RECLAMATION

Managing Water in the West

Windy Gap Firming Project

Stream Water Quality Modeling and Methods Report

U.S. Department of the Interior
Bureau of Reclamation
Great Plains Region

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Stream Water Quality Modeling and Methods Report

Windy Gap Firming Project

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CONTENTS

LIST OF TABLES

LIST OF FIGURES

APPENDIX

ABBREVIATIONS

CBOD	Carbonaceous Biochemical Oxygen Demand
cfs	cubic feet per second
CWQCC	Colorado Water Quality Control Commission
EPA	Environmental Protection Agency
DMR	Data Monitoring Report
GCWIN	Grand County Water Information Network
HSS	Hot Sulphur Springs
ISDS	Individual Sewage Disposal Systems
NCWCD	Northern Colorado Water Conservancy District
SSTEMP	Stream Segment Temperature Model
TDS	Total dissolved solids
USGS	United States Geological Survey
WGFP	Windy Gap Firming Project
WWTP	Wastewater treatment plant

WINDY GAP FIRMING PROJECT
STREAM WATER QUALITY MODELING AND METHODS REPORT

1.0 INTRODUCTION

This report describes the methods used to simulate the water quality of the Colorado River, Willow Creek, and East Slope streams within the South Platte River basin for the direct and cumulative effect simulations for the Windy Gap Firming Project (WGFP). The Windy Gap Water Resources Technical Report (ERO and Boyle 2007) provided hydrologic data.

The QUAL2K modeling software was used to develop a water-quality model for the Colorado River between Lake Granby and Gore Canyon, just downstream of the town of Kremmling, Colorado. The model application was developed and calibrated using hydrologic and water-quality data from the reach. Data used for calibration and the modeling results for the calibration period are discussed and the model performance is quantified. The model is described in Section 2.

A nutrient loading model was developed for the Fraser River Basin for cumulative effects simulations. The details of the modeling methods used by this model are included in Section 3.

The Stream Segment Temperature Model (SSTEMP) was used to determine the impacts of reduced streamflows below Willow Creek Reservoir to the temperature of the approximately 3-mile segment of Willow Creek between Willow Creek Reservoir and the Colorado River. SSTEMP handles only single stream segments for a single time period, such as a day, week, or month. Model operation and calibration is described in Section 4, as well as model results for two simulated dates.

For streams in which water quality could be changed below the outfall of a wastewater treatment plant (WWTP) due to changes in the amount of effluent discharge or changes in streamflow, a mass-balance analysis of ammonia and metal concentrations was completed. The calculations and assumptions are described in Section 5.

In 2005, the Colorado Water Quality Control Commission (CWQCC) adopted new total ammonia criteria for surface waters. The criteria are described in Section 6, and the equations are provided for calculating the ammonia standards.

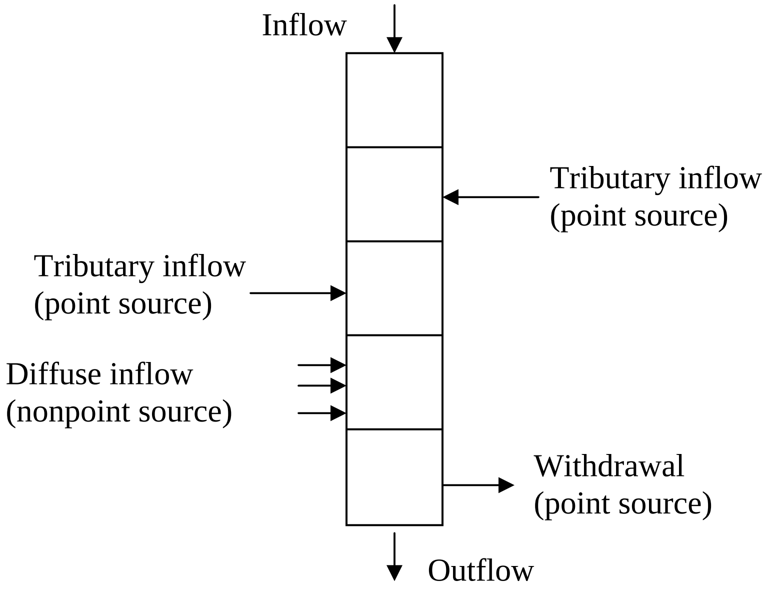
2.0 QUAL2K MODEL

The QUAL2K model is a one-dimensional, steady-state, numerical model that simulates flow, temperature, and water quality along a river reach (Chapra, et al. 2006). QUAL2K is distributed by the United States Environmental Protection Agency (U.S. EPA) and is a modernized version of the widely used QUAL2E model. QUAL2K can predict in-stream flows and water depth, water temperature, conductivity, and concentrations of inorganic solids, dissolved oxygen, biochemical oxygen demand, nutrients (e.g., organic nitrogen, ammonia, nitrate, organic phosphorus, and inorganic phosphorus), pH, alkalinity, phytoplankton concentration, and periphyton biomass.

QUAL2K calculates the steady-state water quality along a river reach as a result of external driving forces, such as heat.

QUAL2K simulates a river as a set of interconnected segments, where water quality constituent values are computed for each segment. A segment is defined as a river reach with point and nonpoint inflow sources, as well as withdrawals that drive changes in water quality (Figure 1). Each segment of the river reach is modeled as having a trapezoidal channel shape, and the water depth is calculated from steady flow in the segment using the Manning equation. Water mass balances are performed by QUAL2K for each segment to determine the discharge longitudinally throughout the river reach.

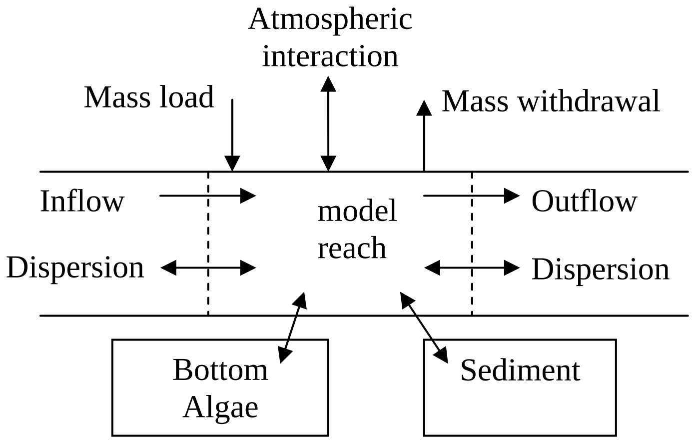
Figure 1. Example QUAL2K segments describing a river reach.



For the simulation of water temperature, a heat balance approach is used that describes the sources and sinks of heat for each model segment. The heat fluxes between the water and the atmosphere include short- and long-wave solar radiation, shading and cloud cover attenuation, conduction, wind convection, evaporation, and condensation. The heat budget is calculated using a diurnal time scale. Mixing of water between adjacent segments is modeled through water movement from upstream to downstream and dispersive mixing at segment boundaries. Heat fluxes between the water and sediment are also included in QUAL2K.

For each water quality constituent, mass balances are calculated that describe external loading, segment interaction, sediment interaction, and bottom algae interaction (Figure 2).

Figure 2. QUAL2K water-quality fluxes for model segments.



In addition to mass balances for each constituent, chemical reactions are included to transfer mass between constituent compartments. Chemical kinetics are specific to each water-quality constituent. As a group, these reactions simulate the growth of algae, decay of organic material, and cycling of nutrients that occurs in natural waters. These interactions are fully documented in Chapra et al. (2006). User-defined rate constants for each constituent reaction can be adjusted during model calibration for characterization of processes specific to a certain river system.

Conductivity, total dissolved solids, and selenium are assumed to be conservative; that is, they are not altered by settling or chemical reactions occurring in the water.

QUAL2K is capable of effectively simulating trace metals such as Se given some reasonable assumptions. Selenium chemistry is quite complex but the differentiation into common forms of Selenite and Selenate is controlled via a reduction-oxidation (redox) reaction. The reduced form of Selenite, common in groundwater has been shown to adsorb highly to sediments. This adsorption acts as a loss mechanism for the dissolved species in water. The oxidized form of Selenate, existing nearly exclusively in surface waters tends to not adsorb to sediments and therefore can be assumed to be conservative in surface waters (Lindsay 1979; Sposito 1994).

Water-quality constituents of concern in the Colorado River between Lake Granby and Kremmling, Colorado include conductivity, total dissolved solids, ammonia, inorganic phosphorus, and dissolved selenium. These constituents are the focus of the simulation of the action alternatives, but these are only a subset of the complete chemical system that is simulated in QUAL2K.

2.1. Upper Colorado River Modeling Reach

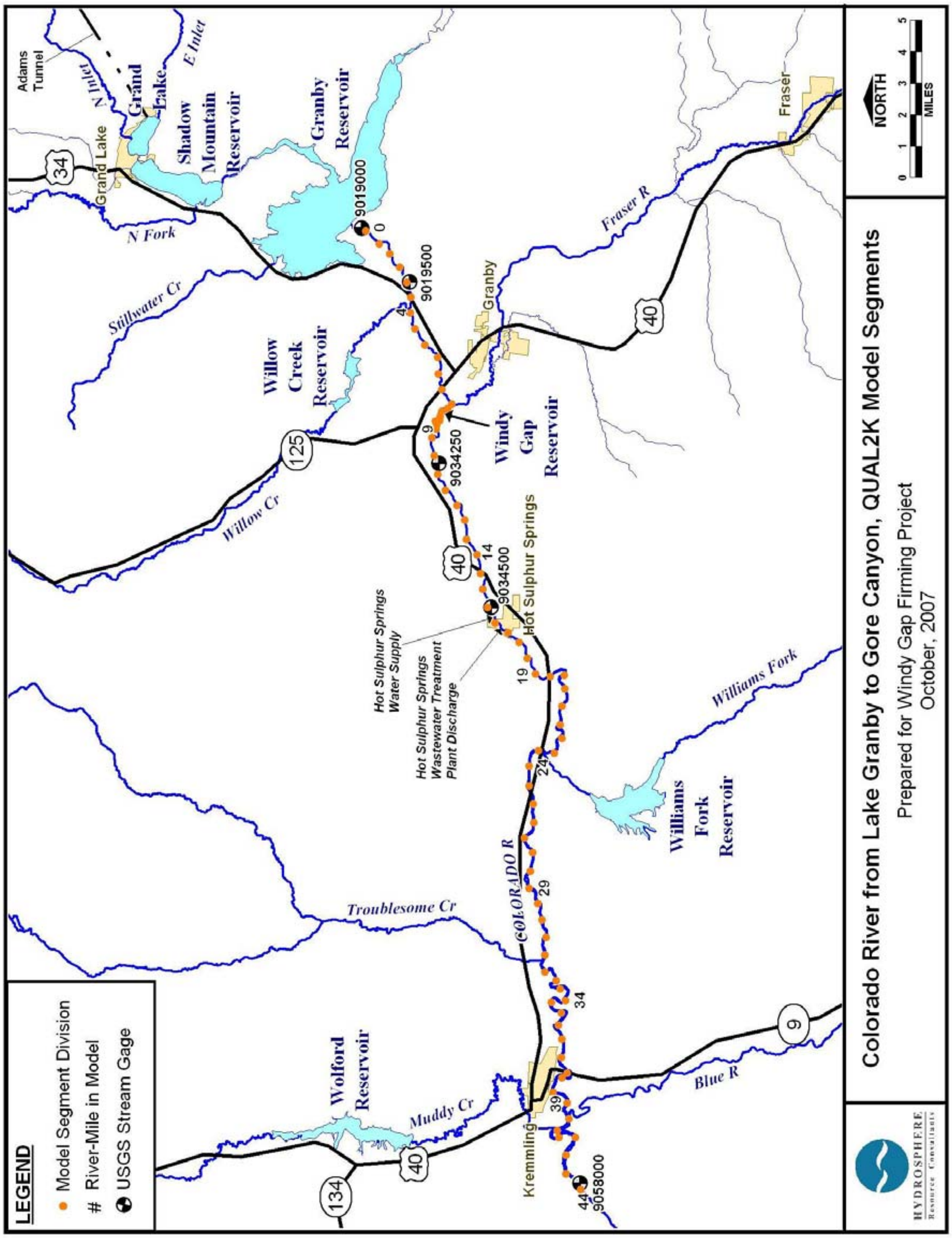
Output from QUAL2K provides a prediction of the flow and water quality at locations along the Upper Colorado River, as influenced by upstream flow quality and quantity, water inflows and diversions, meteorological conditions, and chemical reactions that occur as water flows downstream. This modeling tool effectively simulates the water quality in the Colorado River reach below Lake Granby to the Kremmling gage as a result of several tributary inflows, a WWTP outfall, and diversions from the river for drinking water and at Windy Gap Reservoir and other small diffuse reach gains and losses.

For modeling, the 44-mile section of the Colorado River mainstem between the Lake Granby discharge and the U.S. Geological Service (USGS) gage near Kremmling was divided into 76 segments. Model segments are homogenous sections of river. Most of the segments are 1 kilometer long. Smaller segments of 0.25 and 0.5 kilometer were used to better describe the river in the area of the Windy Gap Reservoir. The model extent, segment boundaries, and tributaries are presented in Figure 3.

Willow Creek, Fraser River, Williams Fork, Troublesome Creek, Muddy Creek, and Blue River are considered point inflow sources of water and constituents. The Hot Sulphur Springs wastewater treatment plant (HSS WWTP) is also considered a concentrated, but low-flow point source. Withdrawals from the Colorado River for drinking water above Hot Sulphur Springs and diversions at Windy Gap Reservoir are simulated as point outflows (abstractions). Diffuse inflow sources of water and constituents due to small gains are also included in the reach. These water sources are included so that inflows and outflows of water can be included to better match river gage data, which is measured by the USGS at four points throughout the reach. The natural hot springs in the town of Hot Sulphur Springs are not included in the model. Testing with the QUAL2K model showed very small changes in water quality as a result of the spring’s inflow. These results are presented in the Sensitivity Analysis section below.

QUAL2K application for the Colorado River includes all the physical attributes of the river and its tributaries, and allows for an adequate characterization of flow and water quality for a 1-day steady-state simulation.

Figure 3. QUAL2K model segment map.



2.2. Model Development and Calibration

The overall model development process involves creation of a set of data that characterizes the physical aspects of the Colorado River and describes the flow and quality at the upstream end of the river and all the tributary inflows. The model was run and the model predictions were compared to a set of measured data describing the in-river water quality. The model was then calibrated by adjusting model parameters to better fit the model prediction to the measured data.

The data requirements for the QUAL2K model for one simulation involve flow, water quality, and meteorological data. Data are required for input to the model, as well as data to be used for comparison with model output for calibration purposes.

The calibration flow data set consisted of data at several points in the Colorado River reach, at the mouths of the six tributaries, withdrawals for drinking water at Hot Sulphur Springs, withdrawal at Windy Gap Reservoir and the HSS WWTP outfall discharge. Meteorological conditions are represented by hourly data for air temperature, dew point temperature, wind speed, and cloud cover. Water-quality data consisted of measures of water quality at the headwaters and all water inflow points. These data consisted of values of conductivity, pH, and concentrations of dissolved oxygen, nutrient species, phytoplankton, and alkalinity.

The model was calibrated for a day in July for three reasons: 1) during the month of July, the flows in the Colorado River are low and air temperatures are high, 2) Windy Gap diversions can occur in July, and 3) the combination of those conditions would indicate the likely worst-case water quality impacts because flow would be lowest. Under low flow conditions, typically, the concentration of nutrients would be higher, stream temperature would be higher, and dissolved oxygen concentrations would be lower. The required set of flow and water-quality sampling data for all measurements at all locations were not available for any single day. To best characterize typical July conditions, a dataset was developed to create a full set of conditions representative of a typical July day. For a given site, the median values of all measured data during July for the period of record for a given constituent were calculated. The medians of data were used as a measure of typical July conditions instead of the arithmetic mean to ensure that one outlying data point did not skew the results. This method was used to create representative water-quality measurements and concentrations for all inflow water sources to the modeled reach. The minimum and maximum measurements for July from the period of record of the data were computed and used to define the expected range of conditions during July. The minimum and maximum data were developed for comparison with the calibrated model output to provide visual bounds of expected water quality conditions.

Hourly meteorological conditions are required for QUAL2K simulations. These data, represented by hourly data for air temperature, dew point temperature, wind speed, and cloud cover, were developed from NOAA weather station data at Grand Lake and Kremmling. Relationships between the daily average air and dew point temperatures and the hourly pattern over the day were developed using data from the Kremmling station. The 50th percentile of daily average air and dew point temperatures were used to develop the hourly air and dew point temperatures used for the calibration simulation. A model simulation day of July 15 was used to simulate sunlight representative of a day during July.

A listing of flow and water-quality measurement locations and data used for model calibration are presented in Table 1 to Table 4. The largest sets of data exist for water temperature, conductivity, and dissolved oxygen. Limited data exist for nutrients for some tributaries. Estimates based on professional judgment and knowledge of the area were used if no other measured data existed.

Historic water temperatures measured near the mouth of the Williams Fork by the USGS indicated a median July water temperature of 20.5 ºC. Recent Colorado River water temperature data collected by Grand County Water Information Network (GCWIN) in July 2006 and July 2007 indicated that the Williams Fork tributary acts to cool the Colorado River during the end of July (GCWIN 2007). A data set was developed to back calculate water temperatures in the Williams Fork during July. This dataset consisted of: water temperatures measured twice per hour during July 31, 2006; temperatures measured four times per hour during July 25-31, 2007; Colorado River discharge data measured by the USGS gage at Windy Gap; flow estimates for Hot Sulphur Springs municipal water supply withdrawal; and WWTP inflow and Williams Fork discharge data measured by the USGS below Williams Fork Reservoir. These data were used to calculate water temperatures in the Williams Fork at the end of July 2006 and July 2007, resulting in an average water temperature of 13.4 ºC.

Table 1. Data measurement stations.

Description	Station ID	T[1]	C[2]	B[3]	F[4]	Period of Record
USGS Data						
Colorado River below Lake Granby	9019000	x	x		x	11/12/1956 - 9/28/2004
Colorado River near Granby	9019500	x	x		x	4/7/1970 - 9/16/2003
Colorado River at Windy Gap	9034250	x	x		x	11/13/1981 - 2/18/2004
Colorado River at Hot Sulphur Springs	9034500	x	x		x	4/1/1947 - 8/18/1994
Colorado River near Kremmling	9058000	x	x		x	10/16/1968 - 8/12/2004
Willow Creek below Willow Creek Reservoir	9021000	x	x		x	11/12/1956 - 8/19/1982
Fraser at Highway 40	400453105554200	x	x		x	4/7/1995 - 7/14/2004
Fraser at mouth	400550105581800	x	x		x	4/7/1995 - 9/21/1998
Williams Fork below Williams Fork Reservoir	9038500	x	x		x	9/16/1964 - 9/2/2004
Williams Fork at mouth	9249750	x	x		x	6/26/1975 - 9/3/2002
Troublesome near Pearmont	9039000	x	x		x	6/11/1958 - 9/15/1993
Muddy Creek below Wolford Mt. Reservoir	9041400	x	x		x	7/71995 - 9/15/2004
Muddy Creek at Kremmling	9041500	x	x		x	4/20/1982 - 9/19/1995
Blue River below Green Mountain Reservoir	9057500	x	x		x	10/13/1964 - 9/2/2004
Blue River at mouth	9057700	x	x		x	7/9/1969 - 9/11/2002

Description	Station ID	T[1]	C[2]	B[3]	F[4]	Period of Record
NCWCD Data						
Willow Creek discharge from Willow Creek Dam	WC-WCRD		x			5/30/1991 - 11/22/2005
Willow Creek upstream of confluence with "No Name" River	WC-2		x			5/30/1991 - 6/24/1991
Willow Creek 0.5 mile upstream of Colorado River	WC-3		x			5/30/1991 - 6/7/2004
Willow Creek discharge from Willow Creek Dam	WC-WCRD		x			5/30/1991 - 11/22/2005
Willow Creek @ USGS Gage near C-Lazy-U Ranch	WC-WCRU		x			6/9/1999 - 6/7/2004
Fraser River upstream of Lake Granby	FR-3		x			5/30/1991 - 6/28/1991
Fraser River upstream of Colorado River	FR-4A		x			4/21/1992 - 9/14/1995
Fraser River upstream of Colorado River	FR-4B		x			4/21/1992 - 5/20/1993
Fraser River upstream of Colorado River by NCWCD station	FR-WGU		x			5/30/1991 - 9/12/2005
Grand County Water Information Network (GCWIN)						
Colorado River below Windy Gap	CO River below Windy Gap	x				7/31/2006, 7/25/2007 – 7/31/2007
Colorado River above HSS WTP	CO River above HSS WTP	x				7/31/2006, 7/25/2007 – 7/31/2007
Colorado River at Lone Buck (above Williams Fork inflow)	CO River at Lone Buck	x				7/31/2006, 7/25/2007 – 7/31/2007
Colorado River below Parshall, CO (below Williams Fork inflow)	CO River below Parshall, CO	x				7/31/2006, 7/25/2007 – 7/31/2007

[1]Temperature, [2]Chemistry, [3]Biology, [4]Flow.

Table 2. Flow and key chemistry data for Colorado River headwater, tributaries, and point sources for July.

Point Source	Calibration Value	Data Source
River Mile (mi)		
Lake Granby Release	0.0	Calculated using GIS
Willow Creek	4.5	Calculated using GIS
Fraser River	8.2	Calculated using GIS
Windy Gap diversion	8.8	Calculated using GIS
Hot Sulphur Springs water supply intake	16.7	Calculated using GIS
Hot Sulphur Springs WWTP	17.1	Calculated using GIS
Williams Fork	23.9	Calculated using GIS
Troublesome Creek	32.0	Calculated using GIS
Muddy Creek	40.4	Calculated using GIS
Blue River	40.4	Calculated using GIS
Kremmling	44.2	Calculated using GIS
Flow (cfs)		
Lake Granby Release	75	Median of USGS data for July
Willow Creek	45	Median of USGS data below reservoir for July
Fraser River	62	Median of USGS data at Hwy 40 for July
Hot Sulphur Springs WWTP	0.09	July 2005 WWTP average flow DMR data
Williams Fork	91	Median of USGS data at mouth for July
Troublesome Creek	20	Median of USGS data for July
Muddy Creek	37	Median of USGS data for July
Blue River	449	Median of USGS data below reservoir for July
Diffuse Sources		Accretion flows calculated using mass balance with USGS gage data
Kremmling	921	Median of USGS data for July
Water Temperature (°C)		
Lake Granby Release	12.0	Median of USGS data for July
Willow Creek	10.5	Median of USGS data below reservoir for July
Fraser River	16.0	Median of USGS data at Hwy 40 for July
Hot Sulphur Springs WWTP	16.1	September WWTP DMR data
Williams Fork	13.4	Calculated using GCWIN data
Troublesome Creek	13.5	Median of USGS data for July
Muddy Creek	18.5	Median of USGS data for July
Blue River	11.0	Median of USGS data at mouth for July
Diffuse Sources	12.0	Estimated for calibration fit

Point Source	Calibration Value	Data Source
Conductivity (µS/cm)		
Lake Granby Release	61	Median of USGS data for July
Willow Creek	240	Median of NCWCD data near mouth for July
Fraser River	135	Median of USGS data at Hwy 40 for July
Hot Sulphur Springs WWTP	633	September WWTP DMR TDS data
Williams Fork	470	Median of USGS data at mouth for July
Troublesome Creek	87	Median of USGS data for July
Muddy Creek	1,125	Median of USGS data for July
Blue River	174	Median of USGS data at mouth for July
Diffuse Sources	165	Estimated for calibration fit
Inorganic Solids (mg/L)		
Lake Granby release	10	Estimate from Three Lakes model
Willow Creek	20	Median of NCWCD July
Fraser River	6	Median of NCWCD July
Hot Sulphur Springs WWTP	30	Estimate based on DMR data
Williams Fork	15	Median of July (USGS)
Troublesome Creek	10	Estimate
Muddy Creek	100	Median of July (USGS)
Blue River	10	Estimate
Diffuse Sources	0	Estimate
Dissolved Oxygen (mg/L)		
Lake Granby Release	8.8	Median of USGS data for July
Willow Creek	8.9	Median of all NCWCD data near mouth
Fraser River	8.0	Median of USGS data at Hwy 40 for July
Hot Sulphur Springs WWTP	8.1	September WWTP DMR data
Williams Fork	7.0	Median of USGS data at mouth for July
Troublesome Creek	8.0	Estimate, no data
Muddy Creek	7.2	Median of USGS data for July
Blue River	7.9	Median of USGS data for July
Diffuse Sources	7.0	Estimate, no data
CBOD slow (mg/L)		
Lake Granby Release	1	
Hot Sulphur Springs WWTP	10	Estimate, no data
Tributary sources	1	Estimate, no data
Diffuse sources	0	Estimate, no data

Point Source	Calibration Value	Data Source
CBOD fast (mg/L)		
Lake Granby release	1	Estimate, no data
Hot Sulphur Springs WWTP	11	August WWTP DMR data
Tributary sources	1	Estimate, no data
Diffuse sources	0	Estimate, no data
Organic Nitrogen (μg/L)		
Lake Granby release	176	Median of July data for Lake Granby hypolimnion
Willow Creek	144	Median of NCWCD at dam for July
Fraser River	106	Median of NCWCD near mouth for July
Hot Sulphur Springs WWTP	6,400	Typical of low concentration influent (Metcalf and Eddy 1991) 20% removed by conventional treatment
Williams Fork	400	Median of USGS data at mouth for July
Troublesome Creek	150	Estimate, no data
Muddy Creek	600	Median of USGS data for July
Blue River	400	Median of USGS data at reservoir for July
Diffuse Sources	176	Assumed same as Lake Granby hypolimnion -- reservoir seepage
Ammonia (μg/L as N)		
Lake Granby Release	4	Median of July data for Lake Granby hypolimnion (2001-2003, N = 5)
Willow Creek	25	Median of NCWCD data at dam for July
Fraser River	32	Median of NCWCD data near mouth for July
Hot Sulphur Springs WWTP	5,560	September 2005 WWTP DMR data
Williams Fork	20	Median of USGS data at mouth for July
Troublesome Creek	7	Estimate, no data
Muddy Creek	55	Median of USGS data for July
Blue River	25	Median of USGS data at reservoir for July
Diffuse Sources	4	Assumed same as Lake Granby hypolimnion -- reservoir seepage
Nitrate plus Nitrite (μg/L as N)		
Lake Granby Release	2	Median of July data for Lake Granby hypolimnion
Willow Creek	25	Median NCWCD data near mouth for July
Fraser River	87	Median of USGS data Hwy 40
Hot Sulphur Springs WWTP	0	Typical of medium concentration influent (Metcalf and Eddy 1991); treatment has no effect
Williams Fork	100	Median of USGS data at mouth for July

Point Source	Calibration Value	Data Source
Troublesome Creek	20	Estimate, no data
Muddy Creek	75	Median of USGS data for July
Blue River	150	Median of USGS data at reservoir for July
Diffuse Sources	2	Assumed same as Lake Granby hypolimnion -- reservoir seepage
Organic Phosphorus (μg/L)		
Lake Granby Release	14.5	Median of USGS data for July
Willow Creek	3	Median of NCWCD data at dam for July
Fraser River	34	Median of USGS data Hwy 40
Hot Sulphur Springs WWTP	800	Typical of low concentration influent (Metcalf and Eddy 1991); 20% removed by conventional treatment
Williams Fork	13	Median of USGS data at mouth for July
Troublesome Creek	5	Estimate, no data
Muddy Creek	5	Median of USGS data for July
Blue River	25	Median of USGS data at reservoir for July
Diffuse Sources	5	Assume phosphorus adsorbed to soil particles; assume low concentration
Inorganic Phosphorus (μg/L)		
Lake Granby Release	4.5	Median of USGS data for July
Willow Creek	30	NCWCD data near mouth for July
Fraser River	22	Median of USGS data Hwy 40
Hot Sulphur Springs WWTP	2,400	Typical of low concentration influent (Metcalf and Eddy 1991); 20% removed by conventional treatment
Williams Fork	10	Median of USGS data at mouth for July
Troublesome Creek	7	Estimate, no data
Muddy Creek	10	Median of USGS data for July
Blue River	10	Median of USGS data at reservoir for July
Diffuse Sources	5	Assume phosphorus adsorbed to soil particles; assume low concentration
Phytoplankton (mg/L)		
Lake Granby Release	0.1	Estimate from Three Lakes model
All other sources	0	Assumed, no data
Alkalinity (mg/L as $CaCO_3$)		
Lake Granby Release	26	Median of USGS data for July
Willow Creek	26	Estimate, no data
Fraser River	58	Median of all USGS data near mouth
Hot Sulphur Springs WWTP	100	Typical of medium concentration influent (Metcalf and Eddy 1991)

Point Source	Calibration Value	Data Source
Williams Fork	170	Median of USGS data at mouth for July
Troublesome Creek	25	Estimate, no data
Muddy Creek	205	Median of USGS data for July
Blue River	78	Median of all USGS data at mouth
Diffuse Sources	100	Estimate, no data
pH (s.u.)		
Lake Granby Release	7.3	Median of USGS data for July
Willow Creek	8.0	NCWCD data near mouth for July
Fraser River	8.3	Median of USGS data at Hwy 40 for July
Hot Sulphur Springs WWTP	7.0	DMR data for July
Williams Fork	8.3	Median of USGS data at mouth for July
Troublesome Creek	7.0	Estimate, no data
Muddy Creek	8.4	Median of USGS data for July
Blue River	7.7	Median of USGS data at mouth for July
Diffuse Sources	7.0	Estimate, no data
Dissolved Selenium (μg/l)		
Lake Granby Release	0.5	Assumed, no data
Willow Creek	0.5	Assumed, NCWCD data below detection
Fraser River	0.5	Assumed, NCWCD data below detection
Hot Sulphur Springs WWTP	0.5	Assumed, no data
Williams Fork	0.5	Median of all USGS data at mouth
Troublesome Creek	0.5	Assumed, no data
Muddy Creek	2.8	Median of July USGS data at mouth
Blue River	0.5	Assumed, no data
Diffuse Sources	0.5	Assumed, no data

Table 3. Locations for Colorado River water-quality measurement stations.

Station Description	River mile in model (mi)
Colorado River below Lake Granby	0.00
Colorado River near Granby	2.57
Colorado River at Windy Gap	10.57
Colorado River at Hot Sulphur Springs	17.17
Colorado River near Kremmling	44.17

Table 4. Colorado River observed data for a typical July.

Constituent	Colorado River below Lake Granby	Colorado River near Granby	Colorado River at Windy Gap	Colorado River at Hot Sulphur Springs	Colorado River near Kremmling
Temperature (ºC)	12.0	12.9	13.9	15.5	14.8
Conductivity (μmhos/cm)	61	72	118	135	286
Dissolved Oxygen (mg/L)	8.8		8.7	8.6	7.6
Organic Nitrogen (μg/L)	176			180	280
Ammonia (μg/L as N)	4			20	10
Nitrate (μg/L as N)	2			25	59
Organic Phosphorus (μg/L)	14.5			30	13
Inorganic Phosphorus (μg/L)	4.5			15	7.5
Alkalinity (mgCaCO$_3$/L)	25			51	82
pH	7.6		8.2	8.8	8.4
Total Nitrogen (μg/L)	176			225	303
Total Phosphorus (μg/L)	19			45	21
Selenium (μg/L)			0.5	0.5	0.5

Meteorological conditions, flow, and water-quality data at upstream and tributary locations were input to the model and a simulation of all water-quality constituents was performed. Model calibration parameters were adjusted slightly from the default values to better match the model prediction to the measured data. The model output represents the water quality throughout the Colorado River for a typical July day. Data measured in the Colorado River at USGS gage locations (Table 3 and Table 4) were used for comparison with model predictions. The median of measured data for July and the maximum and minimum July measurements are plotted with each constituent of interest in Figure 4 to Figure 13. The upstream point of the modeled reach is Lake Granby release at river mile 0. The downstream point of the model is below Kremmling at river mile 44.2.

Figure 4. Comparison of model output with measured data for discharge.

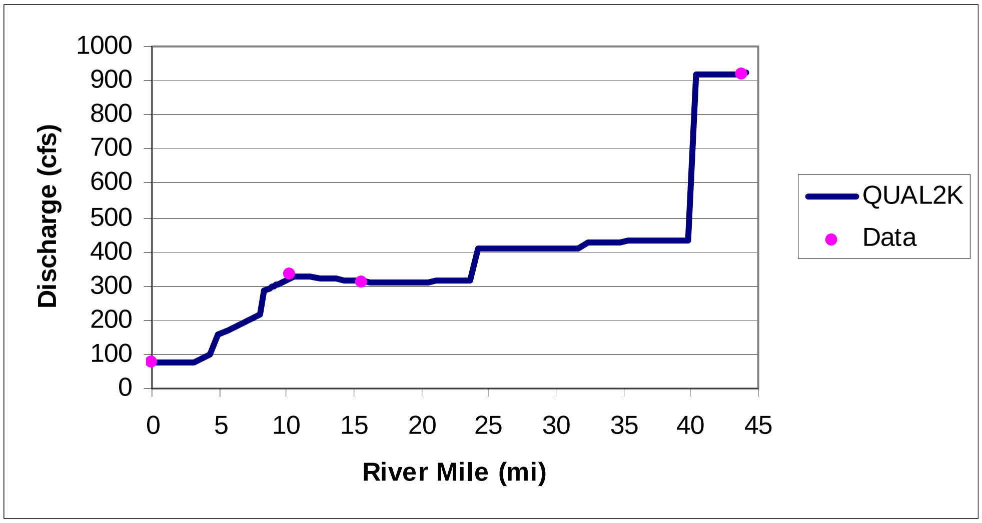


Figure 5. Comparison of model output with measured data for water temperature.

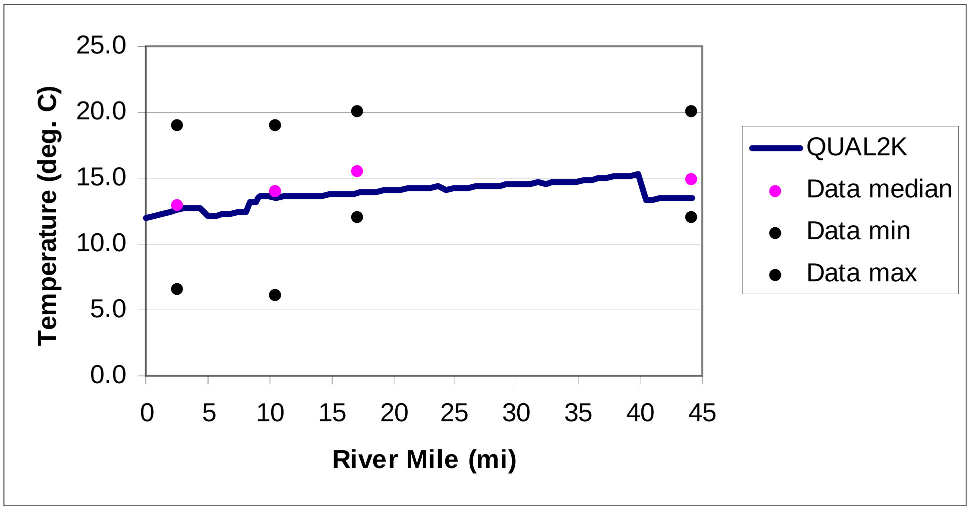


Figure 6. Comparison of model output with measured data for conductivity.

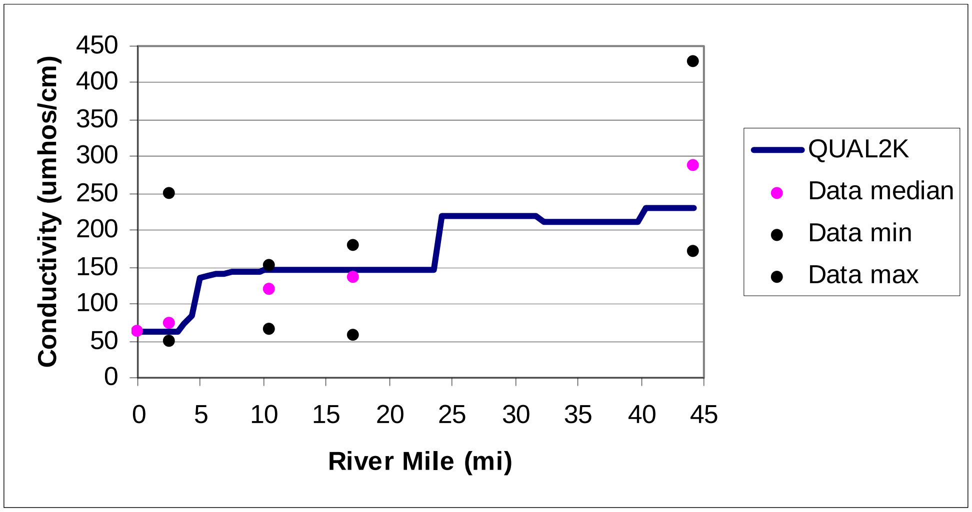


Figure 7. Comparison of model output with measured data for dissolved oxygen.

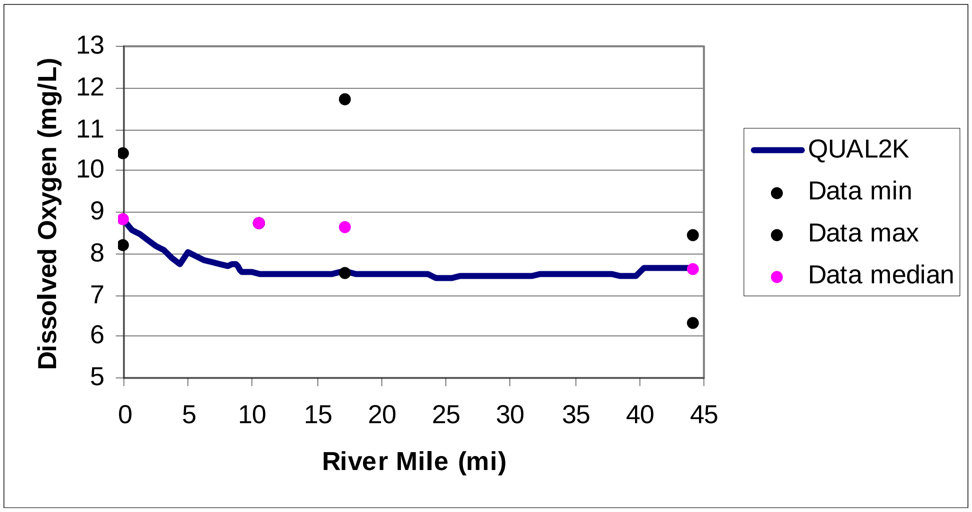


Figure 8. Comparison of model output with measured data for organic nitrogen.

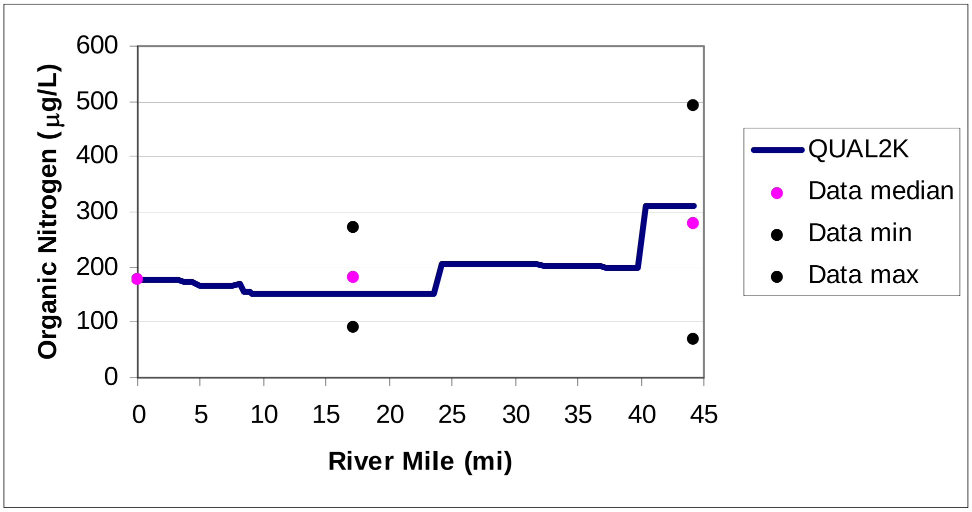


Figure 9. Comparison of model output with measured data for ammonia.

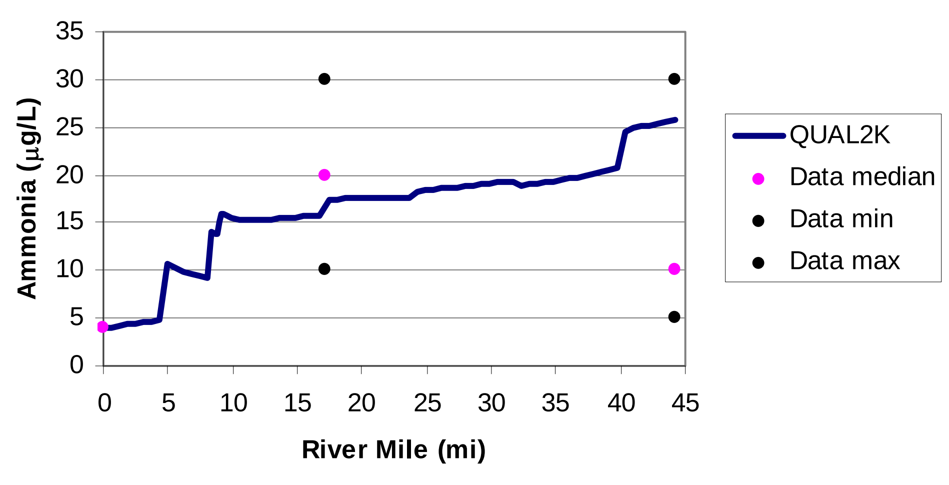


Figure 10. Comparison of model output with measured data for nitrate plus nitrite.

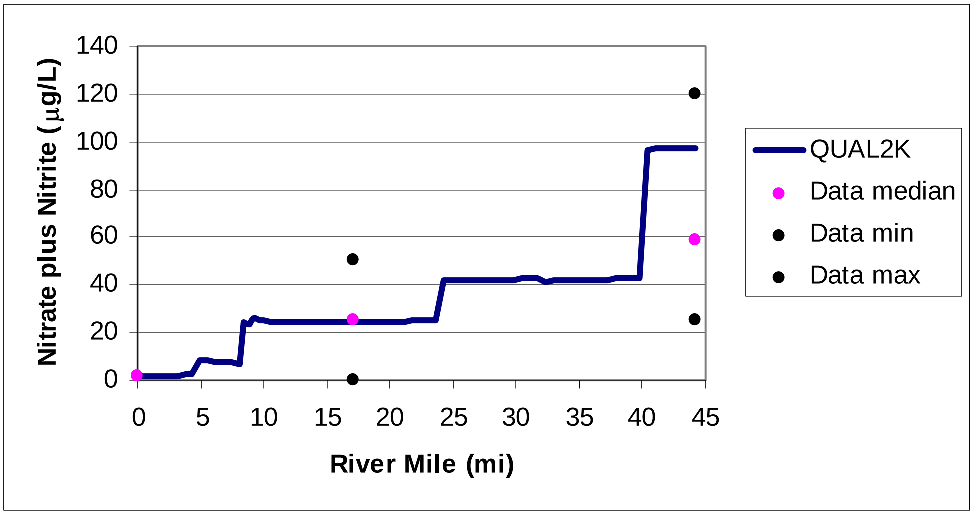


Figure 11. Comparison of model output with measured data for organic phosphorus.

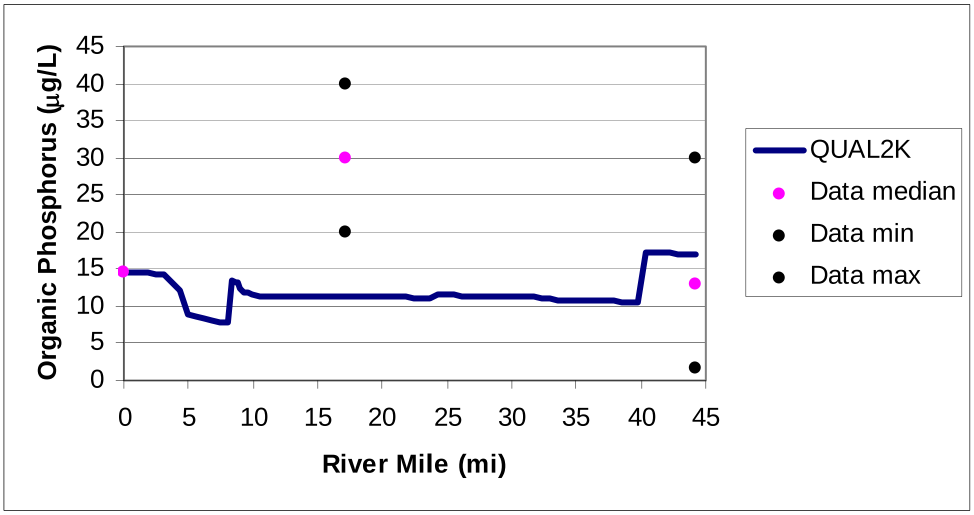


Figure 12. Comparison of model output with measured data for inorganic phosphorus.

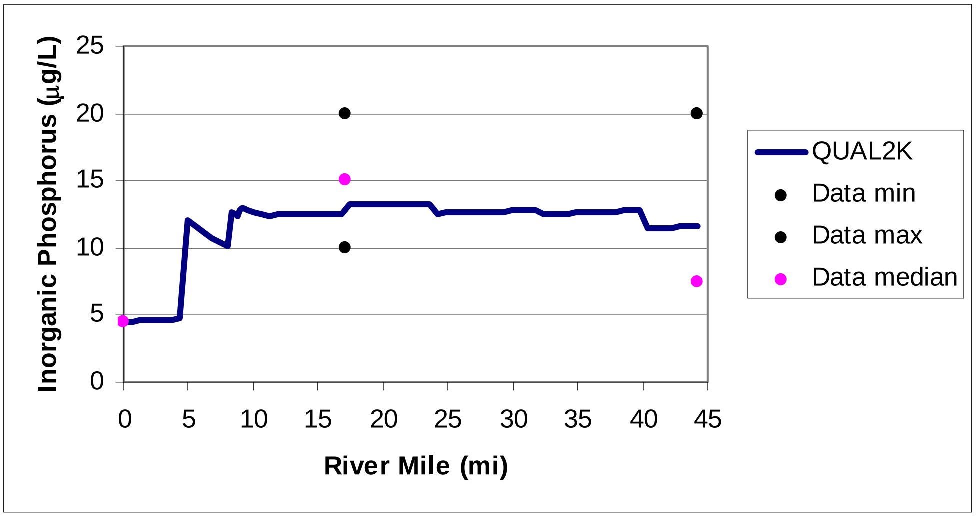
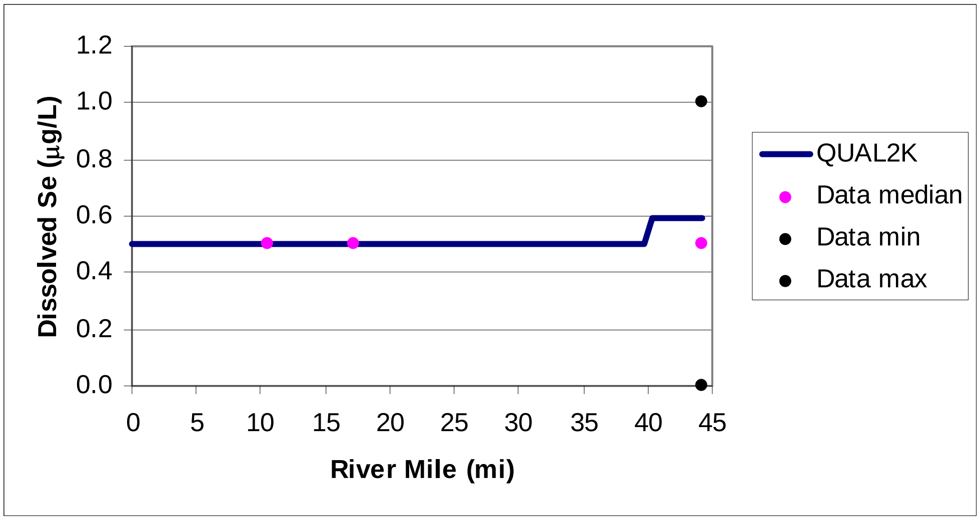


Figure 13. Comparison of model output with measured data for dissolved selenium.



The mean error (ME) has been calculated to quantify the discrepancies between the model predictions and the measured data. The values for each constituent of interest are presented in Table 5.

Table 5. Model calibration error statistics

Constituent	Mean Error
Temperature (ºC)	-0.92
Conductivity (μmhos/cm)	-5.55
Dissolved Oxygen (mg/L)	-0.61
Organic Nitrogen (μg/L)	1.08
Ammonia (μg/L as N)	4.41
Nitrate (μg/L as N)	12.65
Organic Phosphorus (μg/L as P)	-4.86
Inorganic Phosphorus (μg/L as P)	0.80
Dissolved Selenium (μg/L)	0.03

2.3. Discussion of Calibration Goodness of Fit

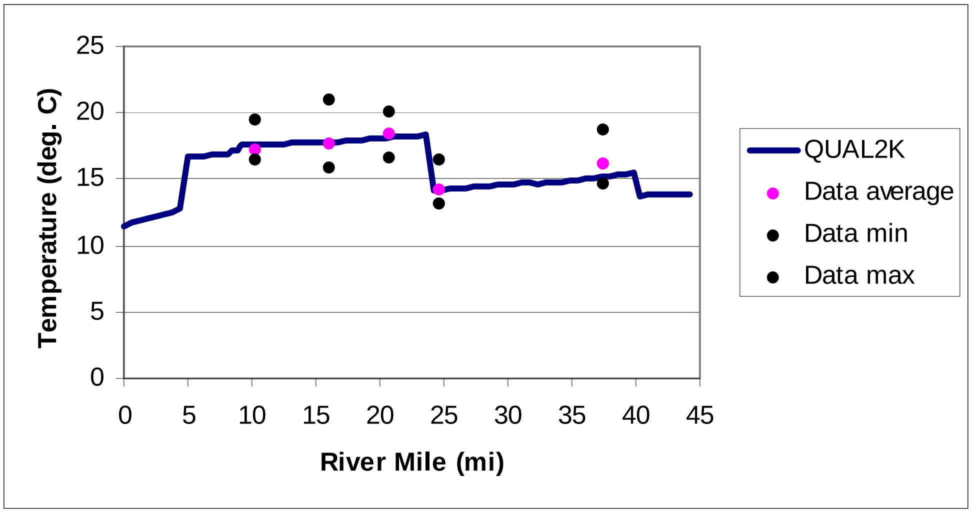
Visual comparisons of model predictions to median, maximum, and minimum ranges of water-quality measurements during July in the Colorado River yield overall good fit for all constituents. Model predictions for all constituents fall within the expected range of data at nearly all measurement locations. Model goodness of fit does vary slightly at different Colorado River measurement sites. Model predictions of water temperature, conductivity, and dissolved oxygen fall within the measured bounds of July data and very close to the in-stream July data median for all measurement locations. Goodness of fit for model predictions of nutrients varies slightly between species. Model predictions for organic nitrogen and inorganic phosphorus (the bioavailable form of phosphorus) match the range and median of measured data well. Model predictions of ammonia and nitrate plus nitrite match the data measured at Hot Sulphur Springs well, but predictions are higher than the median near Kremmling. Model predictions of organic phosphorus are below measured ranges in the center of the reach near the Town of Hot Sulphur Springs, but match well with measured data downstream near Kremmling. Model predictions of dissolved selenium match well with the limited Colorado River data.

For all constituents, the mean of differences between model predictions and the median of data are small; model predictions for all constituents fall within the expected range of data at nearly all measurement locations. Model predictions for water temperature, conductivity, dissolved oxygen, and organic phosphorus are slightly under predicted compared with median data. Organic nitrogen, ammonia, nitrate plus nitrite, inorganic phosphorus, and selenium are slightly over predicted throughout the reach by the model.

2.4. Additional Validation for Water Temperature

A recent dataset for water temperature became available during the model calibration and validation process. These data, made available by Grand County Watershed Information Network (GCWIN) at five sites in the Colorado River during July 31, 2006, two times per hour were used for an additional validation for water temperature. Another set of water temperature data for July 31, 2006 were developed from USGS and NCWCD data for tributaries for QUAL2K. QUAL2K was run and Colorado River water temperature predictions were compared with the GCWIN data, with very favorable results. This comparison is presented in Figure 14.

Figure 14. Comparison of model output with measured data for water temperature on July 31, 2006.



2.5. Discussion of water quality throughout the study reach

The calibrated QUAL2K model of the Upper Colorado River between Lake Granby and Kremmling is a tool for evaluating the factors that effect water quality throughout the reach. Model output, representative of conditions for July, can be analyzed, and the major influences of each water-quality constituent investigated. The results indicate that tributaries have a wide range of flows and concentrations that influence the Colorado River with different magnitudes of change depending on the water quality constituent.

Contributions of water from different tributaries are evident from the plot of Colorado River discharge throughout the study reach. Willow Creek, Fraser River, and the Williams Fork are fairly large contributors of flow, nearly equal to that of the Lake Granby release. Troublesome Creek has a small inflow. Muddy Creek and the Blue River combined are substantial inflow sources, doubling the flow in the Colorado River downstream of their inflow.

Tributary sources of Willow Creek, Williams Fork, and Blue River reduce Colorado River water temperatures with their inflows. For the representative July simulation used for model calibration, the Williams Fork only slightly decreases water temperature in the Colorado River downstream of its confluence. However, the validation simulation of the model showed that on July 31, 2006, the Williams Fork reduced Colorado River water temperatures downstream to a greater degree.

Willow Creek, the Fraser River, Williams Fork, Muddy Creek, and the Blue River are sources of high conductivity water compared to the Colorado River. Conductivity in the Colorado River was predicted by the model to increase downstream of each of these tributaries. The contribution of Troublesome Creek was predicted to slightly dilute downstream river concentrations.

Dissolved oxygen concentrations were predicted to gradually decrease as water moves downstream. The Fraser River, Blue River, and Muddy Creek inflows increase Colorado River dissolved oxygen concentrations locally.

Nutrient concentrations increase in the Colorado River as a result of tributary inflows. Nearly all tributaries and the Hot Sulphur Springs WWTP increase ammonia slightly with their inflows to the Colorado River. Similarly, elevated concentrations of nitrate plus nitrite were predicted by the model downstream of tributary confluences, with the largest increase seen below the Fraser River, Williams Fork, Blue River, and Muddy Creek. The Fraser River, Muddy Creek, and Blue River are contributors of organic phosphorus. Willow Creek, the Fraser River, and the HSS WWTP are contributors of inorganic phosphorus; the Williams Fork, Blue River, and Muddy Creek offered reduced inorganic phosphorus concentrations, diluting the Colorado River downstream of their inflows.

Water released from Lake Granby and most of the tributaries do not contain significant measurable selenium concentrations; most measured data are near the analytical detection limit of 0.5 μg/L. Muddy Creek, however, contributes measurable concentrations in the 2 to 3 μg/L range. This tributary increases downstream dissolved selenium concentrations slightly in the Colorado River.

2.6. Model Sensitivity

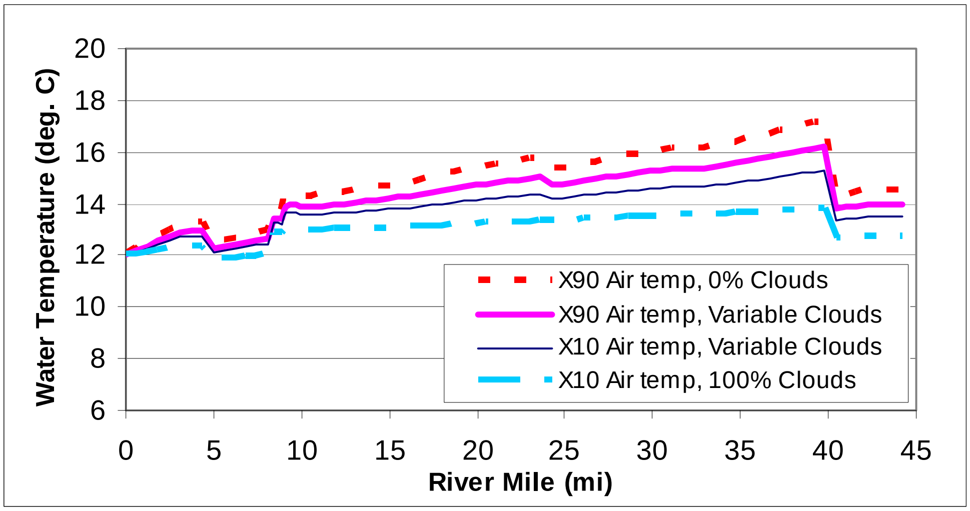
QUAL2K's sensitivity to meteorological conditions was tested. From the period of record of meteorological conditions at Grand Lake and Kremmling, the 10th and 90th percentile of daily average air temperatures were determined. From hourly temperatures at Kremmling, a relationship between temperatures throughout the day and daily average air temperature was developed. This relationship was used to develop hourly temperatures corresponding to the 10th and 90th percentile of air temperatures. These data were used to drive QUAL2K for simulations in order to quantify the magnitude that daily average water temperatures might change for the range of expected air temperatures measured in the area in July.

The impact of cloud cover on the model prediction of daily average water temperature was also investigated using a sensitivity analysis. In addition to the range of air temperatures, a range of cloud cover was simulated. Two simulations were performed describing the 10th percentile of air temperature and 100% cloud cover for the day and 90th percentile air temperature and 0% cloud cover for the day.

The change in air temperature alone was predicted to drive a change in daily average water temperature of up to a maximum of 0.9 ºC, just upstream of the inflow of Muddy Creek and the Blue River. Adding cloud cover conditions, simulation of a cool day with clouds versus a hot day with clear skies result in water temperature predictions that range up to 3.4 ºC. The maximum predicted change is seen just upstream of the inflow of

Muddy Creek and the Blue River. The longitudinal water temperature plots for these four simulations are presented in Figure 15.

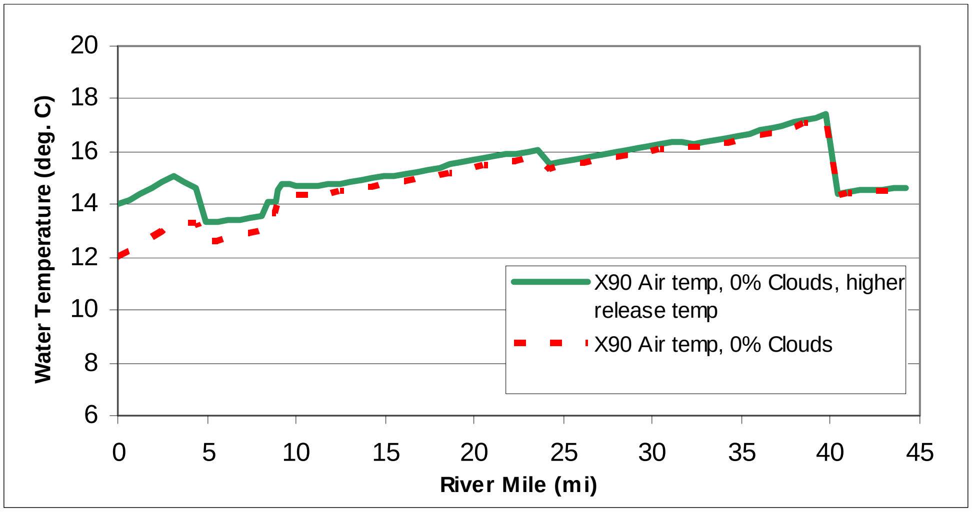
Figure 15. Range of model sensitivity to air temperature and cloud cover.



These results quantify the range of predicted water temperatures that could occur depending on the air temperature and cloud cover observed on a day in July. The greatest predicted change is up to plus or minus 3.4 ºC near the Muddy Creek and Blue River confluences.

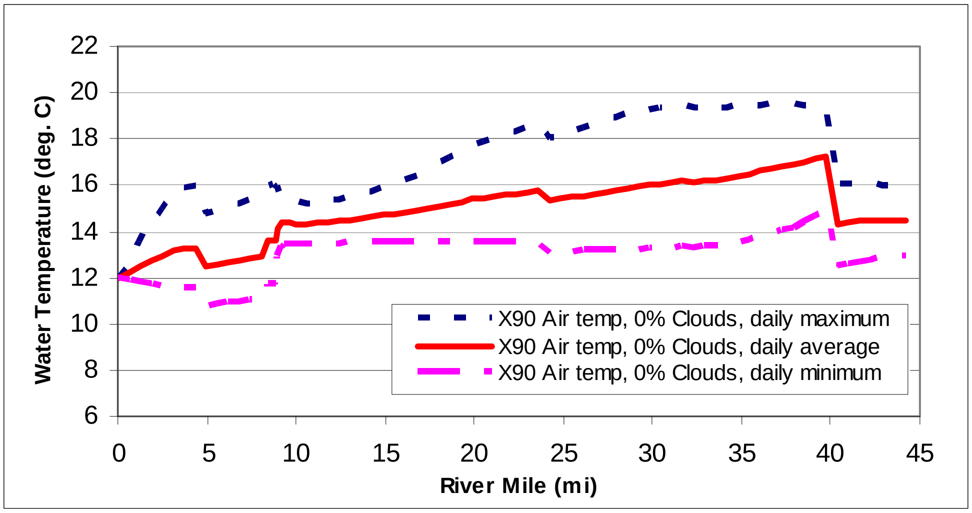
Another sensitivity analysis was performed to quantify how Colorado River daily average temperatures are influenced by Lake Granby release water temperatures. Another simulation with 90th percentile air temperature, 0% cloud cover was performed, where the temperature of water released from Lake Granby was increased by 2 ºC (Figure 16). Model results show that the impact of this higher upstream water temperature is attenuated as water moves downstream, resulting in a temperature increase of no more than 0.5 ºC below Windy Gap Reservoir. Farther downstream, water temperatures move toward equilibrium with the meteorological conditions.

Figure 16. Model sensitivity to Lake Granby release temperature.



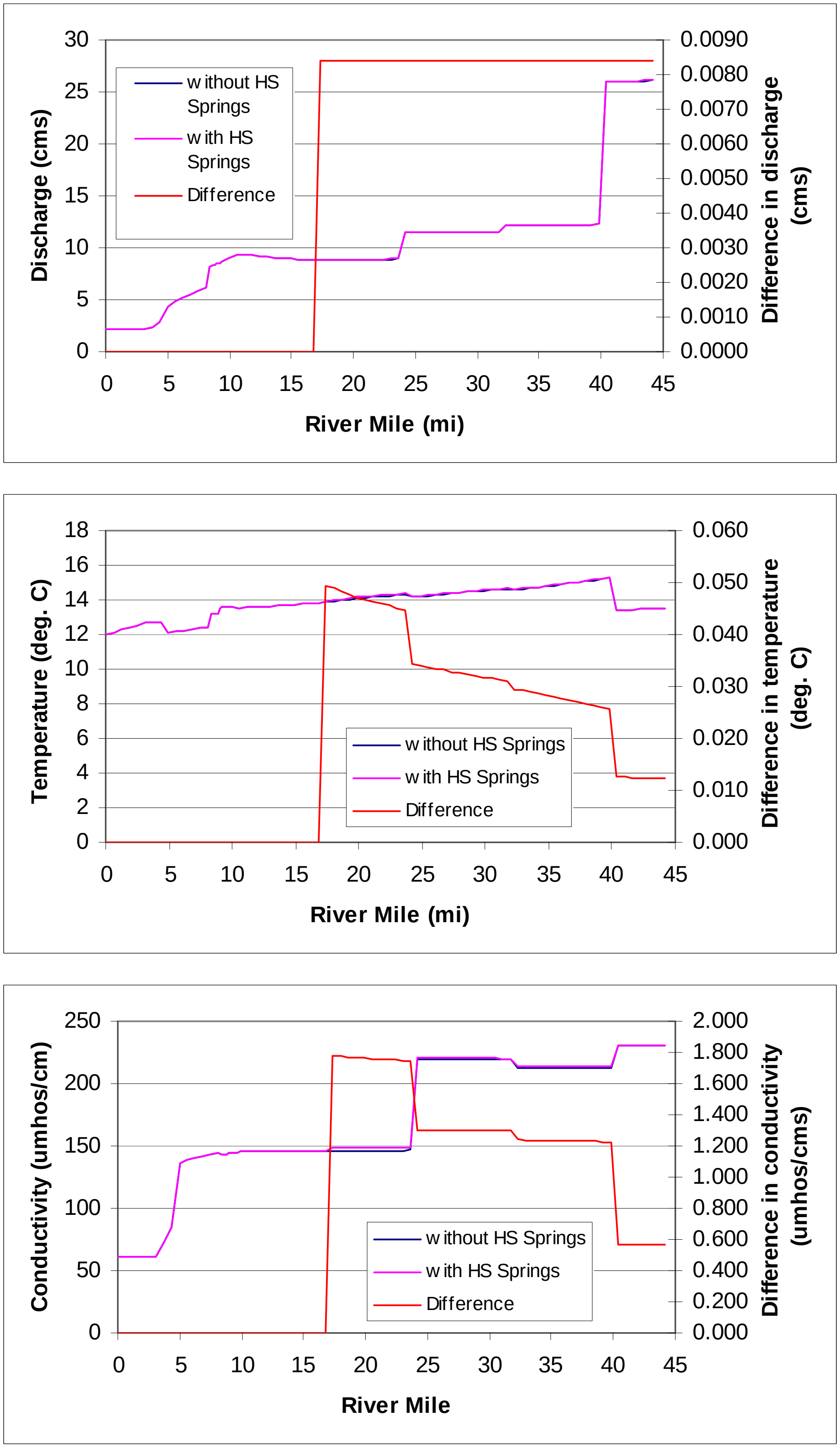
Hourly meteorological conditions were entered into the QUAL2K model. These conditions were used in the model to compute daily average temperature and water quality conditions. QUAL2K also outputs the diurnal range of conditions for each constituent. Most water quality constituents were not predicted to be influenced by hourly changes in meteorological conditions and do not vary throughout the day. However, water temperature was predicted to vary throughout the day. The range of predicted temperatures, shown in Figure 17, varies up to a maximum of 6 ºC above the Troublesome Creek confluence during the course of a hot July day with no cloud cover. Water temperatures in the Colorado River were predicted to exceed 20 ºC for portions of the day between the Williams Fork and the Blue River.

Figure 17. Model prediction of diel range of water temperatures.



The impact of the natural hot springs near the town of Hot Sulphur Springs on the Colorado River was tested in QUAL2K. Data from Barrett and Pearl (1978) indicate spring temperatures of 40 - 44 ºC with 1,200 mg/L TDS, but a small inflow of 50 gal/min (0.0032 m^3/s). The Hot Sulphur Resort and Spa indicates their pools are fed with over 8,000 gallons per hour of spring water ranging from 104 ºF to 126 ºF (40 – 52 ºC) (HSSRAS 2007). Calibrated model simulations with and without the natural hot springs near Hot Sulphur Springs were compared. Given the range in flow rates and water temperatures, 8,000 gallons per hour (133 gal/min) at 150 ºF (66 ºC) and 2,000 µmhos/cm was used to represent the surface and sub-surface inflow from the Hot Sulphur Springs to the Colorado River. The flow, temperature and conductivity predictions are presented in Figure 18. The change in discharge in the Colorado River below the springs was 0.0084 m^3/s. The largest change in water temperature in the Colorado River occurred directly below the springs and was 0.05 ºC warmer than the simulation without the spring's inflow included. The largest change in conductivity in the Colorado River below the springs was 1.78 µmhos/cm directly below the spring's discharge to the river. These simulations show that during a typical July day the model-predicted changes in flow and water quality would be very small in the Colorado River below the natural hot springs. The hot springs inflow was, therefore, not included in the model for alternative analysis.

Figure 18. Sensitivity of model simulation to the inclusion of the natural springs near the Town of Hot Sulphur Springs.



An additional simulation was performed to test the volume of mineral springs water that would result in a significant change in water temperature in the Colorado River. Based on QUAL2K simulations with the calibrated model, 2,800 gal/min of water at 150 ºF (66 ºC) resulted in an increase in Colorado River water temperature of 1 ºC below the springs. A conductivity increase of 37 μmhos/cm occurred in the Colorado River from a source of 2,000 μmhos/cm at this inflow rate. For typical July discharges of 8.77 m^3/s (310 cfs), 133 gal/min (0.3 cfs) is 0.1 % of the flow, and 2,800 gal/min (6.2 cfs) is 2.0% of the flow. During July, an inflow rate much greater than the estimated inflow rate of the Hot Sulphur Springs would be required to raise the Colorado River water temperature by 1 °C. This modeling result reinforces the conclusion that during July the Hot Sulphur Springs inflow would have a small influence on the water quality in the Colorado River and can be ignored for alternative analysis.

2.7. Simulation of Alternatives

The calibrated model was used to simulate water quality in the Colorado River reach as influenced by changes in hydrology as a result of the action alternatives. Water temperatures for some tributaries were adjusted slightly from the calibrated model for alternative simulations. The water temperature in Willow Creek was represented as 11.25 ºC, Troublesome Creek was represented as 19 ºC and Muddy Creek was represented as 12 ºC values for the alternatives. These values were based on data analysis of temperatures on July 25 (simulated for alternatives) as compared to a typical July value (simulated by the calibrated model). Tributary concentrations for all constituents used in the calibrated model are used to model the alternatives. The hydrologic conditions and headwater chemistry are altered for simulation of the alternatives.

3.0 FRASER BASIN NUTRIENT LOADING MODEL

To estimate water quality from the Fraser River in the future, a mass-balance model of nutrient load contributions throughout the Fraser River basin was developed. The predicted Fraser River nutrient concentrations from this model were used by the QUAL2K river model to predict water quality in the Colorado River for the cumulative effects alternatives.

The nutrient loading mass-balance model developed for the Fraser River basin incorporated predictions of load of total nitrogen and total phosphorus from land use, individual sewage disposal systems (ISDSs), and WWTPs to the river. Hydrologic model data from Boyle Engineering for the WGFP were used to develop a model of existing conditions and future condition flows throughout the Fraser River basin. Basin-wide estimates of nutrient source loads from land use and ISDSs were distributed to basin tributary inflow points. WWTP effluent loads entered the Fraser River at outfall locations. Tributary and WWTP inflows were assumed to mix instantaneously in the mainstem of the Fraser River, allowing for a calculation of in-river concentrations and loads.

3.1. Model Development for Existing Conditions

An export coefficient method was used to predict the total basin-wide nutrient load from the range of land use types throughout the basin. This coefficient model was based on data from Corbitt (1990) and Reckhow and Chapra (1983). Loading from the tundra areas was estimated based on information on atmospheric deposition in Colorado (Wolfe et al. 2003) (Table 6).

Table 6. Export coefficient data used for the Fraser River basin nutrient loading model.

Land Use	Total Nitrogen (kg/ha/yr)		Total Phosphorus (kg/ha/yr)	
	Minimum	Maximum	Minimum	Maximum
Residential	5	7.3	0.4	1.3
Commercial	1.9	11	0.1	0.9
Utilities	1.9	14	0.9	4.1
Mixed/Other Urban	1.9	14	0.9	4.1
Agriculture	1.5	30.9	0.1	4.9
Forested	1.4	6.3	0.02	0.8
Open Water	NA	NA	0.2	0.5
Wetland	NA	NA	0.2	0.5
Tundra/Bare Ground	2	4	NA	NA

Table 7 includes percentages of the 213,000-acre Fraser River basin area for each land use type for existing conditions and for predicted future build-out (Grand County 2001).

Table 7. Land use distribution used by the Fraser River basin nutrient loading model.

Land Use	Percent of Basin Existing Conditions	Percent of Basin Future Build-out
Residential	0.61%	0.74%
Commercial	0.26%	0.26%
Utilities	0.07%	0.07%
Mixed/Other Urban	1.03%	1.00%
Agriculture	19.01%	19.04%
Forested	67.28%	67.17%
Open Water	0.11%	0.11%
Wetland	0.63%	0.63%
Tundra/Bare Ground	11.01%	10.99%

Not all of the nutrients entering the Fraser River from land uses reach the mouth of the river. The nutrients associated with sediment attenuate through deposition and filtering as it travels from the source areas to the mouth of the watershed. This attenuation was accounted for through the use of a sediment delivery ratio. This ratio, which is a function of watershed size, was estimated using a generally accepted procedure as described by Mills et al. (1985). The ratio was applied to the particulate portion of the total nutrient concentrations as opposed to the dissolved portion.

Data from Chen et al. (2001) were used to estimate the nutrient loading from ISDSs in use in the Fraser River basin. This study used a water-quality model to predict ISDS impact on Lake Dillon in Summit County, Colorado. Total nutrient loads from effluent leaving a standard-design ISDS cited in this study were 0.04 lbs nitrogen per person per day and 0.006 lbs phosphorus per person per day. Of the 4,600 people living in the Fraser River basin (Grand County 2001), an estimated 30% utilize ISDSs. Results from this study indicate that about 10% of total nitrogen and less than 0.1% of total phosphorus in ISDS effluent is predicted to reach a downstream water body. Decay processes and adsorption in the soil and ground water are responsible for attenuation of nutrients, reducing the impact of ISDSs in rural settings. The total predicted ISDS nutrient load for the Fraser River basin is modeled as being evenly distributed to tributaries of the Fraser River.

Effluent concentration data for the three major WWTPs in the Fraser River basin (Winter Park WWTP, Fraser WWTP, and Town of Granby WWTP) and information from Metcalf and Eddy (1991) were used to estimate total nitrogen and phosphorus entering Fraser River via WWTP effluent. Effluent concentrations of ammonia and nitrate were available from data monitoring reports. Total nitrogen concentrations of 12,000 μg/L and total phosphorus concentrations of 3,200 μg/L were assumed for treated WWTP effluent.

A monthly nutrient loading model was developed and calibrated to predict concentrations and loads of total nitrogen and total phosphorus at the mouth of the Fraser River. To match measured nutrient concentrations at the Fraser River outlet, a monthly attenuation coefficient was used to simulate decay reactions and biological uptake of nutrients. This coefficient was used primarily as a calibration parameter to develop a nutrient model for existing conditions. Total annual loads of nutrients from the three sources included in the nutrient model for the Fraser River basin for existing conditions are presented in Table 8.

Table 8. Total annual nutrient loads at the mouth of the Fraser River.

Source	Total Nitrogen Contribution (kg/yr)	Total Phosphorus Contribution (kg/yr)
Land Use (Includes Atmospheric Deposition)	120,000	5,000
ISDSs	1,000	1
Three WWTPs	24,000	6,300

3.2. Future Conditions Simulations

Hydrologic simulations for future conditions in the Fraser River basin assume that all increased indoor water use returns via WWTP effluent. All population growth within the Fraser River basin is assumed to utilize WWTPs. Using the future conditions hydrologic data and following this assumption, a future conditions nutrient loading model was developed. Nutrient loading from land use assumed future build-out land use distributions. The influence of changes in land use was predicted to increase the total annual nutrient loads by 0.4% for total nitrogen and 0.2% for total phosphorus. Nutrient loading from ISDSs was assumed to remain the same for future conditions.

The future conditions hydrologic simulations indicate that the annual average outfall discharges through the WWTPs are predicted to increase by a factor of 2.3 for the Winter Park WWTP, 4.2 for the Fraser WWTP, and 8.2 for the Town of Granby WWTP. Hydrologic simulations of reasonable foreseeable actions indicate increased diversions through the Moffat Tunnel, resulting in reduced flow in the Fraser River. The nutrient loading model for future conditions indicated that effluent concentrations at existing condition treatment levels with increased future discharge volume greatly elevated the nutrient concentrations in the Fraser River. Therefore, it is assumed that to support future population growth in the Fraser River basin utilizing WWTPs, advanced treatment processes are likely to be required.

Advanced treatment processes for nutrient removal were investigated. Effluent concentrations of 5,000 μg/L for total nitrogen and 15 μg/L for total phosphorus were found in the literature for advanced treatment and are in place at other locations in Colorado (Lesjean and Luck 2006). This level of nitrogen reduction can be achieved through membrane bioreactor technology. With respect to phosphorus, the town of Breckenridge, Colorado has successfully achieved phosphorus removal down to 15 μg/L through advanced treatment (Stantec 2006). These advanced treatment nutrient concentrations (total nitrogen of 5,000 μg/L and total phosphorus of 15 μg/L) were applied to Fraser River basin effluent concentrations for future conditions. The assumption of advanced treatment in the Fraser basin in the future was based on treatment technology that is already in place a similar environment in Colorado. The Fraser River basin nutrient model was used to calculate the concentrations and loads of total nitrogen and total phosphorus leaving the basin under future hydrologic conditions. The resulting total basin nutrient loads are presented in Table 9. The Fraser River basin nutrient model predicts that for future conditions utilizing advanced treatment, there will be an increase in total nitrogen load and a decrease in total phosphorus load.

Table 9. Total annual nutrient loads at the mouth of the Fraser River.

Simulation	Total Nitrogen Load (kg/yr)	Total Phosphorus Load (kg/yr)
Existing Conditions	60,000	6,500
Future Conditions	76,000	3,300

Based on nutrient concentration data for the Fraser River from the calibrated QUAL2K model, fractions of nutrient totals for individual species of organic nitrogen, ammonia, nitrate plus nitrite, inorganic phosphorus, and organic phosphorus were developed. The Fraser River nutrient concentrations for July are presented in Table 10. For future conditions with slightly reduced flow, increased population utilizing WWTPs and advanced treatment implementation, the model predicts higher nitrogen species concentrations and lower phosphorus species concentrations compared to existing conditions. Ammonia concentration was conservatively assumed to be the same fraction of total nitrogen as used for existing conditions (14% of total nitrogen), but could be lower with advanced treatment.

3.3. Model Output for Simulation of Cumulative Effects Alternatives

The values presented in Table 10 were used to characterize the quality of the Fraser River for all cumulative effects alternatives simulated by the QUAL2K model. Analyses of the results from these simulations were presented in the Stream Water Quality Technical Report (ERO and AMEC 2008).

Table 10. Comparison of Fraser River outflow nutrient concentrations for existing conditions and future cumulative effects simulations.

Alternative	Organic Nitrogen (μg/L)	Ammonia (μg/L)	Nitrate and Nitrite (μg/L)	Organic Phosphorus (μg/L)	Inorganic Phosphorus (μg/L)
Existing Conditions	106	32	87	34	22
All Cumulative Effects Alternatives	209	63	172	20	13

4.0 WILLOW CREEK TEMPERATURE MODEL

The SSTEMP model was developed and is provided by the USGS in Fort Collins, Colorado (Bartholow 2002). SSTEMP may be used to evaluate alternative reservoir release proposals, analyze the effect of changing riparian shade or the physical characteristics of a stream, and examine the effects of different stream depletions and returns on instream temperature. The model handles only single stream segments for a single time period (e.g., day, week, or month) in any given model run. It can be used to perform sensitivity and uncertainty analyses. Model assumptions are discussed in the model documentation (Bartholow 2002).

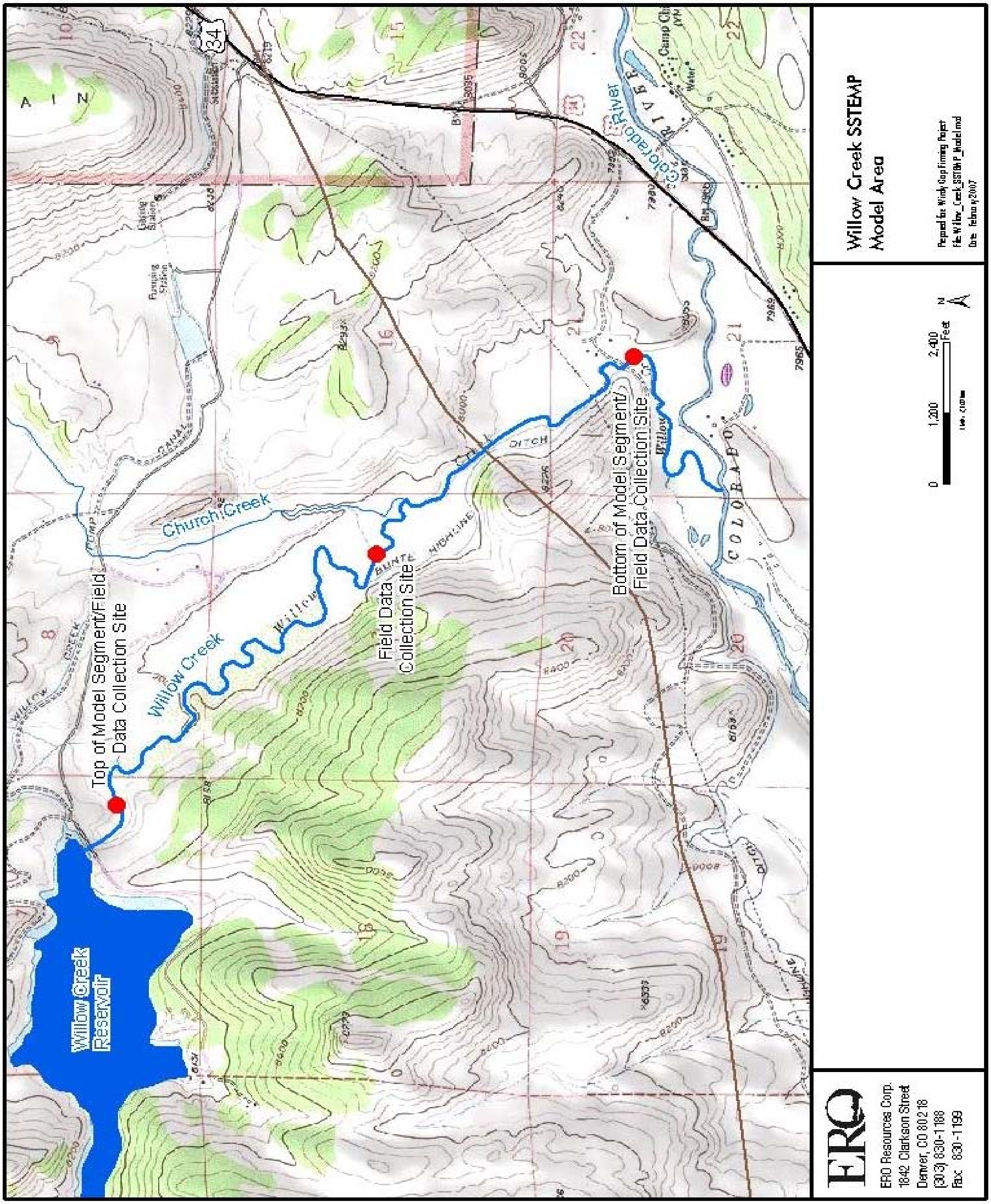
Because the flow of Willow Creek below Willow Creek Reservoir would decrease during part of the year under all of the WGFP alternatives, SSTEMP was used to simulate temperature changes that may occur in the segment of Willow Creek below Willow Creek Reservoir to the Colorado River. To determine worst-case conditions for aquatic life in the stream, July 15th was chosen to simulate Willow Creek during hot, sunny, lower flow conditions. For both direct and cumulative effects, the maximum average monthly percent decrease in the flow of the creek would occur under all of the WGFP alternatives during July of an average year.

SSTEMP requires inputs describing the average stream geometry, stream shading, steady-state hydrology, and meteorology. The model estimates the combined topographic and vegetative shade, as well as solar radiation penetrating the water. It then predicts the mean daily water temperatures at specified distances downstream. The model handles the case of a dam with steady-state release at the upstream end of the segment. In this case, the top of the model segment is located on Willow Creek at the gaging station just below Willow Creek Reservoir, and the bottom of the segment is located in the vicinity of the former USGS/NCWCD gaging station located ½ mile upstream of the stream's confluence with the Colorado River (Figure 19). The 3-mile segment of Willow Creek below Willow Creek Reservoir was modeled as one segment, meaning it was assumed that average channel geometry, shading variables, and meteorology were the same for the entire segment. Based on model calibration, this assumption appears reasonable.

On September 15, 2006, an ERO hydrologist collected the following information at three locations along Willow Creek (Figure 19):

1. stream flow velocity (ft/sec)
2. stream channel width (ft)
3. stream depth (ft, average of several locations where width measured)
4. stream temperature (ºF)
5. air temperature (ºF)
6. soil temperature, collected near the creek bank (ºF)
7. description of channel bottom (sandy, cobbly, etc.)
8. description of streamside vegetation shading creek, including species, density, height, crown diameter and distance from edge of stream bank
9. percent cloud cover
10. wind speed (mph)
11. topographic altitude, which is a measure of the average incline to the horizon from the middle of the stream looking perpendicular to the direction of flow, measured for both sides using a Brunton compass clinometer (degrees).

Figure 19. Willow Creek SSTEMP model area.



The three locations were the top and bottom of the model segment and a point in between that was easily accessible. The stream geometry, shading variables, and meteorological data were averaged and used in the first model run, which was for September 15th. Other factors needed for model input were:

- latitude, taken from a USGS topographic map of the site
- upstream and downstream segment elevation, taken from the topographic map
- azimuth, which is the general orientation of the stream with respect to due north (degrees)
- relative humidity, taken from the Town of Granby's weather station data for September 15, 2006 (Granby 2006)
- ground water temperature, collected from nearby USGS well data (Earthinfo 2005)
- stream width's A and B term, which are derived from developing the relationship between stream width and flow volume (see model documentation)
- Manning's number, which is based on the segment's roughness (0.065 was used, based on channel bottom description)
- thermal gradient, which is a measure of the rate of thermal input from the streambed to the water (used default value of 1.65)
- dust coefficient, which is the amount of dust in the air (used provided median values for season)
- ground reflectivity, which is a measure of the amount of radiation reflected from the earth back into the atmosphere (used provided value for meadows and fields).

After the model was run, the sensitivity analysis showed which parameters most affected the model results (on September 15th, this was air temperature and ground water temperature, followed by stream inflow temperature). The model was calibrated by slightly adjusting some of the shading variables and meteorological input values. After the model was calibrated for September 15th, the stream segment outflow temperature at the bottom of the 3-mile segment closely matched the measured stream temperature at that location. Model results are provided in Appendix A.

The model was then calibrated for July 15th, using the Boyle model (Boyle 2006) existing conditions streamflow for Willow Creek, average meteorological data from the Town of Granby weather station for that date (Granby 2006), and stream segment inflow and outflow temperatures estimated from existing flow and temperature data collected in Willow Creek below Willow Creek Reservoir and at the downstream gage location, which is located close to the bottom of the model segment (Earth Info 2006; NCWCD 2006). In this case, the sensitivity analysis showed that stream inflow temperature most affected the model results, followed by air temperature, and then ground water temperature. The stream segment outflow temperature at the bottom of the 3-mile segment closely matched measured stream temperatures at that location. Model results are provided in Appendix A.

To determine the worst-case impact to Willow Creek due to reduced streamflows, the model was run with segment inflow reduced by 36%, which is the estimated largest average monthly flow reduction (July) under any alternative for both direct and cumulative effects. The flow reduction resulted in a slight decrease in the downstream temperature of the stream segment (about 0.11 ºC). With stream inflow temperature and air temperature remaining the same, the parameter most strongly influencing the model results was ground water temperature. Field streamflow measurements (of the main channel and the tributary within the model reach) and the model results showed that ground water is a major source of supply to Willow Creek and controls the temperature of this segment of Willow Creek. The maximum change in streamflow that would occur under all of the WGFP alternatives would result in a negligible change in the temperature of Willow Creek below Willow Creek Reservoir. An infrared aerial photo taken by the U.S. Department of Agriculture in August 1985 also shows that ground water is a major source of water to Willow Creek. Shallow ground water, much of it likely return flows from irrigated meadows, can be seen entering the creek along almost the entire east side of the 3-mile model segment. The modeling results are provided in the Stream Water Quality Technical Report (ERO and AMEC 2008).

5.0 WATER QUALITY MASS BALANCE CALCULATIONS

Changes in water quality to some of the stream segments affected by the WGFP alternatives were estimated by completing mass balance calculations at certain locations. Ammonia is not a conservative water quality parameter; ammonia concentrations can decrease downstream as a result of biogeochemical processes. The mass balance calculations provide an in-stream ammonia value before these changes would occur. The results, therefore, show the highest ammonia concentrations that might occur under the alternatives. Results from the mass balance analyses are provided in the Stream Water Quality Technical Report (ERO and AMEC 2008). The locations were:

- Willow Creek below the Church Creek tributary into which the Three Lakes WWTP discharges its effluent, where the relative contribution of effluent would increase because the flow of Willow Creek would decrease during some months under the alternatives.
- Big Thompson River above the Dille Tunnel, where the river would receive an increase of up to 18 cfs of additional water from the Adams Tunnel under the alternatives under both direct and cumulative effects.
- East Slope streams below Participants' WWTPs, where WWTP effluent return flows would increase during some months under the alternatives. The locations include the Big Thompson River below Loveland's WWTP, St. Vrain Creek below Longmont's WWTP, the Cache la Poudre River below Greeley's WWTP, Big Dry Creek below Broomfield's WWTP, and Coal Creek below Superior's, Louisville's, Lafayette's, and Erie's WWTPs.

Changes in nutrient and metal concentrations were calculated for parameters for which water quality data were available for both the stream and the WWTP effluent or Adams Tunnel water. For streams affected by WWTP effluent, mass balance calculations were completed for the month in which the largest change in the flow of Willow Creek would occur (July), or when the largest increase in WWTP return flows would occur relative to average monthly streamflow (September or October for most East Slope streams, November or January for the Poudre River). For the Big Thompson River above the Dille Tunnel, mass balance calculations were completed for the Proposed Alternative, which would have the largest increase in Adams Tunnel water to the upper Big Thompson River. For the purpose of comparing calculated changes in ammonia concentrations to the ammonia standards, it was assumed that the changes in flows or water quality would not significantly change the stream pH or temperature. The mass balance approach used assumes that the water quality constituents are conservative, which is not the case for ammonia. Ammonia concentrations change downstream as a result of biogeochemical processes in the stream; calculated ammonia values are in-stream values before these changes occur.

Several examples of the mass balance calculations used to assess water quality impacts to stream segments affected by the WGFP alternatives are provided below.

1. For Willow Creek, with decreased flows above the WWTP under the alternatives, an example of the one of the mass balance calculations is provided below. These computations are used to compute the change in in-stream concentrations downstream of the WWTP discharge as a result of the alternatives. This example is for iron concentrations in Willow Creek downstream of the tributary into which the Three Lakes Water Sanitation District discharges its WWTP effluent.

The water mass balance is:

$$Q_{upstream} + Q_{WWTP} = Q_{downstream}$$

Where Q = flow. The constituent mass balance is:

$$C_{upstream}Q_{upstream} + C_{WWTP}Q_{WWTP} = C_{downstream}Q_{downstream}$$

where C = iron concentration.

The known values are Willow Creek flows upstream of the tributary (existing conditions and for the alternatives), the existing average downstream iron concentration (92.5 µg/L), and the maximum permitted WWTP effluent discharge (0.53 cfs) and iron concentrations (260 µg/L) (which are assumed to remain unchanged in the future).

First, the upstream iron concentration is calculated:

$C_{upstream} = (C_{downstream}Q_{downstream} - C_{WWTP}Q_{WWTP})/Q_{upstream}$ = (92.5 µg/L*(143 cfs +1.3 cfs)– 260 µg/L*1.3 cfs)/143 cfs = 91.0 µg/L.

This value is then used to calculate the downstream iron concentration that would result based on the modeled reduced flow in Willow Creek, which for June under Alternative 2 would be a reduction from 143 cfs to 127 cfs:

$C_{downstream} = (C_{upstream}Q_{upstream} + C_{WWTP}Q_{WWTP})/Q_{downstream}$ = (91.0 µg/L*127 cfs + 260 µg/L*1.3 cfs)/(127 cfs + 1.3 cfs) = 92.7 µg/L.

This is an increase in the iron concentration of 0.2 µg/L from existing conditions.

2. For the Big Thompson River above the Dille Tunnel, the mass balance calculation is as follows:

$C_{new} = C_{present}Q_{present}(\%) + C_{AdamsTunnel}Q_{AdamsTunnel}(\%)$

An example is for phosphorus concentrations in the Big Thompson River when an additional 18 cfs of water is added to the Big Thompson from Adams Tunnel (Alternative 2). The average existing phosphorus concentration in the river is 0.05 mg/L and the estimated phosphorus concentration in the Adams Tunnel water is 0.09 mg/L. The average flow of the river was estimated to be 186 cfs under Existing Conditions (ERO and AMEC 2008). Under the Proposed Alternative, the added inflow from Adams Tunnel would be 9 percent of the total flow of the river. Therefore, for the Proposed Alternative, the phosphorus concentration in the river would be:

C_{new} = 0.05*0.91 + 0.09*0.09 = 0.0536 mg/L. Thus, the increase from the existing phosphorus concentration (0.05 mg/L) would be 0.0036 mg/L.

3. In the case of the East Slope streams with increased WWTP return flows under the alternatives, an example of one of the mass balance calculations is provided below. These computations are used to compute the change in in-stream concentrations downstream of the WWTP discharge as a result of the alternatives. This example is for manganese concentrations in Big Dry Creek downstream of the Broomfield WWTP.

The water mass balance is:

$$Q_{upstream} + Q_{WWTP} = Q_{downstream}$$

Where Q = flow. The constituent mass balance is:

$$C_{upstream}Q_{upstream} + C_{WWTP}Q_{WWTP} = C_{downstream}Q_{downstream}$$

where C = manganese concentration.

The first step is to solve these equations for existing conditions. Average flow and concentration data includes the following:

$Q_{downstream}$ = mean Big Dry Creek flow below the WWTP = 10.1 cfs

$C_{downstream}$ = 80 ug/L

Q_{WWTP} = mean Broomfield WWTP discharge = 5.8 cfs

C_{WWTP} = 9.74 ug/L.

Thus,

$$Q_{upstream} = Q_{downstream} - Q_{WWTP} = 10.1 - 5.8 = 4.3\ cfs$$

and

$$C_{upstream} = \frac{C_{downstream}Q_{downstream} - C_{WWTP}Q_{WWTP}}{Q_{upstream}} = 174.8 \ \mu g/L$$

The second step is to increase the effluent discharge and compute the new downstream concentration. The upstream concentration and flow is assumed to remain at existing condition values. Flow through the WWTP is estimated to increase with the alternatives. The WWTP concentration is assumed to remain constant. The downstream in-river concentration is then calculated for the alternatives.

Based on increased return flow from the Broomfield WWTP in October of 3.4 cfs under all alternatives during an average year, the new flow values include:

Q_{WWTP} = 3.4 cfs + 5.8 cfs = 9.2 cfs

$Q_{downstream}$ = 3.4 + 10.1 = 13.5 cfs

The resulting downstream concentration becomes:

$$C_{downstream} = \frac{C_{upstream}Q_{upstream} + C_{WWTP}Q_{WWTP}}{Q_{downstream}} = 62.3\mu g / L$$

As a result of the alternative actions, the manganese concentration in Big Dry Creek is predicted to decrease by about 17.7 µg/L below Broomfield’s WWTP.

6.0 AMMONIA STANDARDS CALCULATIONS

In June 2005, the CWQCC adopted new ammonia criteria for surface waters (CWQCC 2007). The new criteria are in the form of equations for total ammonia. The new ammonia criteria became enforceable standards in all river basins in Colorado on July 1, 2007. The new total ammonia standards were calculated and used in the Stream Water Quality Technical Report (ERO and AMEC 2008).

The toxicity of ammonia to aquatic life is strongly dependent on the pH and temperature of a stream. At higher pH and temperature levels, toxicity is higher and ammonia standards are lower. The acute criterion (applicable to the daily maximum value in a discharge permit) depends on whether trout (salmonid) species are present in the stream. Trout are especially sensitive to ammonia. Numerical standards for total ammonia are calculated as follows (CWQCC 2007):

For trout present: Acute ammonia standard=(0.275/(1+10 $^{7.204\text{-pH}}$)+(39/(1+10 $^{\text{pH-}7.204}$)

For trout absent: Acute ammonia standard=(0.411/(1+10 $^{7.204\text{-pH}}$)+(58.4/(1+10 $^{\text{pH-}7.204}$)

The chronic criterion (applicable to the 30-day average value in a discharge permit) depends on whether or not fish early life stages are expected to be present in the stream.

For fish early life stages present: Chronic ammonia standard=0.854*((0.0676/(1+10 $^{7.688\text{-pH}}$)+(2.912/(1+10 $^{\text{pH-}7.688}$))*MIN (2.85, 1.45*10 $^{0.028(25\text{-Temperature }^{\circ}\text{C})}$)

For fish early life stages absent: Chronic ammonia standard=$0.854*((0.0676/(1+10^{7.688\text{-pH}})+(2.912/(1+10^{\text{pH-}7.688}))*1.45*10^{0.028*(25\text{-MAX(Temperature °C, 7))}}$

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Appendix A
SSTEMP Model Results—Output Tables