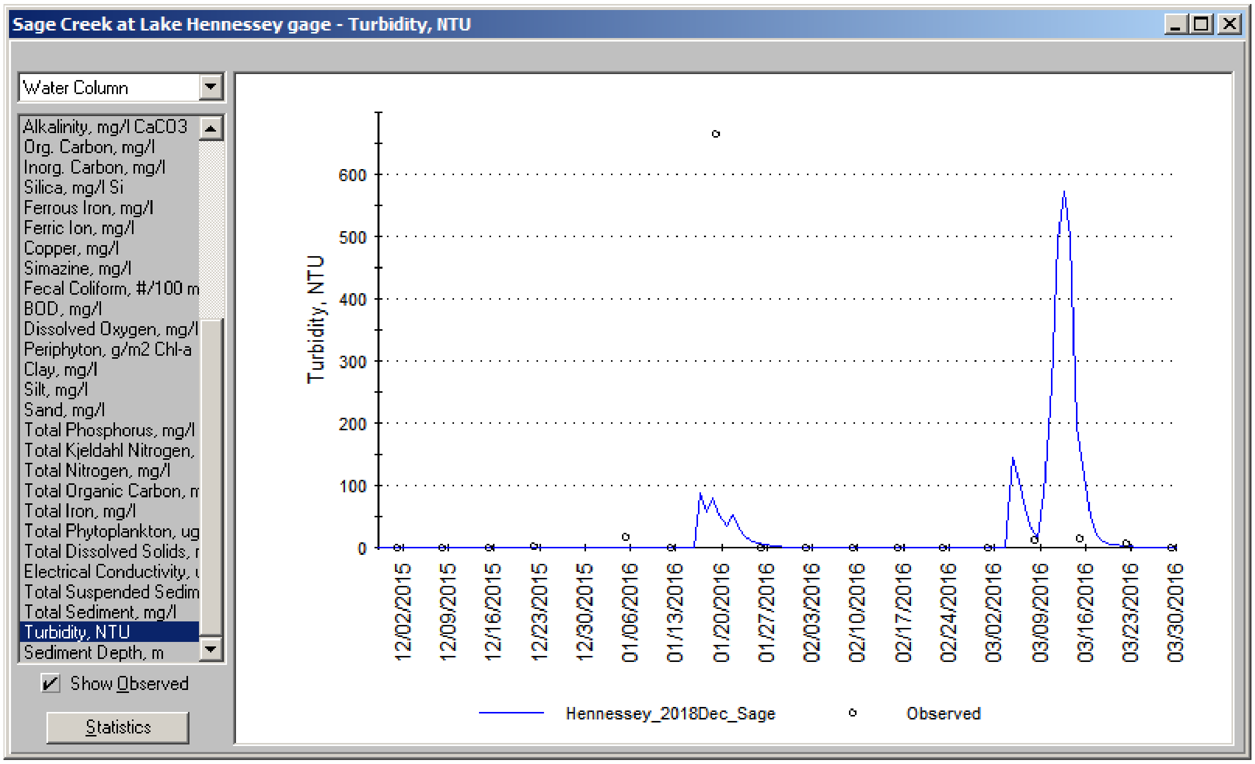


Figure 1.43 Simulated vs Observed Turbidity 12/15-3/16, Sage Creek at Lake Hennessey

In both observed data and WARMF simulation, conservative substances follow the typical pattern of higher concentration in the summer dry season and lower concentration in winter as shown in Figure 1.44 through Figure 1.48. WARMF is able to simulate both the winter and summer concentrations with similar accuracy between summer and winter.

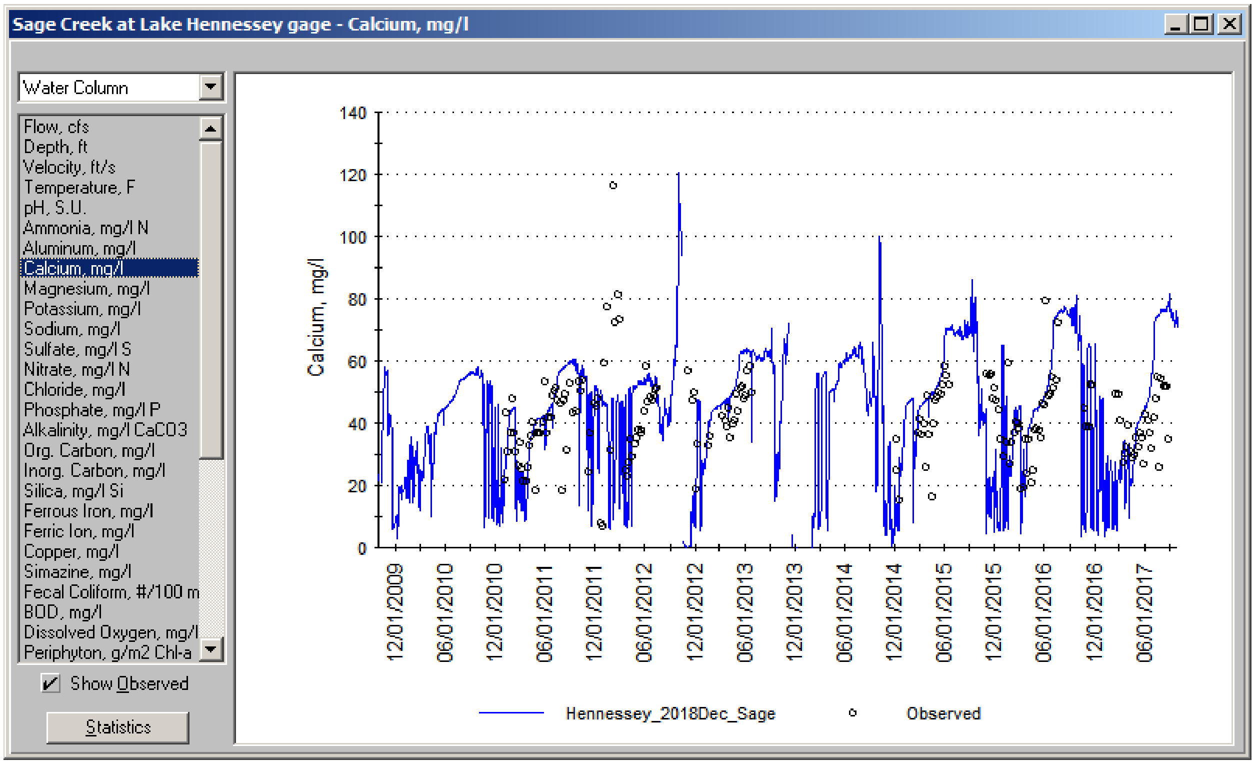


Figure 1.44 Simulated vs Observed Calcium, Sage Creek at Lake Hennessey

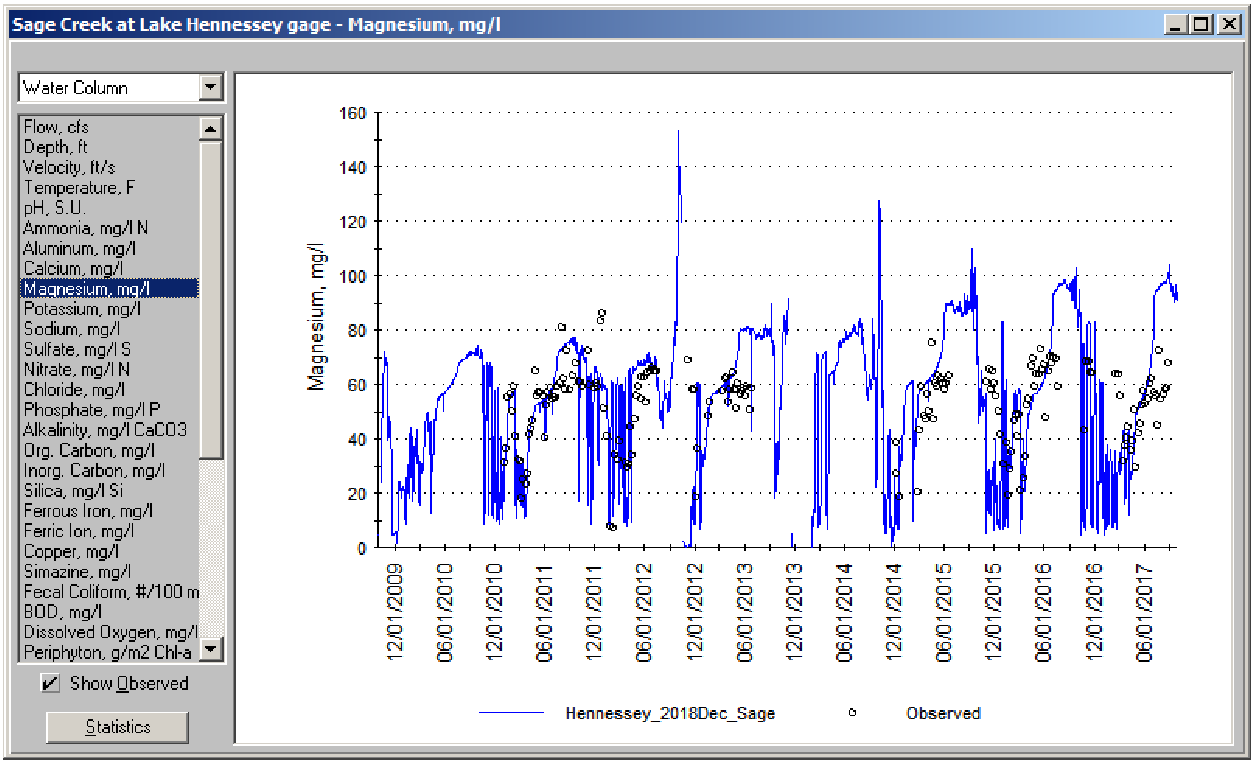


Figure 1.45 Simulated vs Observed Magnesium, Sage Creek at Lake Hennessey

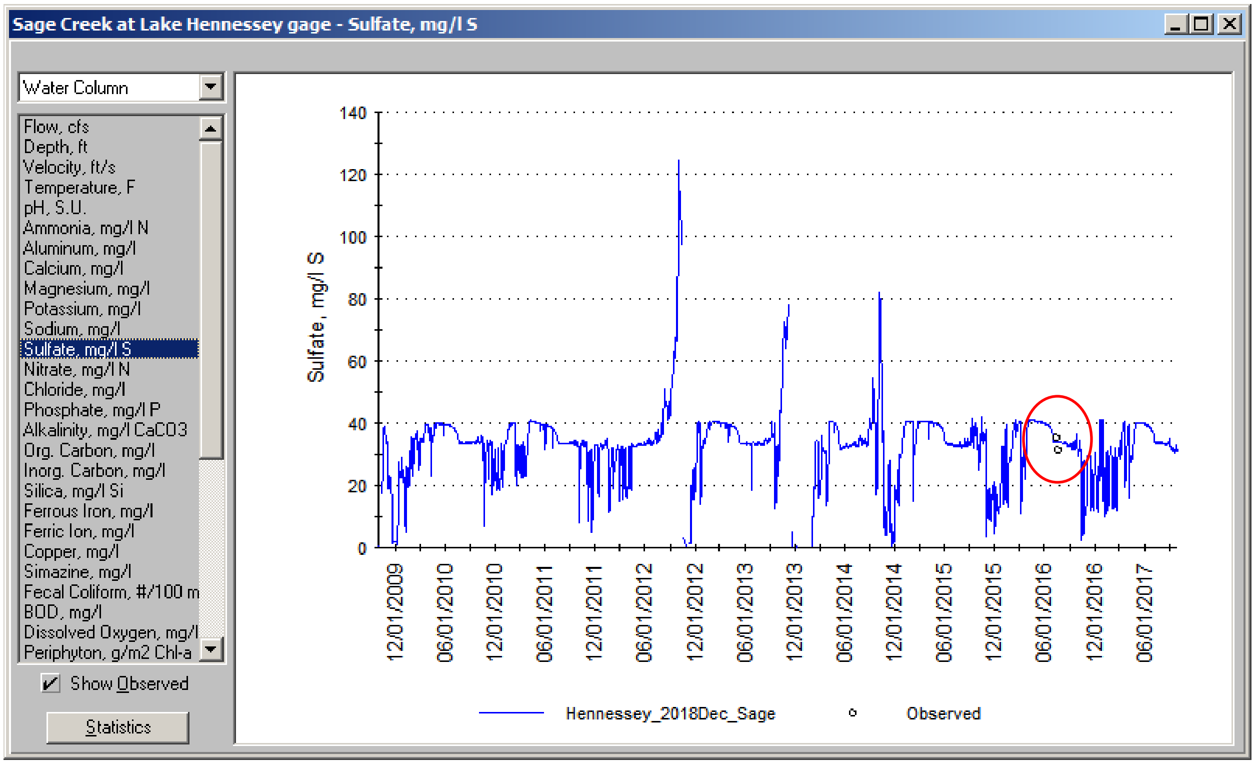


Figure 1.46 Simulated vs Observed Sulfate, Sage Creek at Lake Hennessey

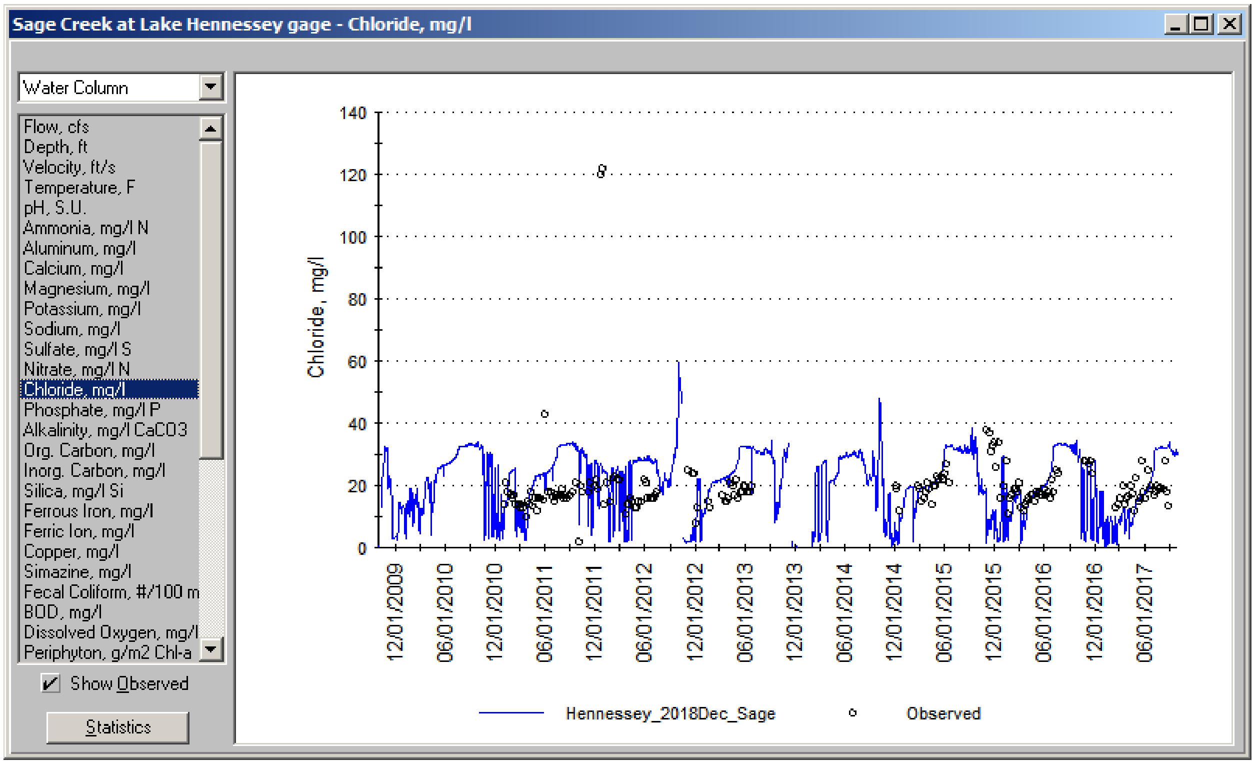


Figure 1.47 Simulated vs Observed Chloride, Sage Creek at Lake Hennessey

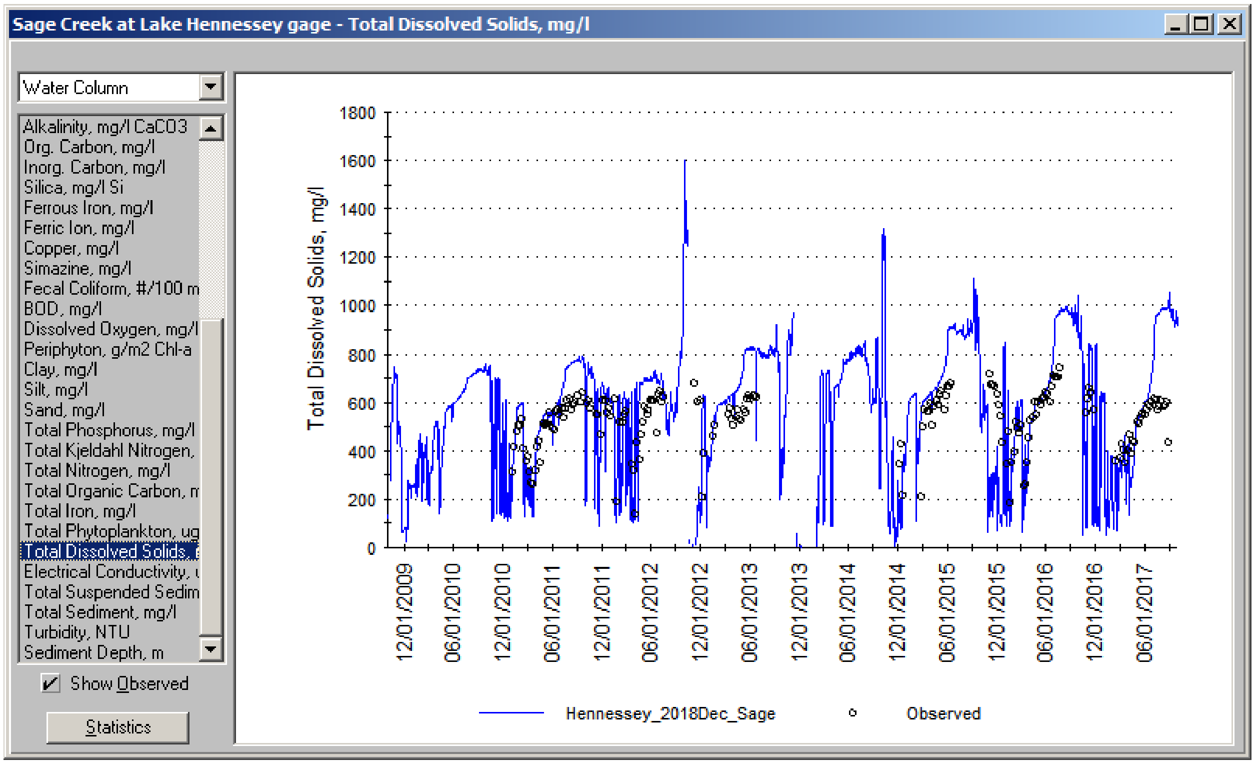


Figure 1.48 Simulated vs Observed Total Dissolved Solids, Sage Creek at Lake Hennessey

Nutrient data for Sage Creek is quite limited, especially for the wet season when the vast majority of nutrient loading to Lake Hennessey occurs. Calibration was performed on the available data, but the accuracy of WARMF simulations during the rest of the simulation time period is not known. Simulated vs observed ammonia, nitrate, and phosphate are shown in Figure 1.49 through Figure 1.51. Note the observed data in 2016. The model was calibrated to match the data closely.

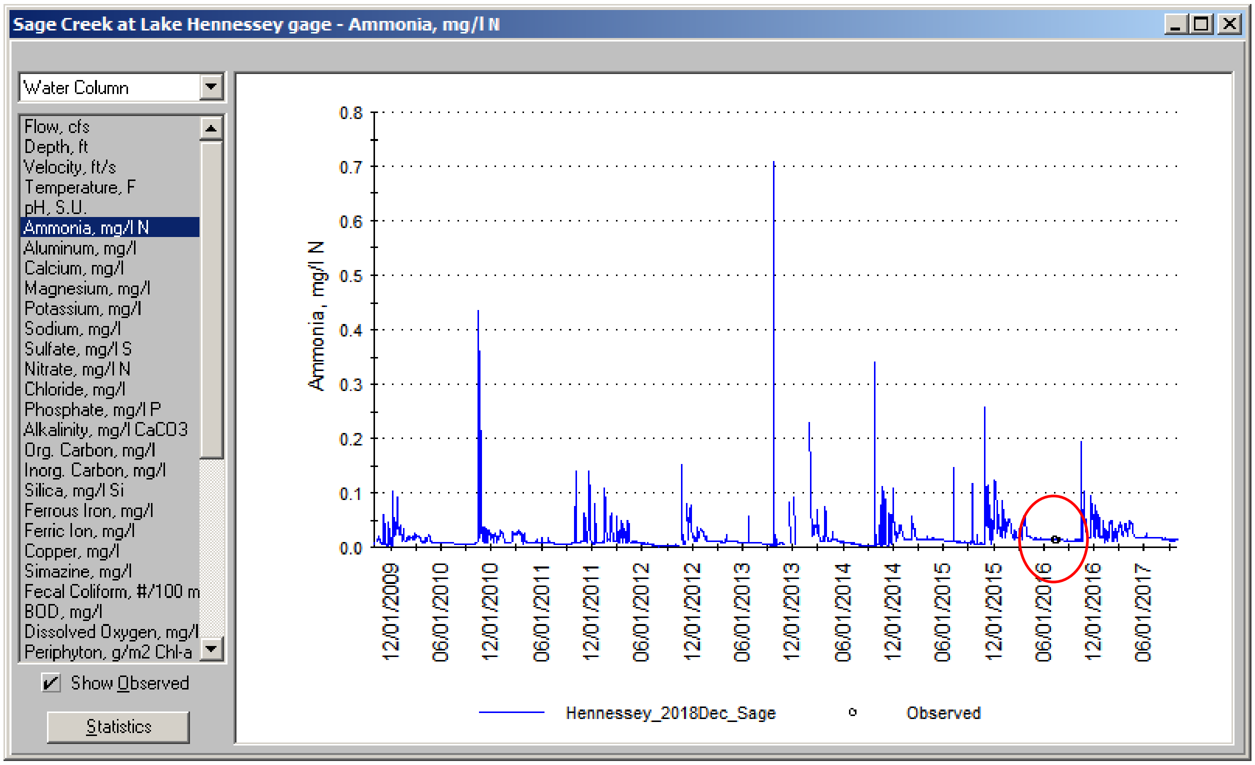


Figure 1.49 Simulated vs Observed Ammonia Nitrogen, Sage Creek at Lake Hennessey

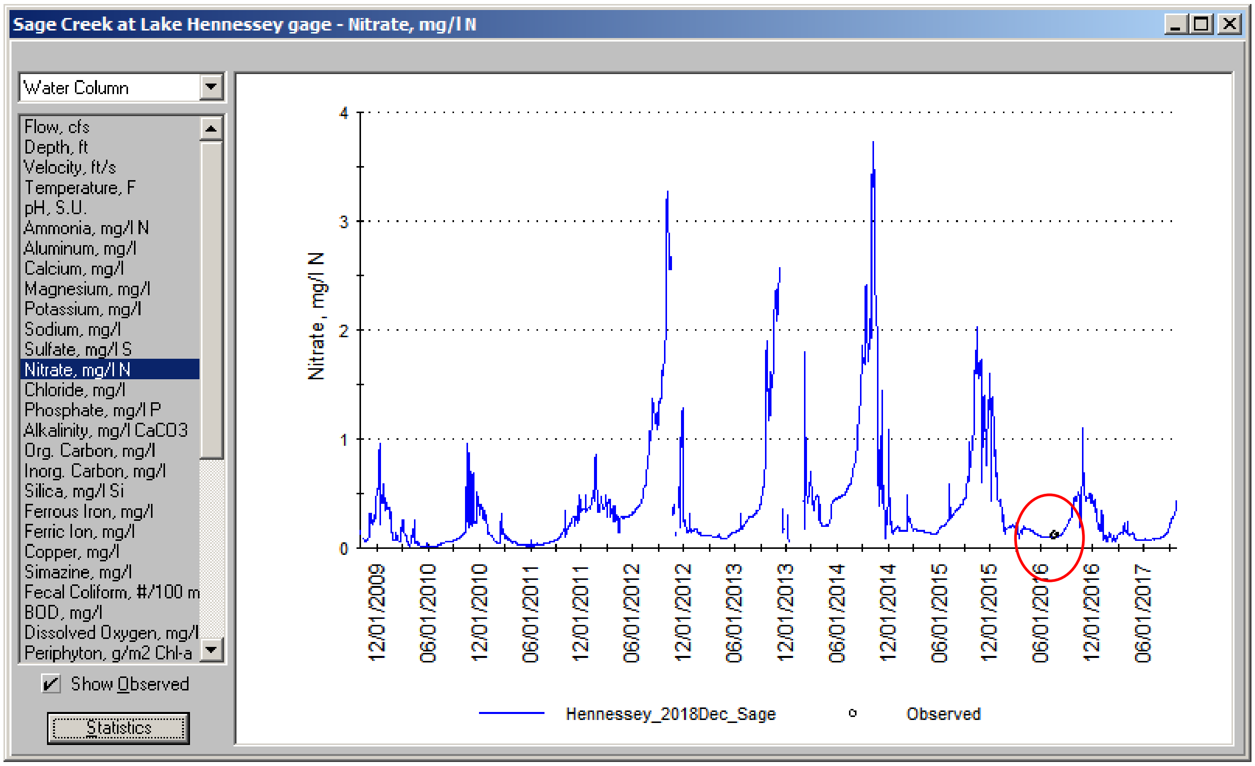


Figure 1.50 Simulated vs Observed Nitrate Nitrogen, Sage Creek at Lake Hennessey

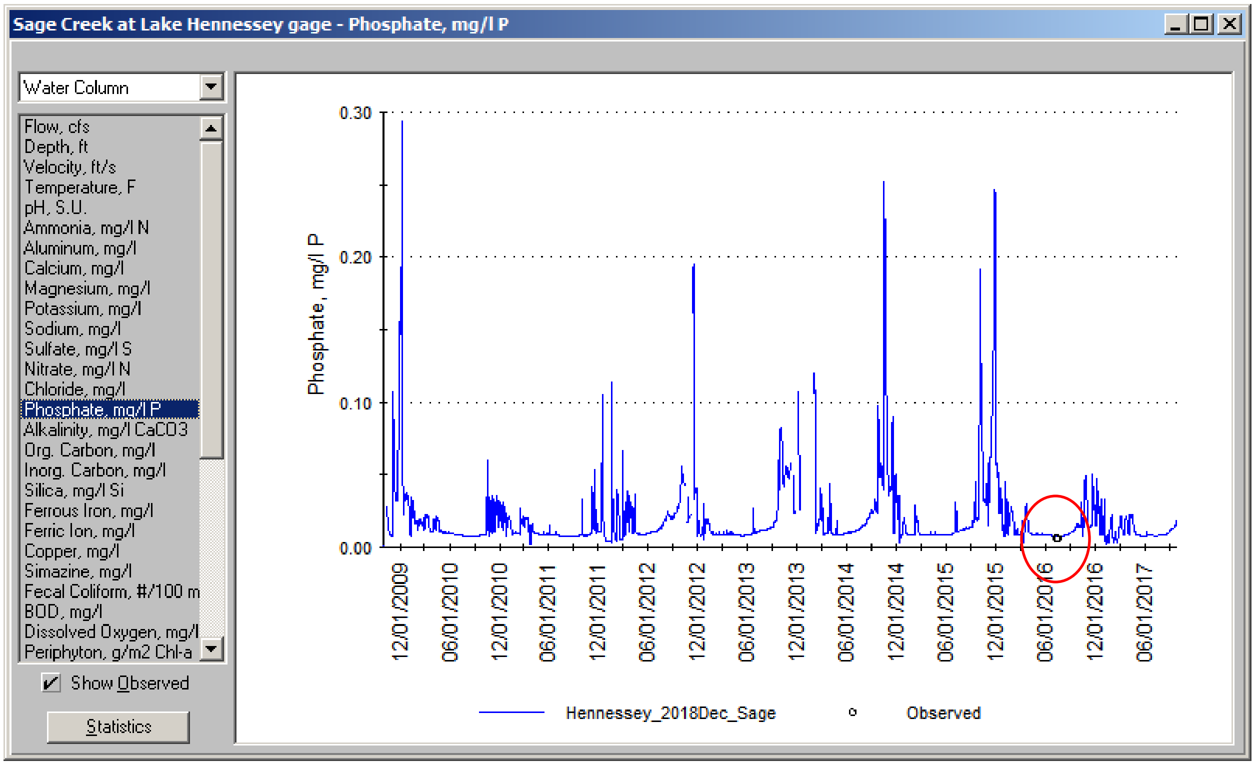


Figure 1.51 Simulated vs Observed Phosphate, Sage Creek at Lake Hennessey

Table 1.13 provides a summary of model errors for each constituent at the Sage Creek at Lake Hennessey monitoring site. Relative errors are low, but absolute errors are higher for those constituents with long observed data records. Readers should note that statistics generated for sulfate and nutrients are based on very few observations.

Table 1.13
Summary of Model Errors for Sage Creek at Lake Hennessey

Water Quality Parameter	Relative Error	Absolute Error
Temperature[1]	+ 0.9 °F	5.2 °F
Turbidity	-2.0 NTU	8.0 NTU
Calcium	+0.3 mg/l	14.2 mg/l
Magnesium	+0.9 mg/l	14.2 mg/l
Sulfate	+0.4 mg/l	2.2 mg/l
Chloride	+0.1 mg/l	9.5 mg/l
Total Dissolved Solids	+30.3 mg/l	139 mg/l
Ammonia	+ 0.00 mg/l	0.00 mg/l
Nitrate	-0.02 mg/l N	0.02 mg/l N
Phosphate	+0.00 mg/l P	0.00 mg/l P

1 Temperature statistics exclude January – April 2016 and 9/1/2016 data which appear to be outliers

Milliken Creek near Walt Ranch

The watershed of Milliken Reservoir is 43% forested, 35% scrubland, 11% grassland, 9% vineyards, and 1% developed. 86% of the flow in Conn Creek occurs from December through March, and the average flow is less than 0.1 cfs in July, August and September. A limited amount of water quality data were collected for Milliken Creek at locations upstream and downstream of the Walt Ranch planned vineyard development in March-April 2016 and was used for initial water quality calibration.

Figure 1.52 shows the simulated and measured temperature. The measured water temperature was higher than the simulated temperature in March 2016 but lower than simulated in April 2016 at both the monitoring locations on Milliken Creek.

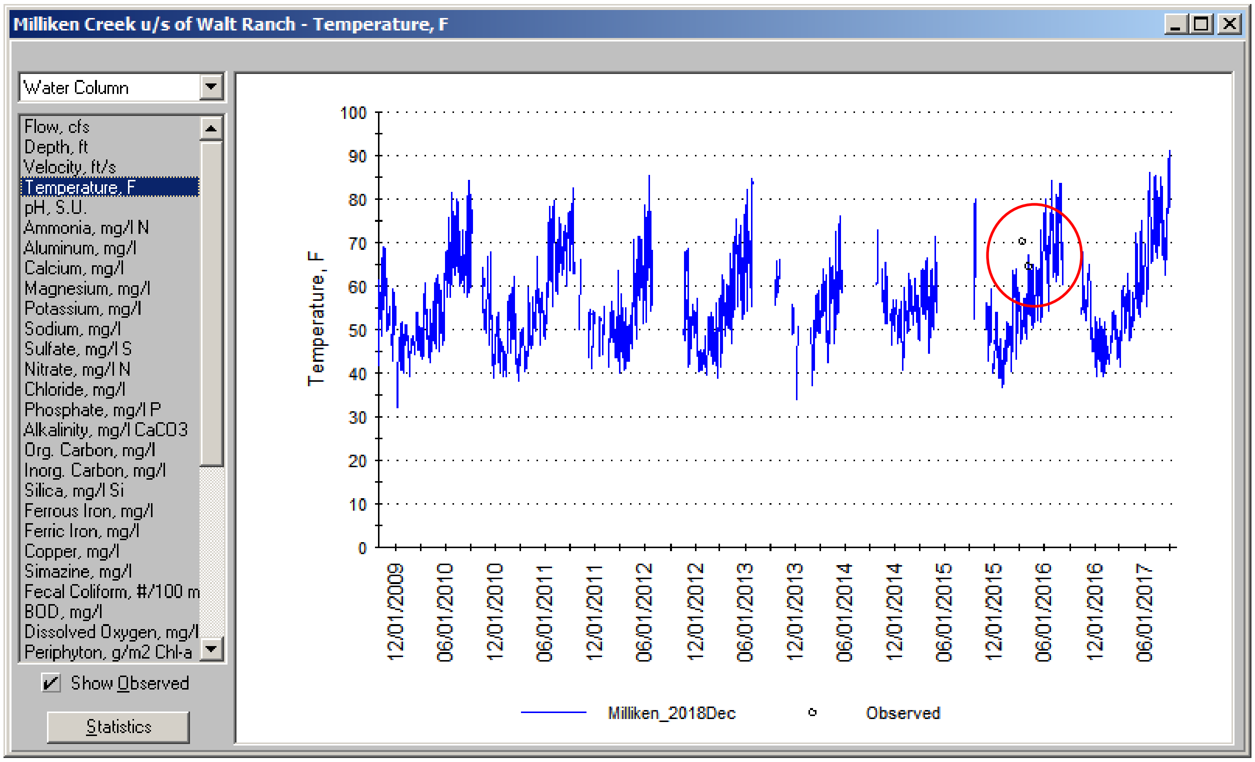


Figure 1.52 Simulated vs Observed Temperature, Milliken Creek near Walt Ranch

The comparison of turbidity calculated by WARMF and measured turbidity across the entire modeling time period is shown in Figure 1.53. Figure 1.54 shows the simulation during the time period when the two observations were recorded. Note that the observed data were not collected during the turbidity peak but the simulated turbidity was close to the observations on the days when turbidity levels were recorded.

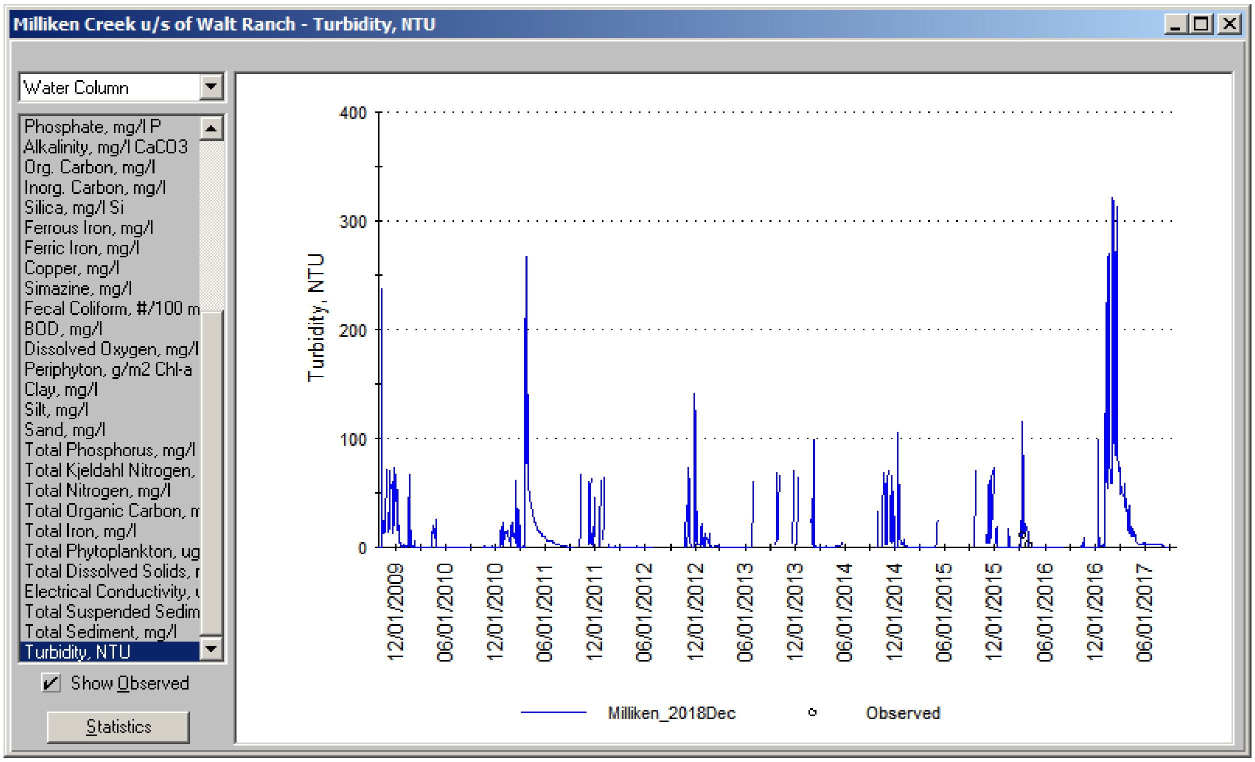


Figure 1.53 Simulated vs Observed Turbidity, Milliken Creek near Walt Ranch

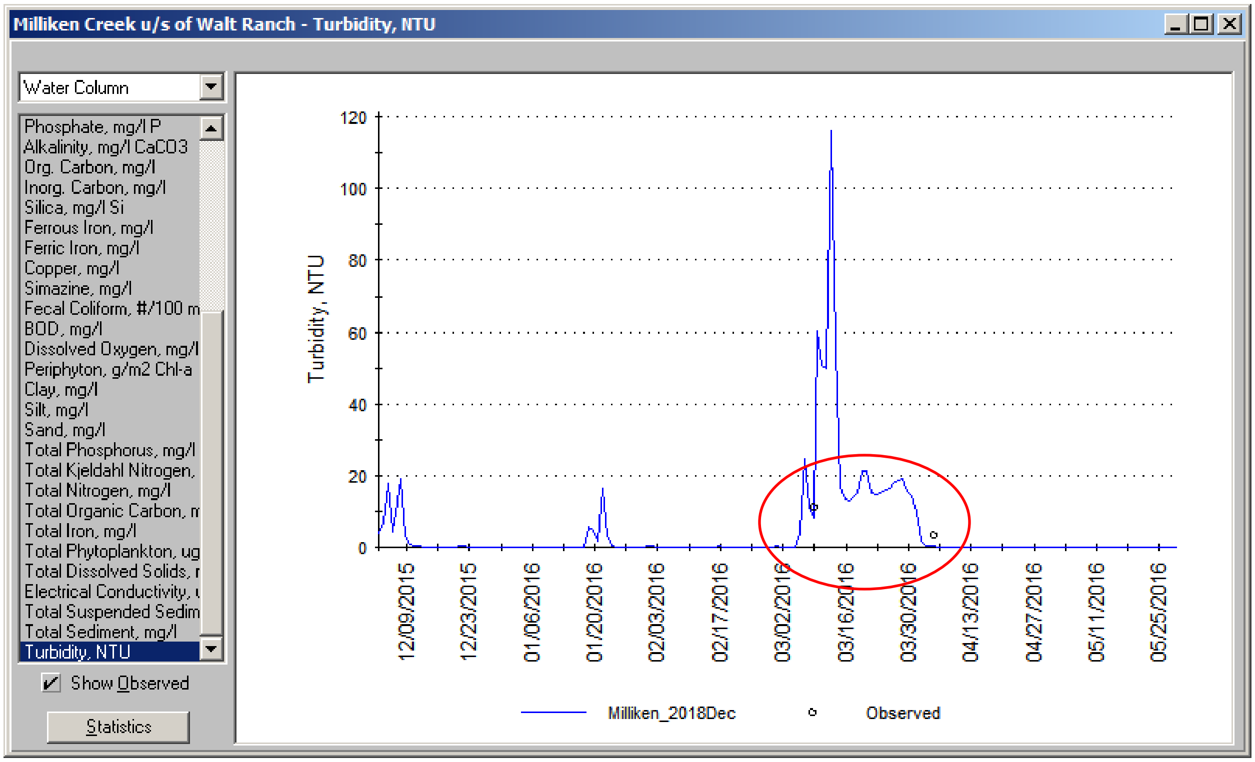


Figure 1.54 Simulated vs Observed Turbidity 12/15-5/16, Milliken Creek near Walt Ranch

The seasonal pattern of conservative substances in Milliken Creek is not discernible from the limited data. WARMF was calibrated to match the existing data, and to simulate a seasonal concentration pattern similar to the creeks that flow into Lake Hennessey.

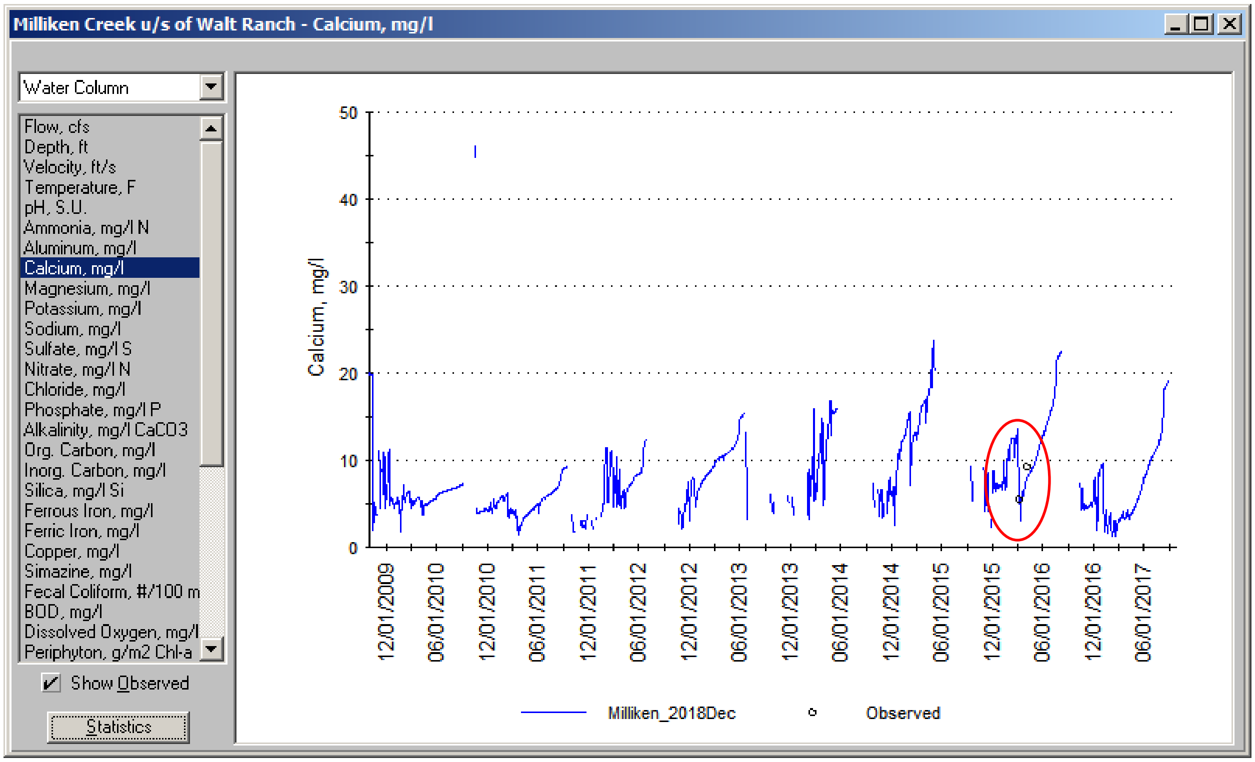


Figure 1.55 Simulated vs Observed Calcium, Milliken Creek near Walt Ranch

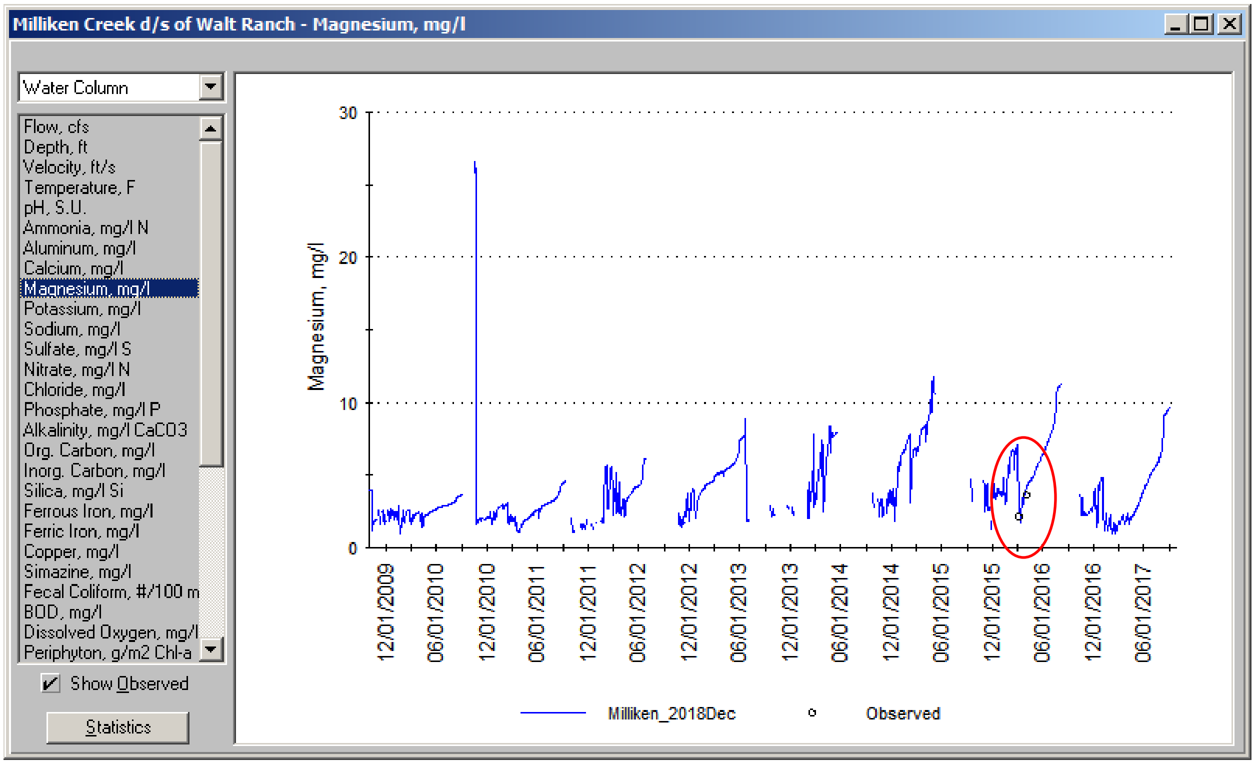


Figure 1.56 Simulated vs Observed Magnesium, Milliken Creek near Walt Ranch

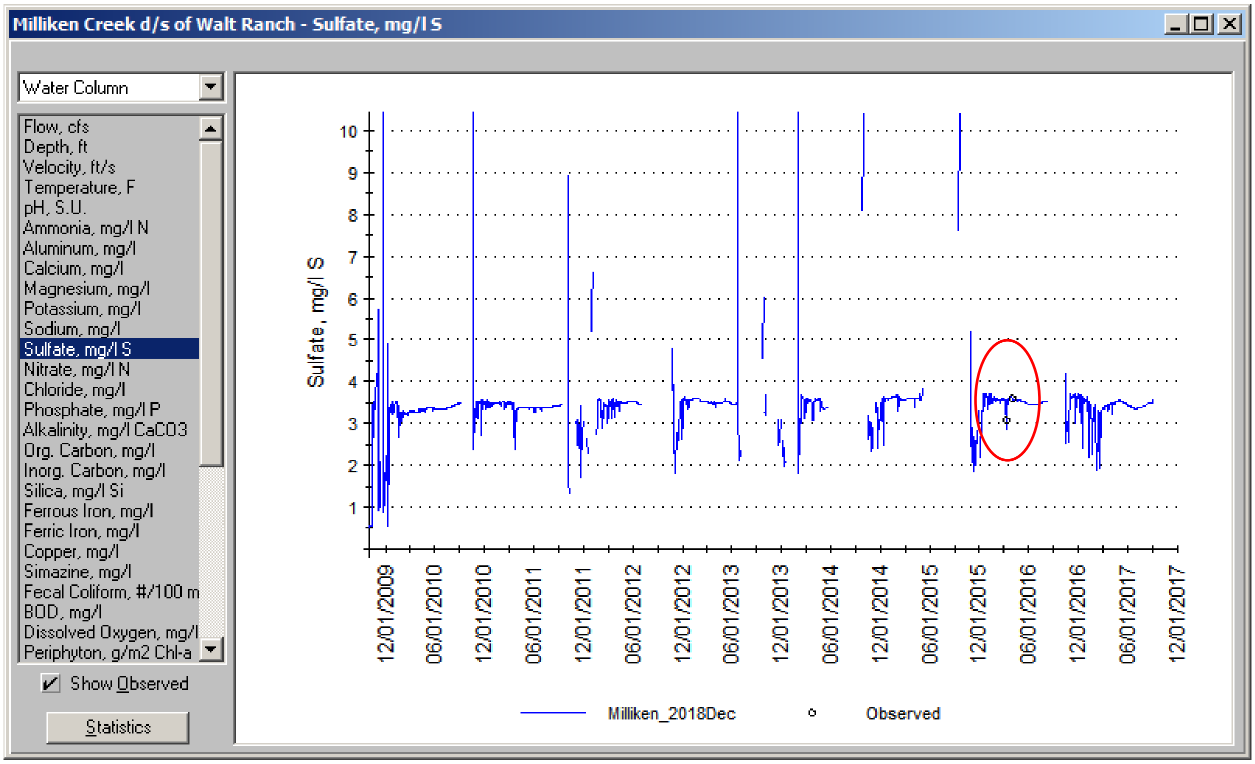


Figure 1.57 Simulated vs Observed Sulfate, Milliken Creek near Walt Ranch

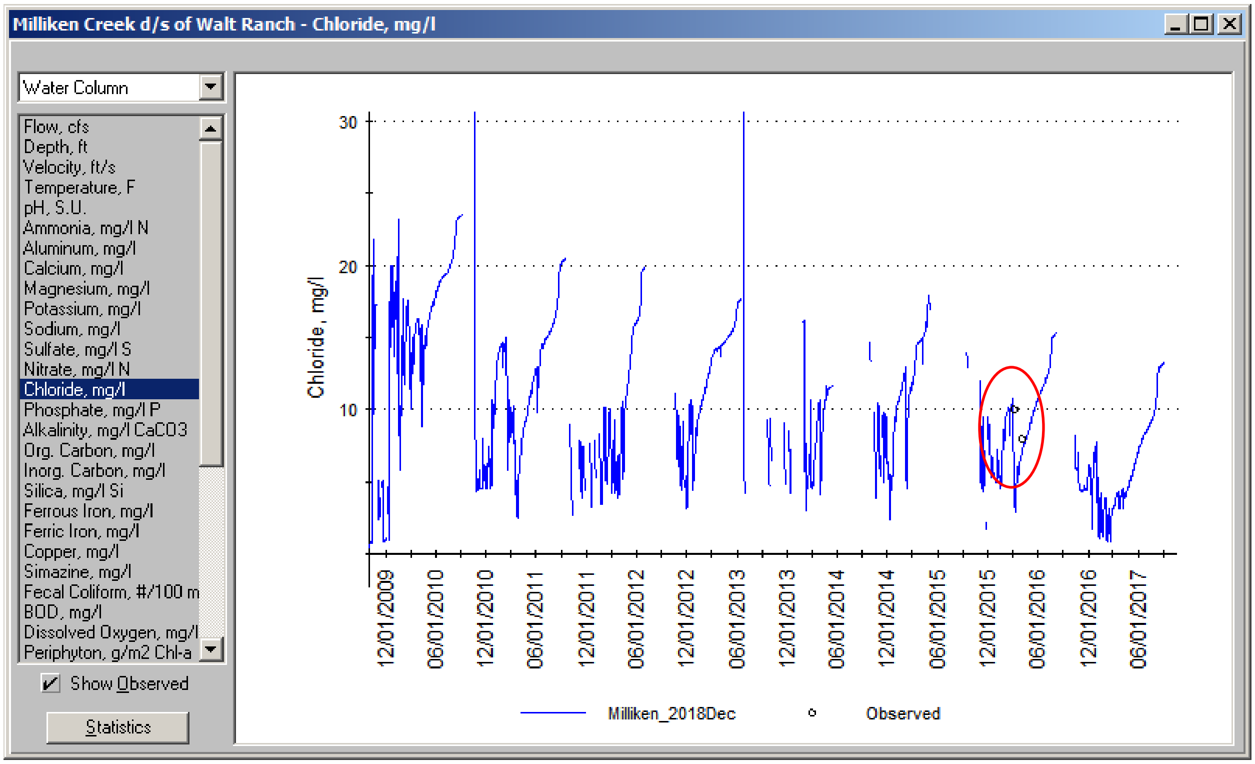


Figure 1.58 Simulated vs Observed Chloride, Milliken Creek near Walt Ranch

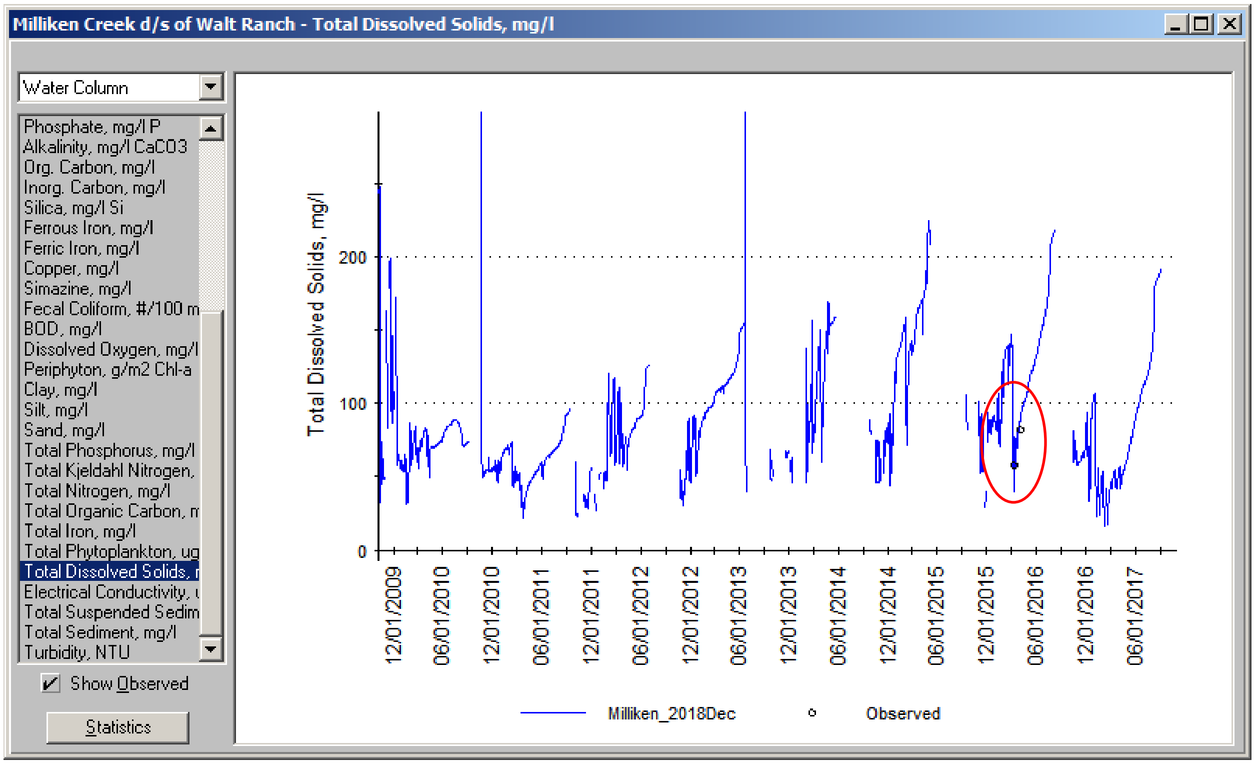


Figure 1.59 Simulated vs Observed Total Dissolved Solids, Milliken Creek near Walt Ranch

Simulated vs observed (2016) ammonia, nitrate, and total phosphorus are shown in Figure 1.60 through Figure 1.62. The WARMF simulation was calibrated to match the measured ammonia concentration. WARMF simulated more nitrate than observed at the site downstream of Walt Ranch but less nitrate than observed upstream of Walt Ranch. The phosphate data were matched closely by the simulation.

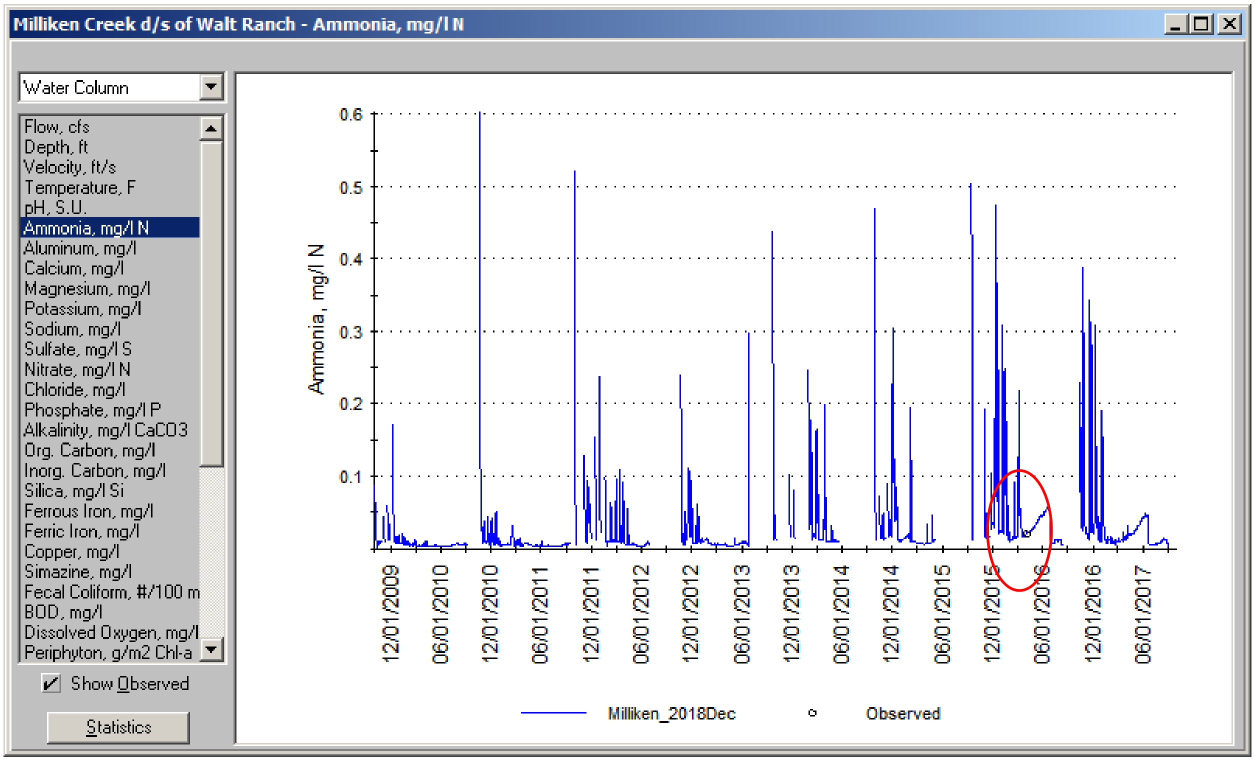


Figure 1.60 Simulated vs Observed Ammonia Nitrogen, Milliken Creek near Walt Ranch

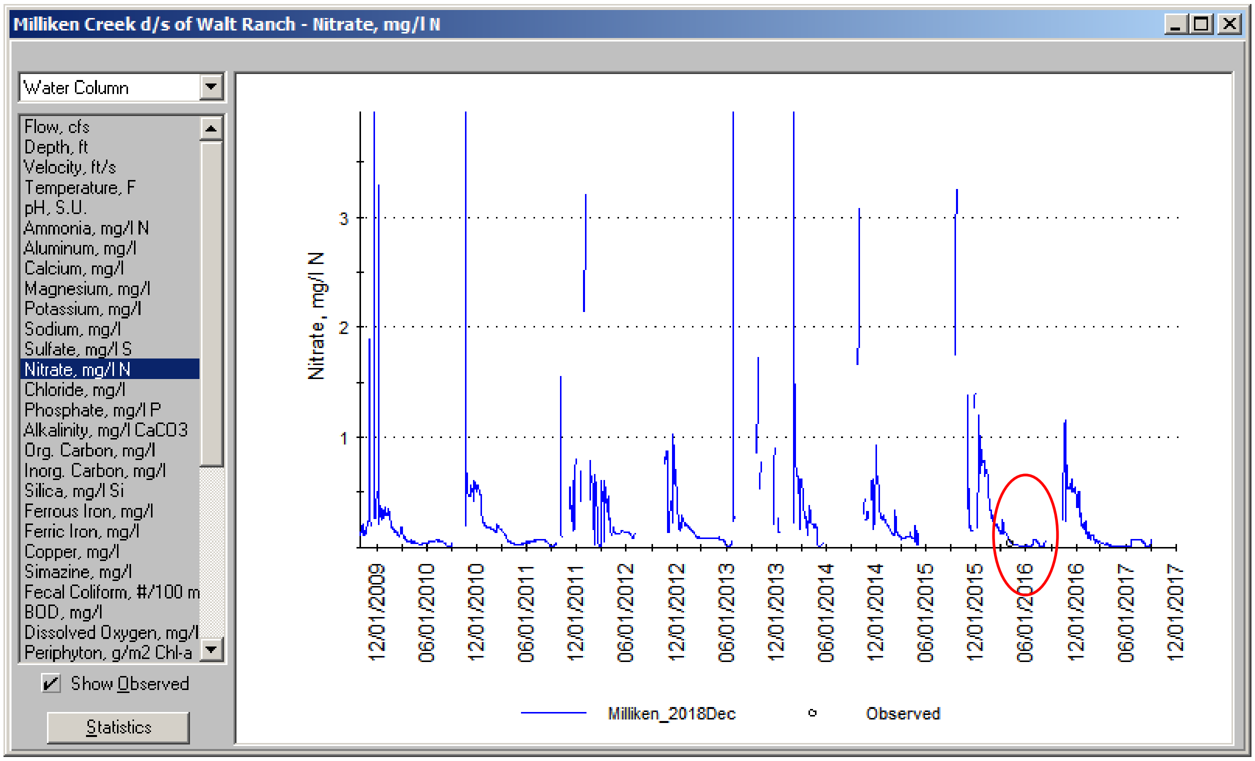


Figure 1.61 Simulated vs Observed Nitrate Nitrogen, Milliken Creek near Walt Ranch

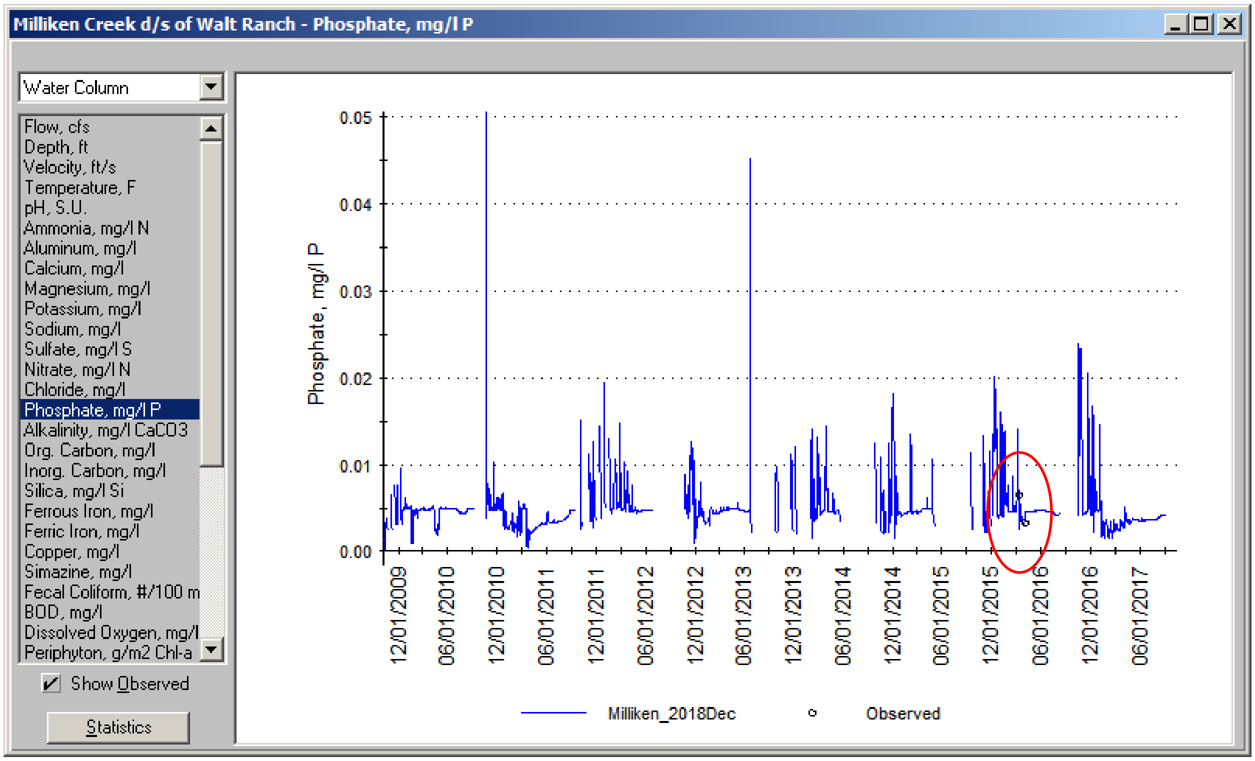


Figure 1.62 Simulated vs Observed Phosphate, Milliken Creek near Walt Ranch

Table 1.14 provides a summary of model errors for each constituent at the Milliken Creek near Walt Ranch monitoring sites.

Table 1.14
Summary of Model Errors for Milliken Creek near Walt Ranch

Water Quality Parameter	Relative Error	Absolute Error
Temperature	-5.7 ^{o}F	9.1 ^{o}F
Turbidity	-1.95 NTU	1.95 NTU
Calcium	+0.77 mg/l	1.39 mg/l
Magnesium	+0.35 mg/l	0.78 mg/l
Sulfate	-4.1 mg/l	4.45 mg/l
Chloride	-3.00 mg/l	3.00 mg/l
Total Dissolved Solids	+9.7 mg/l	12.7 mg/l
Ammonia	+0.00 mg/l N	0.00 mg/l N
Nitrate	+0.01 mg/l N	0.01 mg/l N
Phosphate	+0.00 mg/l P	0.00 mg/l P

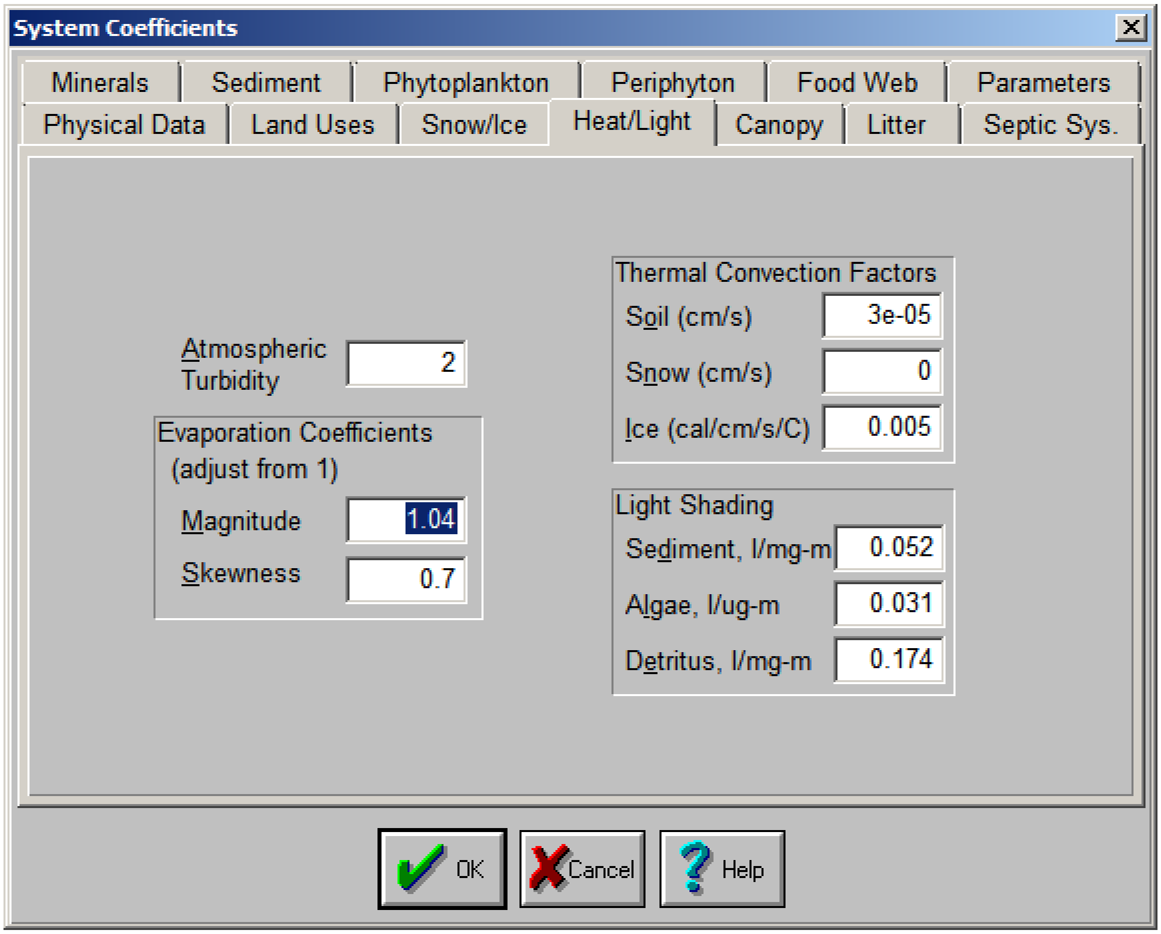
Summary

This report summarizes the preliminary calibration of the WARMF to the Lake Hennessey and Milliken Reservoir watersheds as of December 2018. The comparisons of predicted and observed values were made for a large number of variables. Hydrology calibration was performed primarily at the reservoirs themselves to take advantage of the highest quality data. The hydrology calibration was able to track the observed surface elevation of the reservoirs and maintain a good balance between reservoir inflows and outlfows. The correlations between WARMF simulation results and observations were generally good for water quality as well, although the WARMF model was not able to simulate high flow concentrations of conservative substances in Conn and Chiles Creeks. When additional data is collected, the WARMF model calibration can be updated to reduce uncertainty and model error.

2 SENSITIVITY ANALYSIS

The purpose of a sensitivity analysis is to determine the effect of model inputs on key model outputs. There are thousands of coefficients in the WARMF model, so it is not practical to run a sensitivity analysis on all of them. Many of them have been adjusted in model calibration to minimize model errors. To demonstrate the methodology, 3 sensitivity analysis simulations were run.

The first simulation was adjusting the systemwide evaporation multiplier. This is a key parameter in model calibration which affects how much simulated evapotranspiration occurs across the watershed. The calibrated value for this coefficient is 1.3. The sensitivity analysis test reduced its value by 20% to 1.04



Atmospheric Turbidity: 2

Evaporation Coefficients (adjust from 1)

Magnitude: 1.04

Skewness: 0.7

Thermal Convection Factors

Soil (cm/s): 3e-05

Snow (cm/s): 0

Ice (cal/cm/s/C): 0.005

Light Shading

Sediment, l/mg-m: 0.052

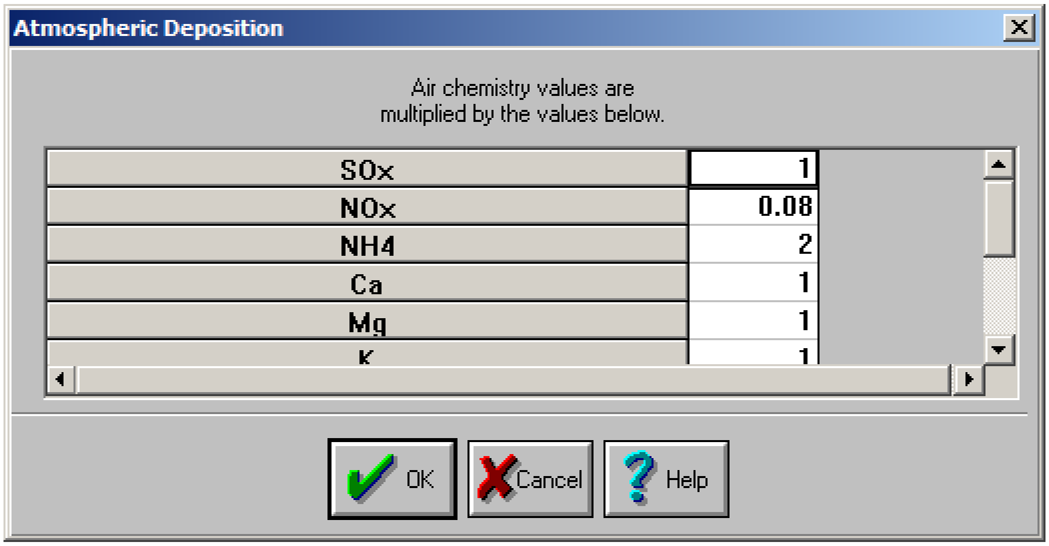
Algae, l/ug-m: 0.031

Detritus, l/mg-m: 0.174

Figure 2.1 Reducing the Evaporation Magnitude Coefficient by 20%

Nutrient loading to Lake Hennessey and Milliken Reservoir are concerns for water supply because of the potential for eutrophication. Two key model inputs of nutrients are atmospheric deposition and vineyard fertilization. Atmospheric deposition is highly spatially variable, and with air & rain concentration data coming from Napa, Hopland, and Pinnacles National Park there is significant uncertainty regarding the deposition in the Hennessey and Milliken watersheds. To test the sensitivity of the watersheds to atmospheric deposition, the air & rain concentrations were doubled using the WARMF Consensus Module as shown in Figure 2.2. The NOx concentration had been calibrated to 0.04 times the concentration in Napa, but in this example it is doubled to 0.08. The multipliers for ammonia and nitrate are set to 2 instead of 1. The third example changes the NPK fertilizer application rate from the current input of 51 pounds per acre pear year to 102. After unit conversions, it appears as shown in Figure 2.3 and then is applied to all catchments in the watershed.

The results for the calibration scenario and each sensitivity analysis simulation can be plotted together on one time series graph for any location in the watershed.

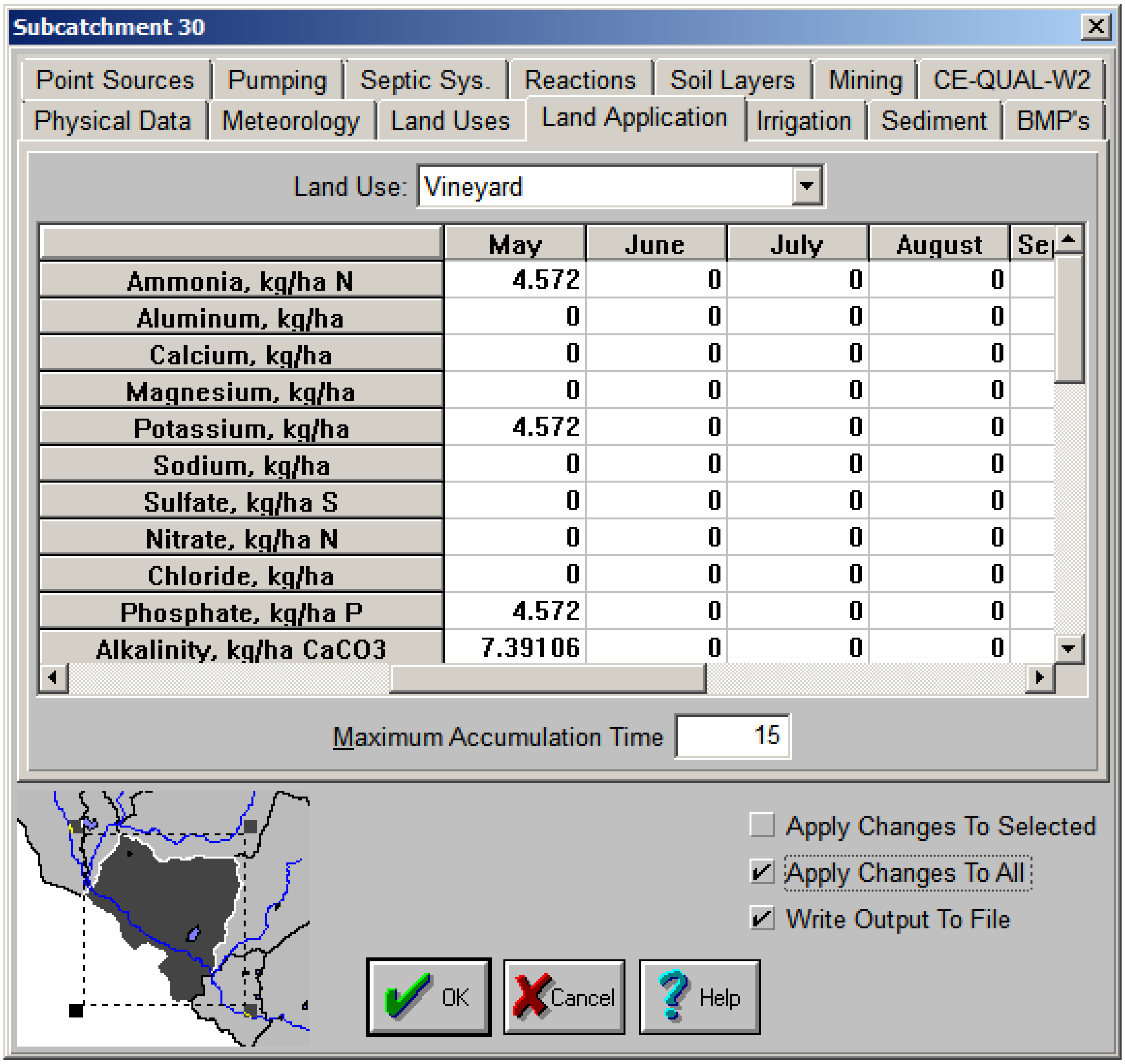


Atmospheric Deposition

Air chemistry values are multiplied by the values below.

SOx	1
NOx	0.08
NH4	2
Ca	1
Mg	1
K	1

Figure 2.2 Doubling the Atmospheric Deposition of Nitrogen



Land Use: Vineyard

	May	June	July	August	Se
Ammonia, kg/ha N	4.572	0	0	0	
Aluminum, kg/ha	0	0	0	0	
Calcium, kg/ha	0	0	0	0	
Magnesium, kg/ha	0	0	0	0	
Potassium, kg/ha	4.572	0	0	0	
Sodium, kg/ha	0	0	0	0	
Sulfate, kg/ha S	0	0	0	0	
Nitrate, kg/ha N	0	0	0	0	
Chloride, kg/ha	0	0	0	0	
Phosphate, kg/ha P	4.572	0	0	0	
Alkalinity, kg/ha CaCO3	7.39106	0	0	0	

Maximum Accumulation Time 15

☐ Apply Changes To Selected
☑ Apply Changes To All
☑ Write Output To File

Figure 2.3 Doubling the Fertilizer Application to Vineyards

The three scenarios were run for the Lake Hennessey watershed. Time series output of reservoir surface elevation is shown in Figure 2.4. While changing the rate of fertilizer loading and atmospheric deposition had a negligible effect on water surface elevation, reducing the evaporation magnitude coefficient by 20% (in green) increased inflow to the lake by 5.8 cfs, resulting in a higher surface elevation and increased spill to Conn Creek below the dam.

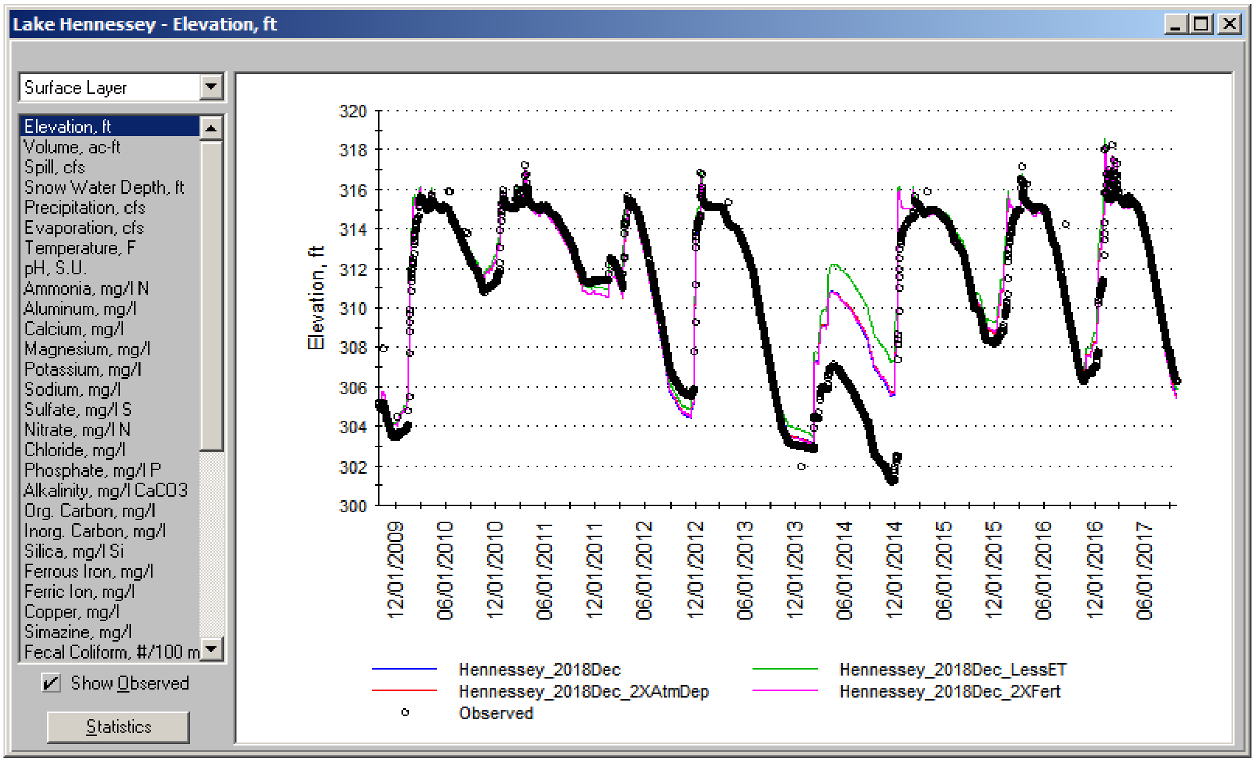
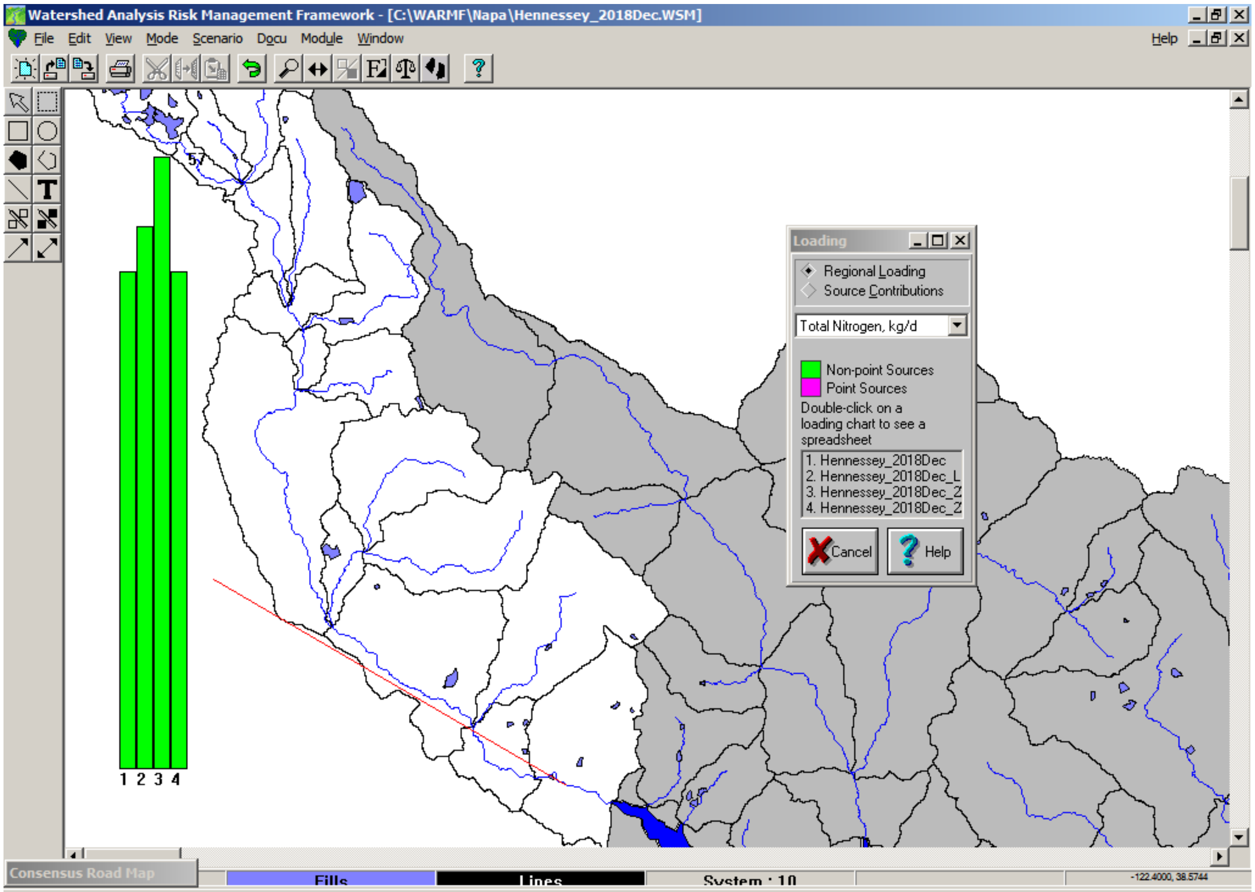


Figure 2.4 Lake Hennessey Surface Elevation, Base Case and Sensitivity Simulations

Figure 2.5 shows total nitrogen loading to Conn Creek under each of the four scenarios. The bar at the left is the base (calibration) case. The next 3 bars from left to right are the reduction in evaporation, doubling atmospheric deposition, and doubling vineyard fertilization. Reducing evaporation increased loading because it increased flow from the land to the creek. Changing atmospheric deposition had much more effect than increasing fertilizer use because most of the atmospheric deposition is in the form of nitrate, which is very mobile in the watershed. Ammonia adsorbs strongly to soil particles, so much of the additional ammonia put on the land went to storage in the soil.



◆ Regional Loading
◇ Source Contributions

Total Nitrogen, kg/d

🟩 Non-point Sources
🟪 Point Sources

Double-click on a loading chart to see a spreadsheet

1. Hennessey_2018Dec
2. Hennessey_2018Dec_L
3. Hennessey_2018Dec_Z
4. Hennessey_2018Dec_Z

Figure 2.5 Total Nitrogen Loading to Conn Creek for Base Case and Sensitivity Analyses

3 REFERENCES

Brown & Caldwell. (2012). *City of Napa Watershed Sanitary Survey.* Rancho Cordova, CA.

California Department of Water Resources. (1974). *Evaporation from Water Surfaces in California.* Sacramento, CA: California Department of Water Resources.

California Soil Resource Lab. (2018, 12 6). *SoilWeb*. Retrieved from University of California Davis: https://casoilresource.lawr.ucdavis.edu/gmap/

Cooper, M. L., Klonsky, K. M., & De Moura, R. L. (2012). *Sample Costs to Establish a Veneyard and Produce Winegrapes.* University of California Cooperatve Extension.

Sheeder, S., & Herr, J. (2017). *Watershed Analysis Risk Management Framework: User's Guide and Documentation of the Graphical User Interface.* Walnut Creek, CA: Systech Water Resources, Inc.

Systech Water Resources. (2017). *Watershed Analysis Risk Management Framework: Technical Model Documentation.* Walnut Creek, CA: Systech Water Resources.

University of California Integrated Pest Management Program. (2016, 12). *Herbicide Treatment Table*. Retrieved from UC IPM Pest Management Guidelines: Grape: http://ipm.ucanr.edu/PMG/r302700311.html

-