Prepared for:
Barr-Milton Watershed Association
Denver, Colorado

Watershed and Lake Modeling for a TMDL Evaluation of Barr Lake and Milton Reservoir

Second Revision - Final

AECOM, Inc.
August 2009
Document No.: 12301-001

AECOM

Prepared for:
Barr-Milton Watershed Association
Denver, Colorado

Watershed and Lake Modeling for a TMDL Evaluation of Barr Lake and Milton Reservoir

Second Revision - Final

Revised by:

Kenneth J Wagner, Ph.D., CLM
Water Resources Manager
ken.wagner@aecom.com

AECOM, Inc.
August 2009
Document No.: 12301-001

AECOM

Contents

List of Appendices

List of Tables

List of Figures

List of Acronyms

B-O – Burlington-O'Brian Canal

BMP – Best Management Practice

BMW – Barr-Milton Watershed

CDPHE – Colorado Department of Public Health and Environment

DEM – Digital Elevation Model

DIA – Denver International Airport

DO – Dissolved Oxygen

EPA – Environmental Protection Agency

FRICO - Farmers Reservoir and Irrigation Company

GIS – Geographic Information System

GUI – Graphical User Interface

HRU – Hydrologic Response Unit

HSPF – Hydrologic Simulation Program: FORTRAN

LAI – Leaf Area Index

LA – Load Allocation

MOS – Margin of Safety

MRLC – Multi-Resolution Land use Consortium

MS4 - Municipal Separate Storm Sewer System

NLCD – National Landcover Dataset

NPDES – National Pollution Discharge Elimination System

PVC – Platte Valley Canal

SACWSD - South Adams County Water and Sanitation District

SPR – South Platte River

STATSGO – State Soil Geographic Database

S.U. – Standard Units

SWAT – Soil and Water Assessment Tool

TMDL – Total Maximum Daily Load

TN – Total Nitrogen

TP – Total Phosphorus

UNC – University of Northern Colorado

USDA – United States Department of Agriculture

USGS – United States Geological Survey

VB – Visual Basic

WASP – Water Quality Analysis Simulation Program

WLA – Waste Load Allocation

WWTP – Wastewater Treatment Plant

Executive Summary

Barr Lake and Milton Reservoir are two off-channel waterbodies in the South Platte River system, northeast of Denver, Colorado. These reservoirs are used mainly as irrigation supplies, but also serve other uses, including wildlife habitat and human recreation, with human water supply potentially increasing in importance with development in the area. Both reservoirs suffer from high pH, well above perceived natural background levels and in excess of the state standard. Algal blooms are believed to be responsible for elevated pH through removal of carbon dioxide during photosynthesis, and high alkalinity in the reservoirs sustains higher pH levels once established. Complete support of designated uses requires a reduction in pH, and a Total Maximum Daily Load (TMDL) development process has been initiated to determine an appropriate set of target conditions for achieving compliance. Lowering of phosphorus loads to reduce algal production and limit instances of high pH is desired.

Water quality data have been collected, assimilated, and applied in other analysis and modeling efforts. This investigation revisited those data and analyses, and incorporated relevant aspects into the model. Additional effort was put into evaluating linkages between phosphorus, chlorophyll *a*, and pH in these reservoirs and estimating logical target values for compliance with the state standard for pH, which is a value of <9.0 SU for >85% of the time.

The watershed and lake modeling investigation presented in this report represents a detailed mathematical evaluation of the Barr-Milton Watershed. The objective of the investigation was to develop a reliable predictor of water quality in the lake and reservoir for use in dividing the current load among important sources and testing alternative management scenarios aimed at reducing the number of exceedences of the pH standard in the two waterbodies. AECOM worked closely with the Barr-Milton Watershed Association Technical Committee to ensure that the project objective was met and that the predictions made using the numerical models would be applicable to the development of the TMDL for pH.

The complexity of the Barr-Milton watershed investigation required a novel approach to the development of the watershed and the inlake models. The number and magnitude of water transfers greatly complicated load accounting and required adjustments to the watershed model that were not previously available. AECOM used a modified version of the SWAT model developed by the USDA for the watershed simulation. This modification made it possible to acceptably simulate complex water transfers throughout the simulation.

Processes in the reservoir were influential enough to warrant a separate reservoir water quality model. A recently released version of the WASP model developed by the EPA was applied, as it adequately addressed important inlake processes without overcomplicating spatial aspects of the model for which little calibration data were available. The recently released version of the WASP model included an “Advanced Eutrophication“ module that can incorporate multiple taxonomic groups of phytoplankton in a water body. This version of the WASP model proved helpful in simulating the progression of algal types in Barr Lake and Milton Reservoir during the year and the related interaction with water quality.

The level of complexity associated with the multitude of discharges and water transfers in the Barr-Milton watershed required an extensive dataset for model development and calibration. Data from sources at various levels of detail were applied to generate the best possible representation of current conditions and processes in the watershed and reservoirs. AECOM first worked with the Technical Committee to develop a detailed flow diagram of the Barr-Milton watershed and then to acquire both flow and water quality data for the 2003-2004 simulation period. Data gaps were filled using simple estimation techniques. In general, the larger the water discharge or withdrawal, the more effort was put into data coverage to reduce the potential for error.

Assessment of available data for Barr Lake, Milton Reservoir, the associated watershed, and other area reservoirs indicate important baseline conditions:

- Background pH for waters unimpacted by human activities appears to be on the order of 7.6 SU. Based on observed variability at high phosphorus concentrations, a mean pH near 8.5 SU is predicted to result in a pH distribution that meets the standard.
- The highest total phosphorus value that could be reasonably expected to support achievement of the pH standard is 0.1 mg/L in each lake, although a lack of data for conditions in the reservoirs at phosphorus levels <0.25 mg/L adds uncertainty.
- The mean chlorophyll *a* concentration that leads to pH compliance appears to be approximately 20 to 25 µg/L, although conditioning of water in Barr Lake that is then discharged to the Beebe Canal and eventually Milton Reservoir suggests that lower chlorophyll *a* levels may be required to achieve compliance in Milton Reservoir.
- Nutrient loading to Barr Lake and Milton Reservoir is excessive. As phosphorus levels rise above 0.1 mg/L, there is a diminishing linkage with productivity measures as other factors become more important in controlling algae growth. Phosphorus concentrations in these two reservoirs average >0.5 mg/L.
- Water exiting Chatfield Reservoir into the South Platte River exhibits phosphorus levels <0.04 mg/L, but becomes overloaded with nutrients through sequential discharges to the South Platte River prior to diversion into Barr Lake and Milton Reservoir.

An evaluation of the flow and water quality data identified several important components of the hydrologic and nutrient loads in the Barr-Milton watershed, including:

- Water transfer rates to Barr Lake from the South Platte River and through the Burlington-O'Brian Canal vary throughout the year but averaged 158 cfs during 2003-04. This represents approximately 70% of the average 2003-04 flow of 223 cfs, as measured at the upstream USGS gage (06714000 – South Platte River at Denver).
- The water transferred to Barr Lake from the South Platte River contains wastewater from the Littleton-Englewood WWTP. The average estimated total phosphorus concentration from the Littleton-Englewood plant during 2003-04 was 2.9 mg/L. This phosphorus concentration was diluted to 0.45 mg/L based on the average 2003-04 flow of 223 cfs as measured in the South Platte River at the upstream USGS gage (06714000 – South Platte River at Denver).
- During the period from November through April, wastewater from the Metro WWTP has been discharged through the Pump Works into the Burlington-O'Brian Canal to enhance the Barr Lake refill rate. Metro does not operate this pump station, but it is treated Metro wastewater that is discharged. The discharge rate has averaged 35 cfs and the total phosphorus concentration averaged 2.8 mg/L during 2003-04. Current legal action may suspend or eliminate this transfer.
- Water transfer rates to Milton Reservoir from the South Platte River through the Platte Valley Canal vary throughout the year, with the greatest transfer in late winter and spring. This transfer averaged 81 cfs during 2003-04.
- The water transferred to Milton Reservoir from the South Platte River through the Platte Valley Canal contains wastewater from the Metro and Littleton-Englewood WWTPs, and others that discharge to the mainstem or tributaries of the South Platte River upstream of the Platte Valley Canal diversion. The average predicted total phosphorus concentration entering Milton Reservoir from the Platte Valley Canal is 1.8 mg/L.
- Water also reaches Milton Reservoir through the Beebe Canal, which contains overflow from Barr Lake and any inflows to the canal between Barr Lake and Milton Reservoir, which includes two small WWTPs, irrigation return water, and some seepage. The average predicted total phosphorus concentration entering Milton Reservoir from the Beebe Canal is 0.44 mg/L.

These generalizations cover the main influences on the water and nutrient budget to Barr Lake and Milton Reservoir, but the complexities associated with the point sources, consumptive uses, and transfers all have a role in modifying water quality in the various stream channels and canals in the system, and ultimately in the reservoirs.

The watershed model predictions were compared over the 2003-04 simulation period with measured lake and reservoir volumes and inflow nutrient concentrations during that same period. The SWAT model was able to predict water volumes and total nitrogen and phosphorus influent concentrations over the two year period at an acceptable level of agreement and provided suitable inputs for the WASP model for each reservoir.

The primary challenge in calibrating the lake models involved matching the succession of algae during the two year simulation period in response to a highly dynamic input of water and nutrients to the lakes. In addition to adjusting rates and constants during the calibration of the lake models, two processes were identified as playing important roles in controlling phosphorus and chlorophyll concentrations as predicted in the reservoirs:

- *Settling of particulate phosphorus* - During the calibration of the lake model it was determined that even though the watershed model proved to acceptably predict the concentrations of phosphorus entering the lake and reservoir, the model initially over-predicted inlake phosphorus during the late winter and springtime infill period. To counteract this, a process of associating phosphorus with predicted TSS and then settling the TSS was applied. An acceptable calibration was achieved in both reservoirs during the later winter and springtime infill period by adjusting the phosphorus:TSS partitioning coefficient and the settling rate of the TSS.
- *Internal loading of phosphorus* – Incorporating an internal load of phosphorus also proved to be an important step in achieving a favorable calibration during the summer months. The diffusion of dissolved phosphorus from the lake sediments to the water column, which occurs under low DO conditions at the sediment-water interface, is not uncommon in eutrophic systems. Resuspension of particulates, with some dissolution of attached phosphorus, is also expected in these shallow systems through the influence of wind and bottom feeding fish. Without incorporating internal loading processes into the lake models, the predicted phosphorus concentrations during the summer months were consistently lower than actual data indicated. With continued settling of particulates, the net internal load is much lower, as reflected in other mass balance estimation efforts.

The seasonal nature of phosphorus settling and resuspension appears very important in the BMW system and was adequately simulated by this process, although the exact mechanisms may deviate from the way the model portrays them. Further investigation is recommended.

The variability in the chlorophyll data did not permit a point-by-point calibration; actual data and predictions may not be directly comparable on any given date. The model assumes an even distribution of algae, while the actual data are subject to the effects of mixing, algal buoyancy and light limitations. Model calibration sought to match the distribution of chlorophyll values over the course of the simulation period, with some attention to seasonal variation. Scatter plots and box and whisker plots were used to compare measured and predicted total phosphorus and chlorophyll concentrations throughout the simulation period. The magnitude and distribution of total phosphorus was favorably mimicked, but chlorophyll concentrations proved more challenging to simulate. Control of chlorophyll production (i.e., algal growth) by factors other than phosphorus at such high phosphorus levels is to be expected.

The calibrated model provides indications of several important aspects of current conditions in Barr Lake and Milton Reservoir and limitations of the modeling approach:

- The SWAT model tends to overpredict nutrient loading while the WASP model underpredicts resultant inlake phosphorus concentrations. Important processes appear adequately simulated, however, and predictions of the direction and magnitude of change in response to possible management actions are considered to be reliable enough to be useful for TMDL development.

- The Metro WWTP and Littleton-Englewood WWTP are the largest dischargers of phosphorus to the system, providing approximately 90% of the load to Barr Lake and 80% of the load to Milton Reservoir. Of these two sources, Littleton/Englewood WWTP is slightly more influential on Barr Lake and Metro WWTP is much more influential on Milton Reservoir.
- Internal loading is difficult to quantify with existing data, but the model indicates that internal loading of phosphorus may be an important input source in at least Barr Lake now. Internal loading in both reservoirs is sufficient to support algal blooms and contravene the pH standard, and is expected to increase substantially if external loading is decreased. Additional investigation into this compensatory mechanism has been recommended.
- It is not possible to achieve a meaningful reduction in phosphorus loading without addressing the dominant point sources and the internal load. More than a 90% reduction in each is needed, and it may take a 99% reduction in the external load to achieve phosphorus concentrations believed to correspond to compliance with the pH standard. This would require major reductions from many sources in the watershed, not just the dominant point sources.

With the development of the calibrated watershed and lake models, AECOM and the Technical Committee developed a series of alternative management scenarios for simulation. The simulation of the management alternatives demonstrated the flexibility of the watershed and lake models and provided a way to quanitatively test the relative improvement in reservoir water quality given a defined management scenario. The simulated management alternatives were designed to consider potential controls that included:

Reductions to WWTP phosphorus loads – Simulations included reductions of phosphorus from the largest WWTPs and then all WWTPs to levels of 1 mg/L, 100 µg/L, and 50 µg/L. The simulations indicated that total phosphorus and chlorophyll concentrations in Barr Lake and Milton Reservoir are linked largely to concentrations of phosphorus discharged from the Metro WWTP and the Littleton-Englewood WWTP. Under current conditions, the loads of phosphorus from the remaining point sources are too small to have a significant impact on inlake water quality. The simulations also indicated that controlling other (nonpoint source) loads of phosphorus to the lake and reservoir would not adequately lower inlake concentrations because such a large portion of the lake water is derived from WWTP discharges.

- *Alternative flow management* – Simulations included eliminating the discharge of wastewater to the Burlington-O'Brian Canal during the late winter and spring refill period and then augmenting that water with an additional transfer of water from the South Platte River. This simulation indicated moderate improvement in water quality in Barr Lake, but a decline in Milton Reservoir water quality coincident with the degradation in South Platte River water quality from additional wastewater discharge to the river.
- *Reductions to other phosphorus loads* – Simulations intended to quantify the loads of phosphorus from stormwater runoff conveyed through MS4 permitted and non-permitted areas did not indicate any appreciable load from these sources. Under current conditions the loads of phosphorus from these sources are too small to have a significant impact on inlake water quality.
- *Reductions to internal loads of phosphorus* – Simulations intended to quantify the effect of internal phosphorus loads indicated that this is a significant process that needs to be addressed coincident with a reduction in external loads of phosphorus. Reduction of internal phosphorus loading by at least 70% during the summer months dramatically improved water quality when simulated along with reductions in phosphorus loads from the Metro WWTP and the Littleton-Englewood WWTP.

The results of the alternative management simulations indicated that appreciable reductions in phosphorus and chlorophyll concentrations in Barr Lake and Milton Reservoir would require a multi-pronged approach. Options include: 1) reductions in phosphorus loads from WWTPs, with the Metro and Littleton-Englewood facilities as the top priority, 2) a reduction in the internal load of phosphorus in Barr Lake and Milton Reservoir, 3) reductions from other watershed sources, especially other WWTPs, and 4) an optimization of the water quality through selective water transfers to the reservoirs. The flexibility of the watershed and lake models makes it possible to simulate additional combinations of management alternatives and the model calibration should be revisited as new data are collected.

Conclusions drawn from the scenario modeling include:

- Almost all scenarios examined in this exercise do not result in mean phosphorus and/or chlorophyll levels as low as may seem desirable from the evaluation of possible target values. Guaranteed compliance through phosphorus input reduction will require extremely stringent discharge limits and strong control of internal loading. However, it appears more important to avoid high values than to lower the mean or median by an extreme amount, and it may be easier to change the shape of the distribution of values than to shift the entire distribution to a much lower level. On a practical level, implementation should consider how to achieve compliance with the pH standard and support of designated uses, not simply how to drastically reduce phosphorus levels in this wastewater dominated system.
- For phosphorus load control to work as a pH management strategy, many smaller inputs will have to be addressed as well as the few identified large ones. Any source to which more than about 0.1 to 0.3% of the total load can be attributed will require some attention, as the load reduction necessary to guarantee compliance is so extreme.
- Management of water transfers in the watershed offers potential to improve water quality in Barr Lake, but potentially at the expense of the water quality in Milton Reservoir, and not enough to meet the pH standard. Water transfer management that will benefit both reservoirs may be possible, but would involve water rights issues and is likely to reduce certainty of summer water supply from the reservoirs.
- Additional inlake approaches for minimizing algal production and moving toward pH compliance are available, but a watershed-based effort may be necessary to consistently achieve water quality goals. TMDL development is based on reducing phosphorus loading and inlake concentrations to a point at which algal growth will be limited and high pH will be minimized. Still, with the extreme effort necessary to reduce external loads to the necessary level, inlake actions that could achieve pH compliance bear further scrutiny. Aeration/mixing, chemical treatments to control algae (phosphorus inactivation or algaecides), and even dredging should be considered. Some options may provide at least interim relief, and others may be essential as part of an overall program to achieve pH compliance.

1.0 Introduction

The all-inclusive Barr-Milton watershed is very large, extending well south of Denver along the path of the South Platte River, and north from Denver onto the plains, with Barr Lake and Milton Reservoir as the defined terminal points. Not all water from the watershed passes through these reservoirs, as neither is directly on the South Platte River; diversions from the river represent the primary source of water for the two reservoirs. As the drainage system south and west of the Denver metropolitan area is captured by reservoirs and several creeks that are monitored and can be treated as distinct inputs to the more immediate watershed, the watershed for purposes of planning has been simplified to an area termed the “datashed” (BMW 2008). Five major drainages flow into the Barr-Milton datashed, all of which have established watershed associations, and some of which are governed by water quality control authorities. These organizations include the Cherry Creek Basin Authority, Chatfield Watershed Authority (upper South Platte River), Bear Creek Watershed Association, Upper Clear Creek Watershed Association, and Big Dry Creek Watershed Association.

The datashed, or immediate watershed, or simply the watershed for the purposes of this report, covers over 833 square miles (533,000 acres) on the central Colorado plains and encompasses portions of six counties: Adams, Weld, Arapahoe, Denver, Jefferson, and Douglas. The watershed generally flows south to north, paralleling the foothills of the Front Range of the Rocky Mountains located to the west. Over 500 miles of streams and rivers drain this area. Adding to the hydrologic complexity of the watershed, these natural waterways are supplemented by over 550 miles of man-made canals, ditches, and pipelines (BMW 2008).

Approximately 89% of the Barr-Milton watershed is privately owned. Nearly 55% of the watershed supports agriculture, including grasslands, pasture, small grains, and row crops. Cattle and calves are the primary livestock. Residential and commercial/industrial areas, including most of the Denver metropolitan area, cover 38% of the watershed and are located primarily in the southwestern extent of the watershed and along the South Platte River. Less than 2% of the watershed is covered by open lands (BMW 2008). This Barr-Milton watershed area includes over 75% of the Denver metropolitan area. Additionally, urban growth is occurring near the reservoirs, especially near Barr Lake where dry-land acreage is transitioning to dense subdivisions.

Denver International Airport (DIA) and the Rocky Mountain Arsenal are two large facilities of note within the watershed. Forty-two major dischargers hold National Pollutant Discharge Elimination System (NPDES) permits in the watershed, including industrial, wastewater and drinking water treatment, and other facilities. The largest discharger is the Denver Metro Wastewater Reclamation District (metro) at a capacity of 227 million gallons per day (mgd), followed by the Littleton-Englewood Wastewater Treatment Plant at a capacity of 36.3 mgd. Each other discharger has a capacity of less than 9 mgd, with some as small as 1 mgd. There are also three Municipal Separate Storm Sewer Systems (MS4) permits in place for municipalities that are greater than 100,000 in population (Denver, Aurora, and Lakewood), plus a MS4 permit covering the Colorado Department of Transportation facilities and activities in this area. Phase II stormwater permits are held by many smaller communities in the urbanized and urbanizing area around Denver, including Arvada, Brighton, Broomfield, Commerce City, Englewood, Federal Heights, Littleton, Northglenn, and Thornton, Westminster, Wheat Ridge, and all six counties. Due to the influence of permitted inflows from publicly owned treatment works (POTWs, referred to as wastewater treatment plants, or WWTPs, in this report), the mainstem of the South Platte through the watershed is described as effluent-dominated (BMW 2008).

Recreational use is significant for Barr Lake, Milton Reservoir, and the South Platte River corridor. Land surrounding Barr Lake is managed by Colorado State Parks. Nature enthusiasts enjoy combinations of activities from wildlife watching and educational programs to hunting and fishing at Barr Lake State Park. The Beebe Draw Metropolitan District controls recreational use of Milton Reservoir. The District allows members to boat, fish, and bird-watch in and around the reservoir. The South Platte River is also an important recreational resource; biking and walking trails, as well as river-front parks, exist along the mainstem of the South Platte River within the watershed (BMW 2008).

1.1 Statement of problem

Barr Lake (Barr) and Milton Reservoir (Milton) are listed on the 2004 303(d) list as water quality-impaired segments due to exceedences at the upper pH standard of 9.0 standard units (S.U.), resulting in non-attainment of the Warm-water, Class 2 Aquatic Life use classification. The Colorado Department of Public Health and Environment (CDPHE) rates the Barr and Milton pH Total Maximum Daily Load (TMDL) priorities as “medium.”

Although pH is the parameter cited on the 303(d) list, the water quality issues are much broader. Both reservoirs are “hyper-eutrophic” (AMEC 2008a, 2008b) due to excessive nutrient loading. This is evidenced by the typical summertime water clarity of two feet, chlorophyll *a* levels of 20–150 µg/L, and total phosphorus concentrations of 500–1,500 µg/L. Both reservoirs exhibit severe algae blooms from July to October. Photosynthetically elevated pH, low clarity, low species diversity, and dissolved oxygen sags are all symptoms of a persistent water quality problem in the reservoirs.

These symptoms impact other designated uses of the reservoirs than those noted on the 303(d) list. For example, the reservoirs are used for agricultural irrigation by approximately 400 farmers. Additionally, the lakes are used for recreation, where approximately 80,000 visitors/yr visit the park at Barr Lake and 68 households having recreational access to Milton Reservoir.

The water quality problems in Barr Lake and Milton Reservoir may be the result of both nonpoint and point source pollution, but the eutrophication problems currently experienced would be expected just on the basis of the discharge of wastewater to receiving waters that ultimately end up in Barr Lake and Milton Reservoir. The potential solutions to the water quality impairment (i.e., TMDL implementation) must address wastewater discharges, although some nonpoint source controls may be necessary as well.

1.1.1 Summary of Barr Lake and Milton Reservoir water quality

The CDPHE implements water quality regulations that come under the jurisdiction of the Water Quality Control Commission. These include several regulations adopted by the State Board of Health (5 CCR 1003-1, 5 CCR 1003-3, 5 CCR 1003-6, 5 CCR 1003-7 and 5 CCR 1003-8) for which rulemaking authority was transferred to the Water Quality Control Commission by the Legislature in 2006. The following descriptions of water quality classifications for Barr Lake and Milton Reservoir are described in Regulation 38, “Classifications and Numeric Standards for South Platte River Basin, Laramie River Basin, Republican River Basin, Smoky Hill River Basin (amended 1/14/08, effective 3/1/08)”.

The focus of this report is on support of the effort to develop a TMDL for pH, for which the state has a standard of 9.0 S.U. for at least 85% of the time. The pH values for both reservoirs most often exceed 9.0 S.U. from June to October, coinciding with algae blooms in the warm-water season, although winter exceedences have been recorded as well. The maximum pH value recorded for Barr Lake was 10.2 S.U. (09/13/00) and 9.5 S.U. (08/11/99) for Milton Reservoir. In 2003, Barr Lake exceeded the 9.0 S.U. standard 253 times out of a total of 756 readings (85th percentile = 9.42 S.U.), while Milton Reservoir exceeded the standard 253 times out of 474 readings (85th percentile = 9.62 S.U.).

1.1.1.1 Barr Lake water quality

Barr Lake is an off-stream reservoir located southeast of Brighton, Colorado. The largest volume of flow enters Barr Lake through the Burlington-O’Brian Canal that diverts from Segment 14 of the South Platte River in the north part of the City and County of Denver. Both Barr Lake and the Burlington-O’Brian Canal are owned and operated by FRICO. First, Second and Third Creeks discharge directly into the Burlington-O’Brian Canal and are part of the watershed. First Creek flows through Commerce City and the Rocky Mountain Arsenal. Second Creek drains a newly developed area of Commerce City. Third Creek flows from the DIA.

Under an agreement among FRICO, Denver Water, and the Metro Wastewater Reclamation District (Metro), Barr Lake receives flows from a pumping station operated by Denver Water and located at the Metro facility. This station can discharge up to 100 cubic feet per second (cfs) of treated effluent directly into the Burlington-O'Brian Canal. However, if a recent water court ruling is upheld on appeal, it would result in reduction or elimination of Metro effluent added from the pumping station.

Summary of Barr Lake Water Quality Classification (from Regulation 38):

- Middle South Platte River Basin, Segment 4 (Barr Lake)
- Classification: Water Supply, Aquatic Life Warm Water Class 2, Recreation Class 1a, Agriculture
- Physical/Biological Numeric Standards: Oxygen 5.0 mg/l, pH 6.5 to 9.0 S.U., E. coli 126/100 ml.

Barr Lake has a capacity of 32,000 acre-feet and varies between 10,000 acre-feet and 32,000 acre-feet over the course of the irrigation season. Water exiting Barr Lake is currently used for agricultural irrigation and more and more the lake water is being used for drinking water purposes.

A perpetual easement (835 acres) granted to the State of Colorado in 1976 includes Barr Lake in the State Park system, providing non-contact, recreational uses such as bird watching, picnicking, fishing and boating (swimming is prohibited). Barr Lake State Park is also a significant migratory bird refuge with a designated "Wildlife Sanctuary" around the southern half of the reservoir. Over 350 bird species have used the Barr Lake area, including nesting bald eagles, great blue herons, and white pelicans.

Barr Lake was described in the 2004 Colorado 305(b) report (CDPHE 2004) as impaired for pH and not meeting the warm water class 2 aquatic life use classification. This characterization remains valid (CPDHE 2008). The 303(d) listing of Barr Lake is for exceedence of the 9.0 pH standard. The attainment of chronic chemical standards is based upon the 85th percentile of available data based on the Water Quality Control Division's Basic Standards and Methodology (Regulation 31). An analysis of pH data from five years of record for Barr indicates an 85th percentile ranking for pH of 9.4 S.U. The applicable pH standard for Barr ranges from 6.5 to 9.0 S.U.

Barr Lake nutrient loadings have averaged over 71,000 kg/yr of phosphorus and almost 600,000 kg/yr of total nitrogen per year, with annual variability depending on the amount of water physically available to be diverted into the reservoir (AMEC 2008a). Barr Lake experiences extensive algal blooms. This high productivity during the summer is the apparent cause of the high pH, although high alkalinity can maintain elevated pH once established, even if algal blooms subside. Blooms are dominated by blue-green algae in summer, and these algae can produce toxins and may pose a potential threat for humans, livestock, and wildlife. The blooms may also cause taste and odor problems, but this is not directly correlated with toxicity and is therefore considered a separate problem. These blooms may also cause fluctuating and sometimes low dissolved oxygen (DO) conditions, which promote increased internal nutrient loading.

1.1.1.2 Milton Reservoir water quality

Milton Reservoir is an off-stream reservoir situated approximately 30 miles northeast of Barr Lake. The largest inflow enters Milton Reservoir via the Platte Valley Ditch that diverts from Segment 1 of the Middle South Platte reach, north of Fort Lupton. Water released from Barr Lake can also flow into Milton through the Beebe Canal, and this canal can also drain some of the land between Barr Lake and Milton Reservoir. FRICO owns and operates Milton Reservoir and the Beebe Canal for agricultural purposes.

Summary of Milton Reservoir Water Quality Classification (from Regulation 38):

- Middle South Platte River Basin, Segment 4
- Classification: Water Supply, Aquatic Life Warm Water Class 2, Recreation Class 1a, Agriculture

- Physical/Biological Numeric Standards: Oxygen. 5.0 mg/l, pH 6.5 to 9.0 S.U., E. coli 126/100 ml.

Milton Reservoir has a capacity of 33,000 acre-feet and typically varies between 10,000 acre-feet and 33,000 acre-feet over the course of the irrigation season. Milton Reservoir is used for recreation including boating and waterfowl hunting under a lease to the Beebe Draw Municipal District.

Based on previous work (AMEC 2008b), phosphorus loading to Milton Reservoir averaged 40,600 kg/yr of phosphorus and 242,000 kg/yr of nitrogen. Nutrient levels in Milton Reservoir are high and thought to be responsible for high algal productivity and exceedences of the pH standard. Milton Reservoir is also included on the 2004 303(d) list for exceedences of the pH standard and nonattainment of the warm water class 2 aquatic life use classification.

1.2 Current project

A grant to support the development of the Barr-Milton watershed and lake models was received through the Environmental Protection Agency's 319 nonpoint source water quality program. The 319 grant funding is intended to be used for TMDL development for Barr Lake and Milton Reservoir, organized into several phases, including the development of project goals, a description of the project, and several phases that ultimately culminate in the development of a TMDL for pH for each of Barr Lake and Milton Reservoir. More details on the funding and overall process are provided in the Watershed Management Plan (BMW 2008). AECOM has been working with the BMW Association to develop both watershed and lake models to facilitate representation of current conditions and an evaluation of alternative management scenarios.

The funded project includes watershed planning, development of watershed group stability, modeling, and pH TMDL development. The CDPHE Water Quality Control Division (the Division) manages and implements the Nonpoint Source Program in Colorado. The goal of Colorado's Nonpoint Source Program is to restore to full use those waters impaired by nonpoint sources of pollution, and to prevent future impairments, using an open process that fully involves the public. Although point sources are perceived as a major influence in the Barr-Milton system, this project fits with the goals of the CDPHE, and is intended to support attainment of all designated uses for Barr Lake and Milton Reservoir.

1.3 Description of multi-part TMDL evaluation

According to the 40 CFR §130.2, the TMDL determined for a waterbody is equal to the sum of the individual loads from point sources (i.e., wasteload allocations or WLAs), and load allocations (LAs) from nonpoint sources (including natural background conditions). Section 303(d) of the CWA also states that the TMDL must be established at a level necessary to implement the applicable water quality standards with seasonal variations and a margin of safety (MOS) which takes into account any lack of knowledge concerning the relationship between effluent limitations and water quality. In equation form, a TMDL may be expressed as follows:

$$\text{TMDL} = \text{WLA} + \text{LA} + \text{MOS}$$

Where:

- WLA = Waste Load Allocation (i.e., loadings from point sources);
- LA = Load Allocation (i.e., loadings from nonpoint sources including natural background); and
- MOS = Margin of Safety.

TMDLs can be expressed in terms of either mass per time, toxicity or other appropriate measure (40 CFR, §130.2 (i)). However, in light of legal action, the EPA has issued guidance that TMDLs should be expressed on a daily timescale to meet the wording of the legislation that created the program. Yet for lakes, daily nutrient loading limits are of little use in management, as lakes integrate loading over a much longer time period to manifest observed conditions. Expression of nutrient loads on seasonal to annual time scales is appropriate, although daily loads are to be reported in the TMDL to meet program guidelines.

The MOS can be either explicit or implicit. If an explicit MOS is used, a portion of the total allowable load is allocated to the MOS. If the MOS is implicit, a specific value is not assigned to the MOS. Use of an implicit MOS may be appropriate when assumptions used to develop the TMDL are believed to result in a prediction of greater loading than is actually occurring, sufficiently accounting for the MOS. The MOS is intended to adjust for uncertainty, providing a buffer where predictability is limited.

In the case of Barr Lake and Milton Reservoir, it is assumed, based on a thorough review of the water quality data relevant to eutrophication, that the elevated pH conditions are a direct result of excessive algal growth, either in the impoundments or in upstream areas (the river or other impoundments). Furthermore, it is assumed that the excessive algal growth is a direct result of excessive nutrients in the water column. While AECOM uses the term “excessive nutrients” as the primary cause, it is generally understood, and for purposes of this TMDL, that phosphorus is the limiting nutrient for plant growth in these waters or can be made to limit algal production if sufficient reductions in loading are achieved. Therefore, the most common approach is to derive numeric total phosphorus (TP) target values that are both protective of the water uses and correlate to lake conditions under which chlorophyll *a*, the presence of cyanobacterial blooms and DO and pH assessment criteria are met. Phosphorus is used as a surrogate for impairments related to chlorophyll *a*, cyanobacteria, DO and pH.

There is no question that nitrogen plays an important role in these reservoirs and in the South Platte River in general. Low N:P ratios tend to favor cyanobacteria, some of which can fix atmospheric nitrogen dissolved in the water; dominance of cyanobacteria may be taken as an indication that nitrogen is more limiting than phosphorus in an aquatic system. However, at the levels observed in Barr Lake and Milton Reservoir, neither phosphorus nor nitrogen may actually be the limiting factor for algal production in these systems. Light, temperature, or even forms of carbon (i.e., at elevated pH, carbon dioxide is scarce) may limit algal growth in these reservoirs. Yet control of phosphorus holds the greatest promise of longer term control through human management.

Data available for Barr Lake and Milton Reservoir allow relationships between phosphorus, chlorophyll *a*, and pH to be explored. Various empirical approaches are employed to estimate the conditions necessary to meet the pH standard and develop responsive target loads of phosphorus. The load estimates developed through the model development and statistical evaluations presented in this investigation provide a starting point for assessing needed reductions. Watershed and lake models developed in this effort are calibrated with actual data and suggest current loads that result in the existing range of conditions. These models are then used to test possible management scenarios that might lead to lower phosphorus loads and compliance with the pH standard.

1.4 Report layout

With the above background laid out, this report will go on to describe the development and use of the models intended to guide the TMDL derivation process. Section 2 describes the objectives of this effort. Section 3 evaluates existing relationships between phosphorus, chlorophyll *a* and pH, along with other variables such as temperature which may modify the influence of phosphorus on chlorophyll *a* and pH. Potential target values for total phosphorus and chlorophyll *a* in the reservoirs that could lead to compliance with the pH standard are derived as a result. Section 4 describes the necessity and development of both a watershed model and a linked lake model to effectively simulate processes in this system and facilitate prediction of management action results. Descriptions of the watershed model setup and calibration and the lake model setup and calibration follow within Section 4. Section 5 of the report details the development, simulation, and interpretation of several management alternatives designed to investigate potential long-term improvement of water quality in Barr Lake and Milton Reservoir. These simulations provide indications of the level of effort that will be necessary to achieve compliance through watershed-based management of phosphorus inputs that in turn limit chlorophyll *a* (algae) levels that are linked to pH.

Sections 3 through 5 set the stage for TMDL development, providing evaluations of targets, partitioning of the current load, and an understanding of how the range of management actions might affect compliance with a pH standard. However, there are a number of complications and issues associated with TMDL development and implementation for Barr Lake and Milton Reservoir, and these are addressed in Section 6. Included are: water quality and loading target selection and expression; load partitioning among sources; assessment of internal loading; uncertainty associated with available data, investigated relationships among variables, and model predictions; and competing watershed and inlake management options that might affect achievement of compliance and even loading target selection.

Section 7 draws conclusions from the work embodied in this report and recommends an approach to TMDL development. Finally, Section 8 includes a list of the references used throughout the report.

2.0 Objectives

The objectives of this investigation included determining the range of possible concentration and load targets for achieving pH compliance, constructing models of the watershed and Barr Lake and Milton Reservoir that would allow reasonable prediction of current loading and resultant inlake conditions that could be verified with actual data, and use of those models to predict future conditions under a variety of plausible management scenarios. This project supports the overall goal of the Barr-Milton Watershed Association of developing a TMDL for achievement of a pH <9 S.U. for 85% of the time in the two off-channel waterbodies.

Taken from a strictly scientific perspective, the objective of determining load and concentration targets that will meet the state standard for pH involves evaluation of the causative factors in current pH exceedences and assessment of available data to determine the conditions necessary to avoid such exceedences at least 85% of the time. Given multiple causative factors and variability in the data, there is considerable uncertainty associated with any choice of a target. For the purposes of deriving a TMDL with a high probability of success, this translates into lower loads and concentrations, providing a larger margin of safety. Direction was given not to consider economic (load reduction costs), legal (water rights issues), or even technical feasibility (level of treatment necessary) factors in this evaluation, but some consideration will be necessary in any final target selection. This analysis simply provides the scientific background upon which a TMDL may be based.

The bulk of the effort in this investigation was expended on developing the models to be used in the TMDL development and implementation process. Development of a numerical modeling tool to facilitate loading evaluation and the development of the TMDL required assimilation of existing information to characterize and quantify the boundary conditions in the Barr-Milton watershed and then to apply this knowledge to the construction and utilization of a set of numerical modeling platforms to predict water quality in Barr Lake and Milton Reservoir. After evaluation of model options, the numerical modeling platforms applied to the Barr-Milton watershed investigation were the SWAT (Soil and Water Assessment Tool) watershed model and the WASP (Water-quality Analysis Simulation Program) surface water model. The combination of these two models, where the SWAT model provided background information in the form of predicted loads to Barr Lake and Milton Reservoir and the WASP model predicted inlake concentrations based on processing of those loads, was used to facilitate the prediction of relevant water quality features and provide information necessary to estimate pH in Barr Lake and Milton Reservoir.

Specific objectives necessary to construct and properly apply the models included:

- Develop a detailed understanding of water movement throughout the watershed
- Gather water quality information to support model calibration
- Develop a watershed model to track nutrient load generation and delivery to the impoundments
- Develop an inlake model to predict phosphorus and chlorophyll levels in the reservoirs
- Translate the predicted phosphorus and chlorophyll concentrations into pH
- Determine model scenarios that represent applicable management alternatives
- Interpret scenario results in terms of TMDL needs and constraints

Cooperation between AECOM and the BMW Association and the many organizations and agencies represented within that entity was essential to achieving the above objectives. No one party has the extensive knowledge necessary to construct models appropriate to the very complicated hydrology of the South Platte River in this area, which involves many inputs and water transfers. The complexity of this project required that the methods used to achieve these objectives were subject to adaptive adjustment during development and application of the models, but the overall objectives remained consistent throughout the investigation.

3.0 Attainment of pH compliance through phosphorus control

3.1 Background

A TMDL is to be developed to meet a pH standard of <9.0 standard units (S.U.), whereby no more than 15% of all values exceed 9.0 S.U. Central to this effort is the assumption that high pH values are a function of algal activity; abundant algae remove carbon dioxide during photosynthesis (the preferred carbon source), and this raises the pH. This is a reasonable assumption, but one that translates into predictions and conclusions for necessary loading reductions only with additional assumptions or data that support more quantitative analysis. For example, different types of algae have different ratios of chlorophyll to productivity, and more CO_2 is very likely to be removed with more chlorophyll, but the relationship is not necessarily linear. Other factors, including geology and the composition of wastewater and runoff, will also affect pH and are largely independent of chlorophyll levels. We are working from the premise that controlling algae populations can result in control of pH, at least to the extent that pH values >9.0 S.U. will not be experienced more than 15% of the time. The control of algal populations can be accomplished by algaecide treatments (copper or peroxides in most cases), but it is preferred that the nutrients that support algal growth be reduced to levels that limit growth and biomass accumulation, and therefore limit pH increases. There are other ways to achieve pH compliance, including aeration and mixing or direct addition of carbon dioxide, and these methods may be explored in the implementation phase of the investigation, but this assessment addresses algal control through nutrient control.

3.2 Data from area reservoirs

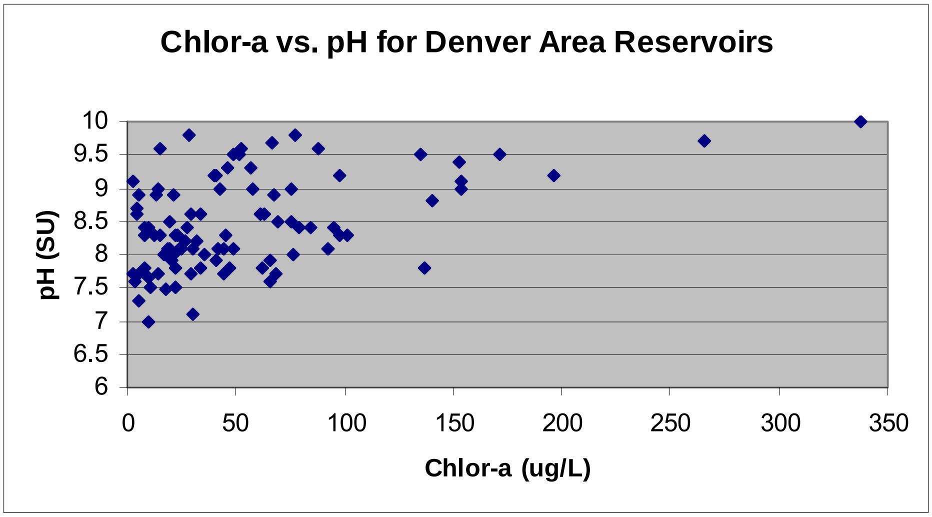
For reference purposes, data representing other reservoirs in the Denver area were graphed (Figures 3-1 and 3-2) to examine relationships between key variables in this region. Reservoirs for which data were provided include Aquagolf, Barnum, Berkeley, Duck, Ferril, Garfield, Grasmere, Harvey, Huston, Lollipop, Overland, Rocky Mountain, Sloans, Smith and Vanderbilt. Data from any sampling surveys during which excessive benthic algal or rooted plant growth was noted were removed, as such growths would affect pH and other water chemistry variables of interest. Some of these reservoirs receive reused water and many are influenced by wastewater by virtue of flow sources that receive effluent. A range of water quality is represented by these data.

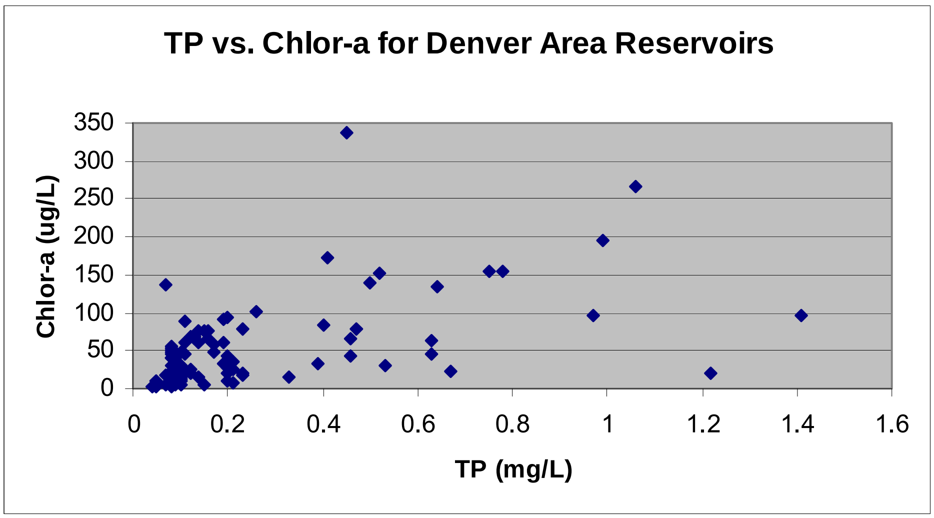
Chlorophyll-a (Chl) clearly influences pH, but there is considerable variability (almost 77%) not accounted for in the Chl-pH relationship (Figure 3-1). Detection limits restrict interpretation at the low end of the scale for relationships involving total phosphorus (TP) and total nitrogen (TN), but it is apparent that neither accounts for a majority of variation in Chl levels (linear regression $r^2 = 0.27$ for TP vs Chl and 0.05 for TN vs. Chl) (Figure 3-1). By extension, the relationship between TP or TN and pH is weak as well (Figure 3-2). At high levels of TP and TN, nutrients may not be the controlling influence on Chl or pH. It does appear, however, that the "background" pH for this geographic area is slightly above neutral; a value of 7.6 S.U. is projected for a system with no Chl, based on a logarithmic curve fit to the reservoir data.

It is apparent that high pH values are to be expected at high Chl levels, consistent with ecological concepts. However, low pH is not necessarily to be expected with low Chl levels. This sets up a conundrum for management of pH. If Chl is too high (>150 µg/L from the Denver area reservoir data set), a pH >9.0 S.U. is expected, but at Chl <10 µg/L, a fairly low value, pH >9.0 S.U. can still occur. If we work from the necessity of a probability distribution in which pH>9.0 S.U. occurs <15% of the time, a Chl target much lower than 150 µg/L will be needed. From the Denver area reservoir data, the target Chl limit would be about 25 µg/L.

The observed pH pattern is likely related to high alkalinity in these reservoirs; once a high pH is achieved by algal activity, it can be maintained chemically for an extended period of time even when algal abundance declines. This means that the thrust of pH management through algae management must focus on preventing blooms that raise the pH substantially, rather than just lowering the average algal density or Chl level. It may be sufficient to reduce peak algal abundance without lowering the median algal level.

Figure 3-1. Denver area reservoir water quality, part 1





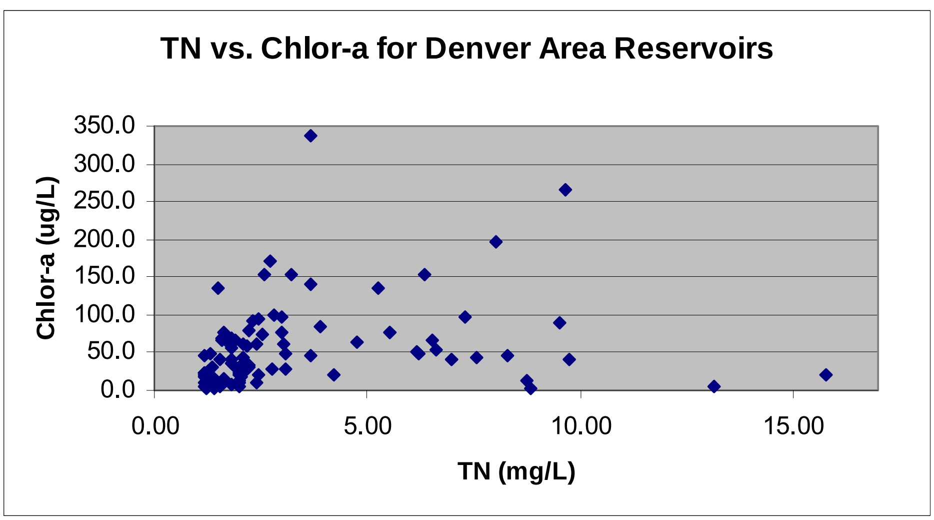
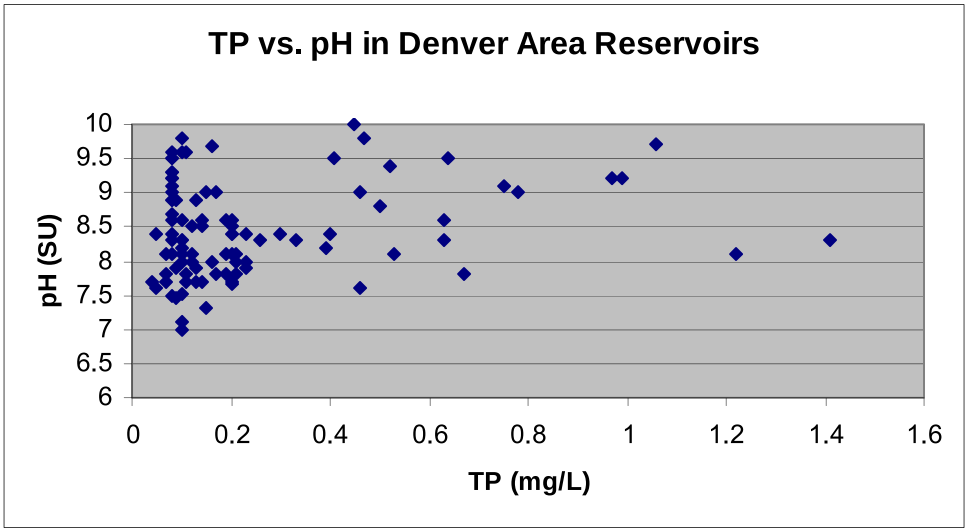
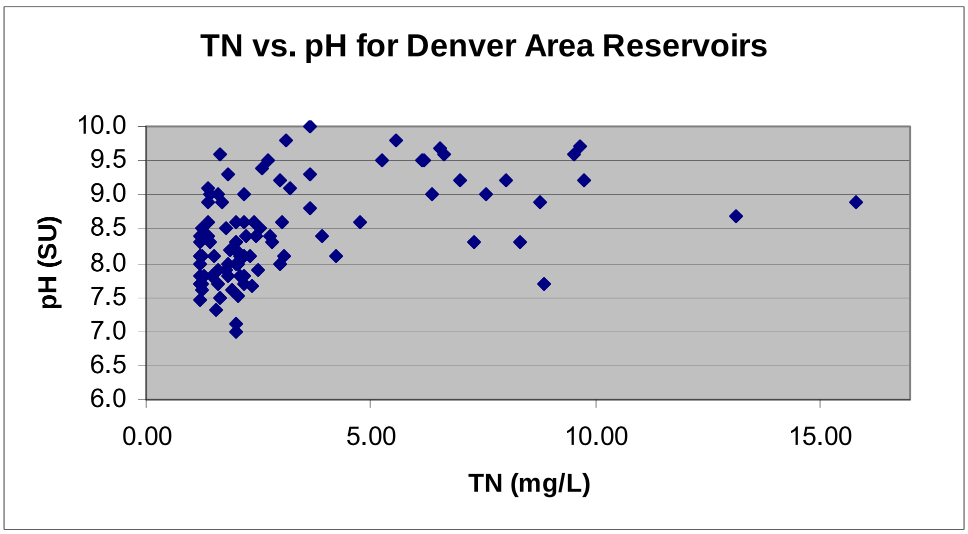


Figure 3-2. Denver area reservoir water quality, part 2





3.3 Data from Barr Lake and Milton Reservoir

For the Barr and Milton systems, we examined simple relationships between seemingly important variables, including TP, Chl, season, and pH, to determine the strength of possible linkages. Comparisons are shown in Figures 3-3 to 3-7, and references to “all” data refer to the available database for 2002-2007. Reference to “summer” data reflects use of only data from the summer season from the 2002-2007 database.

There is a relationship between Chl and pH for all data from either system, but the correlation is weaker in Milton Reservoir, to the point where there is no significant relationship between Chl and pH in Milton Reservoir for summer data (Figure 3-3). It can be seen (Figure 3-4 for all data, Figure 3-5 for summer data) that higher TP or TN allows for higher Chl, but the relationship is very weak; there are many cases where higher TP or TN coincides with lower Chl. The maximum Chl level increases, and to a lesser extent the mean Chl also increases, but not the minimum value. A direct relationship between TP or TN and pH is hard to discern (Figure 3-6); if anything, it is a negative relationship over the range of values obtained.

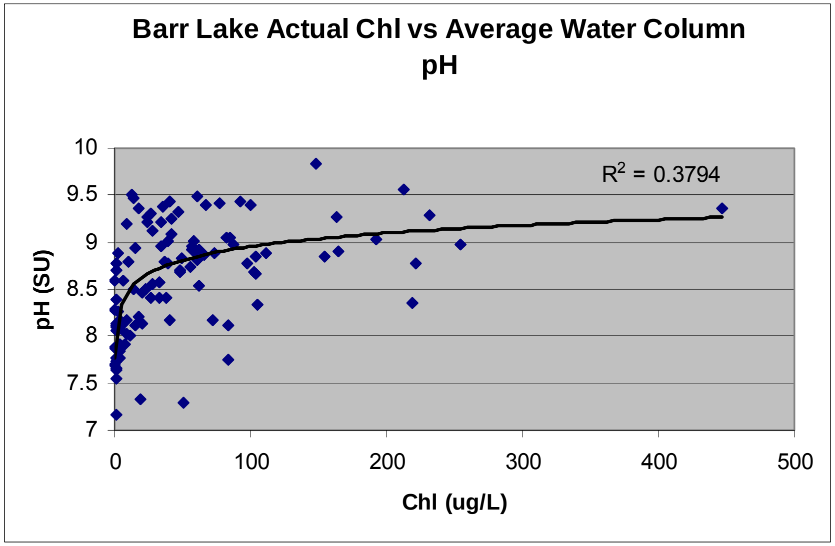
The cause of the lack of strong relationships for either TP or TN and variables like Chl or pH has two component parts (Figure 3-7). First, TP and TN are correlated. That is, they tend to covary positively, although more weakly in Milton Reservoir than in Barr Lake. Essentially, the refill of Barr Lake over the winter results in very high levels of both TP and TN, most of which is in an available form; there is much more available TP than algae need to bloom. Secondly, at such high TP and TN levels, other factors, such as light, temperature, mixing, or even carbon supply, can become primary determinants of algal composition and abundance. Milton Reservoir is filled after Barr Lake is filled, with the possibility of additional water direct from the South Platte River through the Platte Valley Canal. Milton Reservoir is therefore getting water conditioned by passage through Barr Lake or the South Platte River, with substantial potential for denitrification and conversion between various N and P forms.

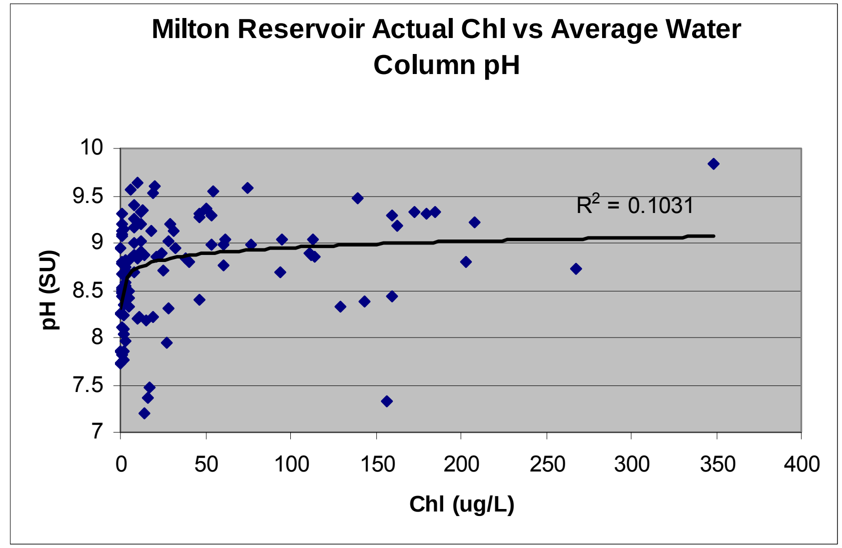
A third and independent factor of importance is alkalinity, which averaged 162 mg/L in Barr Lake and 177 mg/L in Milton Reservoir between 2002 and 2008. High alkalinity buffers the system against changes; if algal activity is sufficient to raise the pH above 9.0 S.U., the pH is likely to remain >9.0 S.U. for days to weeks after the algal bloom has subsided.

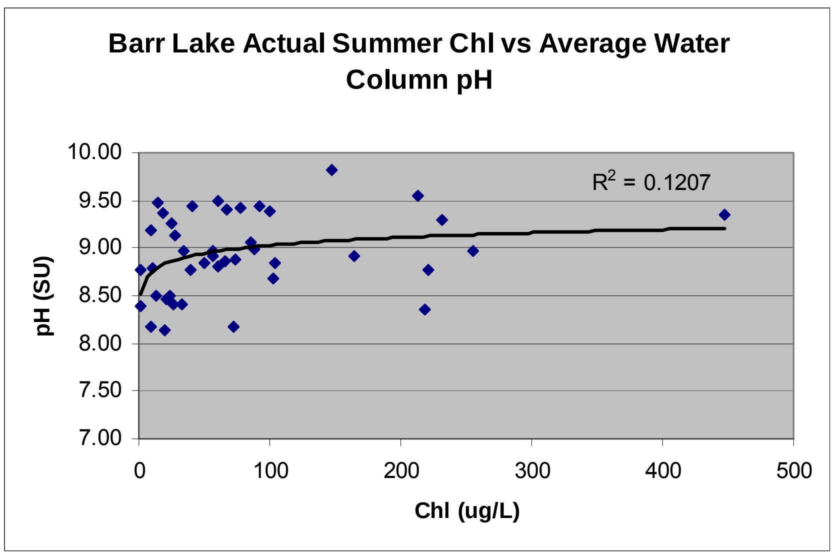
The lower panel of Figure 3-7 shows the summer data for TP and pH in Barr Lake and Milton Reservoir. In both cases, TP values are in excess of 0.2 mg/L, the generally accepted level at which P is overabundant to the point of having little additional influence on Chl or pH. To set a target for TP that will result in an acceptable pH, either working directly or through Chl, we have to know how the system will behave in the TP range between 0 and 0.2 mg/L. The lines drawn in that zone on Figure 3-7 represent a hypothetical logarithmic relationship, a reasonable but undocumented assumption. High detection limits for work on many other reservoirs in the area limits extrapolation from those data, but the postulated logarithmic relationship is consistent with them.

While both TP and TN have some relationship to algal production in the Barr and Milton systems, TP provides generally better correlations and represents a more plausible management target. Nitrogen gas represents 78% of the atmosphere, and will supply N to the water column by equilibration. As some of the bloom-forming blue-green algae (cyanobacteria) can utilize that N source, control of N provides no guarantee of algal control. Control of P, on the other hand, has distinct potential to control algae, but the current concentration range for the two reservoirs is well above the point at which small changes in P will translate into any predictable change in Chl or pH.

Figure 3-3. Cholorophyll vs. pH for all Barr and Milton data and for summer only







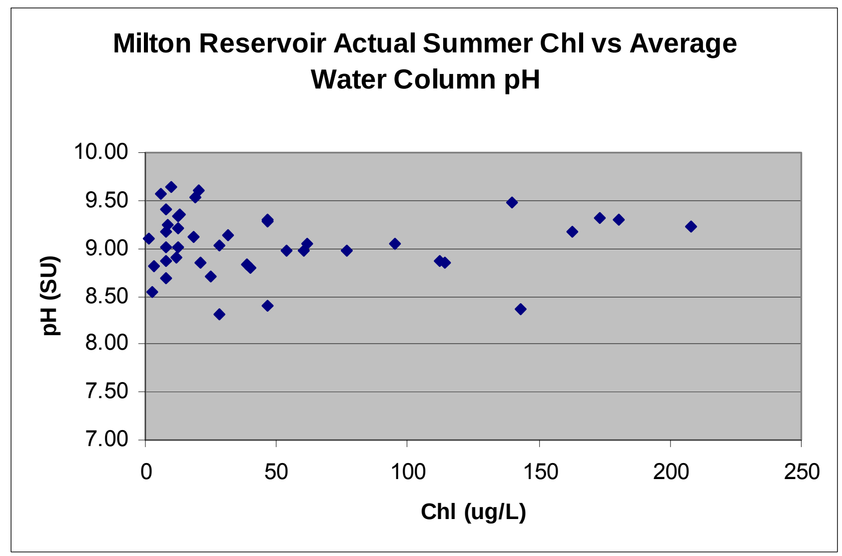


Figure 3-4. Total phosphorous and total nitrogen vs. chlorophyll for all Barr and Milton data

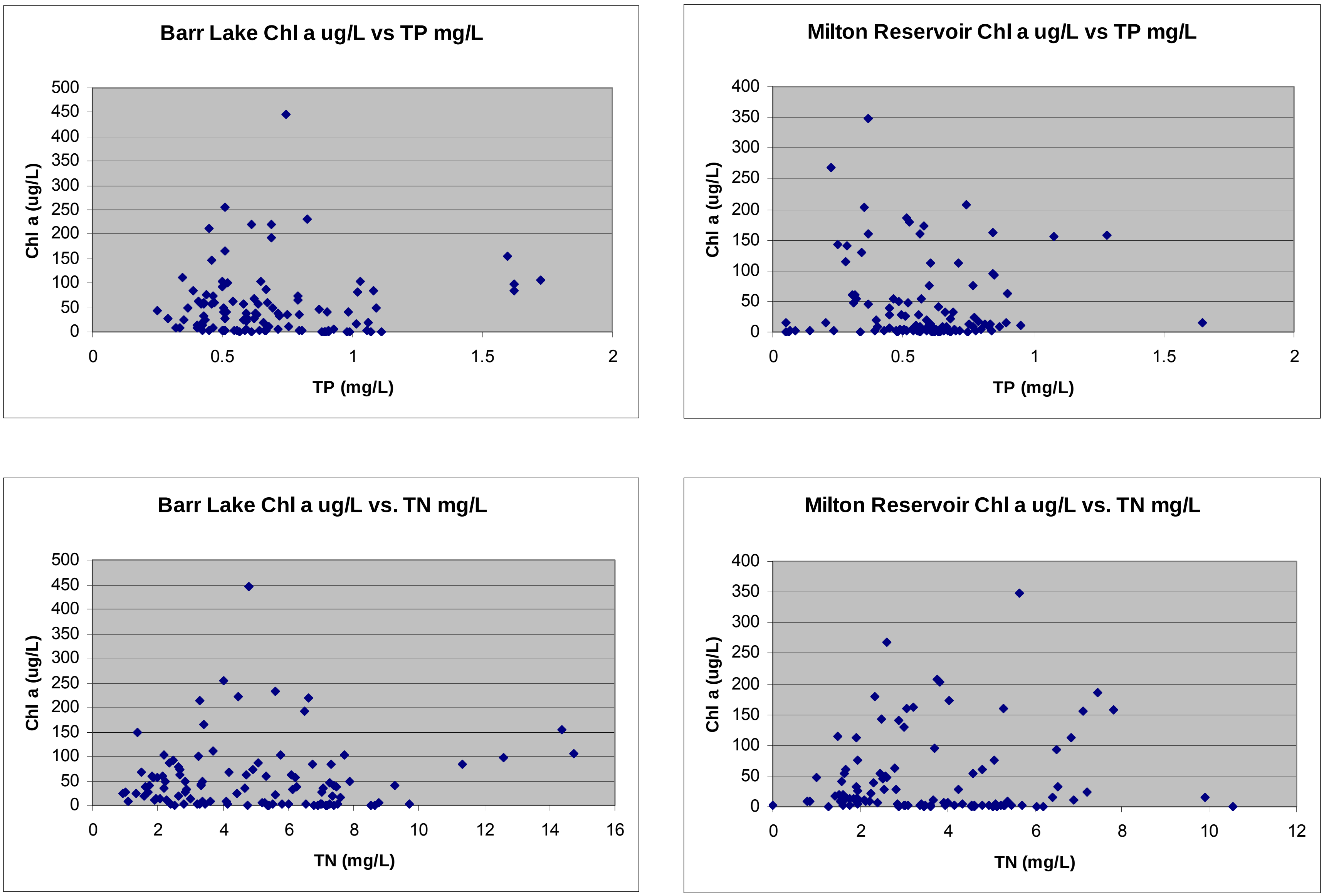
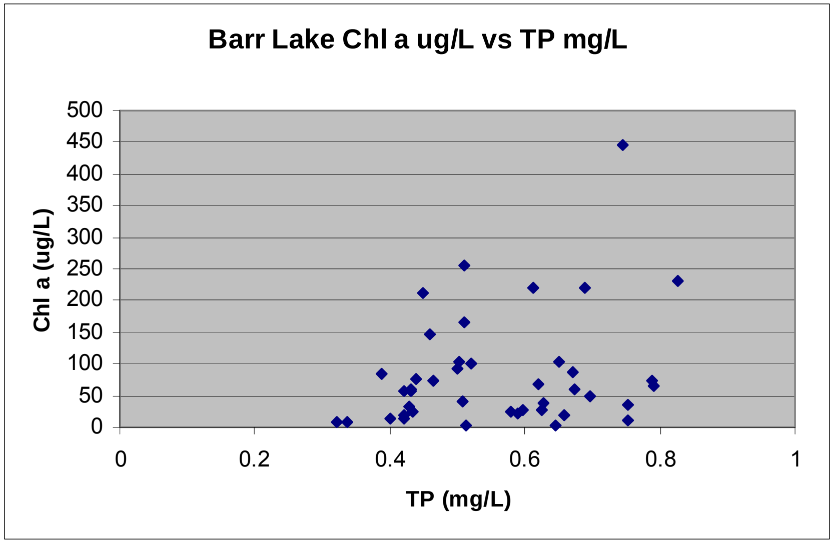
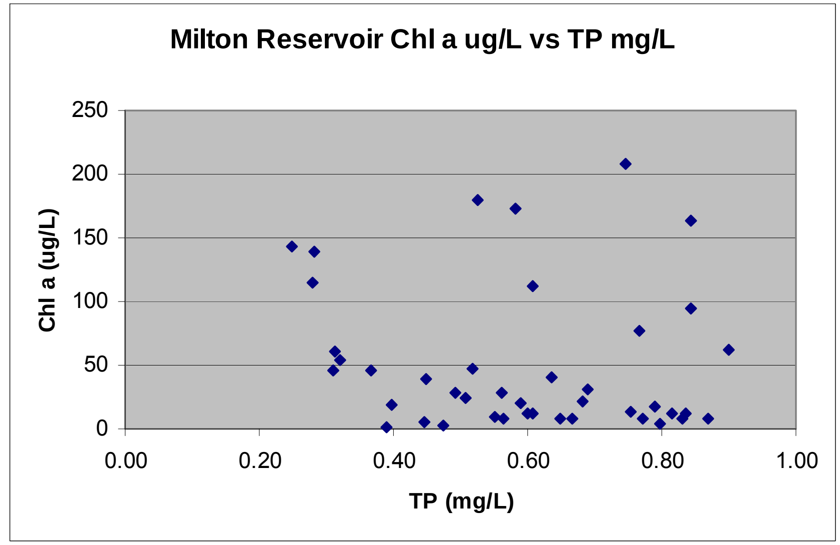
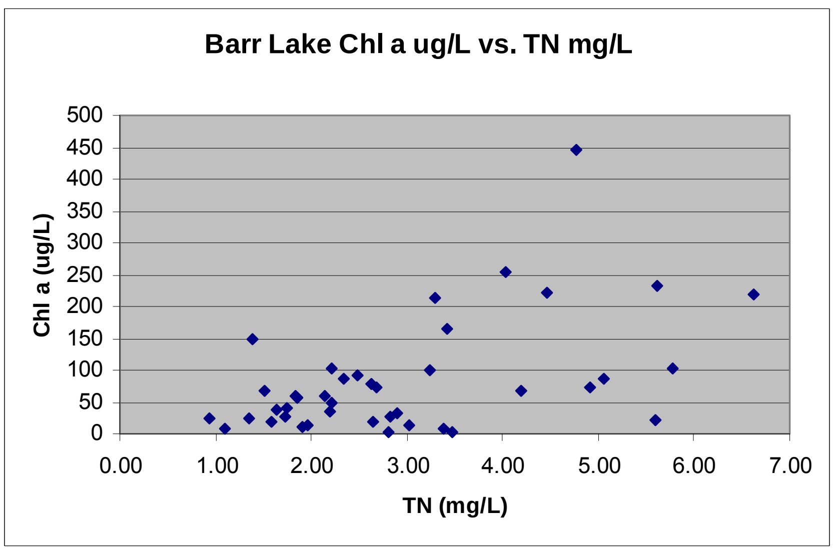


Figure 3-5. Total phosphorus and total nitrogen vs. chlorophyll for summer Barr and Milton data







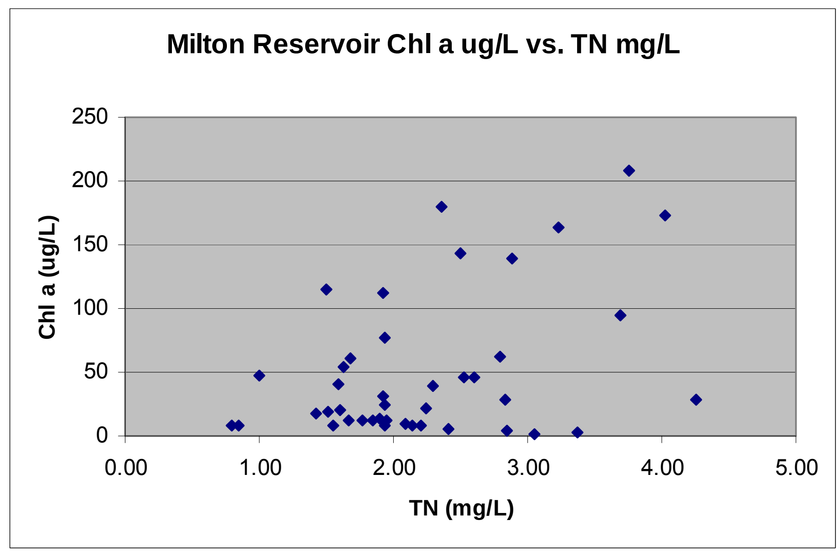


Figure 3-6. Total phosphorus and total nitrogen vs. pH for all Barr and Milton data

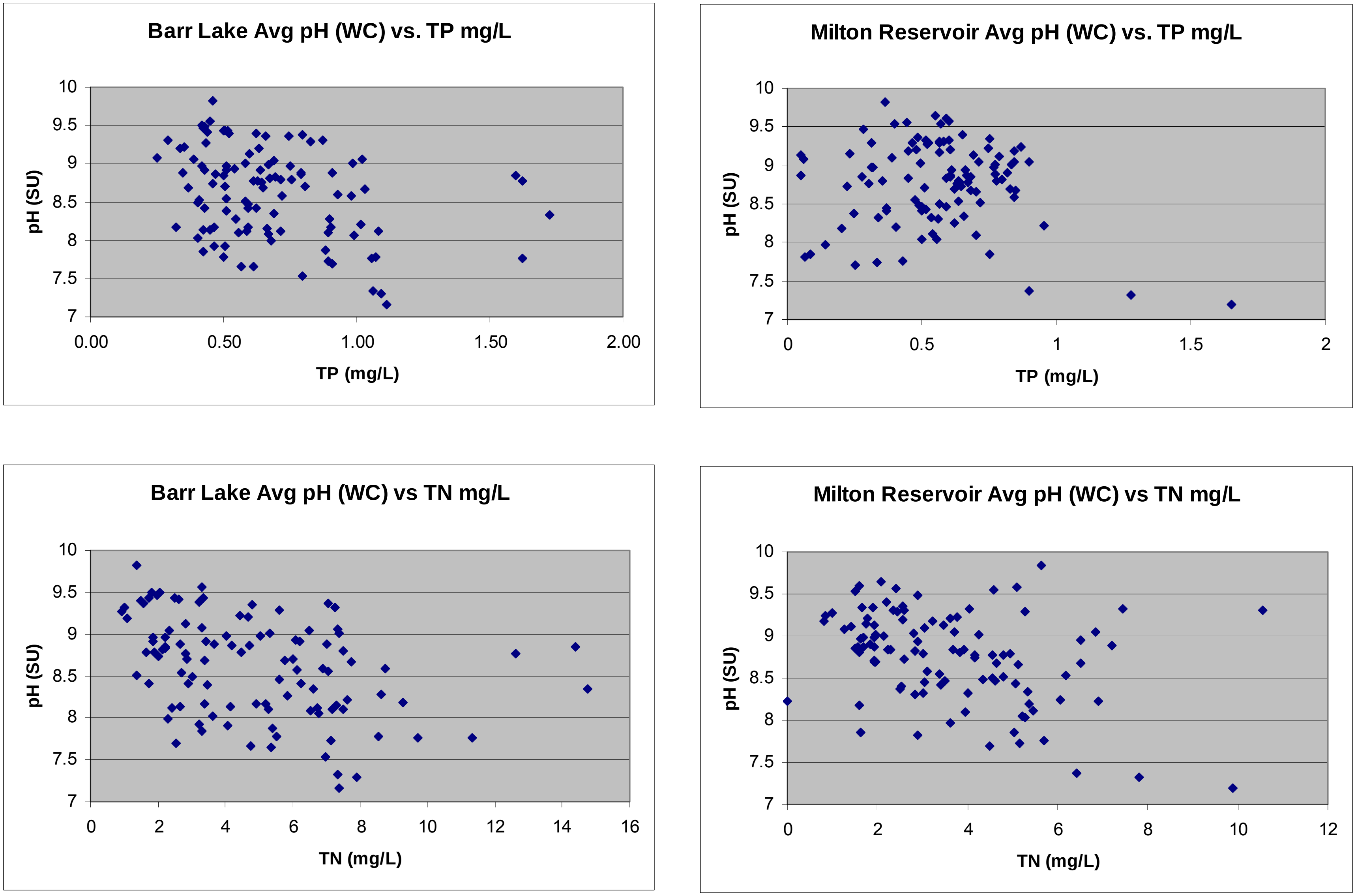
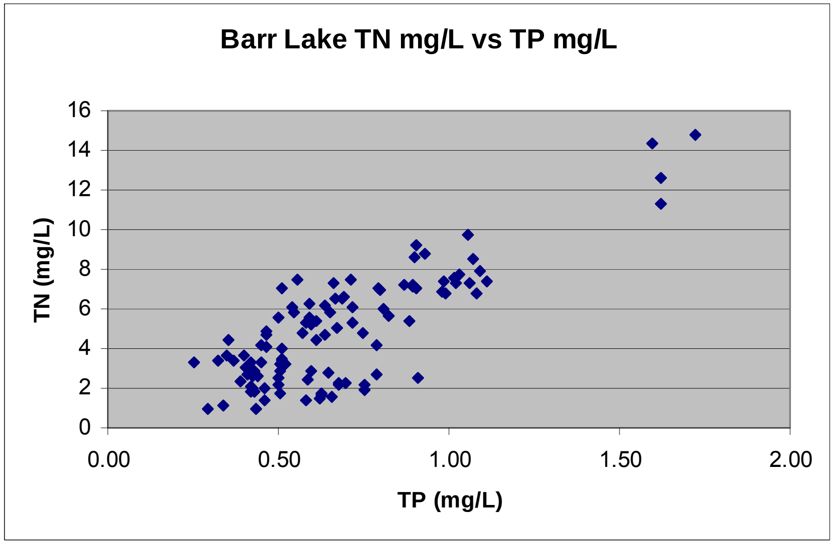
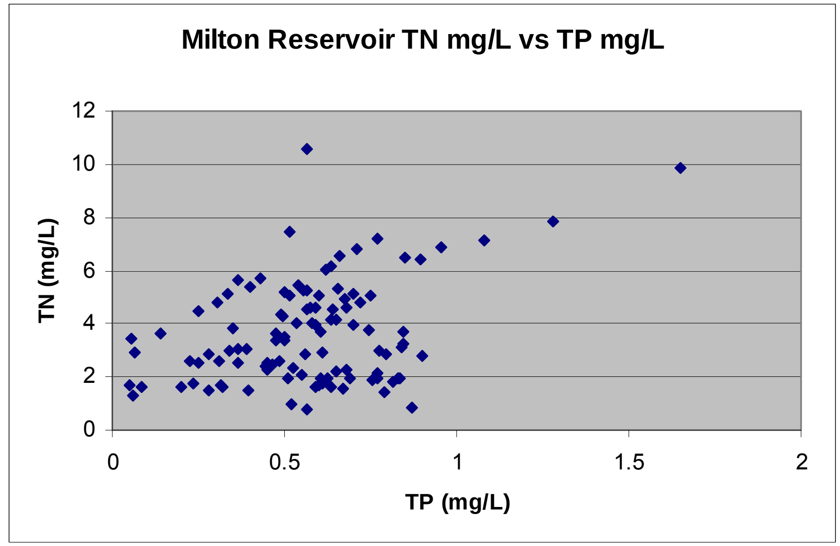
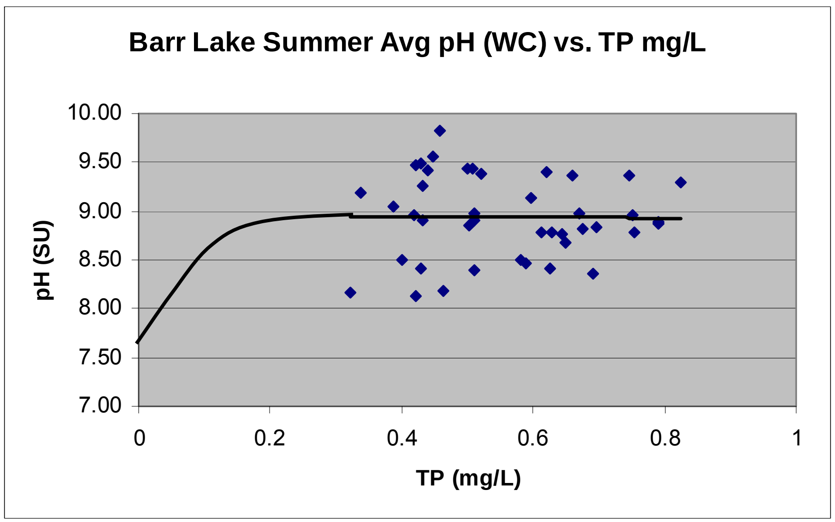
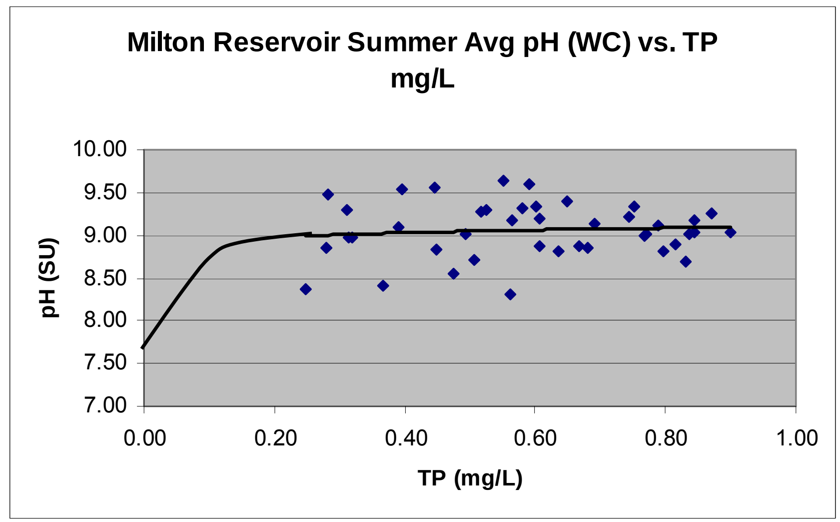


Figure 3-7. Total phosphorus vs. total nitrogen from all Barr and Milton data (top) and total phosphorus vs. pH for summer Barr and Milton data (bottom)









3.4 Setting a target chlorophyll *a* level for Barr Lake and Milton Reservoir

Looking for a mathematical extrapolation for setting a Chl target that will result in a meaningful change in pH, we constructed regression equations to see how much of the variation in pH we could account for with key variables. Using all available data, a little better than 50% of the variation in pH could be explained, which is neither terrible nor excellent. The best fitting regression equations for Barr Lake include:

1) Avg pH (2m) = 7.85 + 0.436 Log Chl + 0.0232 Surf Temp (C). This equation explains 51.4% of variation.
2) Avg pH (2m) = 7.99 + 0.380 Log Chl + 0.0241 Surf Temp (C)- 0.00146 BO Inflow (cfs). This equation explains 54.2% of variation.

The utility of Chl is logical, as it represents algal activity that raises the pH. The influence of temperature is also logical, as higher temperatures increase algal activity. The addition of the Burlington O'Brien Canal (BO) inflow was an effort to see if flushing or nutrient influxes were important. The influence on pH is negative, which means more BO inflow lowers the pH. This may be a function of flushing, mixing or added carbon, among other possibilities, but the added value of this inflow to the regression is minor. The key elements are the temperature and Chl level, with each showing a positive relationship to pH. The unexplained variability could be attributable to many sources, and we have no additional data to shed any real light on them. That unaccounted variability will be a factor in determining the Chl level that must be reached if pH compliance is to be guaranteed, as this appears to be the most controllable factor in the equation.

Unlike at Barr Lake, log Chl alone does not explain much of the variation in pH for Milton Reservoir. The best fit regression equations are:

1) Avg pH = 8.64 - 0.0425 Beebe inflow (cfs) + 0.0107 Surf Temp (oC)+ 0.374 Log Chl. This equation explains 53.3% of variation.
2) Avg pH = 8.66 - 0.0416 Beebe inflow (cfs)-0.000580 PVC inflow (cfs)+0.0103 Surf Temp (C)+0.372 Log Chl This equation explains 53.9% of variation.

The pH is already high when water enters Milton Reservoir, conditioned by either passage through Barr Lake or the South Platte River and subject to productivity influences in those aquatic systems. Consequently, while low levels of Chl could not contribute significantly to increased pH, such low levels do not guarantee compliance.

Of particular concern is the potential for high pH values when chlorophyll levels are low (<10 µg/L), particularly in Milton Reservoir. The starting pH for the regressions is high for Milton Reservoir, and chlorophyll has only a limited effect. Additionally, since loading to both waterbodies is high, and some relationships may be difficult to elucidate with high algal growth potential already, trying to predict how much of a reduction in a variable like TP will be necessary is difficult. We expect the line to pass through 0,0 (no P, no Chl), and know that we have high Chl with high TP, but the shape of the curve in between low and high Chl is not known for these reservoirs. In general, TP>0.2 mg/L is excessive, and nearly all values in both reservoirs exceed this threshold. The factors that yield lower than expected Chl and pH are not well documented (self shading, mixing, grazing, allelopathy [chemical inhibition], and possibly N limitation). In other words, being able to explain 50% of the variation under current conditions may be the most we can reasonably expect, and as inlake conditions improve, better predictability may emerge. TMDLs are quite amenable to this iterative approach; high precision is not required and may not be attainable at this stage.

Utilizing the first regression equation for each reservoir, the Chl value for Barr Lake that results in a pH<9.0 at a temperature of 28^{o}C (a typical summer value) is 14 µg/L. For Milton Reservoir, assuming no inflow from Beebe or Platte Valley Canals, that value is only 1.5 µg/L. Higher values could allow pH compliance in the winter, as a function of lower temperatures, on the order of 127 µg/L for Barr and 5 µg/L for Milton.

Based on the portion of the pH variance explained by the equations, the actual target Chl to get pH<9.0 S.U. for >85% of the time would have to be lower than the values above, which makes the summer values very low relative to typical conditions in these or other area reservoirs.

As a logical alternative, the relationship between pH and Chl for all data or summer data only (Figure 3-3) could be used to determine the Chl value that represents a pH of 9.0 S.U. for 85% of the time. Simply looking at the coordinates for the Chl value that represents the 15th percentile for all pH values that exceed 9.0 S.U. in the top panel of Figure 3-3, the values are 21 µg/L for Barr Lake and 6.8 µg/L for Milton Reservoir, based on all available data. Applying this approach to the summer data (bottom panel of Figure 3-3), the Barr Lake Chl limit would be 17.9 µg/L and the Milton Reservoir Chl limit would be 8.2 µg/L. Based on the available real data for these systems, a Chl concentration less than about 20 µg/L in Barr Lake and a Chl level no more than about 7 to 8 µg/L in Milton Reservoir could be expected to yield pH levels that did not exceed 9.0 S.U. more than 15% of the time.

The primary problem with the above analysis relates only to Milton Reservoir, which has its water conditioned by Barr Reservoir and/or the South Platte River. While the generated values are a correct result of the analysis, if the Chl level in Barr Lake is lowered, there should be room for higher Chl in Milton Reservoir. Therefore, the Chl target for Barr Lake is probably applicable to Milton Reservoir as well.

An additional approach is to use equations developed from other temperate zone lakes that predict the probability of Chl at any level from the average value (e.g., Walker 1985), then use the projected value of Chl that links to pH=9.0 S.U. to predict the mean Chl value that corresponds to a 15% occurrence of pH>9.0 S.U. From the upper panel of Figure 3-3, the value at which the pH is expected to be 9.0 S.U. in Barr Lake is 115 µg/L, while for Milton Reservoir it is 112 µg/L. The relationships upon which these numbers are based are weak, but they are in close agreement. Applying Walker's probability analysis to a Chl of 115 µg/L occurring 15% of the time, the mean Chl that should be achieved to meet pH compliance is estimated at 77.5 µg/L, a rather high value. If we apply the summer relationship from Barr Lake (there is seemingly no relation between Chl and pH for summer Milton data), the Chl concentration at which a pH of 9.0 S.U. is expected is 70 µg/L and a mean value of 47 µg/L would result in Chl >70 µg/L about 15% of the time.

The primary problem with the above approach is that many of the high Chl levels produce lower pH values, as high biomass and high productivity are not the same thing. Self-shading and allelopathic interactions can make large standing crops of algae rather unproductive. The pH is likely to be highly variable, with higher daytime values (photosynthesis in the light) and lower nighttime values (respiration in the dark). Chl above some higher threshold will not aid pH prediction, but all values are included in this analysis. The prediction of the Chl level that will produce a pH value of 9.0 is skewed to the high side.

One way to minimize the above problem is to limit the analysis to Chl data less than some threshold. There is no clear guidance on what that threshold should be, but taking it at 100 µg/L (a high but arbitrary value), the projected Chl at which the pH=9.0 S.U. in Barr Lake is 75 to 90 µg/L, depending upon whether a linear or curvilinear relationship between Chl and pH is assumed. Using the probability distribution for Chl from Walker (1985), the mean Chl necessary to ensure that the pH will be <9.0 S.U. for 85% of the time is between 50 and 60 µg/L, still a fairly high value.

An alternative approach is to rely solely on the data for other Denver area reservoirs (Figure 3-1), which suggests a Chl value of about 25 µg/L will yield a pH <9.0 S.U. about 85% of the time. This value is in the middle of the range (20 to 30 µg/L) over which bloom frequency was found to increase greatly in Cherry Creek Reservoir (WQCD 2009). A value closer to 20 µg/L would provide more margin for error, but 25 µg/L provides a useful starting point for evaluation of phosphorus control needs to potential achieve pH compliance.

To summarize, it appears that the pre-conditioning of water entering Milton Reservoir leaves little room for Chl-induced pH rises, high alkalinity may maintain high pH even after an algal bloom has subsided, and relationships between Chl and pH are unreliable in that reservoir. The target is best set based on Barr Lake data, as whatever target is set for Barr Lake will affect conditions in Milton Reservoir. For Barr Lake, temperature and Chl explain a majority of the pH variation, and projections from regression equations suggest an upper limit of 14 µg/L for the summer and 127 µg/L in the winter. The Chl value above which a pH >9.0 S.U. represents 15% of the values in Barr Lake is about 21 µg/L for all data and 18 µg/L for summer data only. Using the relationship between Chl and pH from actual data, the Chl value that corresponds to a pH of 9.0 is 75 to 115 µg/L, depending on assumptions. Backcalculating the mean Chl value that would result in a Chl value of 75 to 115 µg/L for 15% of the time yields values between 47 and 78 µg/L, which seem rather high and require ignoring the high variability in the data. Finally, the data from other Denver area reservoirs with some wastewater influence suggests that a Chl value of 25 µg/L will yield a pH of <9.0 S.U. for 85% of the time, meeting the standard. Given the range of choices, a target Chl value of 20 to 25 µg/L is recommended as a target for both Barr Lake and Milton Reservoir as part of a TMDL to comply with the pH standard.

3.5 Setting a target phosphorus level for Barr Lake and Milton Reservoir

Management for Chl could be attempted without consideration for TP levels. Mixing, flushing, algaecide application, and biomanipulation techniques have some potential to minimize blooms and potentially meet a target Chl level on the order of 20 to 25 µg/L. But these techniques tend not to be as reliable or as fundamentally acceptable as reducing nutrient inputs to the point at which algal growth is limited.

There is some ongoing controversy over P vs. N as a productivity control, and both are clearly important to algal quality as well as quantity. However, while N appears to be more limiting to algal production than P much of the time in these reservoirs, based on N:P ratios, concentrations of available N and P are routinely high and neither limits algal growth most of the time. Light, temperature, allelopathy, grazing, and other factors are important, sometimes lowering Chl considerably despite high nutrient levels. However, the choice of an individual nutrient to manage for the control of algae must consider that N is available in the atmosphere and that dissolved, gaseous N can be used by many bloom-forming species of blue-green algae. These organisms readily utilize bicarbonate, the dominant form of inorganic carbon at high pH. They also produce taste, odor and sometime toxins, and are therefore a greater threat to most lake uses than other algae. As they cannot be controlled by N manipulation, and almost all algae can be limited by P if lowered sufficiently, P is the logical focus of management efforts. N and P tend to covary in Barr Lake and Milton Reservoir, and management for one will often also reduce the other, although specific processes in wastewater treatment can differentially affect N and P.

TP represents all P in a sample, and is usually an overestimate of available P. Soluble P includes only part of the P that is likely to be available or become available in the aquatic system, and underestimates available P. Total dissolved P is considered by some to be the best estimate of available P, but is seldom assessed. While TP will overestimate available P to some extent, the dominance of wastewater in this system, with most TP as available P, indicates that TP is the best choice for the P form upon which to impose a limit in the Barr-Milton system.

Applying the relationship between TP and Chl for these two reservoirs based on the data in Figure 3-4, the Chl would be predicted to be 25 µg/L in Barr Lake at a TP of 0.37 mg/L and in Milton Reservoir at a TP of 0.39 mg/L. Using the summer data only (Figure 3-5), the TP in Barr Lake would have to be 0.17 mg/L and that in Milton Reservoir would need to be 0.34 mg/L. However, the variability in these relationships is high, calling into question the reliability of these predictions. Even then, values in both reservoirs routinely exceed these seemingly high thresholds.

An alternative relationship between TP and Chl is provided by the Denver area reservoirs (Figure 3-1), although that relationship explains only a small portion of the variability as well and has detection limits that limit interpretation of the low end of the curve. Still, that relationship suggests that a TP concentration of 0.16 mg/L would yield a Chl of 25 µg/L, similar to the summer data projection for Barr Lake. Data for the Denver area reservoirs are nearly all from summer as well.

Yet another approach to deriving a TP target is to apply a range of empirical models based on sets of lakes in the north temperate zone of North America (e.g., Dillon and Rigler 1974, Jones and Bachmann 1976, Carlson 1977, Oglesby and Schaffner 1978, Vollenweider 1982) to predict the TP associated with any chosen Chl level. These relationships suggest that a TP of 0.16 to 0.17 mg/L would yield Chl levels of 73 to 149 µg/L, well above the targeted 25 µg/L. In order to achieve a mean Chl value of 25 µg/L, TP would have to be close to 0.05 mg/L. Given that lakes with features like those in the Denver area may be able to tolerate TP at levels up to twice that of the lakes on which the empirical models were based (Smith et al. 2001, Dodds et al. 2006, Robertson et al. 2007), an inlake TP target of 0.10 mg/L might be justifiable by this approach.

Direct relationships between TP and pH (Figure 3-6) are very poor for the entire data set. For the summer data, values cluster around a horizontal line (Figure 3-7). Summer TP values are less variable than the annual range, and include no values lower than about 0.25 mg/L. Consequently, TP is plentiful and not likely to limit algal production. The hypothetical curve shown in the lower panel of Figure 3-7 shows how the pH might be expected to change as TP decreases below about 0.2 mg/L, but we have no data to verify this relationship. Based on the variability shown further out on the curve (about half a pH unit), TP would have to be slightly less than 0.10 mg/L (0.085-0.091 mg/L) in either Barr Lake or Milton Reservoir to keep the pH below 9.0 S.U. on the order of the 85% of the time mandated by the pH standard.

In summary, relationships between TP and Chl in Barr Lake and Denver area reservoirs suggest that a target Chl of 25 µg/L could be achieved at a TP concentration of 0.16 to 0.17 mg/L. However, there is considerable variability associated with those relationships and this range of values is considerably higher than expected based on experience with other systems. Data for Milton Reservoir suggest an even higher TP could be tolerated, but is even more suspect. Application of a series of empirical models for estimating Chl from TP suggests a TP value of 0.05 to achieve a Chl value of 25 µg/L. Knowledge of the Chl-TP relationship for lakes like those in the Denver area suggests that a TP value up to twice that obtained from the empirical models may be appropriate, or about 0.10 mg/L. Estimation of the TP levels that corresponds to a pH below 9.0 S.U. for 85% of the time based on the hypothetical pH trajectory in Figure 3-7 and associated pH variability yields values slightly less than 0.10 mg/L. A value of 0.10 mg/L is recommended within each reservoir as an appropriate TP target for achieving pH compliance, although a case can be made for values up to 0.17 mg/L in a program that involves adaptive management.

3.6 Corresponding load estimation

A fairly complex model has been set up to estimate the current load to Barr Lake and Milton Reservoir and predict changes associated with possible management actions. Yet a simpler set of empirical models (e.g., Kirchner and Dillon 1975, Vollenweider 1975, Jones and Bachmann 1976, Larsen and Mercier 1976, Reckhow 1977) can be used to provide rough estimates of the TP load that corresponds to suggested TP and Chl targets to achieve pH compliance. Application of these models and averaging of the results indicates that the current TP load to Barr Lake is about 85,000 kg/yr, while that to Milton Reservoir is about 67,800 kg/yr. If we select a target TP of 0.165 mg/L, assuming it will yield a Chl level of 25 µg/L and that will keep the pH under 9.0 S.U. 85% of the time, the target TP load would be 20,500 kg/yr for Barr Lake and 19,600 kg/yr for Milton Reservoir. As the two waterbodies have similar features, the similarity of estimates makes sense.

If we assume at the other extreme that a TP concentration of 0.05 mg/L is needed to yield a Chl level of 25 µg/L by the empirical models based on lakes elsewhere in North America, the corresponding TP load is 6,230 kg/yr for Barr Lake and 5,950 kg/yr for Milton Reservoir. Assuming that Barr Lake and Milton Reservoir are more like lakes studied and found to be able to handle about twice the load suggested by the empirical models, the corresponding TP loads to get a TP concentration of 0.10 mg/L and a Chl level of 25 µg/L would be 12,400 and 11,900 kg/yr, respectively. All of these estimates represent a major decrease from current loading.

3.7 Conclusion

Multiple lines of reasoning and corresponding calculation have been applied to the question of target concentrations and loads for Barr Lake and Milton Reservoir (Table 3-1). We have used available data for these reservoirs from 2002 to 2007, corresponding data from other Denver area reservoirs, and relationships derived from other North American lakes to evaluate possible targets for Chl and TP to achieve a pH that is <9.0 S.U. for at least 85% of the time, meeting the Colorado State Standard. A substantial range of values has been derived, with some more reliable than others, but all based on reasonable approaches supported by considerable data. Uncertainty results from high variability induced by factors not specifically measured, including light fluctuation, possible allelopathy among organisms, grazing pressure by zooplankton as influenced by fish, erratic mixing, and periodic flushing. Additionally, high alkalinity is likely to maintain high pH once established, weakening the TP-Chl-pH linkage for predictive purposes. A lack of TP values lower than 0.25 mg/L in either reservoir during summer hampers projections into the lower range for that water quality variable and establishment of relationships with Chl and pH based on site-specific data. Projections must therefore rely on assumptions.

Relationships between variables tend to be weaker in Milton Reservoir than Barr Lake, and most of the water in Milton Reservoir is conditioned by passage through Barr Lake and a longer stretch of the South Platte River. Consequently, actions taken to improve conditions in Barr Lake will affect Milton Reservoir. It is recommended that one set of target values be applied to both lakes, rather than attempting to establish separate target levels for Chl and/or TP for each reservoir.

Seasonal variation deserves some attention in the TMDL process. Barr Lake and Milton Reservoir can tolerate higher TP and Chl in the winter than in the summer to meet the pH standard. As inflows are not constant in either quantity or quality, consideration of seasonal standards may be warranted. However, the TP load that enters these reservoirs in the winter and spring translates into a TP concentration that largely remains in the summer and fall. Consequently, the implications of loading should still be considered on an annual basis. If inlake treatments are allowed to control TP during the summer, it may be possible to allow higher winter/spring loading and adjust inlake concentrations later in spring, but this is not currently an allowable practice in Colorado.

Selecting values from the range of derived potential target values for Chl and TP (Table 3-1) as part of the TMDL process should include consideration of the scientific basis, feasibility of implementation and economic consequences of each value. From a purely scientific and experiential viewpoint, a Chl level of between 20 and 25 µg/L is recommended, with the most lenient TP concentration we believe could achieve that range of values set at 0.10 mg/L. The more lenient 0.16 to 0.17 mg/L TP level based on local data that suggests possible achievement of the desired 25 µg/L Chl value may not seem like a large difference to some, but it may have major consequences for management actions and associated costs. As wastewater discharges represent the greatest influence on Barr Lake and Milton Reservoir at this time, the chosen target TP concentration will affect decisions about treatment upgrades, and the difference between an inlake value of 0.10 and 0.17 may be highly significant. Consideration of all aspects of implementation is recommended in crafting the TMDL, and the iterative nature of TMDLs over time, with adaptive management, is stressed.

The most problematic aspect of these reservoirs in terms of adaptive management is likely to be manifestation of internal loading. Both resupension of settled particles containing P and soluble release from bottom sediment are involved. The historic load of TP to the reservoirs is large, and it is reasonable to assume that sediment reserves of TP are also large. The fraction of this reserve TP that is potentially available is not known, but may also be substantial. With currently high water column values for TP, soluble release from sediment is unlikely to be as large as it would be if external loads were reduced, simply because of chemical equilibrium; the rate of exchange is proportional to the concentration gradient. But if external loads are decreased substantially, soluble release may increase and compensate for the lowered external load. Internal loading should be included in the TMDL and a means to reduce internal loading should be considered in planning for TMDL implementation.

Table 3-1. Summary of possible target levels for chlorophyll-and total phosphorus, with representative total phosphorus loads

Feature or Scenario	Units	Barr	Milton	Notes
Chlorophyll (ug/L) target based on regressions using Chl and Temp - Summer (constructed from 2002-2007 data)	ug/L	14	1.5	Accounts for only about half the variation in pH
Chlorophyll (ug/L) target based on regressions using Chl and Temp - Winter (constructed from 2002-2007 data)	ug/L	127	5.0	Accounts for only about half the variation in pH; lower temp allows greater Chl
Chlorophyll (ug/L) target based on calculated mean that yields a Chl corresponding to pH=9.0 SU for 15% of the time from all 2002-2007 data	ug/L	77	77	Depends on Chl-pH relationship that is very weak in Barr and Milton; Barr data applied to both
Chlorophyll (ug/L) target based on calculated mean that yields a Chl corresponding to pH=9.0 SU for 15% of the time from summer 2002-2007 data	ug/L	47	47	Depends on Chl-pH relationship that is very weak in Barr and Milton; Barr data applied to both
Chlorophyll (ug/L) target based 15th percentile of pH data >9.0 SU from 2002-2007 data	ug/L	21	6.8	Reflects actual occurrence of high pH over 6 years
Chlorophyll (ug/L) target based 15th percentile of pH data >9.0 SU from summer 2002-2007 data	ug/L	18	8.2	Lower Chl from subset of data, most likely results from influence of higher temperature
Chlorophyll (ug/L) target based 15th percentile of pH data >9.0 SU from 2002-2007 data for other Denver area reservoirs	ug/L	25	25	Mostly summer data from 15 area reservoirs with some wastewater influence but no major benthic algae or rooted plants
		Applies to Barr		
Total Phosphorus (mg/L) target to achieve Chl=25 ug/L based on projections from 2002-2007 data	mg/L	0.17		Relies on weak relationship
Total Phosphorus (mg/L) target to achieve Chl=25 ug/L based on projections from 2002-2007 data from other Denver area reservoirs	mg/L	0.16		Relies on weak relationship, but consistent with findings for Barr-Milton
Total Phosphorus (mg/L) target to achieve Chl=25 ug/L based on projections from empirical models for temperate North America	mg/L	0.05		Uses mean of 5 models constructed from different groups of temperate zone lakes
Total Phosphorus (mg/L) target to achieve Chl=25 ug/L based on empirical models as interpreted for Denver area reservoirs	mg/L	0.10		Doubles empirical model result based on research on plains lakes
Total Phosphorus (mg/L) target to achieve Chl=25 ug/L based on hypothetical trajectory and actual variation in TP-pH relationship from 2002-2007 data	mg/L	0.09		Hypothetical but theoretically sound constructed curve applied; available data do not cover lower range
Average Total Phosphorus - all 2002-2007 data	mg/L	0.68	0.57	
Average Total Phosphorus - summer data only	mg/L	0.56	0.59	
Current TP Load	kg/yr	85000	67800	Converts concentration to load via empirical models
TP load that leads to meeting 0.165 mg/L TP target intended to lead to a 25 ug/L Chl level	kg/yr	20500	19600	Converts concentration to load via empirical models
TP load that leads to meeting 0.10 mg/L TP target intended to lead to a 25 ug/L Chl level	kg/yr	12400	11900	Converts concentration to load via empirical models
TP load that leads to meeting 0.05 mg/L TP target intended to lead to a 25 ug/L Chl level	kg/yr	6230	5950	Converts concentration to load via empirical models

4.0 Numerical modeling

The development of a model of the Barr-Milton Watershed, conducted by AECOM and documented in this report, involved 1) developing a conceptual understanding of the watershed, 2) acquiring enough data to adequately describe the temporally and spatially varying boundary conditions external to and within the watershed, and 3) developing a functional predictive platform for use in testing management scenarios. The numerical modeling portion of the investigation occupied a significant portion of AECOM's effort in this project and is the primary deliverable. The model is intended to support TMDL development, and testing has involved TMDL considerations (see Sections 5 and 6).

The numerical model development portion of the Barr-Milton watershed investigation involved the development and calibration of both a watershed model and a lake model. The watershed modeling platform selected for this investigation was the USDA's Surface Water Assessment Tool (SWAT) and the lake modeling platform selected for the investigation was the USEPA's Water-Quality Analysis Simulation Program (WASP). The stepwise fashion in which the numerical modeling process proceeded included: 1) development and calibration of the SWAT watershed model, including code adjustments to more properly account for water transfers, 2) development of software to extract information from the SWAT model and make the information available to the WASP model, and 3) development and calibration of the WASP model of Barr Lake and Milton Reservoir.

The SWAT model has been used around the world to predict watershed runoff from a myriad of urban and agricultural watersheds. The model has an active users group and technical support, is under continual improvement, and can operate through the ArcSWAT GIS interface for ESRI's ArcGIS application software, allowing easier input of complex data. The SWAT model simulates a multitude of environmental processes including the major components of the hydrologic cycle (both surface and shallow groundwater water discharge to watershed reaches). Rainfall and snowmelt are simulated and routed through the interconnected subwatersheds. Point discharges, water transfers, and consumptive use withdrawals are simulated throughout the watershed. The agricultural component of the SWAT model is complex and robust enough to handle a variety of plantings and crop rotations and allows the user to provide a detailed description of farming processes throughout the simulation.

The inability of the SWAT model to effectively simulate the complex transfer of water around the watershed was at first a limitation but this problem was remedied through modification of the SWAT computer code to meet the needs of the investigation. The ArcSWAT modeling platform facilitates the use of a wide variety of readily available electronic information for the setup of the model network. The modification of the SWAT computer code required some editing of input files outside of ArcSWAT but the modifications were confined to the hydrograph routing portion of the input. The SWAT model includes a reservoir water quality simulation component but this was determined to be of limited use in this case, since the only means of controlling the predicted nutrient concentrations is through settling. Therefore, the use of the SWAT model to provide input loads for a more complex inlake eutrophication model was determined to be most appropriate for Barr Lake and Milton Reservoir. This is a common practice in watershed and lake modeling; the same sequence of models was recently applied to a reservoir in Texas with very effective results (Ernst and 2009).

The WASP surface water model has been developed by the EPA over the past several decades and is one of the more user-friendly models available for complex TMDL evaluations requiring dynamic simulation. The WASP model has been regularly expanded to include more complex processes, in an effort to more realistically represent natural systems. Also, the WASP model has been incorporated into a Windows® based platform that greatly simplifies the setup and execution of the model. The WASP eutrophication model includes an entire suite of nutrient interaction equations and the simultaneous growth and development of multiple phytoplankton types within the model domain. The WASP model also incorporates the simulation of suspended sediment and the settling of sediment and associated nutrients at a predefined settling rate.

Hydraulic parameters within each of the WASP model segments are defined using a hydrodynamic (HYD) interface file that would usually be created by an instream hydrodynamic model, but in the case of the Barr-Milton watershed simulation this information was entered using a Visual Basic® script and the subbasin, reach, and reservoir predictions made by the SWAT model. Nutrient and sediment loads can be applied to the WASP model in a similar fashion using an external file developed using a Visual Basic® script and SWAT model predictions.

The result is a linked watershed-lake model in which loads of water and nutrients are generated by SWAT and entered into WASP for processing in the two reservoirs, resulting in final concentrations of various forms of phosphorus and nitrogen, plus chlorophyll *a*, over time in Barr Lake and Milton Reservoir. The link from chlorophyll *a* to pH is not made within the model and is addressed separately (see Sections 3 and 6). While one should never confuse models with reality, a modeling approach is necessary to sort out the complex interactions in this watershed. It is possible to evaluate overall loading and inlake conditions in a mass balance approach with real data, as was performed by AMEC (2008a, 2008b), but this does not provide the predictive capacity or load partitioning throughout the watershed that are needed for TMDL development. The model system constructed in this project is intended to mimic the existing system to the extent that predictions can be made about the direction and magnitude of change necessary to achieve pH compliance and overall eutrophication control.

4.1 Watershed modeling

Watershed modeling, completed in advance of the inlake model development for Barr Lake and Milton Reservoir, facilitates generation of loading estimates from identifiable sources and subwatersheds and the routing and processing of those loads on their way to the reservoirs. The level of complexity in the model is justified insofar as instream water quality depends not only on discharge concentrations but also on the timing and location of the discharges, water transfers and consumptive uses. The key components of watershed modeling include conceptualizing the movement of water through the watershed, gathering required input data, and enhancing the SWAT model so that it could better represent water transfers.

4.1.1 Watershed modeling approach

The development of a watershed model for the Barr-Milton watershed was complicated by the significant level of water management occurring throughout the watershed. The combination of temporally varying point source discharges, transfers, and consumptive use withdrawals, along with the watershed having two primary outlets (the South Platte River and the Milton Reservoir outlet), made the use of a simplified watershed model impractical. Also, the size of the watershed and multitude of different land uses and soil types necessitated the use of a GIS platform for model development. The watershed modeling approach included:

1. *Review the capabilities of different watershed models and select the most suitable platform* – This was a critical first step for effectiveness and efficiency.
2. *Gather available and necessary geo-spatial data including land use and soils data* – Much of this information was available from the BMW Association's Technical Committee, from state and federal agencies directly, or was available through multiple internet access sites.
3. *Gather existing environmental data from local meteorological stations* – These data were available from NOAA for several sites both within and immediately adjacent to the Barr-Milton watershed.
4. *Gather existing discharge, transfer, and withdrawal rates and loads from appropriate agencies* – Water discharge and management data were largely available from the BMW Association Technical Committee. Even though significant amounts of data were available there were still significant data gaps; these were addressed during the input file development. As such, AECOM relied heavily on the BMW Association Technical Committee and the individual dischargers and water users to provide discharge data.

5. *Acquire flow and water quality data for comparison during model calibration* – Much of the comparative water quality data were acquired from the Hydrosphere (AMEC) database while flow data were made available from the State of Colorado.
6. *Decide on a continuous simulation period for model calibration/validation* – The limited input data and the intensive data requirements of the SWAT model led to the selection of a simulation period of 2003 through 2004. As data become available for more recent years, extension of model calibration and validation are encouraged, but are not part of this effort.
7. *Fill all discharge, transfer, and withdrawal rate data gaps using simple linear interpolation* – Developing complete data sets from the sparse data that was available in some cases required that several interpretations and assumptions be made to fill in the data gaps.
8. *Set up the model for simulation over the calibration/validation period* – Incorporation of real and synthesized data and setting up a working model led to the development of a numerical tool that could be used to simulate current conditions and the long-term effects of alternative management alternatives.
9. *Calibrate the model to reservoir volumes and inflow nutrient concentrations* – The development of reliable predictions of reservoir volume and nutrient loading to Barr Lake and Milton Reservoir is necessary to support the next level of modeling, inlake processes, covered by the WASP model.

The watershed modeling generally progressed as indicated above with a significant amount of unforeseen effort spent on mapping out a reliable flow diagram for the watershed and gathering all the discharge, transfer, and withdrawal rate data used to set up the model. The insight of many members of the BMW Technical Committee was necessary to accumulate essential data, and this report reflects a common base of knowledge that will be needed during TMDL development.

4.1.2 Selection of watershed modeling platform

The evaluation and ultimately the selection of an appropriate watershed model for this application began very early on in the investigation. Of all the models considered there are only two that met the basic requirements set through discussion between AECOM and stakeholders, including:

- *Public domain* – any model used for this application would have to be freely available to the general public so that additional costs were not incurred to the project. Also, public domain models eliminate the problems that go along with software licensing.
- *Technical support* – often overlooked in the process of model selection is the quality of technical support available. This can be a critical factor in the successful execution of a modeling application and problems that could take days to resolve internally can be resolved in a fraction of the time by advanced users and developers.
- *Active users group* – the impetus for a well funded model is often derived from the interest and application of the model to a wide variety of watershed investigations. An active users group presents an invaluable resource of practical information.
- *GIS based* – in recent years there has been a widespread use of Geographic Information Systems to support modeling applications having a significant degree of spatial heterogeneity. Also, the availability of spatial data necessary to support these applications has led to watershed modeling frameworks that can utilize existing spatial data to develop accurate model input files.
- *Ease of use* – the modeling process has been simplified as developers have taken advantage of advances in computing and software capabilities, and while the usability of models has not necessarily translated into more reliable models, it does make the process more accessible to novice users.

The two watershed models that would be suitable to the Barr-Milton watershed included the U.S. Geological Survey's (USGS) Hydrologic Simulation Program - FORTRAN (HSPF) and the U.S. Department of Agriculture's (USDA) Soil and Water Assessment Tool (SWAT). Each of these models meets all the criteria outlined above, but the SWAT model is more suitable for agricultural applications and cases with extensive water transfers. It handles point sources well and is adaptable to changing land uses and complicated routing patterns. While AECOM has experience with both of these models, SWAT has been successfully used in several recent projects with some similarity to the Barr-Milton system and therefore was selected as the most suitable model for the Barr-Milton Watershed application.

4.1.3 SWAT/ArcSWAT model description

SWAT is a river basin, or watershed scale, model developed by Dr. Jeff Arnold for the USDA Agricultural Research Service (ARS). SWAT was developed to predict the impact of land management practices on water, sediment and agricultural chemical yields in large complex watersheds with varying soils, land use and management conditions over long periods of time. The model is physically based and, rather than incorporating regression equations to describe the relationship between input and output variables, SWAT requires specific information about weather, soil properties, topography, vegetation, and land management practices occurring in the watershed. The physical processes associated with water movement, sediment movement, crop growth, nutrient cycling, and related watershed features are directly modeled by SWAT using these input data.

Benefits of this approach include:

- Watersheds with no monitoring data (e.g., stream gage or water quality data) can be modeled.
- The relative impact of alternative input data (e.g. changes in management practices, climate, vegetation, or land use) on water quality or other variables of interest can be quantified.
- The model uses readily available inputs. While SWAT can be used to study more specialized processes such as bacteria transport, the minimum data required to run the model are commonly available from government agencies.
- SWAT is computationally efficient. Simulation of very large basins or a variety of management strategies can be performed without excessive investment.
- The model enables users to study long-term impacts. Many of the problems currently addressed by users involve the gradual buildup of pollutants and the impact on downstream water bodies. To study these types of problems, results are needed from runs with output spanning several decades. Ideally, however, inputs from many years (5+) are desirable to calibrate the model; less data were available to AECOM for this modeling effort.

The SWAT model can be applied to support various watershed and water quality modeling studies. Applications include national and regional scale water resource assessment considering both current and projected management conditions. For example, the Bosque River TMDL in Erath County, Texas determined sediment, nitrogen, and phosphorus loadings to Lake Waco from various sources including dairy waste application areas, waste treatment plants, urban areas, conventional row and cover crops, and rangeland (Santhi 2007). These results were refined and expanded in management plan development (AECOM 2008). In the Poteau River TMDL in Oklahoma/Arkansas, SWAT was used to determine sediment, nitrogen, and phosphorus loadings in Wister Lake and dissolved oxygen, temperature, algae, and CBOD in the river (Srinivasan et al. 2000). Management scenarios regarding poultry waste were analyzed. SWAT is also being used extensively in the U.S. and Europe to assess the impact of global climate on water supply and quality (Rosenberg et al. 1999). It is touted as highly applicable in agricultural settings, but is also quite adaptable to urban areas and situations with multiple point source inputs.

ArcSWAT is an ArcGIS extension and a graphical user input interface for the SWAT2005 (Soil and Water Assessment Tool) model. SWAT is a river basin (watershed) scale model developed to predict the impact of land management practices on water, sediment, and agricultural chemical yields in large, complex watersheds with varying soils, land use, and management conditions over long periods of time. The model is physically based and computationally efficient, uses readily available inputs and enables users to study long-term impacts. For a detailed description of SWAT, see Soil and Water Assessment Tool Theoretical Documentation and User's Manual, Version 2005 (Neitsch et al. 2005a, 2005b), published by the Agricultural Research Service and the Texas Agricultural Experiment Station, Temple Texas.

The important functional components and the analytical capability of ArcSWAT are implemented in several sets of customized and user friendly tools designed to: 1) generate specific parameters from user-specified GIS coverages; 2) create SWAT input data files; 3) establish agricultural management scenarios; 4) control and calibrate SWAT simulations; 5) extract and organize SWAT model output data for charting and display. The most relevant components of the system are: 1) a complete and advanced watershed delineator, 2) a tool for definition of the Hydrologic Response Units (HRU), and 3) the latest version of the SWAT model with an interface. ArcSWAT software is developed as an extension of ArcGIS for the Personal Computer (PC) environment.

Within this system, ArcGIS provides both the GIS computation engine and a common Windows-based user interface. ArcSWAT is organized in a sequence of several linked tools grouped in the following eight modules: 1) Watershed Delineation; 2) HRU Definition; 3) Definition of the Weather Stations; 4) ArcSWAT Databases; 5) Input Parameterization, Editing and Scenario Management; 6) Model Execution; 7) Read and Map-Chart Results; 8) Calibration tool. Once ArcSWAT is loaded, the modules get embedded into ArcGIS, and the tools are accessed through pull-down menus and other controls, which are introduced in various ArcGIS graphical user interfaces (or GUIs) and custom dialogs. The basic map inputs required for the ArcSWAT include digital elevation, soil maps, land use/cover, hydrography (stream lines), and climate. In addition, the interface requires the designation of land use, soil, weather, groundwater, water use, management, soil chemistry, pond, and stream water quality data, as well as the simulation period, to insure a successful simulation. This tool is being applied worldwide and can support water quality analysis at the watershed level as well as at single stream segments, scales required for the support of most TMDL programs.

4.1.4 Simulation period

The simulation period selected for both the SWAT watershed modeling and the WASP lake modeling included the two-year period of January 1, 2003 through December 31, 2004. This time period was selected mainly as a consequence of data availability, but offers several additional features of interest:

- *Simulation period followed period of drought* – in 2003 both Barr Lake and Milton Reservoir were filling from a previous drought year. This suggested that the diversions and water quality measured around the watershed and within the reservoirs would represent conditions relative to water stress.
- *Average precipitation during simulation period* – the SWAT watershed model was calibrated during a relatively brief two-year period, so it was important that the simulation period was representative of average conditions, relative to the amount of precipitation and surface runoff.
- *Point source data coverage* – water quantity and quality data for each of the WWTPs was intermittent or lacking for many of the dischargers in many years. Available data from all the WWTPs was gathered and summarized for the period from 2000 through 2007 and a decision was made to select the two consecutive years with the best data coverage for the simulation period.
- *Comparative data coverage* – water quantity and quality data for the simulation period were also required for each of several points-of-comparison throughout the watershed. These include: 1) the inlet to Barr Lake on the O'Brian Canal, 2) Barr Lake, 3) the inlet to Milton Reservoir on the Beebe Canal, 4) the inlet to Milton Reservoir on the Platte Valley Canal, and 5) Milton Reservoir. These stations all had reasonable data coverage during the two-year simulation period of 2003-2004.

In short, the two-year period from January 1, 2003 through December 31, 2004 was selected as the simulation period 1) because the period coincided with the best available data coverage, and 2) to provide a period that represented a range of reservoir conditions. Certainly a longer period would be preferable, but sufficient data were not available at the time of this effort. The model could be run with additional years of data at some future date, as those data become available.

4.1.5 SWAT model input data

Acquiring and organizing the input data required to set up and execute the SWAT model was a relatively complicated step in the watershed modeling process. This was not because of any complexities introduced by the SWAT model, but because of the many files needed to describe all the point sources, transfers, and water withdrawals around the watershed, and the lack of a single, central source for those data.

4.1.5.1 Watershed composition and boundary

The watershed boundary applied to the SWAT model of the Barr-Milton watershed coincided with the "datashed" boundary provided by the BMW Association, with only minor deviations. The datashed was developed to isolate the portion of the larger watershed, which is relatively self-contained, from a management standpoint, and is the primary portion of the overall watershed directly responsible for water quality in the Barr Lake and Milton Reservoir system. Most of the watershed outside of the datashed contributes to reservoirs that detain and divert much of that water, limiting direct impact on Barr Lake and Milton Reservoir.

The entire Barr-Milton watershed, extending upstream of the reservoirs is approximately 5,230 miles^2 (Figure 4-1. Barr-Milton watershed map). This all-inclusive portion of the watershed extends to the continental divide in the west and includes the watersheds upstream of each of several controlling reservoirs in the smaller "datashed", which, for the purposes of this investigation is being defined as the Barr-Milton watershed area and extending upstream only to each of several well defined control points. The datashed has an area of 833 miles^2, extends from the headwater reservoirs along the Front Range of the Rocky Mountains to approximately 56 miles northeast, and has an average width of approximately 15 miles (Figure 4-2). The highest elevation within the datashed is 7,810 feet above MSL and the lowest elevation is 4,800 feet above MSL. The average elevation within the datashed is 5,300 feet above MSL. The datashed is the relatively low-lying alluvial valley of the South Platte River, which explains why the average elevation is much closer to the minimum elevation than the maximum.

The Barr-Milton datashed is extremely complex, due in large part to water management for municipal and agricultural purposes. The datashed receives water and related materials from several sources along the Front Range, in the form of high mountain reservoirs at the higher elevations in the southwest (Bear Creek Lake, Chatfield Reservoir, and Cherry Creek Reservoir) and creeks along the northwest side (Clear Creek, Cherry Creek, and Big Dry Creek). There are several smaller creeks that are entirely within the datashed, including First Creek, Second Creek, and Third Creek. These are treated as "point sources" in the model.

The datashed also contains several municipal WWTP dischargers (Centennial, Littleton-Englewood, Metro, Aurora, South Adams, Brighton, Fort Lupton, Lochbuie, and Hudson) that discharge to both the South Platte River directly or through tributaries, or to irrigation canals that flow parallel to the South Platte and discharge to the Barr Lake and Milton Reservoir system. Irrigation withdrawals from the South Platte River and from canals served by the two reservoirs are another important component of the hydrologic budget within the Barr-Milton datashed.

Figure 4-1. Barr-Milton watershed map

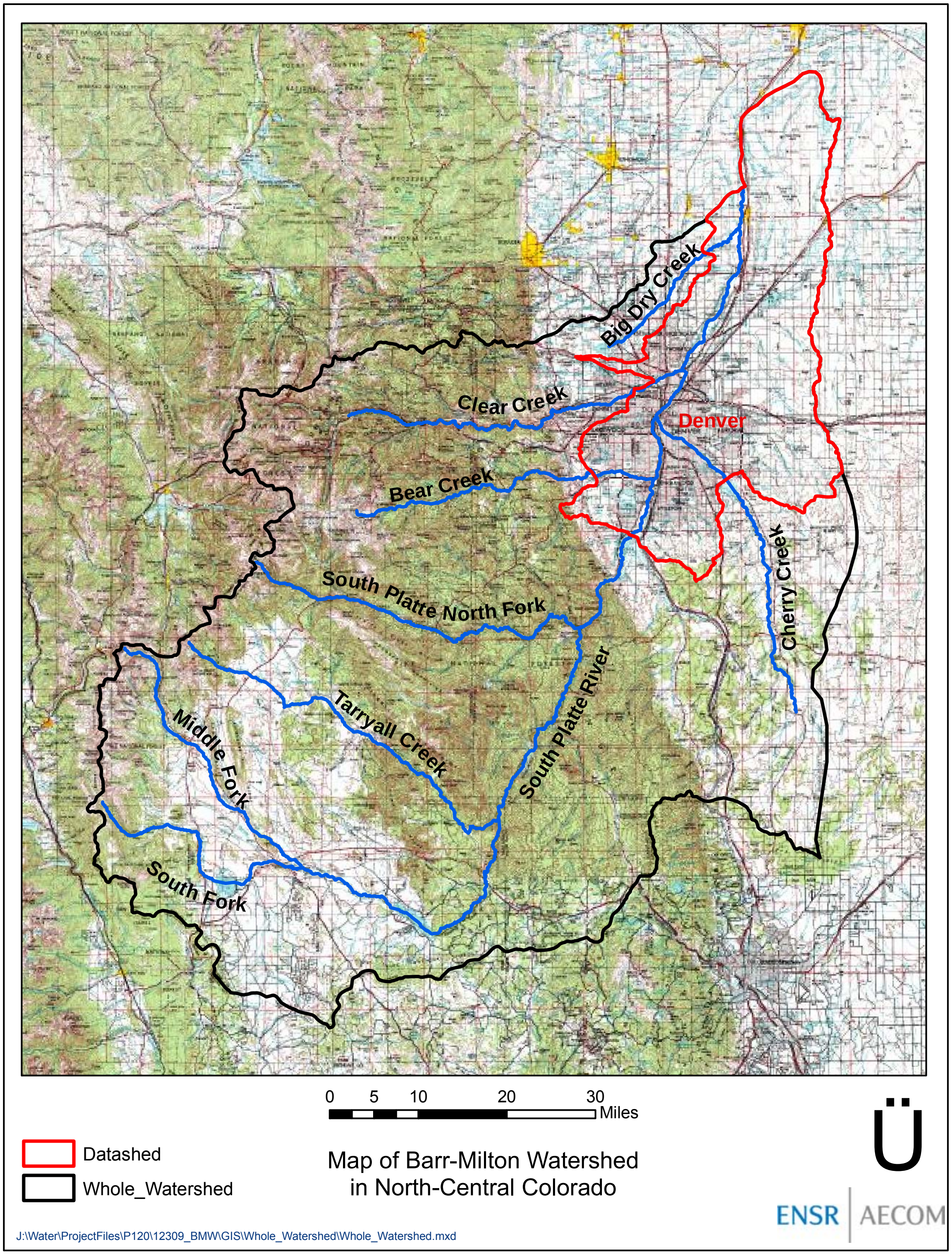
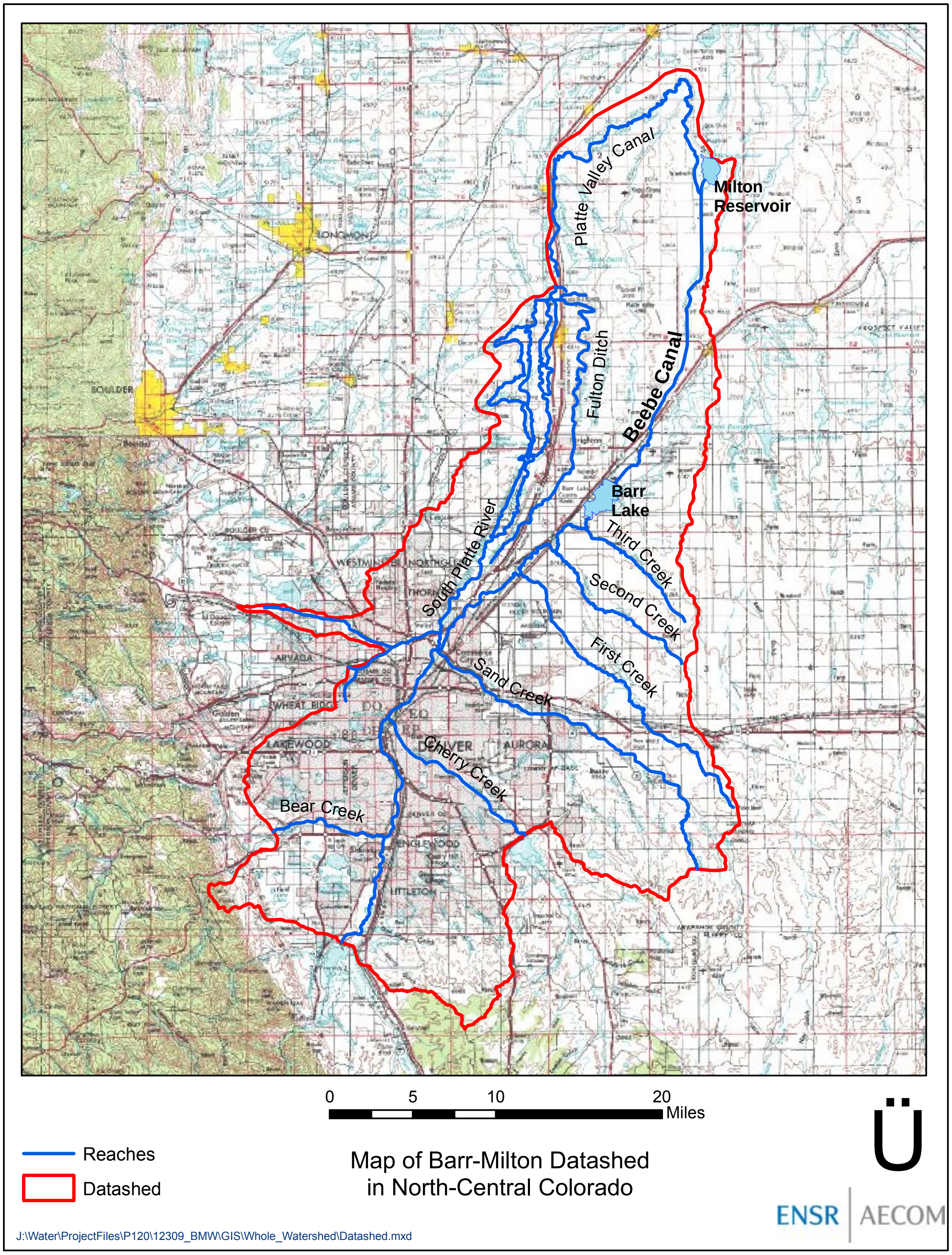


Figure 4-2: Barr-Milton datashed map



Several agricultural withdrawals from the South Platte River are used to irrigate corn and alfalfa on land immediately adjacent to the South Platte River (Brantner Ditch, Brighton Ditch, Lupton Bottom, and Fulton Ditch) and have return flows back to the South Platte. These four agricultural ditches are relatively small, however, compared to the two ditches (Burlington O'Brian and Platte Valley Canal), which transfer water from the South Platte River to the Barr Lake and Milton Reservoir system located between 5 and 10 miles east of the South Platte. These two canals represent the bulk of the inflow to the Barr Lake and Milton Reservoir system and the water quality in these two canals are largely responsible for the water quality in these two impoundments.

Withdrawals of water are common along both the South Platte River and the Burlington-O'Brian Canal to serve both municipal water supply and agricultural purposes. Withdrawals along the South Platte (Meadow Island #1 and the Platteville Ditch), the Burlington-O'Brian canal upstream of Barr Lake (Thornton, South Adams, and Denver-Hudson), the Beebe Canal, which connects Barr Lake and Milton Reservoir, (Bowles Seep and East Neres), and the Platte Valley Canal (Evans #2) all contribute to reductions in river and canal flow throughout the year.

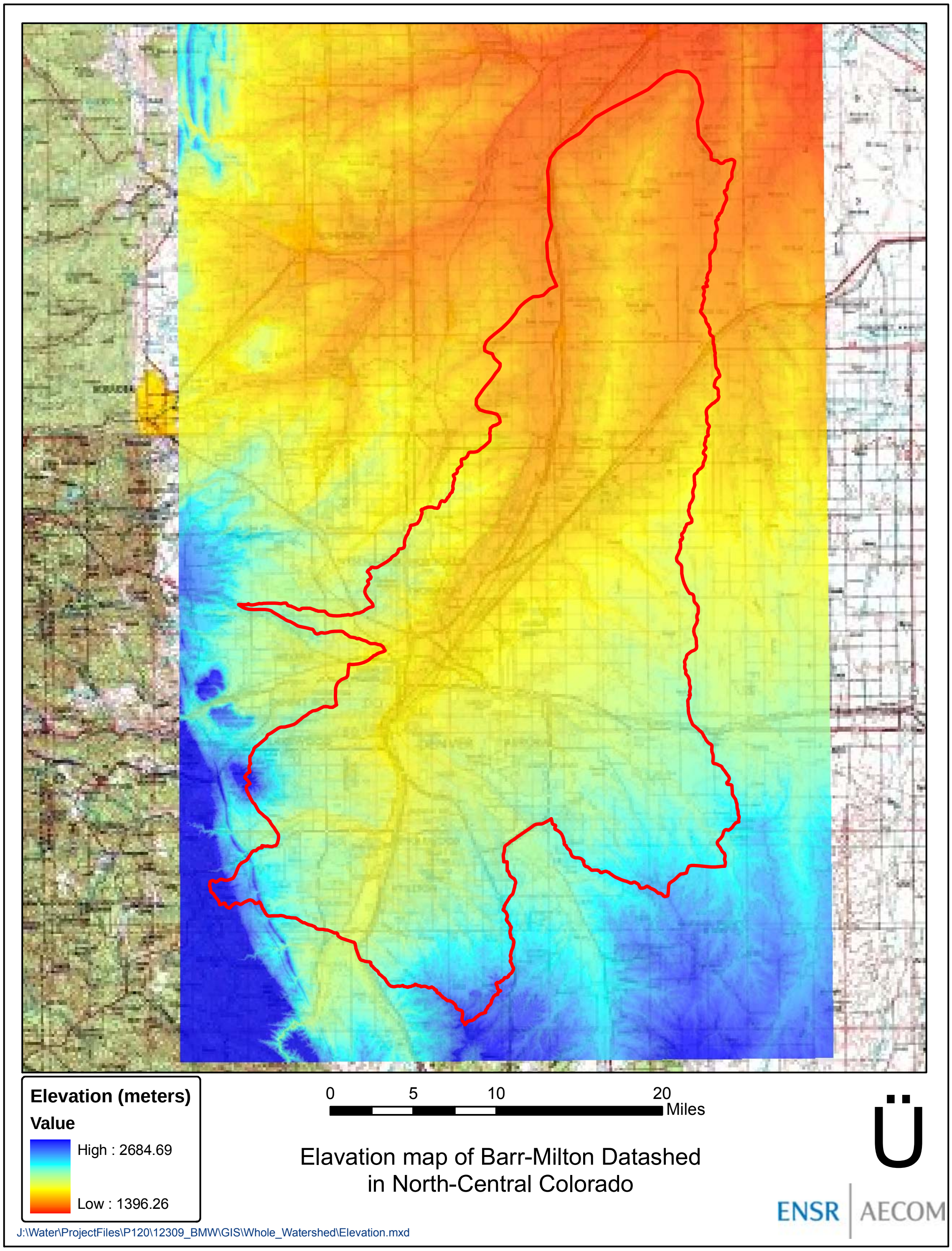
Finally, water withdrawals directly form Barr Lake and Milton Reservoir comprise a significant portion of the hydrologic budget of the respective reservoirs. The reservoirs were originally built and developed to provide an agricultural source of water to adjacent farmlands and are still in use for that purpose today. With regard to the Barr-Milton datashed, the most important withdrawal for agriculture from Barr Lake occurs at the East and West Valves, where water is removed during the summer months to irrigate corn and alfalfa fields north of the lake.

The complexity of the hydrologic system defined by the Barr-Milton datashed is determined by management decisions made to optimize the usage of water in the system to satisfy a multitude of water rights. The simplification of the Barr-Milton Watershed by imposing a "datashed" boundary reduces the area of the investigation and water administration roles, but does not significantly reduce the complexity in that most of the water management occurs within this lower portion of the larger watershed. The datashed boundary, applied to the Barr-Milton watershed and used to develop the SWAT numerical watershed model of the system, encompasses the principal components of the hydrologic budget of the system. The boundary extends upstream far enough to be adequately described by measured discharges and concentrations issuing from each of several upstream reservoirs and maintains the complexity of the system with regard to downstream management control.

4.1.5.2 Digital elevation data

Elevation data is used in the SWAT model to determine a multitude of watershed factors used in establishing a hydrologic budget for each watershed throughout the duration of a simulation. The most important of these characteristics is the subwatershed area. Subwatershed areas are calculated within ArcSWAT using a digital representation of the land surface and by identifying the locations of outlet points and streams within the larger watershed prior to the determination. ArcSWAT uses the digital elevations, modified by "burning in" the streams, and the outlet points to calculate the flow directions and accumulations for each grid cell within the digital elevation data set. The elevation data used to define the Barr-Milton datashed was acquired from the USGS via the seamless data website (http://seamless.usgs.gov). The rectangular elevation dataset was acquired for the entire datashed and represents the datashed elevations on a 30 meter grid (Figure 4-3). Digital elevation data is imported directly into ArcSWAT and processed to ready the data for determination of the subwatershed boundaries based on a set of model determined or user defined outlet points.

Figure 4-3. Elevation map of the Barr-Milton Datashed



The following bulleted list describes the step-by-step sequence for acquiring, processing, and using digital elevation data in ArcSWAT:

- Acquire 30-m digital elevation grid data from the USGS for the area bounded by the Barr-Milton datashed.
- Develop and import digital stream reach shapefiles used to represent major streams and agricultural canals within the Barr-Milton datashed.
- "Burn-in" the stream reach shapefiles onto the digital elevation grid data to insure that the ArcSWAT subwatershed processing algorithms maintain streams and canals flowing where they actually flow. This burning-in step simply lowers the grid elevations along stream reaches, relative to the grid elevations in adjacent cells, so that the flow directions calculated by ArcSWAT are correct.
- Use the tools within ArcSWAT to calculate the cell-by-cell flow direction grid and the flow accumulation grids. This processing step occurs immediately prior to importing outlet locations and subwatershed development.

In addition to being used for Barr-Milton subwatershed delineation, the digital elevation data is used to calculate several parameters used by the multitude of equations internal to the SWAT model. These variables include, but are not limited to, the watershed aspect, slope, and the time of concentration. SWAT ascertains these relevant variable magnitudes for each subwatershed once the ArcSWAT model predevelopment processing is completed and the time comes to actually develop the SWAT model input files. This step is done seamlessly by ArcSWAT and does not require additional user intervention.

4.1.5.3 Digital land use data

Land use data is used to identify specific characteristics within the entire Barr-Milton watershed and each of the subwatersheds. Digital land use data were acquired from the MRLC (Multi-Resolution Land use Consortium) website (www.mrlc.gov). The land use datasets available form the MRLC are from the NLCD 2001, which are the National Land Cover Datasets developed and finalized in 2001. These datasets were derived by the USGS using Landsat imagery and field validation for up to 37 different land use categories. These land use categories cover a wide range of land use types ranging from industrial to suburban to farmland and forested. The NLCD 2001 data acquired from the USGS was used directly and was not checked or modified for this investigation. Digital land use data incorporates myriad information along with each land use designation. Like the elevation data, this information is used by ArcSWAT during the final development of the SWAT model input files prior to model simulation.

The land use map for the Barr-Milton datashed indicates a significantly urbanized area in the southwest and wide expanses of grassland and agricultural areas in the northeast (Figure 4-4). Land use types within the Barr-Milton datashed are represented by several types but predominantly developed open space (9.8%), low to high intensity developed (34.3%), grassland and pasture (21.0%), and cultivated crops (28.9%) (Table 4-1).

The digital land use data were imported directly into the ArcSWAT modeling platform and manipulated using the ArcSWAT tools to provide information necessary to develop the SWAT model input files.

Figure 4-4. Land use map of the Barr-Milton datashed

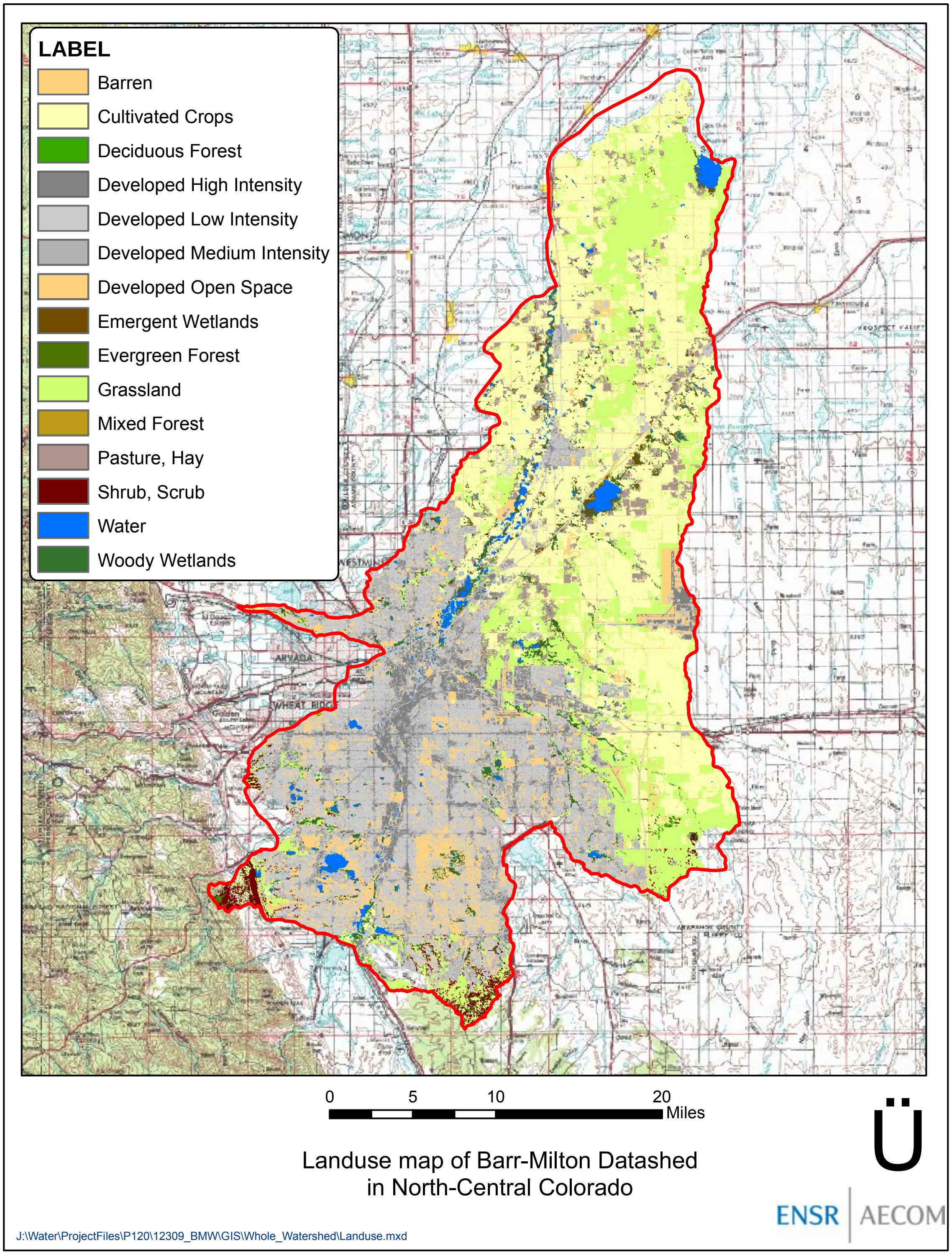


Table 4-1. Percentile breakdown of land use types within Barr-Milton datashed

NLCD ID#	Landuse Type	Area (%)
11	Water	1.7%
21	Developed Open Space	9.5%
22	Developed Low Intensity	20.3%
23	Developed Medium Intensity	9.8%
24	Developed High Intensity	4.2%
31	Barren	0.19%
41	Deciduous Forest	0.28%
42	Evergreen Forest	0.08%
43	Mixed Forest	0.01%
52	Shrub, Scrub	1.1%
71	Grassland	17.7%
81	Pasture, Hay	3.3%
82	Cultivated Crops	28.9%
90	Woody Wetlands	2.0%
95	Emergent Wetlands	0.94%
		100%

4.1.5.4 Digital soils data

Soils data were acquired from the USDA's STATSGO digital soils database. The database of soils information stores a multitude of physical and chemical soils properties into a geographically referenced dataset that can be easily incorporated into any of several existing watershed models. The SWAT watershed model used the STATSGO data directly to determine basic soil characteristics controlling hydrology and erosion throughout the watershed and to facilitate the determination of individual HRUs throughout the Barr-Milton datashed (Figure 4-5). The STATSGO soils data acquired from the USGS were used directly and was not further verified or modified for this investigation.

The soils data derived from the STATSGO database were used to provide additional hydrologic information to the SWAT model. Hydrologic Response Units (HRUs) were developed by superimposing the land use information with the soils information so that a set of unique land use/soils areas could be developed and used by SWAT to set up the model input files.

4.1.5.5 Flow and water quality data inputs

Locating and quantifying the water dischargers, uses and transfers throughout the Barr-Milton datashed led to the development of a detailed flow diagram of the watershed (Figure 4-6). The water budget for the Barr-Milton watershed is a direct result of the degree of water control and regulation throughout the watershed and the relative scarcity of available water during the drier parts of the average water year. The quantification of water use throughout the Barr-Milton datashed was developed for the 2003-2004 calibration period in two phases:

- *Develop a detailed flow diagram of the Barr-Milton datashed* – understanding of the movement of water throughout the basin was a crucial first step in the development of the SWAT watershed model (Figure 4-6). Knowing the locations of all major point sources, transfers, consumptive uses, and agricultural uses of water is necessary prior to setup of the SWAT model and partitioning of the larger watershed into several subwatersheds. The development of the flow diagram occurred early in the SWAT modeling process, was an iterative process, and incorporated input and feedback from representatives of water agencies. The flow diagram provided a map whereby the entire watershed model could be set up to best represent the watershed and to account for all the additions, transfers,

Figure 4-5. Soils map of the Barr-Milton datashed

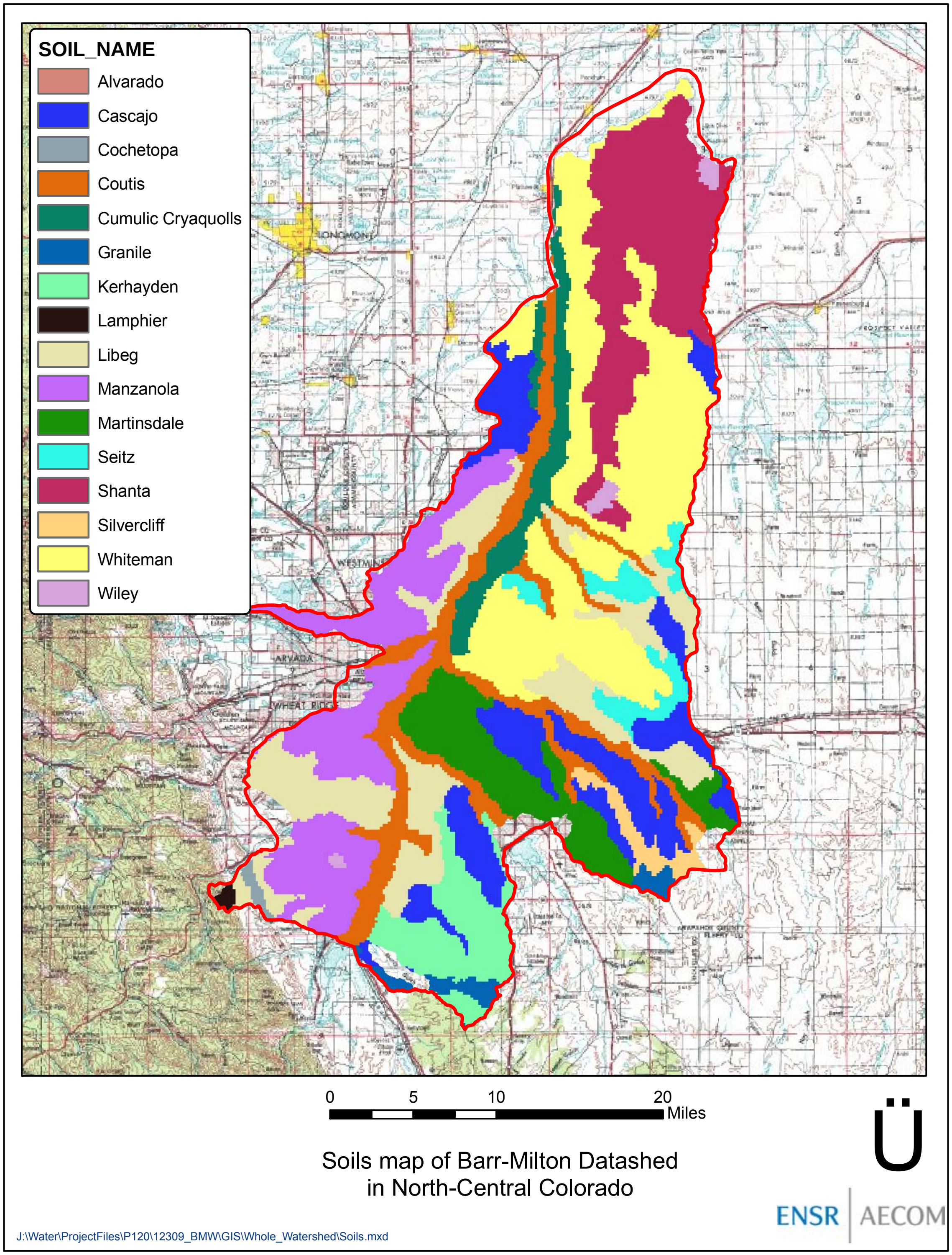
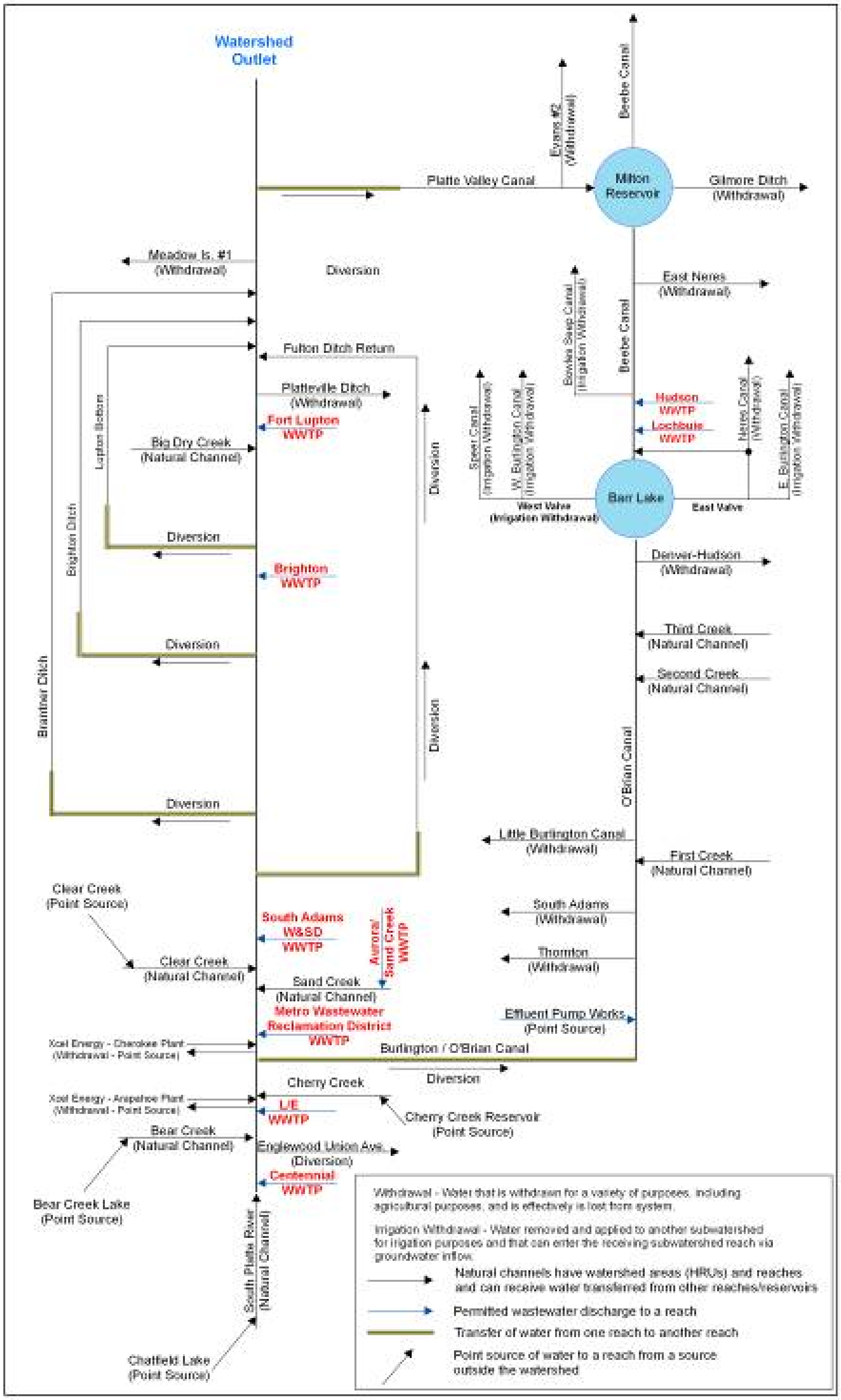


Figure 4-6. Flow diagram describing water movement around Barr-Milton datashed



Schematic Diagram of Water Flow and Transfer within Barr-Milton Watershed
For use in Setup of SWAT2005 Watershed Model

DRAFT

ENSR | AECOM

and withdrawals of water. The flow diagram amounted to a significant effort during the early stages of the investigation but proved to be crucial to set up of the watershed model.

- *Gather and summarize data sets to represent the flow diagram* – the flow diagram mapped the movement of water throughout the basin, but required actual flow data to define the magnitude of water use over the 2003-2004 calibration period. Data sets were derived from each of several sources including, but not limited to:
  - *Hydrosphere database* – includes a significant number data points throughout the Barr-Milton datashed and covering a period from the 1970s to the present. The database developed by Hydrosphere incorporated data from federal, state, and municipal agencies, plus other sources. While the spatial and temporal information included in the database was extensive, there were still significant data gaps at many of the specific locations identified as critical locations during the development of the flow diagram. While the intent of the Hydrosphere database was to consolidate all of the existing water quality data within the watershed, the database was found to be lacking data that are known to have been available at the time of database development; the record is incomplete.
  - *Municipal Wastewater Treatment Plants* – given that wastewater discharge loads were determined to be critically important to the flow and nutrient budget within the Barr-Milton datashed, WWTP flow data were sought out beyond the Hydrosphere database to support the SWAT model input data. Where WWTP discharger data were lacking in the Hydrosphere database, plants were contacted directly and data were requested to ensure that all available data were represented in the SWAT model.
  - *FRICO inflow/outflow database* – FRICO has maintained records of water movement into and out of the reservoirs for many years. While some values are estimates, and changes in approach over time complicate interpretation of some data, this database provides critical information on the use of water from the reservoirs and is the most reliable source of outflow data and water levels for the reservoirs. This database is critical to the calibration of the model in terms of matching actual and predicted water levels in the reservoirs.

The positioning of inlets, point sources, and outlets around the datashed prior to the determination of the subwatershed boundaries was a critical step in the model development process (Figures 4-6 and 4-7). Inlets represent the reservoirs and streams that discharge directly to the datashed and for which there are data to describe the inflow. Point sources represent wastewater discharges to the datashed by the many municipalities. Outlets locations are based on the need for required predicted information and to isolate areas of interest.

<u>Reservoir (and stream) inlets</u>

The SWAT model considers water entering a subwatershed at the upstream end from a source outside of the model domain as an inlet to the subwatershed. Since the Barr-Milton datashed is a sub-area of the entire watershed, the use of inlets in the SWAT model facilitated the representation of each of three reservoirs and two streams that are known to discharge water directly to the system from outside the datashed. By considering the source of water and nutrients as an inlet, the SWAT model determines the change in flow and water quality as the inlet water is transferred through the subwatershed to the outlet point. The reservoirs represented by the SWAT model as inlets include the Cherry Creek Reservoir, the Chatfield Reservoir, and Bear Creek Reservoir. The two streams represented by the SWAT model as inlets include Clear Creek and Big Dry Creek. Table 4-2 is a summary of the monthly inlet data used in the SWAT model of the Barr-Milton datashed.

Figure 4-7. Map of datashed showing inlets, point sources, and outlets

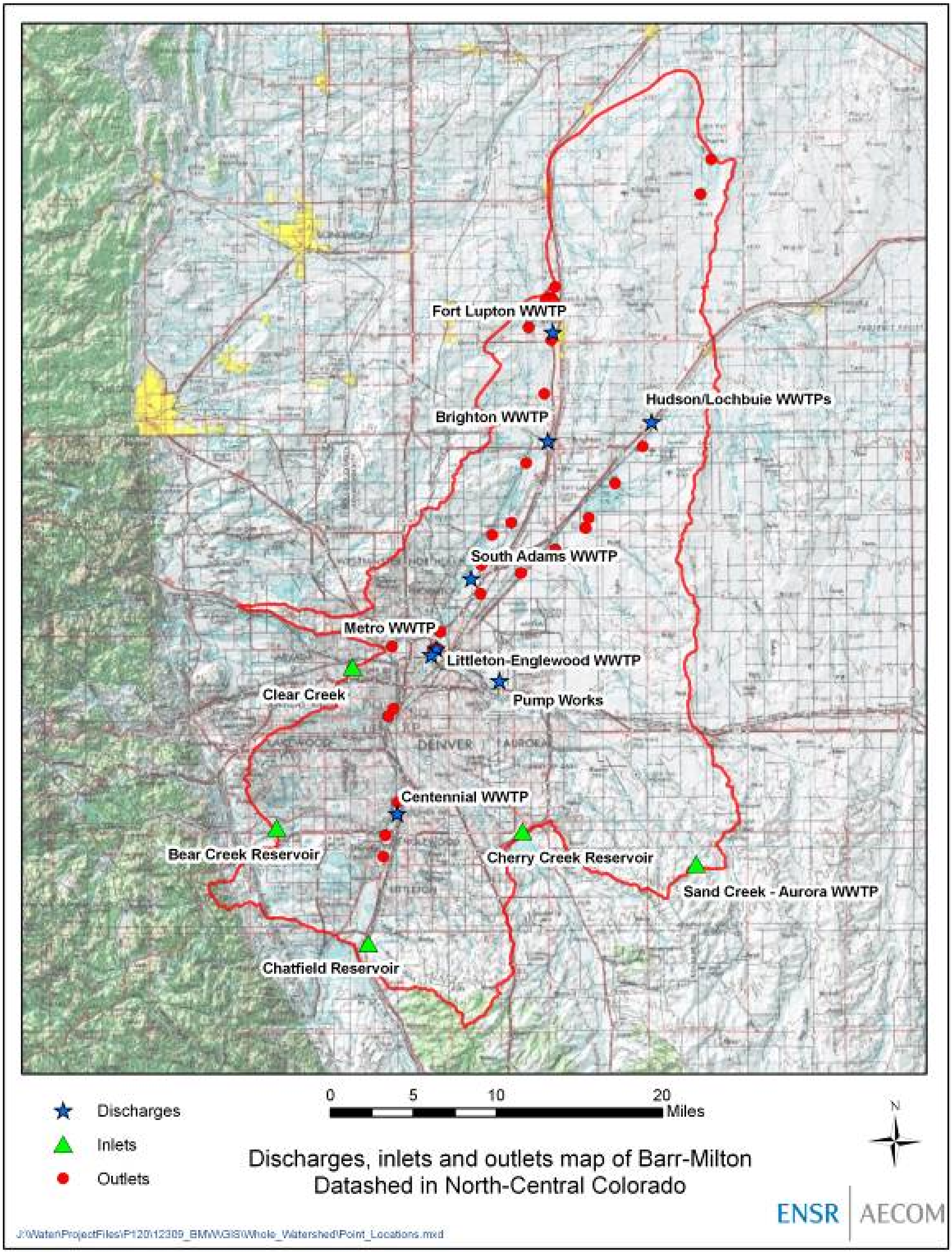


Table 4-2. List of inlet sources and monthly flows and loads

Inlets / Month	Bear Creek Reservoir (Subbasin #40) (m3/day and kg/day)					Cherry Creek Reservoir (Subbasin #38) (m3/day and kg/day)					Chatfield Reservoir (Subbasin #42) (m3/day and kg/day)					Big Dry Creek (Subbasin #8) (m3/day and kg/day)					Clear Creek (Subbasin #32) (m3/day and kg/day)				
	Flow (divided by 1,000	Organic Phosphorus	Ortho Phosphorus	Nitrate	Ammonia	Flow (divided by 1,000	Organic Phosphorus	Ortho Phosphorus	Nitrate	Ammonia	Flow (divided by 1,000	Organic Phosphorus	Ortho Phosphorus	Nitrate	Ammonia	Flow (divided by 1,000	Organic Phosphorus	Ortho Phosphorus	Nitrate	Ammonia	Flow (divided by 1,000	Organic Phosphorus	Ortho Phosphorus	Nitrate	Ammonia
Jan-03	11	1.3	0.6	2.4	0.4	0	0.0	0.0	0.0	0.0	10	0.9	0.1	0.2	0.5	49	13	65	485	147	3	0.1	0.1	0.5	1.8
Feb-03	10	1.1	0.9	2.1	0.3	0	0.0	0.0	0.0	0.0	5	0.4	0.0	0.1	0.5	51	1	86	668	226	27	1.3	14.9	9.7	21.3
Mar-03	44	7.6	6.0	10.2	1.3	53	9.1	1.2	1.5	2.1	111	19.0	0.6	3.3	5.5	163	101	257	881	946	158	4.7	55.3	61.0	142.2
Apr-03	372	33.5	2.1	632.0	14.9	149	13.4	3.7	2.4	1.5	570	51.3	2.3	36.5	16.0	159	52	139	748	126	116	18.0	34.3	30.1	52.4
May-03	268	21.1	1.3	151.6	4.8	137	10.8	2.8	0.7	9.6	509	39.9	2.0	65.6	44.8	138	51	66	592	81	469	53.9	110.2	105.9	140.6
Jun-03	153	11.8	1.7	40.3	13.0	64	4.9	8.2	2.1	0.5	402	30.9	1.6	14.5	41.0	86	28	44	284	81	1,841	73.6	147.3	553.1	920.5
Jul-03	38	6.1	2.8	5.5	1.0	27	4.3	3.1	0.6	0.7	247	39.7	4.4	8.3	42.3	121	8	72	449	115	446	20.1	29.0	63.5	133.8
Aug-03	46	4.5	1.5	0.2	0.8	14	1.4	0.3	0.1	0.3	186	18.2	0.8	0.9	3.5	60	30	20	313	57	58	5.2	9.6	10.3	15.9
Sep-03	54	7.0	2.0	0.9	0.3	40	5.2	0.6	0.8	1.9	236	30.6	2.7	4.7	1.3	91	84	6	525	118	30	0.6	3.9	6.7	8.3
Oct-03	32	4.2	1.9	3.3	3.9	3	0.3	0.0	0.1	0.2	8	1.1	0.0	0.2	0.1	79	15	72	500	238	20	1.5	2.0	7.5	5.5
Nov-03	21	1.5	1.1	0.4	0.3	0	0.0	0.0	0.0	0.0	5	0.5	0.0	2.9	0.1	119	35	191	1190	183	54	2.1	34.0	40.2	13.4
Dec-03	27	1.9	0.8	1.3	0.3	0	0.0	0.0	0.0	0.0	8	0.7	0.0	0.7	0.2	58	18	87	583	5	38	2.6	29.7	25.1	28.2
Jan-04	44	2.2	0.5	18.7	3.1	16	0.8	0.2	0.3	0.5	32	1.6	0.2	5.2	1.4	63	78	11	824	101	31	1.5	1.5	6.1	21.4
Feb-04	50	2.1	0.6	26.7	2.0	39	1.6	0.4	1.6	3.1	77	3.2	0.4	12.9	6.4	46	13	76	428	46	42	2.1	23.4	15.2	33.4
Mar-04	38	1.9	0.4	24.1	0.4	25	1.3	0.4	1.4	1.1	38	1.9	0.2	0.6	1.9	113	34	191	1013	23	49	1.5	17.3	19.1	44.5
Apr-04	129	7.6	0.9	43.4	1.3	69	4.1	1.2	3.8	0.7	238	14.1	1.2	34.8	21.5	202	35	129	930	115	110	17.0	32.3	28.3	49.3
May-04	168	13.1	0.9	52.4	4.8	47	3.6	1.5	2.6	0.4	242	18.9	1.2	34.6	32.9	120	12	34	383	8	53	6.1	12.6	12.1	16.0
Jun-04	104	9.8	1.0	21.4	5.2	10	0.9	0.1	0.7	0.3	205	19.5	1.1	15.6	20.1	105	50	76	682	24	564	22.5	45.1	169.3	281.8
Jul-04	219	16.0	0.8	51.1	8.0	27	1.9	1.0	0.4	1.5	602	43.9	3.6	94.2	53.2	139	33	65	639	26	256	11.5	16.6	36.4	76.7
Aug-04	171	31.9	2.0	18.1	2.7	168	31.3	17.9	17.5	10.6	368	68.7	2.2	17.9	23.6	113	27	68	563	30	138	12.4	22.8	24.5	38.0
Sep-04	75	7.3	6.4	11.7	3.5	13	1.2	0.6	0.6	1.9	79	7.7	0.4	1.7	3.9	144	51	94	895	27	69	1.4	9.0	15.2	18.9
Oct-04	148	8.4	0.6	16.4	1.1	57	3.3	1.5	0.5	2.8	56	3.2	0.4	0.7	1.3	78	20	34	373	9	103	7.7	10.3	38.2	28.2
Nov-04	80	3.2	0.7	13.0	1.0	64	2.6	1.2	0.4	0.8	84	3.4	0.6	0.4	1.2	78	15	54	640	9	89	3.6	56.7	67.0	22.3
Dec-04	97	3.5	0.6	15.7	5.7	52	1.9	0.8	0.3	0.7	23	0.8	0.2	0.4	0.2	71	8	76	657	6	76	5.3	60.3	51.0	57.3
Total	**2,398**	**209**	**38**	**1,163**	**80**	**1,073**	**104**	**47**	**38**	**41**	**4,340**	**420**	**26**	**357**	**323**	**2,447**	**813**	**2,013**	**15,245**	**2,747**	**4,838**	**277**	**778**	**1,396**	**2,172**
% of Inlets	**15.9%**	**11.4%**	**1.3%**	**6.4%**	**1.5%**	**7.1%**	**5.7%**	**1.6%**	**0.2%**	**0.8%**	**28.7%**	**23.1%**	**0.9%**	**2.0%**	**6.0%**	**16.2%**	**44.6%**	**69.4%**	**83.8%**	**51.2%**	**32.0%**	**15.2%**	**26.8%**	**7.7%**	**40.5%**
% of Total	**7.9%**	**11.4%**	**0.1%**	**0.9%**	**0.1%**	**3.5%**	**5.7%**	**0.1%**	**0.0%**	**0.0%**	**14.2%**	**23.1%**	**0.1%**	**0.3%**	**0.3%**	**8.0%**	**44.6%**	**4.7%**	**11.5%**	**2.3%**	**15.8%**	**15.2%**	**1.8%**	**1.1%**	**1.8%**

Table 4-3. List of point sources and monthly flows and loads

Point Sources / Month	Brighton WWTP (Subbasin #9) (m3/day and kg/day)				
	Flow (divided by 1,000)	Organic Phosphorus	Ortho Phosphorus	Nitrate	Ammonia
Jan-03	7.0	0	4.7	68	26
Feb-03	6.8	0	4.6	66	30
Mar-03	6.9	0	4.7	68	48
Apr-03	7.7	0	5.2	75	44
May-03	7.9	0	5.4	78	30
Jun-03	7.9	0	5.3	77	14
Jul-03	7.6	0	5.2	75	8
Aug-03	8.1	0	5.5	79	40
Sep-03	7.8	0	5.3	76	21
Oct-03	7.2	0	4.9	70	5
Nov-03	7.3	0	4.9	71	8
Dec-03	7.0	0	4.7	68	7
Jan-04	7.0	0	4.7	68	26
Feb-04	6.8	0	4.6	66	30
Mar-04	6.9	0	4.7	68	48
Apr-04	7.7	0	5.2	75	44
May-04	7.9	0	5.4	78	30
Jun-04	7.9	0	5.3	77	14
Jul-04	7.6	0	5.2	75	8
Aug-04	8.1	0	5.5	79	40
Sep-04	7.8	0	5.3	76	21
Oct-04	7.2	0	4.9	70	5
Nov-04	7.3	0	4.9	71	8
Dec-04	7.0	0	4.7	68	7
Total	**178**	**0**	**121**	**1,744**	**560**
% of Points Sources	**1.2%**	**0.0%**	**0.3%**	**1.5%**	**0.5%**
% of Total	**0.6%**	**0.0%**	**0.3%**	**1.3%**	**0.5%**

Point Sources / Month	Metro WWTP (Subbasin #30) (m3/day and kg/day)				
	Flow (divided by 1,000)	Organic Phosphorus	Ortho Phosphorus	Nitrate	Ammonia
Jan-03	390	0	1060	1770	3270
Feb-03	480	0	1310	1990	4000
Mar-03	510	0	1410	2150	3380
Apr-03	520	0	1420	2160	3710
May-03	550	0	1510	2300	4610
Jun-03	530	0	1450	2200	4420
Jul-03	520	0	1420	2170	4360
Aug-03	510	0	1390	2110	4250
Sep-03	500	0	1380	2090	4200
Oct-03	480	0	1330	2020	4050
Nov-03	300	0	820	1240	3050
Dec-03	280	0	770	1160	2690
Jan-04	290	0	800	1220	2980
Feb-04	410	0	1120	1700	4210
Mar-04	450	0	1250	1900	3820
Apr-04	470	0	1300	1980	3990
May-04	480	0	1330	2030	4070
Jun-04	490	0	1340	2040	4100
Jul-04	500	0	1380	2100	4220
Aug-04	510	0	1410	2150	4320
Sep-04	480	0	1330	2020	4050
Oct-04	490	0	1350	2060	4130
Nov-04	320	0	880	1340	2640
Dec-04	350	0	970	1480	3030
Total	**10,810**	**0**	**29,730**	**45,380**	**91,550**
% of Points Sources	**70.0%**	**0.0%**	**73.6%**	**39.7%**	**78.8%**
% of Total	**35.4%**	**0.0%**	**68.7%**	**34.2%**	**75.4%**

Point Sources / Month	South Adams WWTP (Subbasin #25) (m3/day and kg/day)				
	Flow (divided by 1,000)	Organic Phosphorus	Ortho Phosphorus	Nitrate	Ammonia
Jan-03	9.2	0	43	131	78
Feb-03	9.0	0	41	106	77
Mar-03	9.2	0	41	113	88
Apr-03	9.2	0	40	92	79
May-03	9.7	0	42	57	95
Jun-03	9.5	0	42	87	102
Jul-03	9.8	0	46	81	105
Aug-03	9.9	0	47	57	66
Sep-03	9.7	0	46	95	20
Oct-03	9.9	0	47	66	86
Nov-03	11.6	0	47	122	119
Dec-03	11.5	0	57	117	136
Jan-04	11.7	0	21	116	138
Feb-04	11.5	0	72	146	90
Mar-04	11.5	0	51	120	38
Apr-04	11.7	0	61	128	49
May-04	11.6	0	65	73	36
Jun-04	11.9	0	55	56	54
Jul-04	11.9	0	51	207	63
Aug-04	12.2	0	48	53	90
Sep-04	12.3	0	69	78	28
Oct-04	11.8	0	53	61	46
Nov-04	12.1	0	53	83	35
Dec-04	12.0	0	50	88	37
Total	**260**	**0**	**1,186**	**2,334**	**1,758**
% of Points Sources	**1.7%**	**0.0%**	**2.9%**	**2.0%**	**1.5%**
% of Total	**0.9%**	**0.0%**	**2.7%**	**1.8%**	**1.4%**

Point Sources / Month	Fort Lupton WWTP (Subbasin #8) (m3/day and kg/day)				
	Flow (divided by 1,000)	Organic Phosphorus	Ortho Phosphorus	Nitrate	Ammonia
Jan-03	7.8	0	5.3	77	3.7
Feb-03	7.8	0	5.3	77	3.7
Mar-03	7.8	0	5.3	77	3.7
Apr-03	7.8	0	5.3	77	3.7
May-03	7.8	0	5.3	77	3.7
Jun-03	7.8	0	5.3	77	3.7
Jul-03	7.8	0	5.3	77	3.7
Aug-03	7.8	0	5.3	77	3.7
Sep-03	7.8	0	5.3	77	3.7
Oct-03	7.8	0	5.3	77	3.7
Nov-03	7.8	0	5.3	77	3.7
Dec-03	7.8	0	5.3	77	3.7
Jan-04	7.8	0	5.3	77	3.7
Feb-04	7.8	0	5.3	77	3.7
Mar-04	7.8	0	5.3	77	3.7
Apr-04	7.8	0	5.3	77	3.7
May-04	7.8	0	5.3	77	3.7
Jun-04	7.8	0	5.3	77	3.7
Jul-04	7.8	0	5.3	77	3.7
Aug-04	7.8	0	5.3	77	3.7
Sep-04	7.8	0	5.3	77	3.7
Oct-04	7.8	0	5.3	77	3.7
Nov-04	7.8	0	5.3	77	3.7
Dec-04	7.8	0	5.3	77	3.7
Total	**187**	**0**	**127**	**1,837**	**89**
% of Points Sources	**1.2%**	**0.0%**	**0.3%**	**1.6%**	**0.1%**
% of Total	**0.6%**	**0.0%**	**0.3%**	**1.4%**	**0.1%**

Point Sources / Month	Littleton-Englewood WWTP (Subbasin #39) (m3/day and kg/day)				
	Flow (divided by 1,000)	Organic Phosphorus	Ortho Phosphorus	Nitrate	Ammonia
Jan-03	81	0	236	2360	350
Feb-03	83	0	242	2220	380
Mar-03	90	0	262	2390	300
Apr-03	93	0	270	2350	230
May-03	89	0	257	2430	250
Jun-03	84	0	243	2310	260
Jul-03	82	0	238	2360	220
Aug-03	82	0	238	2080	180
Sep-03	83	0	239	1720	200
Oct-03	81	0	235	2280	240
Nov-03	85	0	248	2170	290
Dec-03	84	0	244	2260	470
Jan-04	81	0	234	2320	350
Feb-04	81	0	234	2150	370
Mar-04	81	0	235	1990	270
Apr-04	87	0	251	2620	210
May-04	86	0	250	2400	240
Jun-04	86	0	250	2070	260
Jul-04	82	0	238	1830	220
Aug-04	86	0	250	1920	190
Sep-04	83	0	242	2030	200
Oct-04	89	0	258	1960	260
Nov-04	87	0	254	1890	300
Dec-04	85	0	246	2100	470
Total	**2,032**	**0**	**5,893**	**52,210**	**6,710**
% of Points Sources	**13.2%**	**0.0%**	**14.6%**	**45.7%**	**5.8%**
% of Total	**6.7%**	**0.0%**	**13.6%**	**39.4%**	**5.5%**

Point Sources / Month	Lochbuie WWTP (Subbasin #3) (m3/day and kg/day)				
	Flow (divided by 1,000)	Organic Phosphorus	Ortho Phosphorus	Nitrate	Ammonia
Jan-03	2.8	0	1.9	16	3.8
Feb-03	2.8	0	1.9	16	3.8
Mar-03	2.8	0	1.9	16	3.8
Apr-03	2.8	0	1.9	16	3.8
May-03	2.8	0	1.9	16	3.8
Jun-03	2.8	0	1.9	16	3.8
Jul-03	2.8	0	1.9	16	3.8
Aug-03	2.8	0	1.9	16	3.8
Sep-03	2.8	0	1.9	16	3.8
Oct-03	2.8	0	1.9	16	3.8
Nov-03	2.8	0	1.9	16	3.8
Dec-03	2.8	0	1.9	16	3.8
Jan-04	2.8	0	1.9	16	3.8
Feb-04	2.8	0	1.9	16	3.8
Mar-04	2.8	0	1.9	16	3.8
Apr-04	2.8	0	1.9	16	3.8
May-04	2.8	0	1.9	16	3.8
Jun-04	2.8	0	1.9	16	3.8
Jul-04	2.8	0	1.9	16	3.8
Aug-04	2.8	0	1.9	16	3.8
Sep-04	2.8	0	1.9	16	3.8
Oct-04	2.8	0	1.9	16	3.8
Nov-04	2.8	0	1.9	16	3.8
Dec-04	2.8	0	1.9	16	3.8
Total	**68**	**0**	**46**	**393**	**92**
% of Points Sources	**0.4%**	**0.0%**	**0.1%**	**0.3%**	**0.1%**
% of Total	**0.2%**	**0.0%**	**0.1%**	**0.3%**	**0.1%**

Point Sources / Month	Hudson WWTP (Subbasin #3) (m3/day and kg/day)				
	Flow (divided by 1,000)	Organic Phosphorus	Ortho Phosphorus	Nitrate	Ammonia
Jan-03	3.8	0	2.6	37	2.0
Feb-03	3.8	0	2.6	37	2.0
Mar-03	3.8	0	2.6	37	2.0
Apr-03	3.8	0	2.6	37	2.0
May-03	3.8	0	2.6	37	2.0
Jun-03	3.8	0	2.6	37	2.0
Jul-03	3.8	0	2.6	37	2.0
Aug-03	3.8	0	2.6	37	2.0
Sep-03	3.8	0	2.6	37	2.0
Oct-03	3.8	0	2.6	37	2.0
Nov-03	3.8	0	2.6	37	2.0
Dec-03	3.8	0	2.6	37	2.0
Jan-04	3.8	0	2.6	37	2.0
Feb-04	3.8	0	2.6	37	2.0
Mar-04	3.8	0	2.6	37	2.0
Apr-04	3.8	0	2.6	37	2.0
May-04	3.8	0	2.6	37	2.0
Jun-04	3.8	0	2.6	37	2.0
Jul-04	3.8	0	2.6	37	2.0
Aug-04	3.8	0	2.6	37	2.0
Sep-04	3.8	0	2.6	37	2.0
Oct-04	3.8	0	2.6	37	2.0
Nov-04	3.8	0	2.6	37	2.0
Dec-04	3.8	0	2.6	37	2.0
Total	**91**	**0**	**62**	**891**	**47**
% of Points Sources	**0.6%**	**0.0%**	**0.2%**	**0.8%**	**0.0%**
% of Total	**0.3%**	**0.0%**	**0.1%**	**0.7%**	**0.0%**

Point Sources / Month	Pump Works (FRICO) (Subbasin #34) (m3/day and kg/day)				
	Flow (divided by 1,000)	Organic Phosphorus	Ortho Phosphorus	Nitrate	Ammonia
Jan-03	89	0	250	180	1220
Feb-03	0	0	0	0	0
Mar-03	16	0	40	30	170
Apr-03	32	0	90	60	360
May-03	0	0	0	0	0
Jun-03	0	0	0	0	0
Jul-03	0	0	0	0	0
Aug-03	0	0	0	0	0
Sep-03	0	0	0	0	0
Oct-03	0	0	0	0	0
Nov-03	187	0	510	340	2900
Dec-03	199	0	550	360	3000
Jan-04	177	0	490	320	2700
Feb-04	60	0	170	110	920
Mar-04	0	0	0	0	0
Apr-04	0	0	0	0	0
May-04	0	0	0	0	0
Jun-04	0	0	0	0	0
Jul-04	0	0	0	0	0
Aug-04	0	0	0	0	0
Sep-04	0	0	0	0	0
Oct-04	0	0	0	0	0
Nov-04	158	0	440	290	2220
Dec-04	109	0	300	200	1440
Total	**1,028**	**0**	**2,840**	**1,890**	**14,930**
% of Points Sources	**6.7%**	**0.0%**	**7.0%**	**1.7%**	**12.9%**
% of Total	**3.4%**	**0.0%**	**6.6%**	**1.4%**	**12.3%**

Point Sources / Month	Aurora WWTP (Subbasin #35) (m3/day and kg/day)				
	Flow (divided by 1,000)	Organic Phosphorus	Ortho Phosphorus	Nitrate	Ammonia
Jan-03	15	0	2.3	101.6	2.3
Feb-03	16	0	2.1	105.0	2.2
Mar-03	16	0	2.6	98.7	4.4
Apr-03	16	0	2.4	117.7	5.0
May-03	14	0	1.4	102.6	1.4
Jun-03	11	0	3.1	81.7	1.1
Jul-03	5	0	1.8	41.5	1.2
Aug-03	7	0	0.9	66.9	0.7
Sep-03	11	0	0.9	94.3	1.1
Oct-03	11	0	4.0	99.1	1.1
Nov-03	11	0	7.5	109.3	1.2
Dec-03	11	0	1.6	126.6	1.1
Jan-04	17	0	2.4	134.7	2.6
Feb-04	17	0	2.7	117.8	8.5
Mar-04	12	0	1.4	99.5	1.2
Apr-04	13	0	1.6	102.7	1.3
May-04	10	0	1.1	72.4	1.0
Jun-04	9	0	1.6	69.2	7.1
Jul-04	9	0	1.0	77.6	0.9
Aug-04	10	0	1.3	76.1	1.0
Sep-04	10	0	2.0	94.3	1.0
Oct-04	16	0	1.9	146.8	1.7
Nov-04	17	0	2.0	166.8	1.7
Dec-04	18	0	2.3	159.8	1.8
Total	**302**	**0**	**52**	**2,463**	**53**
% of Points Sources	**2.0%**	**0.0%**	**0.1%**	**2.2%**	**0.0%**
% of Total	**1.0%**	**0.0%**	**0.1%**	**1.9%**	**0.0%**

Point Sources / Month	Centennial WWTP (Subbasin #42) (m3/day and kg/day)				
	Flow (divided by 1,000)	Organic Phosphorus	Ortho Phosphorus	Nitrate	Ammonia
Jan-03	19	0.0	21.3	220.6	11.8
Feb-03	20	0.0	8.7	220.0	26.4
Mar-03	22	0.0	14.4	246.0	11.4
Apr-03	23	0.0	8.1	166.5	2.5
May-03	22	0.0	18.5	180.6	5.3
Jun-03	22	0.0	4.2	183.9	2.9
Jul-03	18	0.0	7.4	101.1	28.2
Aug-03	18	0.0	18.7	205.0	5.8
Sep-03	19	0.0	11.8	133.7	2.9
Oct-03	19	0.0	14.0	213.0	5.6
Nov-03	19	0.0	10.3	275.4	24.5
Dec-03	19	0.0	17.8	189.2	65.9
Jan-04	18	0.0	24.4	208.5	36.3
Feb-04	19	0.0	27.6	257.0	22.6
Mar-04	19	0.0	9.3	209.5	8.8
Apr-04	20	0.0	11.6	198.4	2.2
May-04	20	0.0	9.4	205.6	6.4
Jun-04	20	0.0	7.9	210.7	2.1
Jul-04	20	0.0	9.0	224.5	2.1
Aug-04	19	0.0	14.9	196.8	2.3
Sep-04	19	0.0	15.6	249.9	2.9
Oct-04	22	0.0	15.1	302.9	3.9
Nov-04	22	0.0	17.0	317.8	37.9
Dec-04	22	0.0	13.2	262.0	25.0
Total	**483**	**0**	**330**	**5,178**	**346**
% of Points Sources	**3.1%**	**0.0%**	**0.8%**	**4.5%**	**0.3%**
% of Total	**1.6%**	**0.0%**	**0.8%**	**3.9%**	**0.3%**

Point sources

The SWAT model considers water entering a subwatershed at a point within the subwatershed as a point source. This representation of a point source within the SWAT model is different than the inlet representation in that a point source is not routed through the watershed reach but is added to the discharge at the outlet of the watershed. Point sources are generally used to represent WWTP discharges or industrial dischargers within a watershed. The use of point discharges within the Barr-Milton watershed model were used to represent the multitude of wastewater plants discharging to the South Platte River and tributaries to the South Platte and discharging to the Burlington-O'Brian canal and the Beebe Canal. Table 4-3 is a summary of the monthly point source data used in the SWAT model of the Barr-Milton datashed. Despite being defined in a regulatory sense as point sources, permitted municipal separate storm sewer systems (MS4) are not treated as point sources in this part of the model, which covers only wastewater discharges. One can separate subwatersheds into traditional nonpoint source contributors and MS4 dominated systems to quantify point and nonpoint inputs of runoff, as is done later in this modeling effort.

Watershed outlets

Outlets in the SWAT model simply represent locations at the downstream extents of subwatersheds within the larger datashed. These outlets are defined in ArcSWAT prior to the calculation and determination of the subwatershed boundaries and are a means to set the extent of the subwatersheds by the user. Outlets were situated to coincide with several key features and to isolate many of the point sources within the datashed. Also, outlets were used to isolate both Barr Lake and Milton Reservoir so that predictions could be available at a location just prior to entering each of the reservoirs.

4.1.6 Watershed delineation and model setup

The first major step in setting up the SWAT input files is location of the outlet and inlet points for which data are available, along with the elevation data from the USGS DEM, and creation of subwatershed boundaries within the datashed (Figure 4-8). This important step in the modeling process was based on the information used in creating the flow diagram and the subsequent positioning of the watershed outlet points. Once the subwatersheds are developed they become the framework for the entire model setup. The SWAT model is a lumped parameter model that uses weighted average values for all the parameters within each subwatershed to describe runoff, groundwater seepage, and the fate and transport of nutrients entering and leaving each subwatershed.

The SWAT model applies standard hydrologic GIS tools to the digital elevation model for the datashed and using predefined stream reach information calculates several raster files that indicate the flow direction and flow accumulation for the larger watershed. Each of several major streams and canals was used to force elevations along the channel axis to slope appropriately to ensure the correct transport of water and subwatershed determination, particularly in areas with relatively shallow topography. The GIS tools used in SWAT make it easy to develop the subwatersheds and once they are developed, the land use and soils data is applied directly to the subwatershed areas to infer a multitude of SWAT model input parameters (Table 4-4). These parameters, along with the stream reach parameters, are used to control the calculation of all hydrologic processes within each subwatershed and are crucial to developing a reliable watershed model.

4.1.7 Transfers of water and consumptive uses

The final critical step in setting up the SWAT watershed model, following the delineation of subwatersheds and application of point source and inlet data, was to identify and apply all consumptive use and transfer information. This information was acquired from multiple sources and is used to complete the hydrologic budget for the Barr-Milton datashed.

Figure 4-8. Map of datashed showing numbered subwatersheds

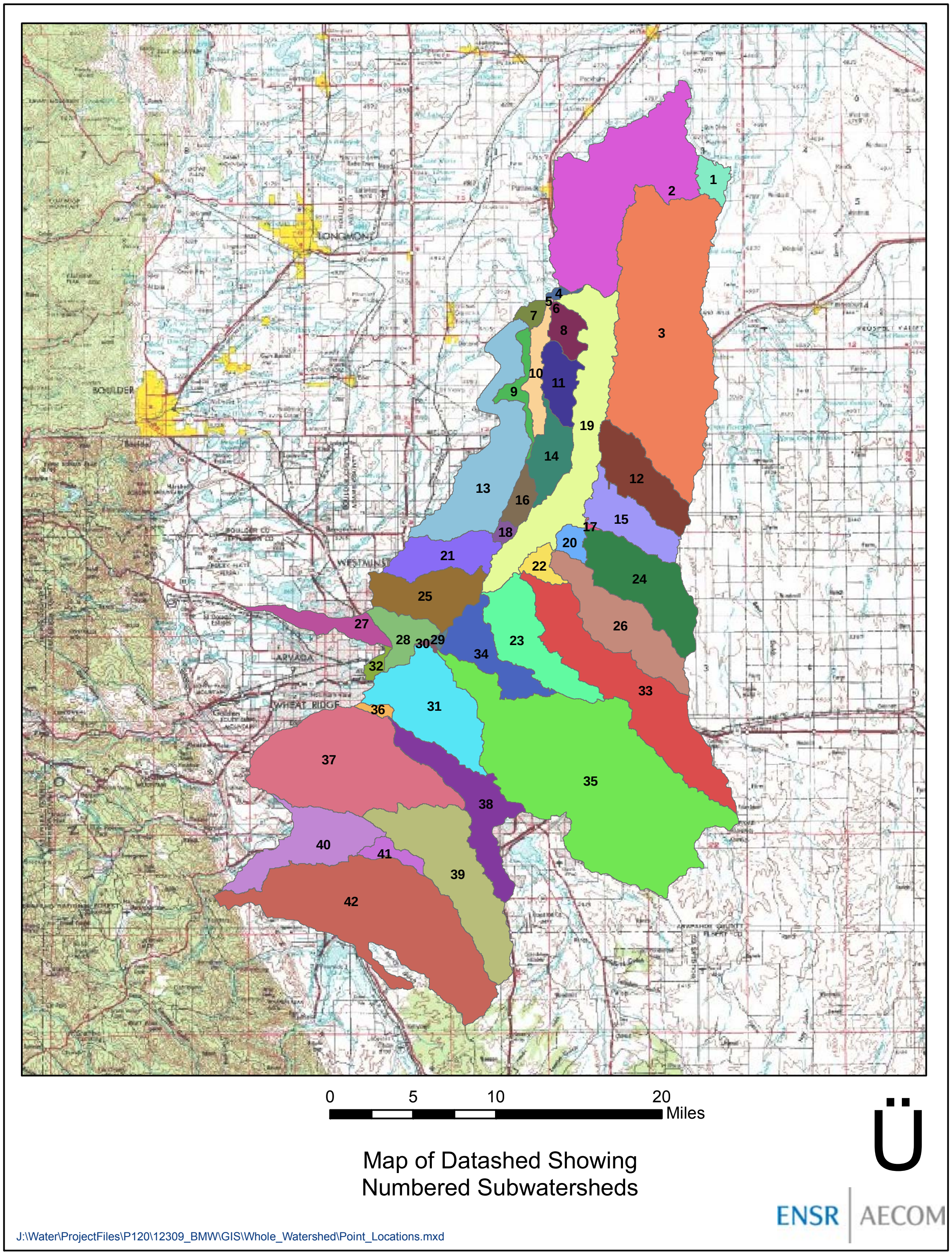


Table 4-4. Subwatershed relevant information

Subbasin	Area (km2)	Slope (%)	Length (m)	Elev (m)
1	1,061	1.03	5,838	1,464
2	15,270	2.20	54,500	1,512
3	23,649	1.80	35,201	1,516
4	212	0.81	3,687	1,487
5	15	0.97	632	1,482
6	11	0.31	609	1,485
7	537	1.60	5,696	1,502
8	1,346	1.16	7,632	1,497
9	1,178	2.00	15,855	1,511
10	1,652	0.65	16,651	1,503
11	2,124	0.92	11,844	1,507
12	4,475	1.76	12,407	1,560
13	8,955	3.15	45,270	1,613
14	2,514	0.70	14,117	1,516
15	3,600	1.68	11,973	1,582
16	1,094	0.96	8,370	1,522
17	64	0.84	2,642	1,558
18	367	0.83	3,347	1,528
19	10,255	1.77	45,653	1,546
20	791	1.67	6,228	1,564
21	3,429	2.81	16,985	1,571
22	901	1.60	9,413	1,565
23	5,450	1.64	24,332	1,612
24	6,469	2.40	19,109	1,599
25	4,409	3.71	17,812	1,594
26	6,193	2.85	23,519	1,624
27	2,085	3.78	16,885	1,689
28	2,037	2.92	9,577	1,571
29	159	2.09	2,113	1,556
30	93	1.24	2,789	1,571
31	7,360	1.75	18,197	1,584
32	390	3.59	5,146	1,603
33	11,339	1.84	37,965	1,687
34	3,684	1.32	20,367	1,604
35	29,029	3.01	43,293	1,708
36	319	3.44	4,748	1,626
37	13,943	3.53	22,136	1,627
38	5,404	2.91	25,593	1,632
39	9,180	4.36	27,975	1,660
40	5,469	5.88	22,040	1,682
41	886	2.79	7,373	1,623
42	18,388	5.90	26,081	1,647

Table 4-5. List of consumptive uses and monthly flows

Month	Denver-Hudson (1000s m3/day)	East Neres (1000s m3/day)	Englewood-Union Ave (1000s m3/day)	Evans #2 (1000s m3/day)	Little Burlington (1000s m3/day)	Meadow Island #1 (1000s m3/day)	Neres (1000s m3/day)	Platteville Ditch (1000s m3/day)	SACWSDS (1000s m3/day)	Thornton (1000s m3/day)	Xcel Arapahoe (1000s m3/day)	Xcel Cherokee (1000s m3/day)
Jan-03	0.00	No Data	21	No Data	0.00	0.00	0.00	0.00	0.02	36	No Data	No Data
Feb-03	0.00	No Data	20	No Data	0.00	0.00	0.00	0.00	0.02	54	No Data	No Data
Mar-03	82	No Data	20	No Data	0.00	0.00	0.00	0.00	0.03	8	No Data	No Data
Apr-03	230	No Data	16	No Data	46	18	6.1	69	0.18	28	No Data	No Data
May-03	317	No Data	19	No Data	89	24	28	118	0.29	20	No Data	No Data
Jun-03	301	No Data	25	No Data	105	32	80	278	0.47	28	No Data	No Data
Jul-03	0.14	No Data	43	No Data	49	52	102	215	0.00	26	No Data	No Data
Aug-03	0.00	No Data	39	No Data	60	41	115	142	0.00	27	No Data	No Data
Sep-03	191	No Data	24	No Data	51	17	47	133	0.00	84	No Data	No Data
Oct-03	6.2	No Data	11	No Data	22	21	0.00	102	18	0.00	No Data	No Data
Nov-03	0.00	No Data	12	No Data	0.00	0.00	0.00	8.3	0.00	0.00	No Data	No Data
Dec-03	95	No Data	12	No Data	0.00	0.00	0.00	0.00	0.00	0.00	No Data	No Data
Jan-04	271	No Data	16	No Data	0.00	0.00	0.00	0.00	0.00	0.00	No Data	No Data
Feb-04	53	No Data	19	No Data	0.00	0.00	0.00	0.00	0.00	0.00	No Data	No Data
Mar-04	0.00	No Data	21	No Data	0.00	0.00	0.00	33	0.00	0.00	No Data	No Data
Apr-04	82	No Data	14	No Data	64	28	0.00	159	25	104	No Data	No Data
May-04	94	No Data	21	No Data	71	35	21	146	7.2	26	No Data	No Data
Jun-04	77	No Data	28	No Data	63	57	69	170	0.00	39	No Data	No Data
Jul-04	27	No Data	29	No Data	65	59	65	160	0.00	57	No Data	No Data
Aug-04	40	No Data	26	No Data	71	70	112	144	0.00	0.00	No Data	No Data
Sep-04	2.3	No Data	25	No Data	68	59	25	140	0.00	79	No Data	No Data
Oct-04	0.00	No Data	13	No Data	18	17	32	116	6.3	16	No Data	No Data
Nov-04	0.00	No Data	19	No Data	0.00	0.00	0.00	0.00	8.2	0.00	No Data	No Data
Dec-04	257	No Data	16	No Data	0.00	0.00	0.00	0.00	0.00	0.00	No Data	No Data
Total	**2,126**	**0**	**508**	**0**	**840**	**529**	**702**	**2,134**	**66**	**632**	**0**	**0**
% of Total	**28%**	**0.0%**	**6.7%**	**0.0%**	**11%**	**7.0%**	**9.3%**	**28%**	**0.88%**	**8.4%**	**0.0%**	**0.0%**

Table 4-6. List of transfers and monthly flows

Month	SPR → B-O Canal (1000s m3/day)	SPR → Fulton Ditch (1000s m3/day)	SPR → Brantner Ditch (1000s m3/day)	SPR → Brighton Ditch (1000s m3/day)	SPR → Lupton Bottom Ditch (1000s m3/day)	SPR → Platte Valley Canal (1000s m3/day)
Jan-03	197	0	0	0	0	0
Feb-03	60	0	0	0	0	0
Mar-03	484	35	0	0	14	152
Apr-03	1,191	104	73	50	34	371
May-03	879	105	57	32	59	513
Jun-03	756	179	149	67	135	319
Jul-03	82	262	156	75	170	317
Aug-03	102	191	84	57	130	160
Sep-03	539	107	127	46	122	116
Oct-03	223	95	171	32	103	95
Nov-03	375	0	30	6	0	30
Dec-03	395	0	0	0	0	0
Jan-04	398	0	0	0	0	152
Feb-04	154	0	0	0	0	206
Mar-04	1	96	42	26	16	315
Apr-04	390	108	119	78	70	186
May-04	353	162	145	74	143	204
Jun-04	341	175	118	52	157	323
Jul-04	320	206	147	80	173	348
Aug-04	423	189	128	81	157	323
Sep-04	235	134	131	47	134	149
Oct-04	384	53	83	28	61	305
Nov-04	589	0	11	4	0	31
Dec-04	434	0	0	0	0	106
Total	**9,305**	**2,200**	**1,769**	**835**	**1,679**	**4,721**
% of Total	**45%**	**11%**	**9%**	**4%**	**8%**	**23%**

Consumptive uses

Consumptive uses of water are presented in the SWAT model as temporally varying volumetric withdrawals of water from the outlet of a subwatershed. Water and associated water quality constituents removed as a consumptive use in the SWAT model are lost from the system. The consumptive use option in SWAT is generally used to represent water withdrawn from the system to support both municipal and industrial uses and water that is transferred out of the entire model domain, regardless of the ultimate use of the water than is withdrawn. Table 4-5 is a summary of the monthly consumptive use data used in the SWAT model.

Transfers

Transfers of water from one subwatershed to another within the SWAT model of the Barr-Milton watershed is a key component of the hydrologic budget in this highly managed system. The version of the SWAT model available for use at the start of this modeling investigation was deficient in its ability to adequately capture the temporal and spatial variability that exists within the system with regard to transfers. Transfer limitations made the use of the transfer command in the SWAT model a non-viable option for reasonably representing the temporally and spatially varying transfers occurring in the watershed. This problem was unexpected by the modeling team, but was resolved by code modification to SWAT to improve its performance in this regard.

This limitation required that several significant modifications be made to the arcSWAT model computer code in order to effectively simulate the managed movement of water around the Barr-Milton watershed. AECOM worked with the developers of SWAT to enhance the model. Modifications included:

1. *Incorporating associated constituent transfer with water transfer* – the inability of the original version of the SWAT model to transfer constituent with water was the first problem that was remedied. The SWAT model code was modified to correct this problem.
2. *Temporal variability associated with transfer command* – the inability of the original version of the SWAT model to facilitate the representation of a temporally varying water transfer was a critical limitation. The SWAT model code was modified to allow for transfers of water from one subwatershed to another that can vary temporally to provide a much more realistic representation of water management in the watershed.

Modification of the SWAT model code was conducted by Stone Environmental in Montpelier, Vermont. Stone Environmental has historically been instrumental in the development of ArcSWAT. Model testing was conducted by both Stone Environmental and AECOM throughout the modification process. Testing was largely completed by developing both simple and complex simulations and reviewing the results and predicted mass balances to ensure that the results were sensible and numerically accurate. Table 4-6 is a summary of the monthly transfer data used in the SWAT model of the Barr-Milton datashed.

Agricultural uses

The simulation of agricultural uses of water by the SWAT model is well developed. Agricultural uses of water tend to dominate the water budget in the Barr-Milton datashed during the summer months when crops of largely alfalfa and corn are irrigated. The SWAT model simulates the withdrawal of water from a water source, such as a stream channel or reservoir and the application of the water to a specific HRU. The SWAT model has the ability to remove water based on plant water demand as indicated by the leaf-area index (LAI) or at a rate that is indicated at the start of the simulation.

The agricultural use of surface water around the Bar-Milton datashed depends on the effective transfer of water through each of several irrigation canals (Figure 4-9). Water taken from the various canals is then used to irrigate agricultural lands in adjacent areas. Table 4-7 lists the types of agriculture irrigated within each of the subwatersheds receiving surface water irrigation.

Figure 4-9. Map of irrigation canals and associated areas receiving irrigation water

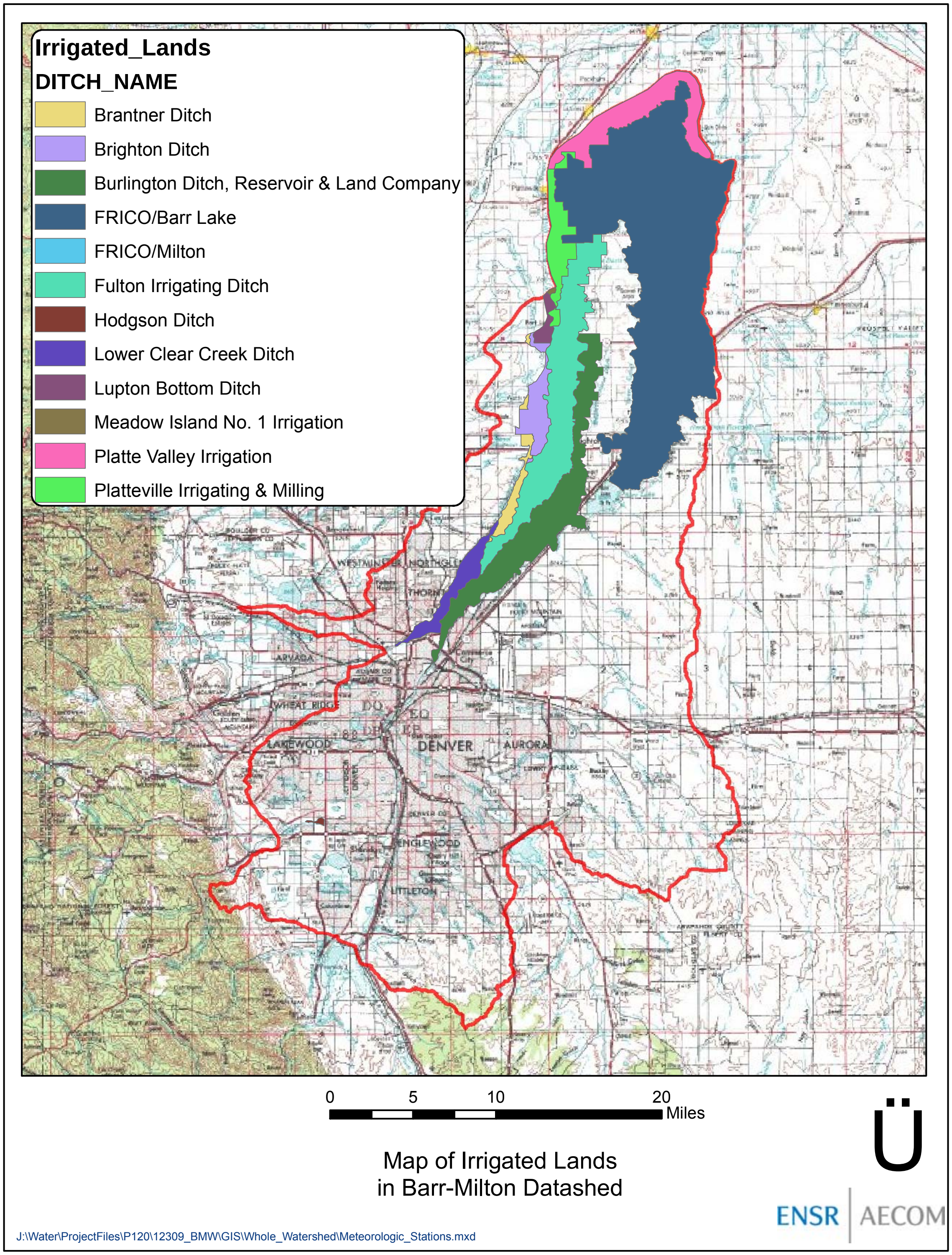


Table 4-7. Table of irrigated areas and crops types

Subbasin	Soil	Landuse	Irrigation Water Source	Area	Crop	Seeding	Harvest	Fertilizer
2	164	AGGR	Platte Valley Canal	10,409	Corn	5/01	9/30	Manure
	173	AGGR	Platte Valley Canal	11,871	Alfalfa	4/01	9/30	Elemental P
3	164	AGGR	Barr Lake	18,585	Corn	5/01	9/30	Manure
	173	AGGR	Barr Lake	17,504	Alfalfa	4/01	9/30	Elemental P
9	164	AGGR	Brighton Ditch	660	Corn	5/01	9/30	Manure
	169	AGGR	Brighton Ditch	1,892	Alfalfa	4/01	9/30	Elemental P
10	162	AGGR	Lupton Bottom Ditch	1,359	Corn	5/01	9/30	Manure
	169	AGGR	Lupton Bottom Ditch	553	Alfalfa	4/01	9/30	Elemental P
	180	AGGR	Lupton Bottom Ditch	1,086	Alfalfa	4/01	9/30	Elemental P
13	164	AGGR	Brantner Ditch	1,995	Corn	5/01	9/30	Manure
	168	AGGR	Brantner Ditch	4,221	Corn	5/01	9/30	Manure
	169	AGGR	Brantner Ditch	9,151	Alfalfa	4/01	9/30	Elemental P
	190	AGGR	Brantner Ditch	2,754	corn	5/01	9/30	Manure
19	162	AGGR	Fulton Ditch	2,879	Corn	5/01	9/30	Manure
	164	AGGR	Fulton Ditch	11,644	Alfalfa	4/01	9/30	Elemental P
	173	AGGR	Fulton Ditch	5,421	Corn	5/01	9/30	Manure

4.1.7.1 Meteorological data

Weather related data coincident with the simulation period are necessary to reliably address interrelated processes considered by the SWAT watershed model. Precipitation data drive the hydrologic simulation and largely control the extent of nonpoint source runoff and nutrient loading from the subwatersheds within the model domain. Similarly, extraneous information including solar radiation, wind speed, average temperature, and relative humidity are all used by SWAT to simulate processes included in both a heat budget and in the predicted life cycles of both terrestrial and aquatic plants.

Meteorologic data were available from a weather station located at the Denver International Airport (DIA). Daily total precipitation, daily average wind speed, daily average temperature, and daily average relative humidity were all available for this site for the duration of the simulation period. In addition to the precipitation data at DIA, daily data were also available from a site at Castle Rock, located immediately south of the watershed, from the former Denver Stapleton Airport, located on the northeast side of Denver, and from the University of Northern Colorado (UNC), located immediately north of the watershed in Greeley, CO. Finally, daily solar radiation data were available from a site in Fort Lupton, located in the north-central portion of the watershed. Figure 4-10 is a map of the meteorological stations where data were acquired for this investigation; Figure 4-11 illustrates the monthly precipitation acquired from each of the four indicated stations; Figure 4-12 illustrates the average monthly maximum and minimum temperatures measured at the DIA; Figure 4-13 illustrates the average monthly wind speed measured at the DIA; Figure 4-14 illustrates the average monthly relative humidity measured at the DIA; and Figure 4-15 illustrates the average monthly solar radiation measured at the DIA.

Figure 4-10. Meteorologic station map of watershed

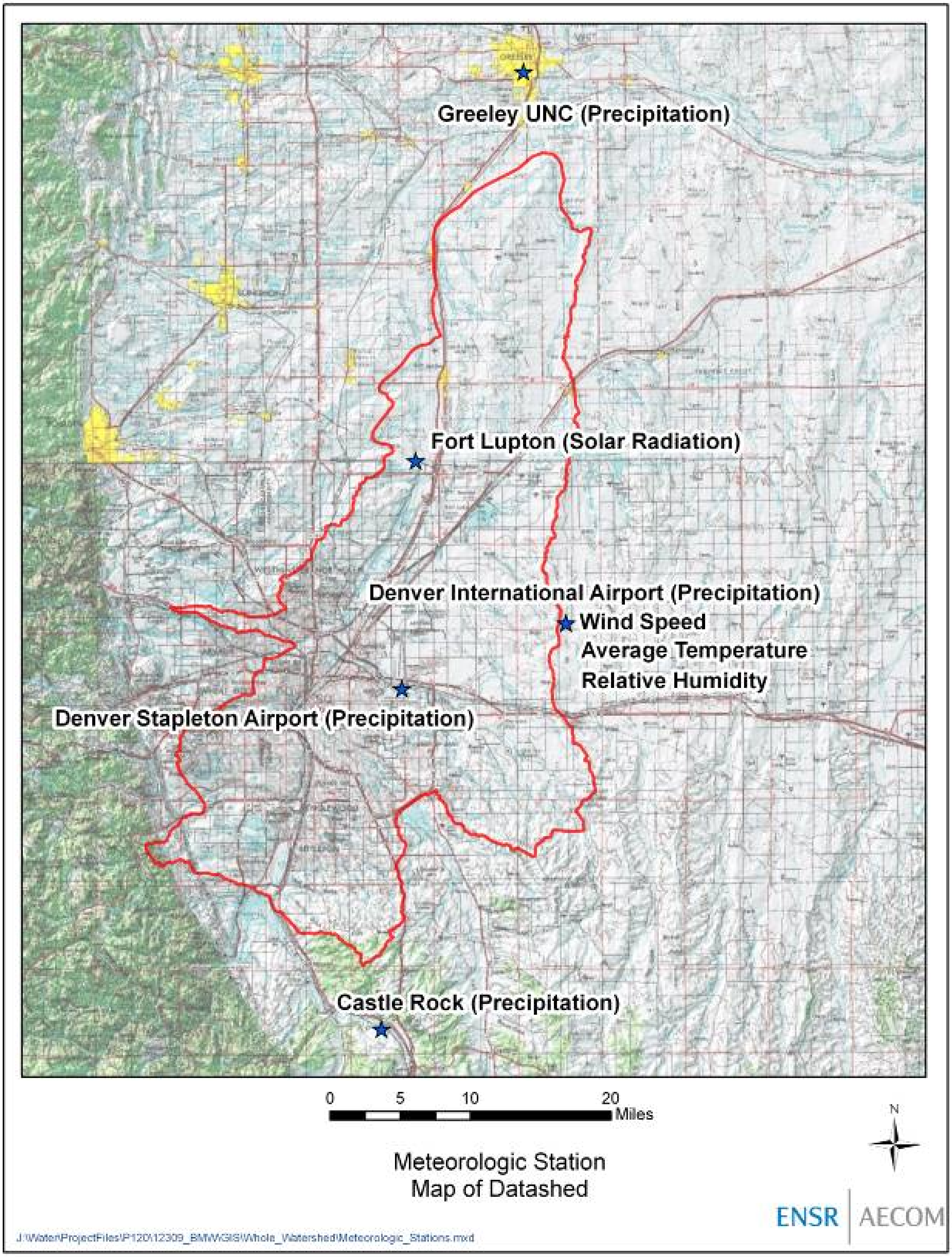


Figure 4-11. Monthly precipitation recorded at modeled station

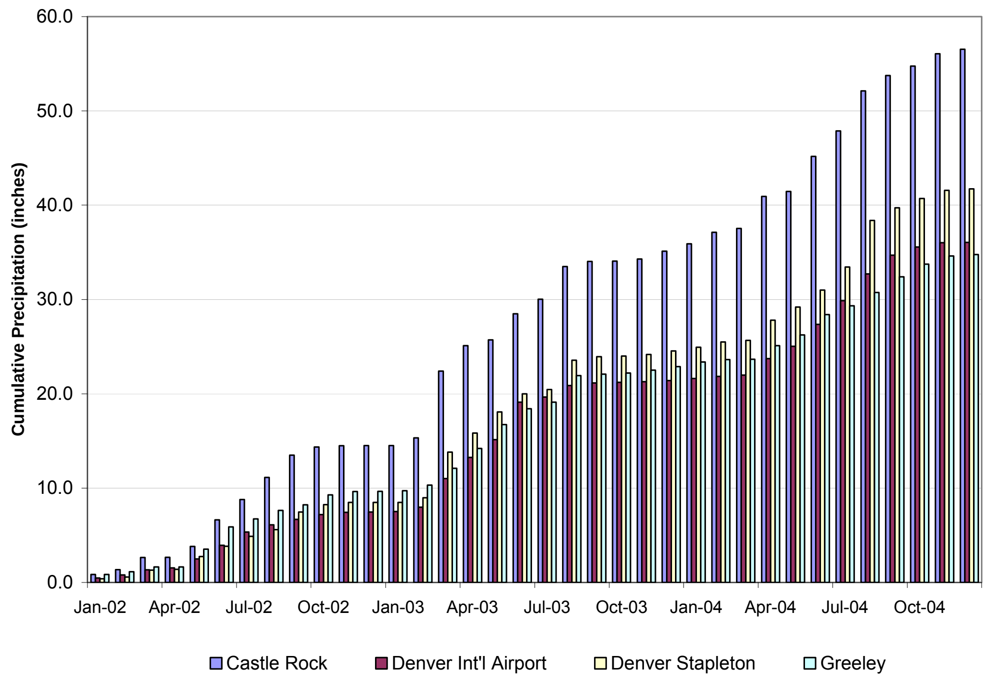


Figure 4-12. Monthly average minimum and maximum temperatures at modeled station

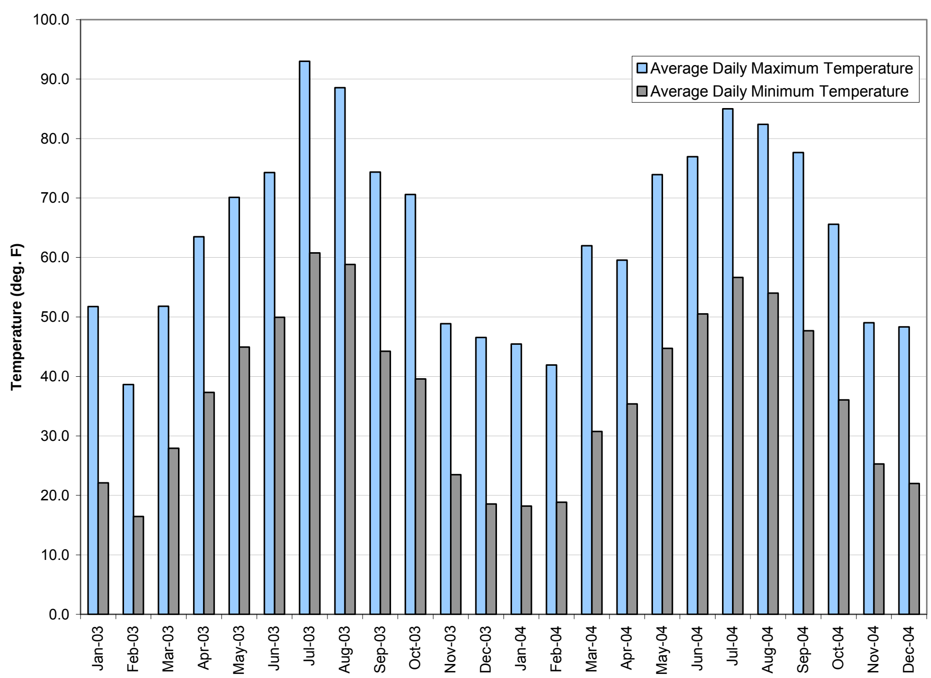


Figure 4-13. Monthly average wind speed at modeled station

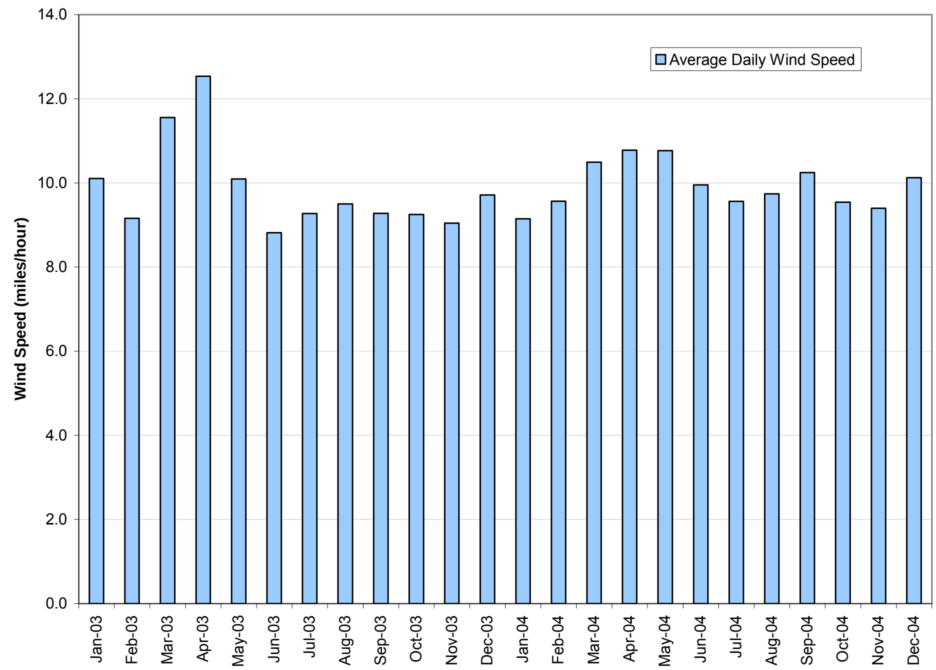


Figure 4-14. Monthly average relative humidity at modeled stations

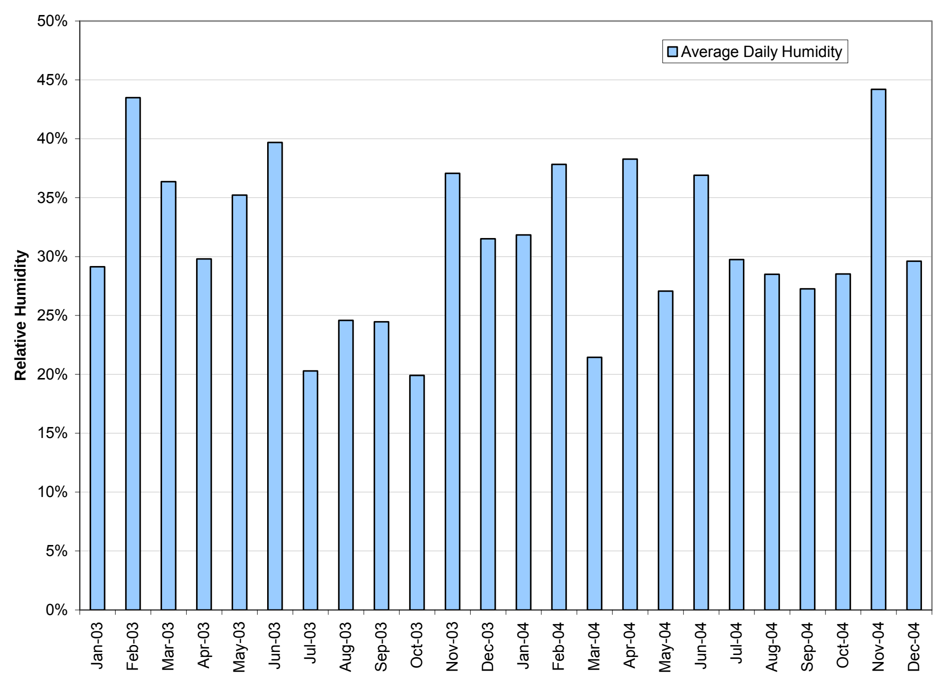
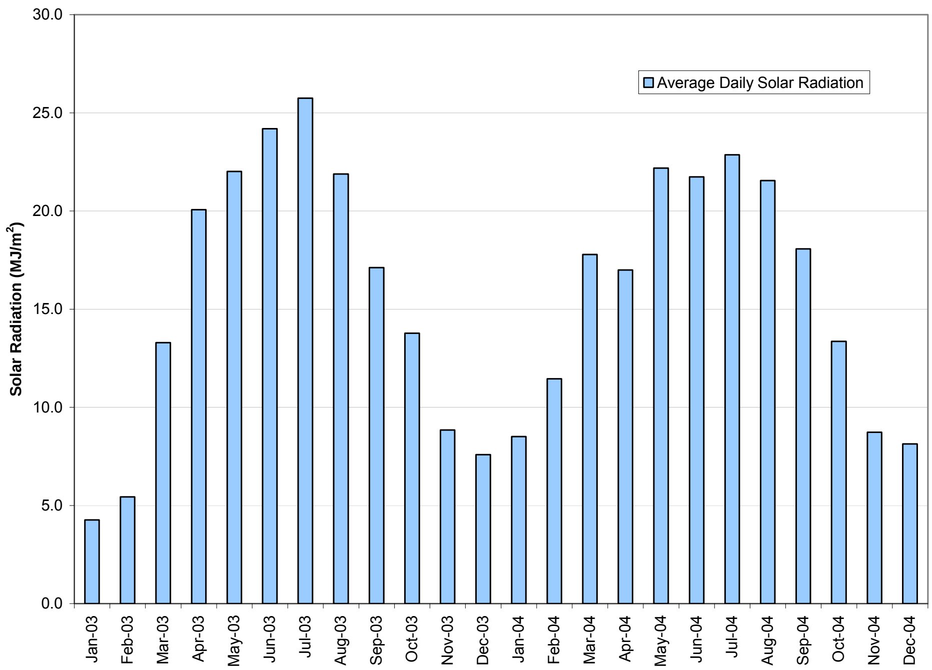


Figure 4-15. Monthly average solar radiation at modeled stations



4.1.7.2 Reservoir hypsography

A hypsograph relates water depth to both surface area and lake volume. The hypsographic data for both Barr Lake (Figure 4-16) and Milton Reservoir (Figure 4-17) were applied directly to the SWAT model to allow for an accurate representation of depth and surface area and a similarly accurate representation of depth and volume throughout the entire simulation. Hypsographic curves relating volume to depth and surface area to depth were developed from information provided by FRICO. The volume and surface area relational information for both Barr Lake and Milton Reservoir is applied directly to SWAT so that the model can track changes in surface area given the predicted volume of water contained in each impoundment. The surface area is an important indirectly predicted variable used in the calculation of evaporation, seepage, light penetration, algal growth, sediment oxygen demand, and benthic release of phosphorus.

Figure 4-16. Hypsograph for Barr Lake

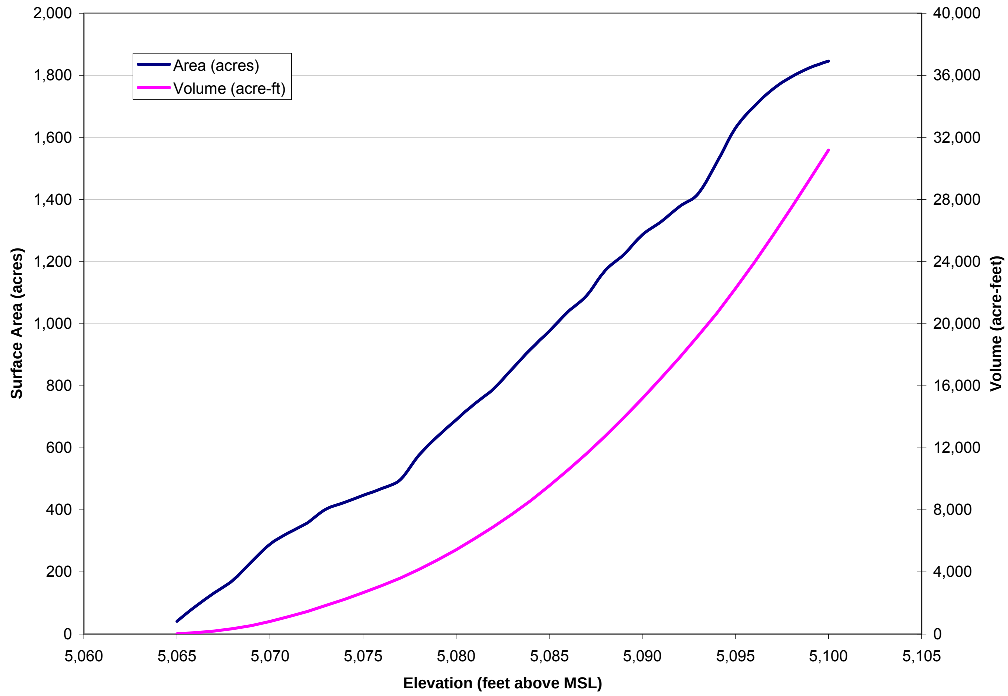
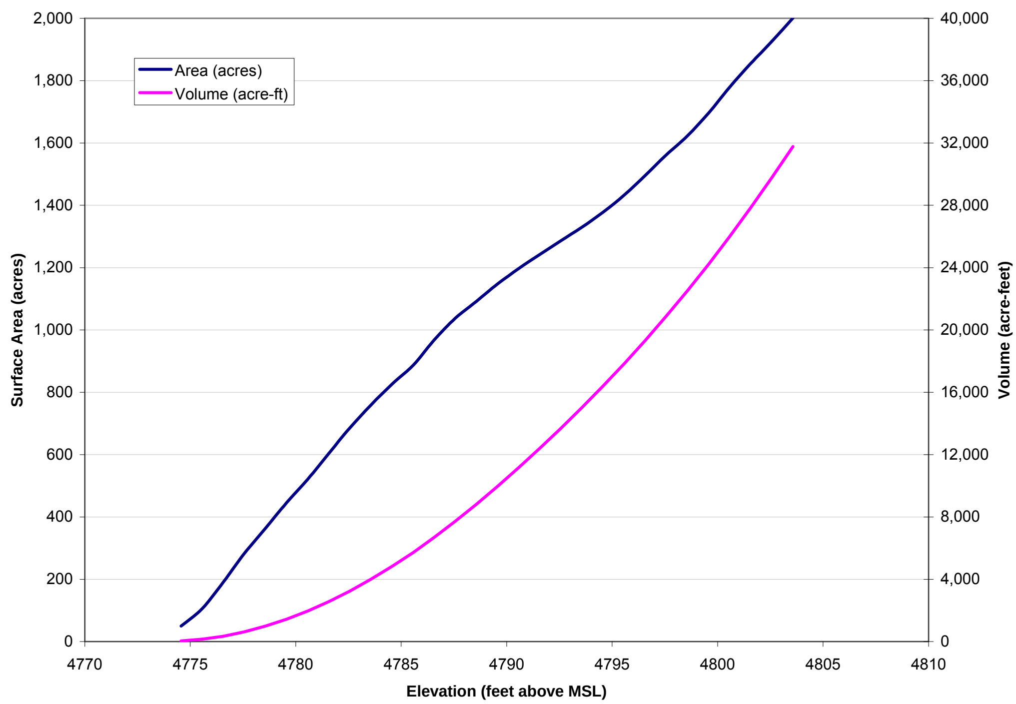


Figure 4-17. Hypsograph for Milton Reservoir



4.2 SWAT watershed model setup and calibration

The SWAT model of the Barr-Milton watershed was set up to simulate the period from January 1, 2003 through December 31, 2004 with the simulation of the entire 2002 year as a startup period. The simulation was conducted using a monthly simulation time step to coincide with the approximately monthly data available to support many of the water discharges and uses around the watershed. The simulation of 2002 conditions is disregarded as it takes most of the year for the model to synchronize, yielding a record for 2003 and 2004 that can be compared to actual data for those years.

4.2.1 Goal and expectations of calibration

For the watershed model, calibration is conducted to get the predicted water and nutrient loads to both Barr Lake and Milton Reservoir to match the magnitude and pattern over time and space as displayed by actual data, thus enabling the SWAT model to provide predicted loads to the WASP water quality model that are considered representative of reality in the watershed. The watershed model was also calibrated by comparing predicted and measured water volumes in Barr Lake and Milton Reservoir to make sure that inflows are realistic over time. As flow data are limited and highly variable over time, flows throughout the simulated watershed were not compared directly to measured flows; rather, the volumes in each of the reservoirs was tracked throughout the simulation period and compared with measured volumes. Matching the volumes in the reservoirs over time is considered the best indication that all inflows and outflows have been properly represented in the model.

In essence, the goal of calibration is to get the best possible match between corresponding predicted and observed values, within the constraints of reasonable variable value ranges and limnological understanding of aquatic processes. The watershed model fuels the lake model in that the watershed model provides the predicted boundary conditions to the lake model. The complexity of the watershed model was largely captured using the SWAT modeling platform. The expectations of the watershed model calibration were that the flows and nutrient loads could be reliably predicted on a monthly basis at two primary locations: 1) the Burlington-O'Brian Canal at the inflow to Barr Lake and 2) the Platte Valley Canal at the inflow to Milton Reservoir.

4.2.2 Comparative data used for watershed model calibration

Water quality data used for comparison during watershed model calibration were collected from a variety of sources and were available either directly from the database developed by Hydrosphere (AMEC) or was made available by the BMW Technical Committee. Because of the spatial aggregation applied to the model and the inconsistent data record, concentrations from several nearby locations were sometimes averaged both spatially and temporally to derive monthly measured values for comparison. This will tend to minimize extreme values in the model, whereas such values may occur in the real system, but helps to avoid misrepresentation of longer term conditions through skewing of the model.

4.2.3 SWAT watershed model calibration results

The SWAT model provides detailed predictions of flows and nutrient loads from sub-basins, from reaches, and within reservoirs. These predicted values for the reaches were available on a monthly time step from the onset of the watershed simulation to the end. As data for many points in the overall system are limited or non-existent, we did not conduct a point-by-point evaluation of predicted and measured values for all reaches covered by the SWAT model; only model predictions at the inlets to Barr Lake and Milton Reservoir were compared with the measured values. Data for any given month were averaged, given the monthly time step of the SWAT model simulation. To determine the ability of the SWAT model to accurately predict water volumes in Barr Lake and Milton Reservoir, the model predictions were compared with measured volumes on a monthly basis. The hydrologic aspect of SWAT is important, as the hydrodynamics for the WASP model were derived from the SWAT model results.

4.2.3.1 Comparison to reservoir loads

<u>Monthly comparison of inputs</u>

The calibration of the SWAT model to the measured phosphorus and nitrogen loads into Barr Lake, through the Burlington-O'Brian Canal, and into Milton Reservoir, through the Platte Valley Canal, was a critically important step in the SWAT modeling process. The effort put into acquiring elevation, land use, and soils data, and into acquiring and developing all the inlet, point source, consumptive use, and transfer data, and applying all the irrigation and meteorologic information, is expended so that the model can develop a complete water and nutrient balance for the system.

The SWAT model predicted monthly average total phosphorus (TP) and total nitrogen (TN) concentrations in discharges to each reservoir that were compared to average monthly concentrations measured at the coincident inlet locations. Initially, predicted TP and TN concentrations were only marginally in agreement with measured values, but refinement of the agricultural practices and use of average annual concentrations for the Metro and Littleton/Englewood WWTP discharges improved the predictions to the point where they can be considered acceptable. At issue with the two largest point source phosphorus concentrations, from which much of the phosphorus discharged to the lake was derived, is that monthly concentrations are based on only a few measurements each month. Occasional high or low measures, which may represent conditions at the time of sampling but not for the month, caused major deviations from observed conditions. Use of longer term average values were considered more representative of discharge quality.

The results of the SWAT model calibration can be described as follows:

- *<u>Total phosphorus discharged through Burlington-O'Brian Canal</u>* – Measured and predicted concentrations of total phosphorus in the Burlington-O'Brian Canal showed a distinct seasonal pattern, where concentrations were elevated during the period when wastewater was discharged to the canal through the Pump Works operated by FRICO (Figure 4-18). Predicted total phosphorus concentrations were generally higher than measured values during the late fall through early spring infilling period. Predictions may be greater than reality, or measurements may be lower than might be the case for a reservoir-wide average, or some combination of the two sources of error.
- *<u>Total nitrogen discharged through Burlington-O'Brian Canal</u>* – Measured and predicted total nitrogen concentrations show a very similar seasonal pattern as the total phosphorus concentrations and the comparison of measured and predicted values shows a similar level of accuracy (Figure 4-19). During the period when the Burlington-O'Brian Canal is active, the model tends to overpredict while the concentrations of total nitrogen during the summer months exhibit greater agreement.
- *<u>Total phosphorus discharged through Platte Valley Canal</u>* – Measurements of total phosphorus in the Platte Valley Canal are less available than in the Burlington-O'Brian and therefore fewer direct comparisons were able to be made between the average monthly measured and predicted values (Figure 4-20). This is particularly true during the 2003 simulation year, where only two values are available to represent the monthly average concentrations. During the 2004 simulation year, there are monthly measured values for most of the year and comparisons between measured and predicted concentrations are in reasonably close agreement. Similar to the Barr Lake results, predictions are consistently greater than the measured average values but still follow the same seasonal trend.
- *<u>Total nitrogen discharged through Platte Valley Canal</u>* – Measured total nitrogen concentrations in the Platte Valley Canal are less available than in the Burlington-O'Brian Canal. The comparison of predicted and measured values is roughly the same as for total phosphorus (Figure 4-21).

While the model would ideally match loads exactly, this is not a realistic expectation of any complex model. What we look for is similar values aligned in spatial and temporal patterns that are consistent with observed conditions.

Figure 4-18. Predicted and measured total phosphorus loads from B-O Canal

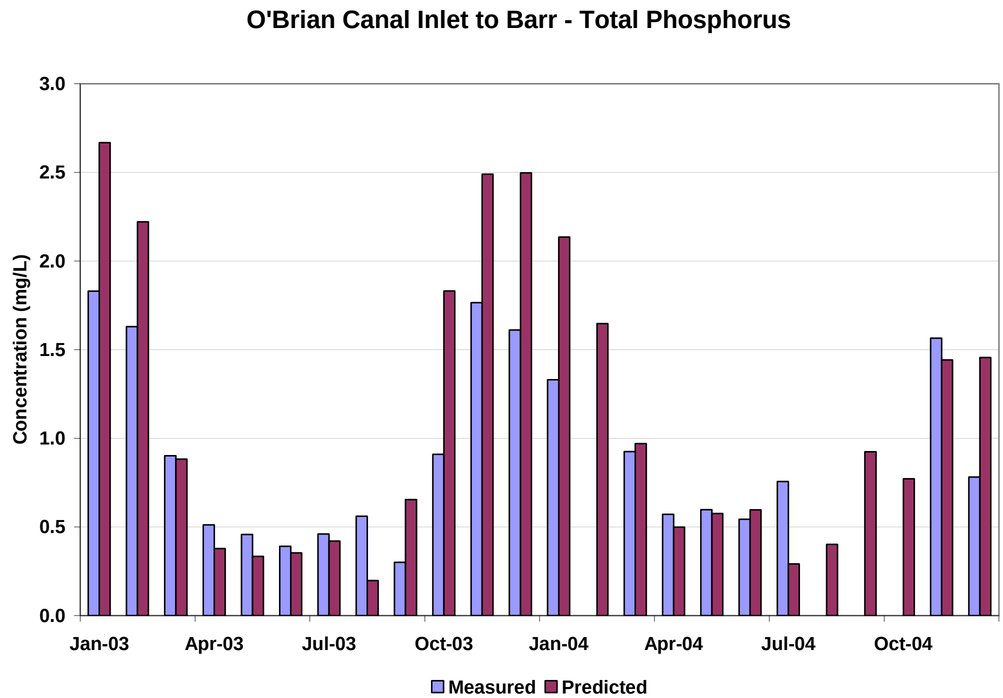


Figure 4-19. Predicted and measured total nitrogen loads from B-O Canal

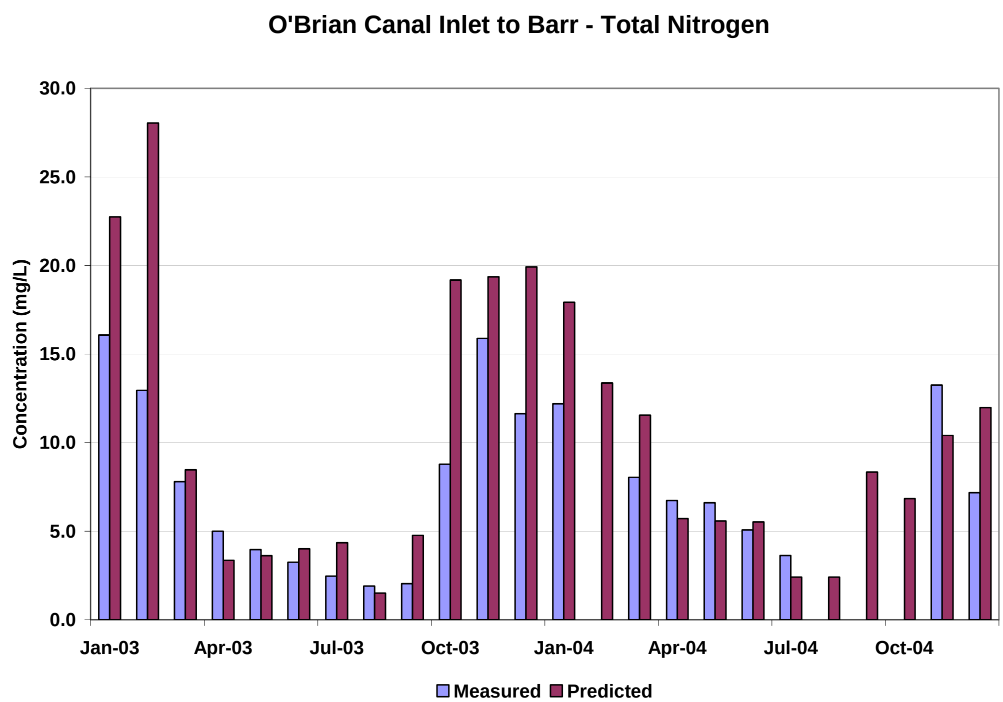


Figure 4-20. Predicted and measured total phosphorus loads from PVC

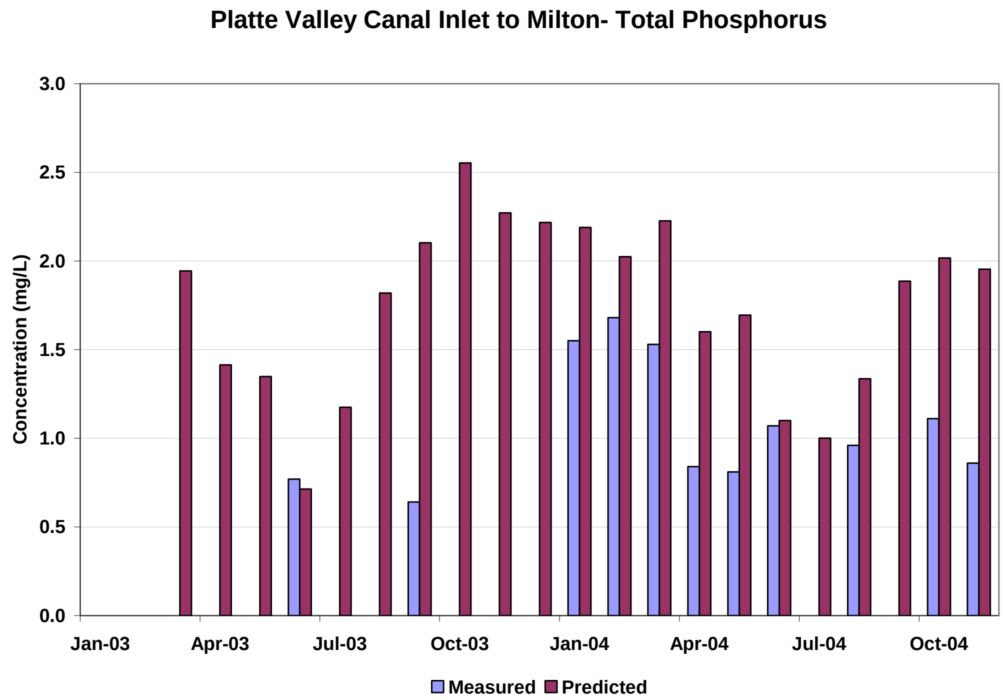
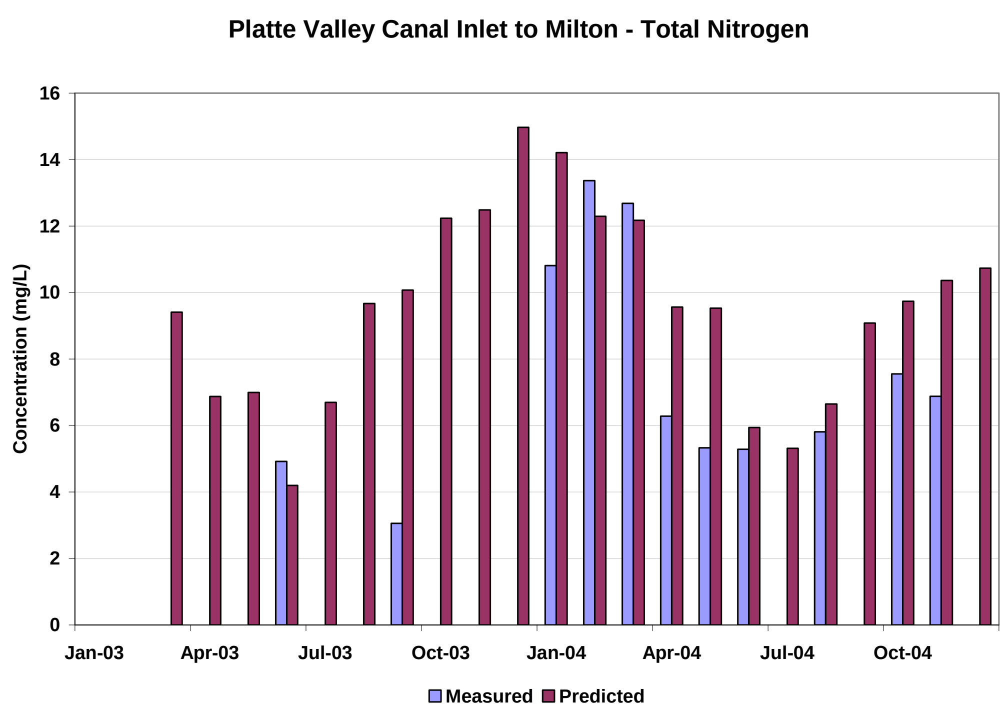


Figure 4-21. Predicted and measured total nitrogen loads from PVC



Comparison to reservoir volumes

The SWAT model relied on a multitude of data input values to predict the reservoir volumes over the two-year simulation period. The predicted Barr Lake and Milton Reservoir water volumes were based on the inlet flows, the point source flows, consumptive withdrawals, transfer rates, surface runoff rates, and groundwater infiltration and discharge in both the reaches and within the reservoirs themselves. The calculation of a volume is dependent on many variables, and can only be as accurate as the hydrologic information upon which it is based.

The calibration of lake volumes was largely completed by adjusting the method used to calculate evapotranspiration and the seepage losses from the lake bottom. The method of evapotranspiration used to calculate the most reliable water volume in each lake was the Hargreaves method (Hargreaves and Samani 1985). This method was selected over the Priestley-Taylor (Priestley and Taylor 1972) and the Penman-Monteith (Penman 1956) methods as it provided the best long-term comparison to measured monthly averaged volumes, particularly with regard to the pattern of volume change. Moderate increases in the seepage rates in both Barr Lake and Milton Reservoir during volumetric calibration resulted in reduced volumes, which tended to bring long-term predictions into close agreement with measured values. Seepage rates were adjusted to 0.2 mm/hr in both Barr Lake and Milton Reservoir and are within a typical range of values which might be expected. Initially, the total volume in each impoundment was continually overpredicted by an increasing margin, but the general variability was captured throughout the two-year simulation period (Figure 4-22 and Figure 4-23).

Comparison to reservoir concentrations

Initially, it was thought that the very simplistic reservoir simulation capabilities of the SWAT model would sufficiently capture water quality in Barr Lake and Milton Reservoir. However, given that the model only simulates nutrient removal through settling and does not allow for any interactions, a more sophisticated inlake approach was deemed necessary. The water quality in the impoundments was initially simulated through SWAT, but the results were unsatisfactory and this effort was abandoned. Instead, lake modeling was conducted using the WASP model. Comparisons within the reservoir are therefore deferred to Section 5, covering the development and calibration of the WASP model.

Comparison to other studies

AMEC (2008a, 2008b) and Lewis and McCutchan (2009) developed estimates of loading at the three key inlet points in this system: the Burlington-O'Brian Canal at its inlet to Barr Lake, the Beebe Canal at its inlet to Milton Reservoir, and the Platte Valley Canal at its inlet to Milton Reservoir. This AECOM effort also provides loading estimates at these points. There are differences in estimates from all three efforts (Table 4-9), highlighting the uncertainty and complexity associated with this system. The 2003 Beebe Canal TP load as calculated by AMEC is much higher than the other two estimates, and both the 2003 and 2004 Platte Valley Canal TP loading estimates from AECOM are much higher than the other two corresponding values. AECOM loading estimates for TN are also higher than derived by the other two estimates. The reasons for these deviations are not readily apparent, but are conferred by the model as a function of exports and processing on the way to the reservoirs.

For the purposes of the AECOM effort, it is not the total load that is of primary interest, but getting the model to mimic the processing of nutrients to allow predictive changes under possible management scenarios in terms of the direction and magnitude of change. It would certainly be desirable to have all loading estimates match closely, but the model will remain useful as a predictor of the percent loading reduction necessary to achieve desired conditions. Choices of total loads to which percent reductions will be applied in TMDL development are probably best based on actual data for inlets or back-calculation from in-lake conditions.

Figure 4-22. Predicted and measured monthly water volumes for Barr Lake

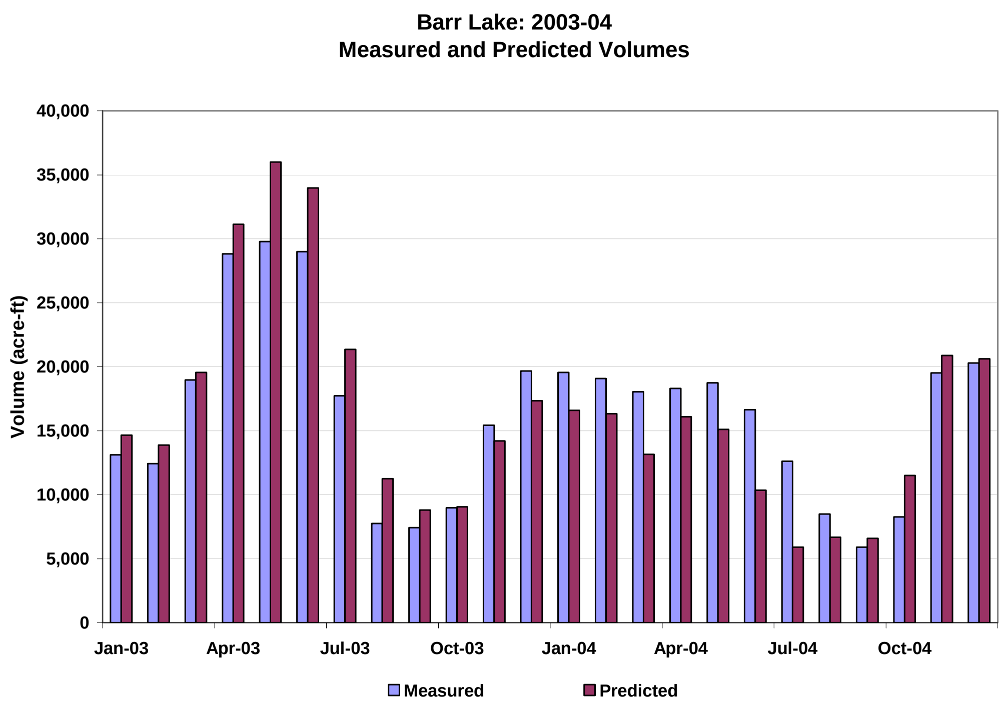


Figure 4-23. Predicted and measured monthly water volumes for Milton Reservoir

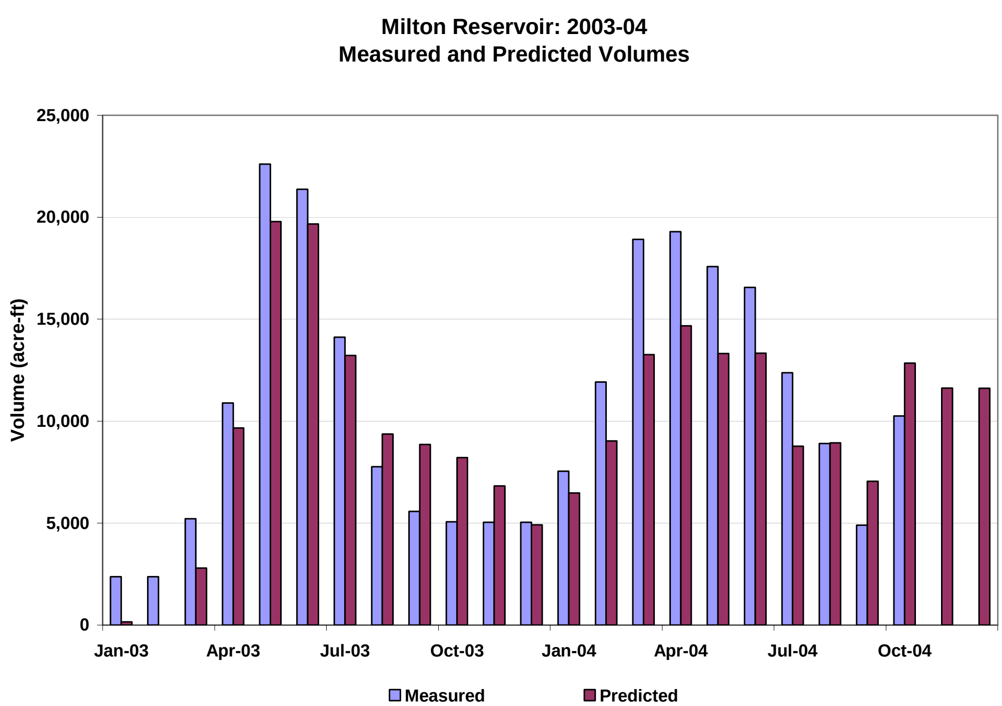


Table 4-8. Comparison of loads to Barr Lake and Milton Reservoir from different studies

		TP (kg/yr) from Selected Canals			TN (kg/yr) from Selected Canals		
Source	Year	AMEC 2008	Lewis and McCutchan 2009	AECOM 2009	AMEC 2008	Lewis and McCutchan 2009	AECOM 2009
Burlington-O'Brian Canal to Barr Lake	2003	55810	62061	92100	466196	463694	1062406
	2004	74838	47317	62200	690017	620343	864661
	Mean	65324	54689	77150	578107	542019	963534
Beebe Canal to Milton Reservoir	2003	21810	7614	5219	72000	30781	44517
	2004	3442	3464	4493	36589		46195
	Mean	12626	5539	4856	54295	30781	45356
Platte Valley Canal to Milton Reservoir	2003	21919	24718	68281	140011	219989	345979
	2004	34888	29262	103507	224465		553737
	Mean	28404	26990	85894	182238	219989	449858

4.2.3.2 Summary of watershed model calibration results

The SWAT watershed model was able to reliably reproduce monthly water volumes in Barr Lake and Milton Reservoir and nutrient concentrations in the Burlington-O'Brian Canal and the Platte Valley Canal at the inflows to each respective reservoir during the simulation period. Predicted values did not always match measured values, but considering that some of the monthly average flows and concentrations are actually only represented by one or two measurements, the model results were considered acceptable. It is difficult to determine when to believe a small quantity of data over the model, and the general guideline is to adjust the model to fit limited data only if there are a disproportionate number of over- or underpredictions (i.e., the model consistently predicts higher or lower values than observed).

4.2.3.3 Necessity of more complex lake model

During the early stages of the watershed modeling it was realize that a more complex lake model would be necessary to accurately represent the complex eutrophication processes occurring in Barr Lake and Milton Reservoirs. The ability of the SWAT model to effectively simulate even simple eutrophication was limited since it only considers reservoirs as a sink for nutrients and sediment and that the only removal mechanism is via direct settling using a first-order removal rate. Also, the SWAT model had no ability to consider algal growth or decay and could not predict chlorophyll concentrations in the reservoirs. These significant limitations in the SWAT reservoir modeling scheme required that a secondary model be used, which would utilize the SWAT watershed model predicted flows, loads, and reservoir volumes in a more detailed eutrophication model.

4.3 Lake modeling

The numerical simulation of limnological processes in Barr Lake and Milton Reservoir followed the development and calibration of the SWAT watershed model of the Barr-Milton watershed. Several lake models were reviewed in advance of the modeling application including: the reservoir water quality component in SWAT, BATHTUB, QUAL2E, CE-QUAL-W2, and WASP. It was determined that the reservoir water quality component in SWAT was too simplistic in that it only simulated nutrient losses through settling and was not meant to simulate eutrophication. The BATHTUB and QUAL2E models were both excluded because of their steady-state capabilities, which would require a gross oversimplification of temporal variability in Barr Lake and Milton Reservoir. The CE-QUAL-W2 was considered because of its simulation of detailed eutrophication processes and dynamic simulation capability. The model was not used because an evaluation of existing water quality data did not demonstrate that a successful simulation would necessitate all the additional work required to develop a two-dimensional model, or that a two-dimensional model could be calibrated with the available data, or that it would add much value in TMDL development and management scenario simulation. The WASP model was selected because of its ability to dynamically simulate detailed eutrophication processes and the ease of use offered by its one-dimensional framework and the pre- and post-processor available for the model. Also, the WASP model has the ability to read in and use both flow files and a loading files developed by another model like SWAT.

4.3.1 Lake modeling approach

The water quality model of Barr Lake and Milton Reservoir was developed to predict water quality concentrations related to eutrophication using the WASP model through a simplified one-dimensional representation. Given the scope of the project and constraints of available data, the use the SWAT model and a simplified WASP model was preferential to developing a multi-dimensional inlake model. Following the development and calibration of the SWAT watershed model, a simple four segment model domain was devised for simulation of the reservoirs using WASP, consistent with the WASP model setup requirements. Additional segments were included within the WASP model domain but were only added to facilitate the movement of water and constituents into and out of the mainstem segments.

The most important assumption that was made prior to selecting this approach was that both Barr Lake and Milton Reservoir could be adequately represented by single, completely mixed model cells. This assumption was developed early on in the modeling process and was validated through a review of the existing water quality data. Previously collected vertical profile measurements of temperature, DO, pH, specific conductivity, and nutrients indicate that while some relatively minor amount of vertical gradation occurs during the year, the lake and reservoir are generally completely mixed. A key factor is the relatively large surface area to depth ratio and the influence of wind on mixing. An assumption of complete mixing is therefore the foundation of the WASP modeling approach used in this application.

The WASP lake model setup and execution takes advantage of WASP's ability to utilize a hydrodynamic interface file and a loading file to describe flow into, out of, and within the model domain and loads to the model domain, respectively. These two files were developed using SWAT predictions and external programs. The lake model was run after the SWAT watershed simulation was completed and focused on the coincident two-year period. Rates, constants, and time variable external forcing functions were applied using either measured data or reasonable approximations based on professional judgment, with adjustment during model calibration as warranted. Model predictions were compared directly to discrete measurements. Adjustments were then made to a select group of model input variables to bring predicted and measured values into the closest agreement sustainable within model and data constraints. The end result is not a unique solution; different values for various variables could provide similar results. However, this approach provides ample opportunity to recognize inconsistencies in the model input and to isolate trends and identify sensitive parameters.

4.3.2 Description of WASP water quality model

EPA's Water Quality Analysis Simulation Program – Version 7.3 (WASP) was chosen as the modeling tool for simulating watershed flows and loads and instream flows and water quality. WASP is a robust and flexible (up to three dimensions) water quality model and includes a graphical user interface (GUI) for viewing input data and results. The WASP model was selected because of its linkage with any of several fully dynamic hydrodynamic models, the ability of the model to predict nutrient cycling, and the EUTRO subroutine that can be used to represent the nutrient cycle at various levels of complexity. Additionally, unlike many other water quality models available, WASP incorporates a Windows® interface to simplify model setup and enhance the evaluation of model results. It was considered appropriate to run the model in only one dimension, meaning that each reservoir is treated as a completely mixed system, without major vertical differentiation of water quality and without strong gradients between the inlets and outlets. These assumptions are consistent with the available inlake data for Barr Lake and Milton Reservoir.

WASP is part of the EPA Region 4 TMDL toolbox of identified models available for analyzing the effects of pollutant loads on natural systems.

4.3.3 Linkage of SWAT and WASP models

The move toward integrating existing modeling applications has progressed in recent years. This is exemplified by the USEPA's BASINS modeling system, where the user has the ability to simulate watersheds and instream processes using any of several watershed and instream models. There has been an ongoing effort to link the SWAT model with WASP, but currently this mechanism is not available through the EPA, so AECOM programmed a link between the two models for application to the Barr-Milton system.

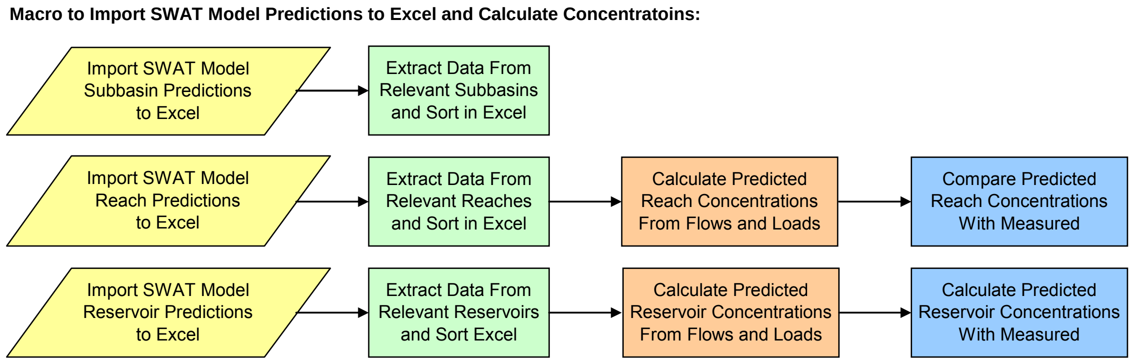
The WASP model is robust in its ability to import properly formatted input files describing flows to and within the model network and loads to the model domain. This includes the ability to read flow information from a hydrodynamic input file and nutrient load information from a loading file. The hydrodynamic input file has a specific format and is generally developed by a hydrodynamic model external to WASP in advance of the WASP model simulation. The hydrodynamic input file (*.hyd) includes information critical to set up the model network within WASP, including the model time step, flow information between each model segment, and velocity, depth, and volume information within each segment. Since the hydrodynamic input file is developed prior to a WASP simulation, and provides information throughout the simulation, the information in this file must coincide with the WASP model time step, which in most cases is relatively small to ensure numerical stability. That is, the model is better able to represent reality in small increments, providing output data that can be graphed as a continuous set of values over time or lumped into larger time units (like months) to match data availability for comparison.

Similarly, the loading file that can be read in and used by the WASP model provides daily loads of material to model segments throughout the model domain. This file is generally used to describe nonpoint source loads but in this application the file was used to describe loads generated by the SWAT model from both point and nonpoint sources, including the Burlington-O'Brian Canal, the Beebe Canal, the Platte Valley Canal, and the adjacent subwatersheds. Unlike the hydrodynamic input file, the loading file operates on a daily time step. In simulations where instantaneous effects are being predicted, this time step restriction could limit the utility of this file. Yet in the Barr-Milton datashed, where effects are long-term and the watershed model time step is already monthly, this application of the load file is appropriate.

The linkage of the SWAT watershed model with the WASP water quality model was accomplished by developing an external processing program using Microsoft Visual Basic (VB) to read in and reformat SWAT results and prepare the model predictions for direct importation into the WASP model. This was done by developing three VB macros within Microsoft Excel® to complete three distinct tasks, including:

- *Import SWAT model results* – The SWAT watershed model predicts flows and loads for three separate model compartments including from subwatersheds and within reaches and reservoirs. The SWAT model generates three output files describing each of these three compartments using a time step coincident with the SWAT model time step, which in the case of the Barr-Milton Watershed modeling application was monthly. The first step in the data processing was to develop a macro-command to import each of the three files directly into Excel® (Figure 4-24). Once in Excel®, the results are automatically sorted in preparation for the second of the three steps involved in data processing.

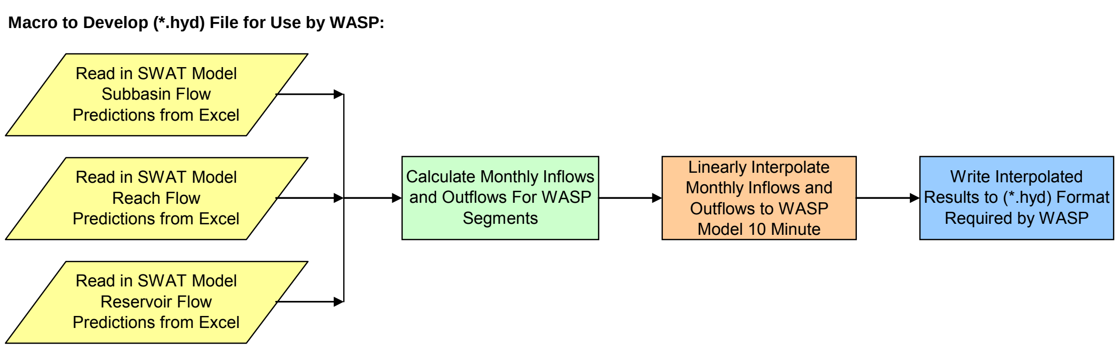
Figure 4-24. Flow chart for VB program to import results



- *Develop the (*.hyd) hydrodynamic input file for use by the WASP model* – This second processing step was the more complicated of the three because of the incorporation of model network information into the hyd file and the interpolation necessary to develop information based on a monthly timestep to information coincident with the WASP simulation timestep. In general, the WASP model domain was set up to have four segments including, in order from upstream to downstream, Barr Lake, the upstream portion of the Beebe Canal, the downstream portion of the Beebe Canal, and Milton Reservoir. In addition to these mainstem WASP model segments, the model domain was set up so that each of the mainstem segments would have two associated segments so that inflows not derived from upstream (i.e., subbasin inflow) and segment outflow (i.e., seepage and evapotranspiration) could be considered properly. These additional segments provided for the flexibility necessary to consider changes in water volume both with and without associated material. Finally, the flow information for WASP had to be either used directly, or calculated based on predicted values, and then interpolated to provide information for the WASP model to coincide with the 10 minute WASP model time step.

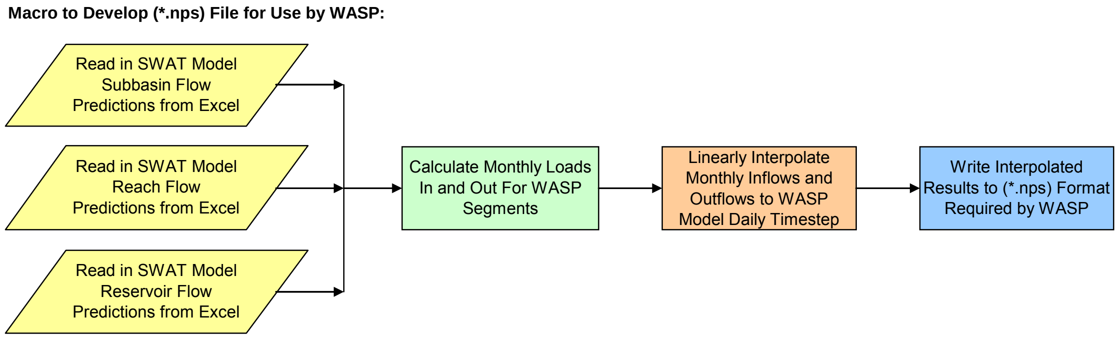
  Figure 4-25 is a flow diagram showing the logic of the VB program used to create the hydrodynamic interface file.

Figure 4-25. Flow chart for VB program to write out HYD file



- *Develop the (*.nps) nonpoint source file for use by the WASP model* – The third and final processing step was to either use the daily loads directly or to calculate the daily loads based on predicted values. Interpolation was still required to get the monthly loads predicted by the SWAT model to daily values, which can be utilized by the WASP model. Figure 4-26 is a flow diagram showing the logic of the VB program used to create the daily nutrient loading interface file.

Figure 4-26. Flow chart for VB program to write out NPS file



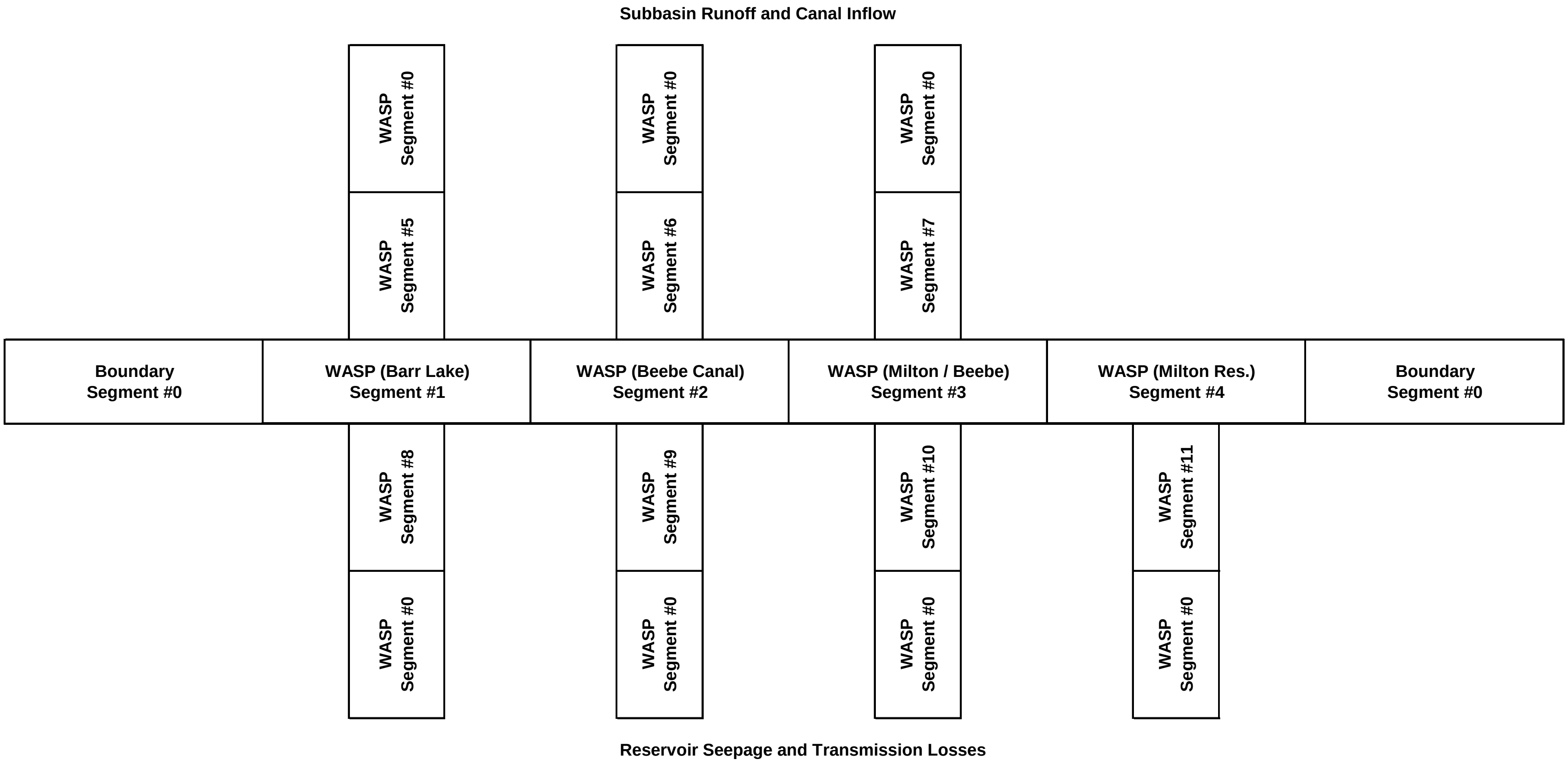
The use of VB Macros to complete each of these three steps greatly simplified the data processing, and the use of both the hyd file and the nps file to drive the WASP simulation resulted in a seamless transition from the SWAT model to the WASP model.

In brief, the linkage requires that the SWAT model be run first and the results processed using the VB Macros to develop the hyd and nps files. Once that step is complete, the WASP simulation can be run directly and seamlessly using the information contained within these two files.

4.3.4 WASP model segmentation and setup

The segmentation applied to the WASP water quality model was accomplished prior to the transferring of hydrodynamic and loading predictions from the SWAT watershed model. Model segmentation was determined by assuming a series of main channel segments to represent Barr Lake, the Beebe Canal, and Milton Reservoir (Figure 4-27). There are a total of four main channel segments including one segment to represent each of the impoundments and two to represent the Beebe Canal. Inputs from the Burlington-OBrian and Platte Valley Canals are provided by SWAT. In addition to the main channel segments, the WASP model was required to include lateral segments connected to the main channel segments. Two lateral segments were associated with each of the three most upstream segments while only one segment was associated with the most downstream segment. The paired lateral segments, to each of the three main channel segments, were used to account for inflow to and outflow from each of the segments. Inflows were generally in the form of either upstream boundary flow to the most upstream main channel segment and subbasin runoff to each of the main channel segments. Outflows were generally in the form of losses due to seepage and outflow at the most downstream main channel segment. The lateral inflow to the most upstream segment and lateral outflow from the most downstream segment effectively eliminates the need for an assignment of boundary conditions to the model, making it significantly easier to develop a seamless transition of SWAT model output to the WASP water quality model. Evaporation losses in the WASP model were accounted for by predicted changes in water volume that were not accounted for by either a direct inflow or outflow. That way, concentrations could either increase or decrease without any direct change in nutrient mass as a result of any change in water volume.

Figure 4-27. Illustration of WASP model network



4.3.5 WASP model setup and calibration

The WASP model calibration occurred following a detailed simulation of eutrophication in the four main channel segments throughout the two-year simulation period. The WASP model was set up using all environmental conditions and all rates and constants were estimated from literature values and applied to the WASP model as a starting point for the model values. The WASP model was then run repeatedly with adjustments to important model parameters until the model predictions were in closest possible agreement with the measured values, within the constraints of professional judgment regarding data and process limits.

4.3.5.1 Adjustment to WASP model parameters

During model calibration, adjustments were made to a multitude of rates and constants associated with a variety of eutrophication processes. The values selected for adjustment were generally those that control nutrient and chlorophyll concentrations in Barr Lake and Milton Reservoir. Under the currently accepted conceptual model of the reservoirs and pH variability, these constituents are key dependent variables. Variables were adjusted in the calibration process under the following considerations:

- *Algal growth rates* – the growth rates of algal groups are first-order, concentration dependent rates that indicate the rapidity at which algal populations can increase in a system. These growth rates generally range from 1 to 3 day^{-1} and are considered to be a growth rate under ideal conditions of nutrient and light. Since chlorophyll concentrations are an indicator of algal populations, the growth rate has a direct effect on the predicted chlorophyll concentrations.
- *Optimum temperatures and shape parameters for growth* – the growth rate of algae is generally given at a standard temperature and is then modified during the simulation to mimic the effect of higher and lower temperatures on the growth of that specific algal group. In the case of WASP 7.3, which facilitates the simulation of up to three algal groups, the ability to apply different optimum temperatures to each group allows WASP to predict a succession of growth throughout the year as temperature conditions change. This then loosely mimics the natural progression of the springtime dominance of diatoms, giving way to the growth of green algae during the early summer and finally to the mid-summer growth of cyanobacteria. In addition to defining an optimum temperature for growth, WASP provides for upper and lower shape parameters to identify the degree of effect both above and below the optimum temperature. As such, these shape parameters can have a significant outcome in the predictions of chlorophyll throughout the year.
- *Light attenuation variables* – the ability of algae to effectively provide light limiting shade and thereby limit its own growth tends to drastically limit the upper end of algal concentrations. In the WASP model, the light attenuation factors related to algal growth includes an exponent and coefficient that were adjusted during model calibration to adjust the predicted levels and variability in the levels of predicted chlorophyll in Barr Lake and Milton Reservoir.
- *Half saturation constants* – the growth of algae can be limited by not only light and temperature, but also by the concentrations of nitrogen and phosphorus. This limitation is numerically characterized by half-saturation constants, indicating the concentration at which the growth rate is equivalent to half of its maximum. These values were only marginally adjusted because the nutrient concentrations in Barr Lake and Milton Reservoir were generally well above the concentrations necessary to be limiting to growth. These values were set at the relatively low concentrations indicated in published literature with the understanding that they would be more important once the nutrient loads to the system were reduced in management alternative scenarios.
- *Zooplankton grazing rates* – the consumption of algae by zooplankton is known to occur to varying degrees in Barr Lake and Milton Reservoir. This process can be simulated by the WASP model by applying a known zooplankton population to the simulation of by using a consumption rate to simulate a loss of algae, which is dependent on its population at any given time. This first-order rate was applied to the WASP model and adjusted during calibration to match measured chlorophyll concentrations.

- *Partitioning and TSS settling* – the ability of dissolved nutrients to bond with TSS is an effective means of removal through settling once the TSS begins to settle in the quiet waters of either Barr Lake or Milton Reservoir. TSS concentrations into the reservoirs were fixed at a value indicated by the average of several measurements and the settling rate of TSS was adjusted so that the inlake concentrations were near that measured in the lakes. The partition coefficient of dissolved phosphorus was then adjusted so reductions in phosphorus concentrations in Barr Lake and Milton Reservoir during the spring and early summer fill periods could be replicated.

Like most model calibrations, the WASP model was run numerous times with successive adjustments being made to different variables each time to bring the measured and predicted into closest possible agreement. The final calibration highlights a balance between the competing rates and constants and provides the most reliable approximation of reality. The model values derived during model calibration are indicated in Table 4-9.

4.3.5.2 Results of lake water quality modeling calibration

The lake water quality calibration required extensive adjustment and interpretation of model input values in order to develop the most reliable simulation possible. Initially, the best estimates were used for each of the input variables used by the WASP model to predict conditions in the reservoirs. In general, the calibration primarily focused on developing an accurate representation of total phosphorus during the period from 2003 through 2004. An important consideration during the evaluation of the model's reliability in reproducing the measured values is that the detailed WASP model predictions are based on interpolated monthly predictions from the SWAT model. Near continuous output by WASP makes it look like a finer level of prediction is supported than can be based on actual data. Comparison at biweekly to monthly time steps is what is afforded by the measurements made in these systems. While effort was expended on matching chlorophyll predictions to measured values, it is unreasonable to expect close agreement at the very high nutrient levels encountered; chlorophyll levels will be influenced more by temperature and light than phosphorus or nitrogen. All of these and other factors (e.g., grazing by zooplankton) are addressed by WASP, but inherent variability is expected to be high under the hypereutrophy exhibited by these reservoirs, and may not be adequately reflected by corresponding model predictions.

Total phosphorus calibration

Calibration of the WASP model to total phosphorus concentrations for Barr Lake and Milton Reservoir provided a generally reliable representation of the measured total phosphorus concentrations over the two-year simulation period. Total phosphorus concentrations were measured to fluctuate substantially throughout the simulation due to significant differences in the sources of water being transferred to each impoundment. Total phosphorus concentrations in Barr Lake are predominantly controlled by phosphorus discharges through the Burlington-O'Brian Canal while total phosphorus concentrations in Milton Reservoir are predominantly controlled by both phosphorus discharges through the Beebe Canal, which are the result of predicted concentrations in Barr Lake, and phosphorus discharges through the Platte Valley Canal.

Seasonal patterns of measured total phosphorus concentrations in Barr Lake and Milton Reservoir are somewhat different. Concentrations in Barr Lake are generally highest during the winter and early spring when the reservoir is being filled with water discharged through the Pump Works. Concentrations then decline into the summer before rising again later in summer, apparently in relation to internal loading. Concentrations again decrease in early fall, then rise again during the later fall infill period. In contrast, the highest total phosphorus concentrations in Milton Reservoir generally occur during the mid-summer then decline in later summer, suggesting less internal cycling. Refill tends to be somewhat later in the spring for Milton Reservoir. Total phosphorus concentrations sometimes decline to <200 µg/L in Milton Reservoir, but never do so in Barr Lake.

Table 4-9. Table of WASP model input showing calibrated values

Parameters		Initial Value	Calibrated Value (1)	Reference
Global Constants & Parameters	Atmospheric Deposition of Nitrate (mg/m2-day)	0.000	0.000	Assumed to be zero
	Atmospheric Deposition of Ammonia (mg/m2-day)	0.049	0.049	NADC Sampling Station (2000-07) http://nadp.sws.uiuc.edu/sites/siteinfo.asp?net=NTN&id=SC06
	Atmospheric Deposition of Orthophosphate (mg/m2-day)	0	0	Assumed to be zero
	Atmospheric Deposition of BOD1 (Ultimate) (mg/m2-day)	0	0	Assumed to be zero
	Atmospheric Deposition of Organic Nitrogen (mg/m2-day)	0	0	Assumed to be zero
	Atmospheric Deposition of Organic Phosphorus (mg/m2-day)	0	0	Assumed to be zero
Inorganic Nutrient Kinetics	Nitrification Rate Constant @20 °C (per day)	0.10	0.10	EPA, 1985; Table 5-3: $NH_3 \rightarrow NO_3$ Range 0.025 - 0.16 day^{-1}
	Nitrification Temperature Coefficient	1.04	1.04	EPA, 1985; Table 5-3: $NH_3 \rightarrow NO_3$ Range 1.02 - 1.08 day^{-1}
	Half Saturation Constant for Nitrification Oxygen Limit (mg O/L)	2.0	2.0	EPA, 1985
	Ammonia Partition Coefficient to Water Column Solids, L/kg	101,347	101,347	Estimated to be the same as phorphorus
	Ammonia Partition Coefficient to Bentic Solids, L/kg	101,347	101,347	Estimated to be the same as phorphorus
	Minimum Temperature for Nitrification (oC)	20.0	20.0	EPA 1985
	Denitrification Rate Constant @20 oC (1/day)	0.09	0.10	Wool, et al, undated. Water Quality Analysis Simulation Program (WASP) Table 9-5: From Potomic Estuary Model
	Denitrification Temperature Coefficient	1.045	1.04	Wool, et al, undated. Water Quality Analysis Simulation Program (WASP) Table 9-5: From Potomic Estuary Model
	Half Saturation Constant for Denitrification Oxygen Limit (mg O2/L)	0.1	2.0	Wool, et al, undated. Water Quality Analysis Simulation Program (WASP) Table 9-5: From Potomic Estuary Model
Inorganic Nutrient	Orthophosphate Partition Coefficient to Water Column Solids 1 (L/kg)	-----	1.00E+04	Calibrated
	Orthophosphate Partition Coefficient to Water Column Solids 2 (L/kg)	-----	7.40E+04	Calibrated
Organic Nutrients	Dissolved Organic Nitrogen Mineralization Rate Constant @20 øC (1/day)	0.25	3.00E-02	EPA, 1985; Table 5-3; Range 0.001 - 0.4 day^{-1}
	Dissolved Organic Nitrogen Mineralization Temperature Coefficient	1.020	1.02E+00	EPA, 1985; Table 5-3
	Dissolved Organic Phosphorus Mineralization Rate Constant @20 øC (1/day)	0.22	2.20E-01	Wool, et al, undated. Water Quality Analysis Simulation Program (WASP) Table 9-2
	Dissolved Organic Phosphorus Mineralization Temperature Coefficient	1.08	1.08E+00	Wool, et al, undated. Water Quality Analysis Simulation Program (WASP) Table 9-2
CBOD	CBOD(1) Decay Rate Constant @20 øC (1/day)	0.11	2.50E+00	Calibrated
	CBOD(1) Decay Rate Temperature Correction Coefficient	1.08	1.07E+00	EPA, 1985; Table 3-13; Range 1.02 - 1.15 day^{-1}
Dissolved Oxygen	Oxygen to Carbon Stoichiometric Ratio	2.67E+00	2.667	Tuffard and McKellar; Ecological Modeling, 1999; Table 1
	Elevation above Sea Level (m)	1.61E+03	1.61E+03	Average elevation of watershed
	Calc Reaeration Option (0=Covar,2=Owens, 3=Churchill, 4=Tsivoglou)	0.00E+00	0.00E+00	Covar Method
	Theta -- SOD Temperature Correction	-----	1.08E+00	Did not simulate dissolved oxygen
Light	Light Option (1 uses input light; 2 uses calculated diel light)	1.00E+00	1	Uses input light
	Include Algal Self Shading Light Extinction in Steele (0=Yes, 1=No)	0.00E+00	0.00E+00	Include algal self shading light extinction
	Background Light Extinction Coefficient (1/m)	1.00E-01	0.0088	Wool, et al, undated. Water Quality Analysis Simulation Program (WASP) Equation 9-5
Phyto-plankton Diatoms	Phytoplankton Detritus to Carbon Ratio for Group 1 (mg D/mg C)	2.50E+00	2.50E+00	Did not simulate detritus
	Phytoplankton Nitrogen to Carbon Ratio for Group 1 (mg N/mg C)	0.18	1.25E-01	EPA, 1985; Figure 6-3
	Phytoplankton Phosphorus to Carbon Ratio for Group 1 (mg P/mg C)	0.025	2.50E-02	EPA, 1985; Figure 6-3
	Phytoplankton Silica to Carbon Ratio for Group 1 (mg Si/mg C)	0.5	7.50E-01	EPA, 1985; Figure 6-3
	Phytoplankton Carbon to Chlorophyll Ratio for Group 1 (mg C/mg Chl)	50	6.00E+01	EPA, 1985; Table 6-4
	Phytoplankton Maximum Growth Rate Constant @20 øC for Group 1 (1/day)	2	1.70E+00	EPA, 1987; QUAL2E Model Documentation; Table III-3: Range 1.0 - 3.0 day
	Optimal Temperature for Growth for Group 1 (øC)	30	8.00E+00	EPA, 1985; Figure 6-3
	Shape parameter for below optimal temperatures for Group 1	6.00E-03	6.00E-03	Values recommended by EPA from previous study
	Shape parameter for above optimal temperatures for Group 1	1.00E-02	1.00E-02	Values recommended by EPA from previous study
	Phytoplankton Respiration Rate Constant @20 øC for Group 1 (1/day)	0.2	5.00E-02	EPA, 1985; Table 6-18; Total Phytoplankton Range 0.005 - 0.8 day^{-1}
	Phytoplankton Respiration Temperature Coefficient for Group 1	1.08	1.04E+00	Wool, et al, undated. Water Quality Analysis Simulation Program (WASP)
	Phytoplankton Death Rate (Non-Zoo Predation) for Group 1 (1/day)	0.08	2.00E-01	EPA, 1985; Table 6-20; Total Phytoplankton Range 0.003 - 0.17 day^{-1}
	Phytoplankton Half-Saturation Constant for N Uptake for Group 1 (mg N/L)	0.10	1.00E-01	EPA, 1985; Table 6-16; Total Phytoplankton Range 0.0014 - 0.2 mg/L
	Phytoplankton Half-Saturation Constant for P Uptake for Group 1 (mg P/L)	0.03	1.00E-01	EPA, 1985; Table 6-16; Total Phytoplankton Range 0.0028 - 0.07 mg/L
	Phytoplankton Half-Saturation Constant for Si Uptake for Group 1 (mg Si/L)	0.05	8.00E-02	EPA, 1985; Table 6-16
	Nitrogen fixation option (0 no, 1=yes) for Group 1	0	0.00E+00	Indicates no nitrogen fixation
	Phytoplankton Optimal Light Saturation for Group 1 (Ly/day)	300	2.25E+02	EPA, 1985; Table 6-8
Phyto-plankton Green Algae	Phytoplankton Detritus to Carbon Ratio for Group 2 (mg D/mg C)	2.50E+00	2.50E+00	Did not simulate detritus
	Phytoplankton Nitrogen to Carbon Ratio for Group 2 (mg N/mg C)	0.18	1.75E-01	EPA, 1985; Figure 6-3
	Phytoplankton Phosphorus to Carbon Ratio for Group 2 (mg P/mg C)	0.025	5.00E-02	EPA, 1985; Figure 6-3
	Phytoplankton Carbon to Chlorophyll Ratio for Group 2 (mg C/mg Chl)	50	4.00E+01	EPA, 1985; Table 6-4
	Phytoplankton Maximum Growth Rate Constant @20 øC for Group 2 (1/day)	2.0	1.60E+00	EPA, 1987; QUAL2E Model Documentation; Table III-3: Range 1.0 - 3.0 day
	Optimal Temperature for Growth for Group 2 (øC)	35	1.50E+01	EPA, 1985; Figure 6-3
	Shape parameter for below optimal temperatures for Group 2	4.00E-03	4.00E-03	Values recommended by EPA from previous study
	Shape parameter for above optimal temperatures for Group 2	1.00E-02	1.00E-02	Values recommended by EPA from previous study
	Phytoplankton Respiration Rate Constant @20 øC for Group 2 (1/day)	0.2	1.00E-01	EPA, 1985; Table 6-18; Total Phytoplankton Range 0.005 - 0.8 day^{-1}
	Phytoplankton Respiration Temperature Coefficient for Group 2	1.08	1.04E+00	Wool, et al, undated. Water Quality Analysis Simulation Program (WASP)
	Phytoplankton Death Rate (Non-Zoo Predation) for Group 2 (1/day)	0.08	1.00E-01	EPA, 1985; Table 6-20; Total Phytoplankton Range 0.003 - 0.17 day^{-1}
	Phytoplankton Half-Saturation Constant for N Uptake for Group 2 (mg N/L)	0.10	1.00E-02	EPA, 1985; Table 6-16; Total Phytoplankton Range 0.0014 - 0.2 mg/L
	Phytoplankton Half-Saturation Constant for P Uptake for Group 2 (mg P/L)	0.03	1.00E-01	EPA, 1985; Table 6-16; Total Phytoplankton Range 0.0028 - 0.07 mg/L
	Nitrogen fixation option (0 no, 1=yes) for Group 2	0	0.00E+00	Indicates no nitrogen fixation
	Phytoplankton Optimal Light Saturation for Group 2 (Ly/day)	150	2.00E+02	EPA, 1985; Table 6-8
Phyto-plankton Blue-Green Algae	Phytoplankton Detritus to Carbon Ratio for Group 3 (mg D/mg C)	2.50E+00	2.50E+00	Did not simulate detritus
	Phytoplankton Nitrogen to Carbon Ratio for Group 3 (mg N/mg C)	0.18	1.00E-01	EPA, 1985; Figure 6-3
	Phytoplankton Phosphorus to Carbon Ratio for Group 3 (mg P/mg C)	0.025	1.00E-02	EPA, 1985; Figure 6-3
	Phytoplankton Carbon to Chlorophyll Ratio for Group 3 (mg C/mg Chl)	100	1.50E+02	EPA, 1985; Table 6-4
	Phytoplankton Maximum Growth Rate Constant @20 øC for Group 3 (1/day)	2.0	2.00E+00	EPA, 1987; QUAL2E Model Documentation; Table III-3: Range 1.0 - 3.0 day
	Optimal Temperature for Growth for Group 3 (øC)	40	2.00E+01	EPA, 1985; Figure 6-3
	Shape parameter for below optimal temperatures for Group 3	7.00E-03	7.00E-03	Values recommended by EPA from previous study
	Shape parameter for above optimal temperatures for Group 3	4.00E-03	4.00E-03	Values recommended by EPA from previous study
	Phytoplankton Respiration Rate Constant @20 øC for Group 3 (1/day)	0.2	1.00E-01	EPA, 1985; Table 6-18; Total Phytoplankton Range 0.005 - 0.8 day^{-1}
	Phytoplankton Respiration Temperature Coefficient for Group 3	1.08	1.04E+00	Wool, et al, undated. Water Quality Analysis Simulation Program (WASP)
	Phytoplankton Death Rate (Non-Zoo Predation) for Group 3 (1/day)	0.08	1.00E-01	EPA, 1985; Table 6-20; Total Phytoplankton Range 0.003 - 0.17 day^{-1}
	Phytoplankton Half-Saturation Constant for N Uptake for Group 3 (mg N/L)	0.10	4.00E-01	EPA, 1985; Table 6-16; Total Phytoplankton Range 0.0014 - 0.2 mg/L
	Phytoplankton Half-Saturation Constant for P Uptake for Group 3 (mg P/L)	0.03	2.50E-01	EPA, 1985; Table 6-16; Total Phytoplankton Range 0.0028 - 0.07 mg/L
	Nitrogen fixation option (0 no, 1=yes) for Group 3	1	1.00E+00	Indicates nitrogen fixation
	Phytoplankton Optimal Light Saturation for Group 3 (Ly/day)	300	2.75E+02	EPA, 1985; Table 6-8
Time Functions	Water Temperature Function 1 (°C)	Variable	Variable	Monthly average from STORET data
	Daily Solar Radiation (Langleys)	Variable	Variable	Measured at Denver International Airport
	Fraction Daily Light (fraction)	Variable	Variable	Measured at Denver International Airport
	Wind Speed Time Function 1 (m/sec)	Variable	Variable	Measured at Denver International Airport
	Sediment Oxygen Demand (mg/m2/day)	-----	0	Did not simulation dissolved oxygen
	Time Variable Ammonia Benthic Flux (mg/m2-day)	Calibration	20 - 35	Variable
	Time Variable Phosphorus Benthic Flux (mg/m2-day)	Calibration	50 - 100	Variable
	Zooplankton Population (count)			
	Air Temperature (°C)	Variable		Measured data from GSP Airport
	Ice Cover (fraction ice free)	100%	0 - 100%	Depended on time of year

References:

Ambrose, R.B., Wool, T.A., and Martin, J.L., 1993. The Water Quality Analysis Simulation Program, WASP5 Part A: Model Documentation. Environmental Research Laboratory. U.S. Environmental Protection Agency. Athens, GA.

Ambrose, R.B., Wool, T.A., Martin, J.L., Connolly, J.P., and Schanz, R.W., undated. WASP4, A Hydrodynamic and Water Quality Model - Model Theory, User's Manual, and Programmer's Guide. Environmental Research Laboratory. Office of Research and Development. U.S. Environmental Protection Agency. Athens, GA.

Chapra, S.C., 1997. Surface Water Quality Modeling. McGraw-Hill Companies, Inc. 844 pages.

EPA, 1985. Rates, Constants, and Kinetics Forumlations in Surface Water Quality Modleing (Second Edition). EPA/600/3-85/040. June 1985.

EPA, 1987. The Enhanced Stream Water Quality Models QUAL2E and QUAL2E-UNCAS: Documentation and User's Manual. EPA/600/3-87/007. May 1987.

Wool, et al, undated. Water Quality Analysis Simulation Program (WASP) Version 6.0. Draft: User's Manual. By Wool, T.A., Ambrose, R.B., Martin, J.L., and Comer, E.A.

Total chlorophyll calibration

Calibration of the WASP model to chlorophyll concentrations for Barr Lake and Milton Reservoir was extremely difficult due to the significant degree of variability in the measured concentrations and the difficulty in getting a mathematical model to predict very different concentrations over very short time scales. While a direct comparative evaluation might conclude that the WASP model proved to be an unreliable predictor of chlorophyll concentrations, the discrepancy is to be expected in hypereutrophic reservoirs. Measured values were not necessarily representative of lakewide average chlorophyll concentrations; an effort is underway in 2009 to characterize lakewide variability in chlorophyll. Additionally, nutrient levels are so high almost all of the time that other factors, some not addressed in the model, will control chlorophyll concentrations. Summer conditions favor cyanobacteria, and measurements confirm their dominance. Some cyanobacteria can fix atmospheric nitrogen dissolved in the water, minimizing the importance of the incoming nitrogen load. Many cyanobacteria are buoyant, altering the distribution of chlorophyll in a manner not covered by WASP, which predicts average concentrations throughout each reservoir. Reliable prediction of chlorophyll under hypereutrophic conditions is beyond the capacity of any model with which we have worked.

With water samples collected at approximately 1 meter from the water surface at a single location and WASP predicting a lakewide average value, it is appropriate to look more at the distribution of predicted and measured chlorophyll over a longer time period, to dampen the impact of extreme individual values. Therefore, the calibration to chlorophyll concentrations was attempted by adjusting each of several parameters so that the WASP simulated chlorophyll concentrations would match the magnitude and distribution of chlorophyll throughout the two-year period to the extent possible. In this way, the model could generally be said to effectively characterize chlorophyll conditions and the relative differences between concentration distributions under different loading assumptions and management scenarios will provide an indication of the relative increase or decrease in concentration resulting from loading changes.

Total phosphorus for Barr Lake

The measured and predicted total phosphorus concentrations for Barr Lake compare favorably (Figure 4-28). The calibrated WASP model was able to effectively capture the magnitude of the seasonal phosphorus concentrations and the long-term seasonal trend. Measured and predicted concentrations increased during the infill period, then declined during the spring and early summer months, then increased again later in summer as water levels declined and phosphorus was released from the bed sediments or resuspended by wind acting on the reservoir under its shallow state.

Total phosphorus for Milton Reservoir

The measured and predicted total phosphorus concentrations for Milton Reservoir do not compare as favorably as for Barr Lake but do generally track the magnitude and distribution of concentration throughout the two-year simulation period (Figure 4-29). Measured concentrations remain elevated longer after refill, but eventually decline in late summer and fall, while predicted concentrations tend to decline throughout the summer months. The discrepancy could mean that either less phosphorus is being removed from the water column than predicted through settling and sequestering by algae, or more phosphorus is being released into the water column through internal loading than currently projected by the model. The latter seems more likely, and although this will not greatly affect development of a TMDL, additional investigation is warranted when considering in-lake load reduction implementation options.

Total chlorophyll for Barr Lake

Measured and predicted total chlorophyll mean concentrations in Barr Lake are generally in agreement, but the measured values exhibit a lot more variability than the predicted values (Figure 4-30). The WASP model effectively captures the distribution of slightly elevated chlorophyll in the spring and then even more elevated concentrations during the summer months, but fails to mimic the largest blooms. This is partly a function of the

Figure 4-28. Time series calibration of monthly total phosphorus in Barr Lake

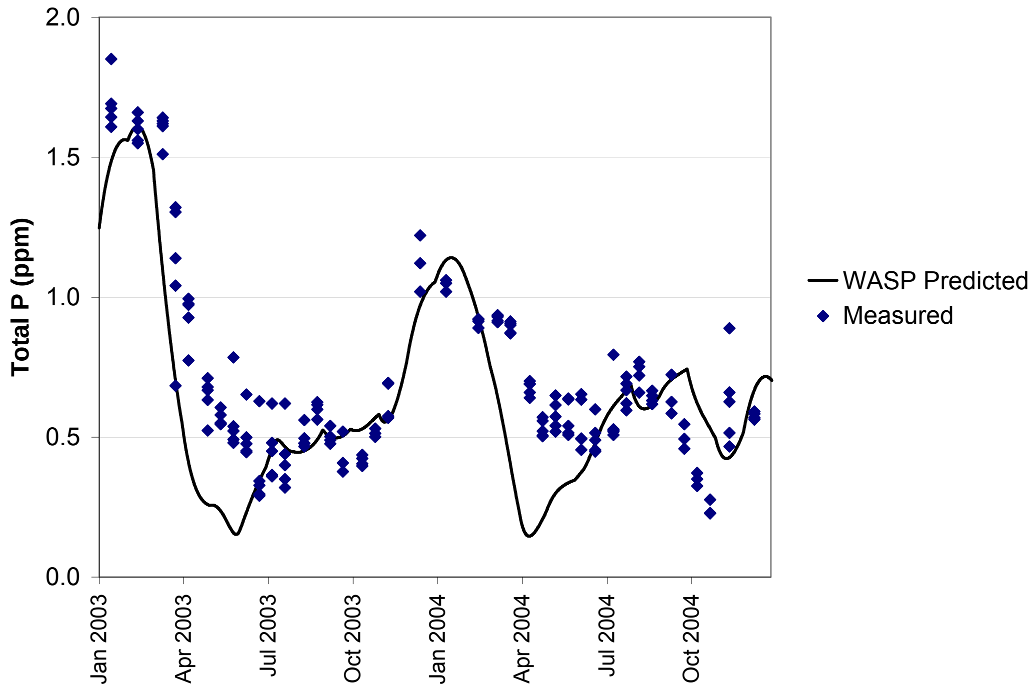


Figure 4-29. Time series calibration of monthly total phosphorus in Milton Reservoir

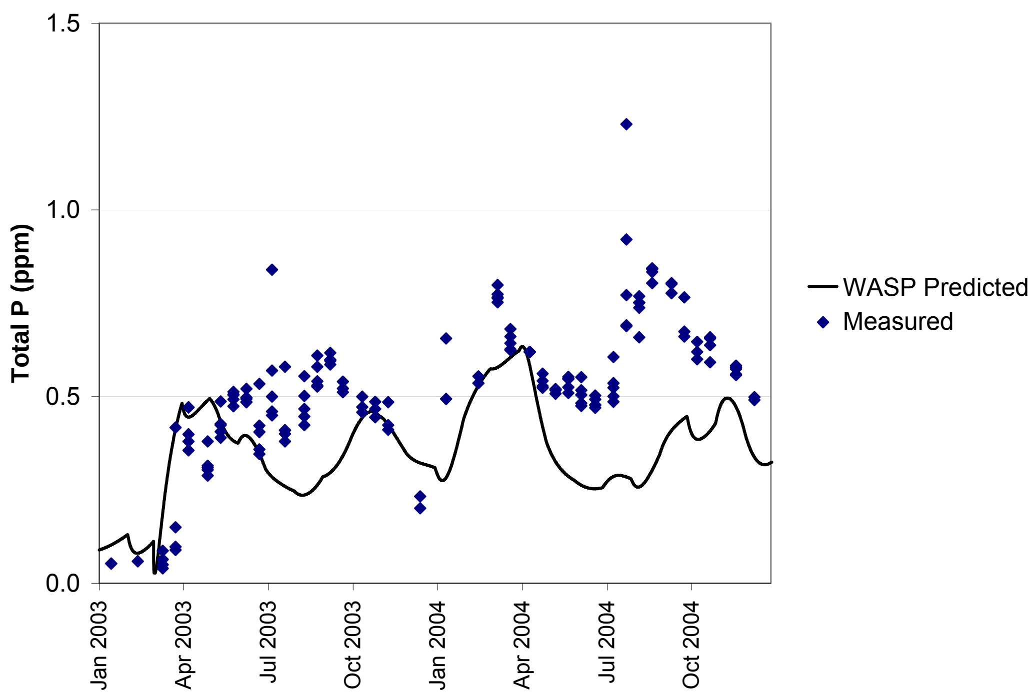


Figure 4-30. Time series calibration of monthly chlorophyll in Barr Reservoir

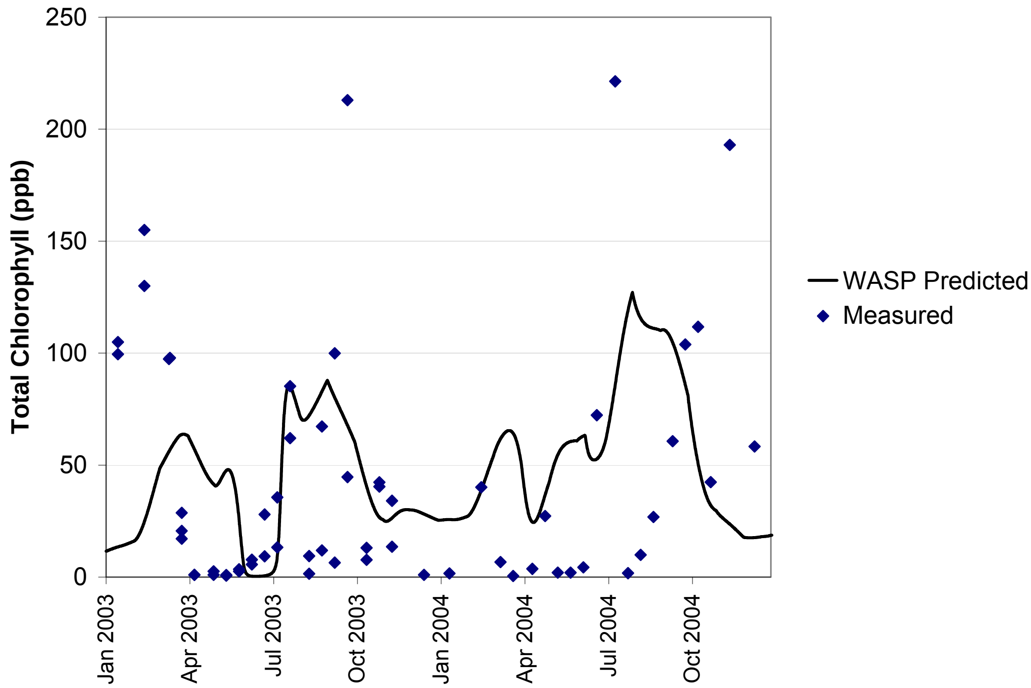
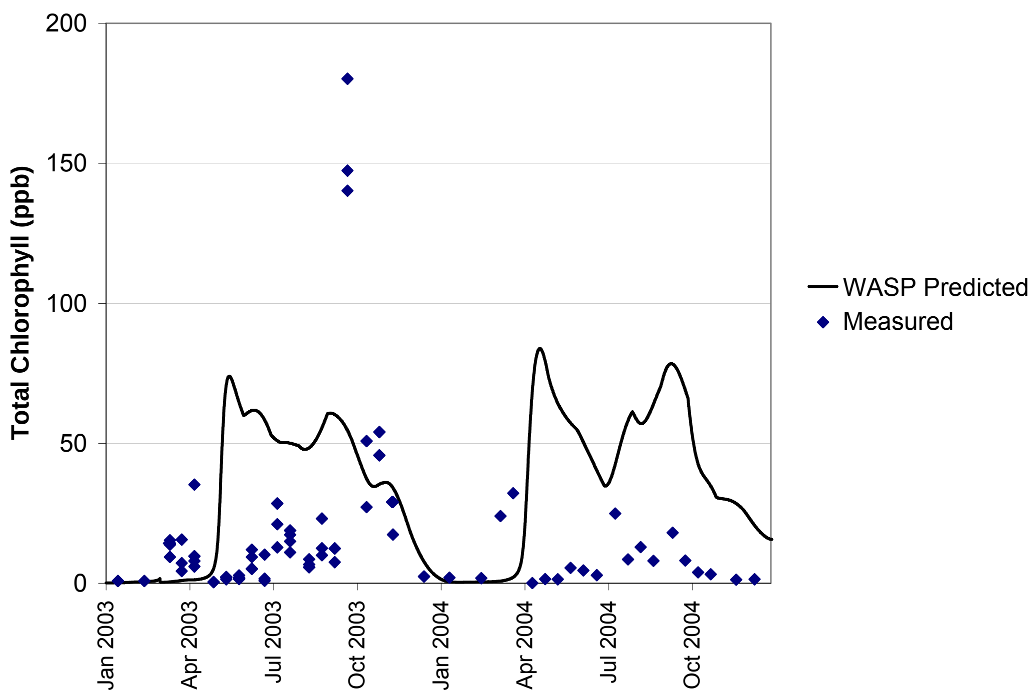


Figure 4-31. Time series calibration of monthly chlorophyll in Milton Reservoir



model being unable to account for surface scum formation by buoyant cyanobacteria and observed clumping of some algae, but the predicted values are believed to reasonably represent the chlorophyll level averaged over the lake vertically and horizontally. Monitoring is underway in 2009 to investigate lakewide variability in chlorophyll that may be useful in interpreting model results.

Total chlorophyll for Milton Reservoir

The magnitude of predicted chlorophyll concentrations in Milton Reservoir were only moderately representative of measured concentrations during the simulation period (Figure 4-31). However, the general distribution of predicted and measured chlorophyll concentrations is generally in agreement. Both the model and the measured values indicated very low concentrations during the winter months and then markedly higher concentrations throughout the summer. The WASP model is a reasonably good predictor during the 2003 simulation year but consistently overpredicts chlorophyll during the 2004 simulation year. Algal controls not accounted for in the model are presumed to be responsible. This situation is not expected to be caused by the limited agreement between predicted and measured phosphorus levels, as phosphorus is high enough all summer to support dense algal blooms. Rather, both the phosphorus and chlorophyll discrepancies may be symptoms of influences not adequately accounted for in the WASP model. Again, further investigation is warranted.

4.3.6 Statistical comparisons of WASP model calibration

In addition to comparison of timing and magnitude of the measured and predicted concentrations, a statistical evaluation of the distribution of values is a desirable means of comparing overall results, especially when further scenarios are to be tested. Graphic illustrations of statistical evaluations are often made using the box-and-whisker format. This format allows for a visual evaluation of an entire dataset, regardless of the number of data points. The box-and-whisker format provides a graphic illustration of percentiles and outliers in a dataset, allowing easy comparison of mean, median, and overall distribution of values over the range encountered.

The box-and-whisker plots applied here illustrate the mean, median, 5th, 25th, 75th, and 95th percentiles, and values that fall outside the 5th to 95th percentile range. These more extreme values are termed “outliers”. All data values are included in the development of each box-and-whisker plot. For comparison purposes, all measured values are used to develop corresponding box-and-whisker plots.

Total phosphorus comparison

The total phosphorus comparison for Barr Lake indicated that the predicted concentrations were, in general, only slightly lower than the measured values (Figure 4-32). The range of concentrations is generally the same between the measured and predicted and the overall character of both the measured and predicted data sets is very similar. The total phosphorus concentrations for Milton Reservoir indicated that the predicted values were generally lower than the measured values by an average of about 0.2 mg/L. The range of concentrations is similar but the measured dataset has more outliers than the predicted dataset. As the external load to Milton Reservoir may be overpredicted, it is striking that the inlake concentrations are being underpredicted. Further model adjustment would involve altering the internal processing of phosphorus, most likely the internal loading coefficient during summer, but does not appear necessary at this time.

Despite some disagreement between measured and predicted values, both of these comparisons suggest that the model is able to provide reasonable predictions of total phosphorus over the longer term in each reservoir, at least in terms of general trophic categories that would relate to use support and specifically to pH compliance. The distributions are reasonably similar and the means are believed to be close enough to be useful for evaluating management alternatives. The variability in Milton Reservoir creates additional uncertainty that we would like to minimize, but within the constraints of model features, closer matches are not possible at this time. As a consequence, results of modeling for chosen scenarios must focus on the direction and magnitude of change, not the exact values obtained.

Figure 4-32. Box plot calibration of monthly total phosphorus in Barr Lake and Milton Reservoir

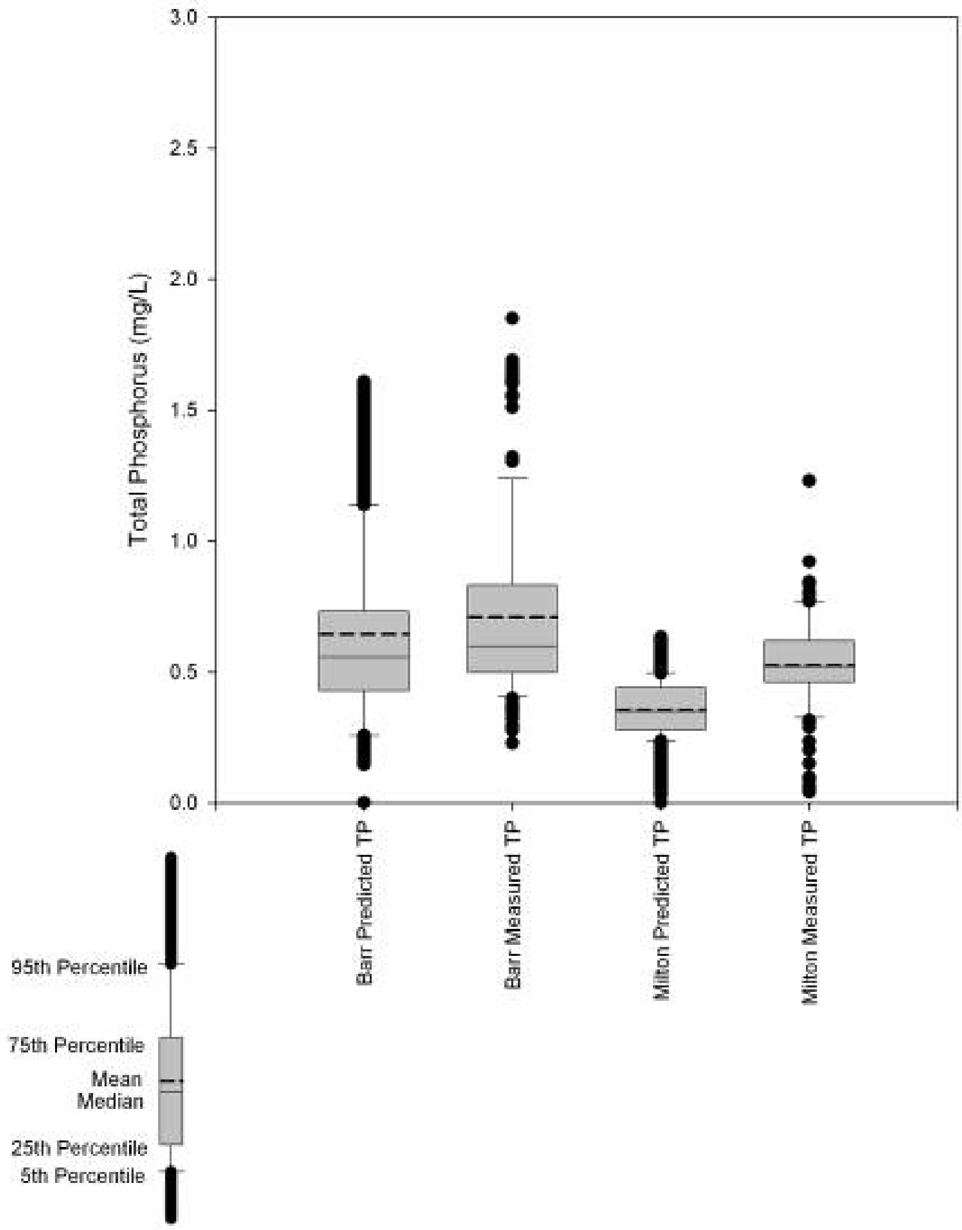
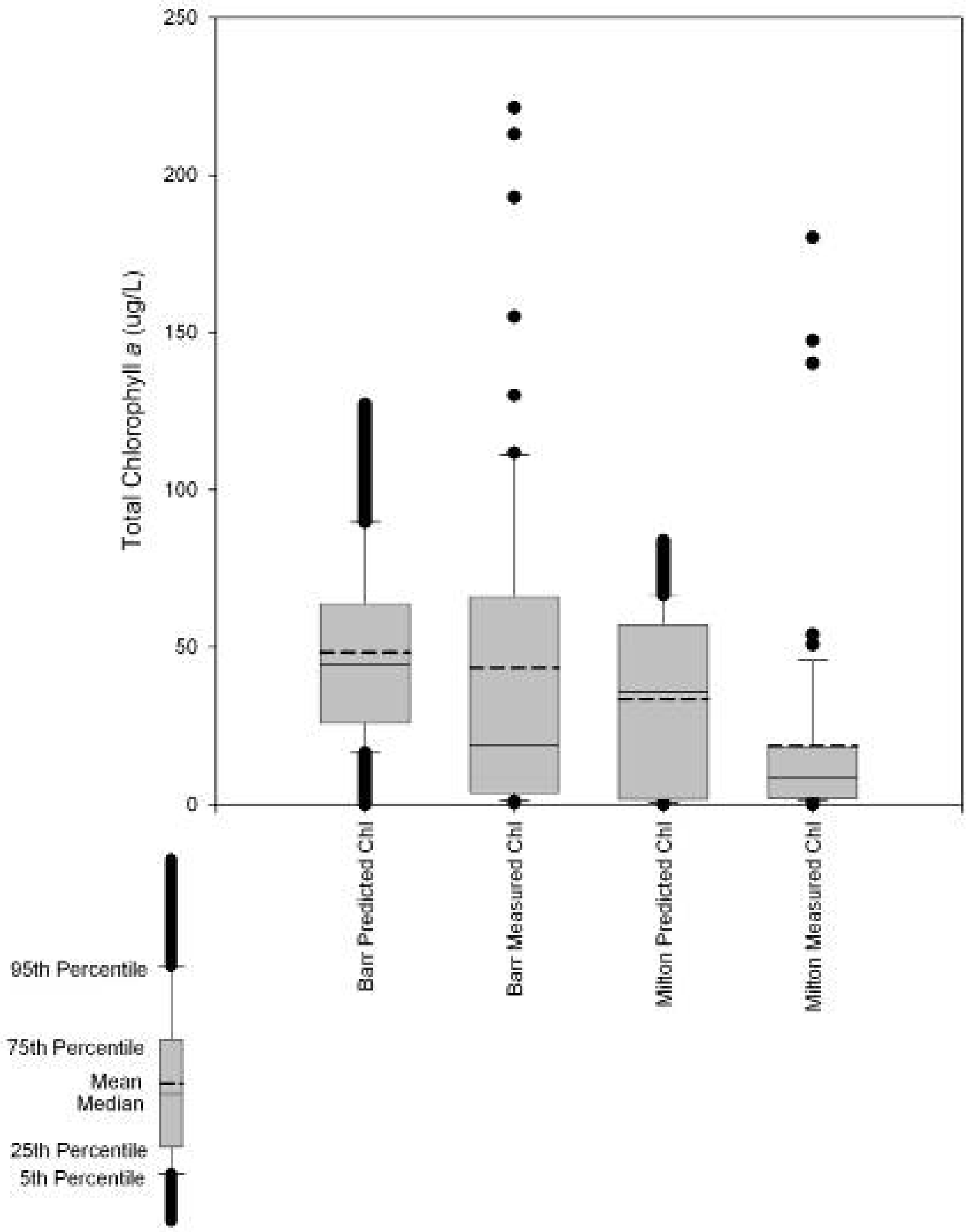


Figure 4-33. Box plot calibration of monthly chlorophyll in Barr Lake and Milton Reservoir



Total chlorophyll comparison

The box-and-whisker evaluation of chlorophyll concentrations (Figure 4-33) provides results that are not as favorable as the total phosphorus comparison (Figure 4-32). In Barr Lake, the average measured and predicted chlorophyll concentrations are nearly identical while the median measured chlorophyll concentration is significantly lower than the median predicted chlorophyll concentration. Low predicted chlorophyll concentrations in Barr Lake are generally lacking, while they tend to be more dominant in the measured data set. Predicted average and median chlorophyll concentrations for Milton Reservoir are significantly higher than the measured concentrations and occur over a much broader range. The model is unable to account for some influences that are apparently important to chlorophyll levels at what are routinely high phosphorus concentrations.

4.3.7 Suitability of SWAT/WASP models for watershed/reservoir predictions

The combination of the SWAT watershed model and the WASP water quality model proved to be an effective tool at replicating the hydrologic and nutrient budget in the Barr-Milton datashed and in Barr Lake and Milton Reservoir. The enhanced version of the SWAT model turned out to be extremely useful at effectively capturing the transfer of water around the basin, which was critical to mimic the hydraulics of this highly regulated and managed watershed.

The SWAT model was able to effectively use GIS files to describe the topography, land use, and soils within the watershed to develop input files for the SWAT model. Environmental data were also easily incorporated into the model to provide some of the important boundary conditions required to execute a simulation. The ability of the SWAT model to use a monthly time step simplified the data requirements of the watershed model without compromising the level of detail necessary to capture the long-term effects of nutrient enrichment on Barr Lake and Milton Reservoir. An evaluation of the SWAT model results indicated that, given the input data applied, the model was able to acceptably predict the general magnitude and variability of the phosphorus and nitrogen loads to both Barr Lake and Milton Reservoir over the two-year simulation period.

The WASP model was viewed as a suitable platform for simulating lake water quality because of the ease of use and the ability to utilize a hydrodynamic linkage file and a loading file. These two files were created using VB Macros and the results from the SWAT monthly watershed modeling simulations. The existing WASP model (Version 7.2) was deficient in that at the onset of this investigation it did not simulate more than one algal group. Fortunately, an updated *beta* test version of the model was available as WASP 7.3. With the multiple phytoplankton group version of WASP 7.3, which includes an “Advanced Eutrophication” routine, the WASP model was able to generally replicate the magnitude and variability of chlorophyll using diatoms, green algae, and cyanobacteria as the three algal groups. The detailed eutrophication simulation offered by WASP 7.3 provided a detailed temporal simulation in Barr Lake and Milton Reservoir. The model provides lakewide averages and does not attempt to capture any vertical or laterally heterogeneity, but this was not viewed as a necessity in these reservoirs based on examination of considerable data.

The SWAT model and the WASP model can be used to simulate the watershed loads and inlake eutrophication independently, but linking the two was necessary to effectively transfer the flow and load information from SWAT to WASP. The linkage of two models provided a suitable platform to automate the watershed and lake simulation processes.

5.0 Simulation of management alternatives

The simulation of management alternatives and providing predictive information to support the development of a TMDL for Barr Lake and Milton Reservoir was the ultimate goal of this investigation. Management alternatives allow the model user to determine the long-term effects of some modification to the Barr-Milton watershed management on lake and reservoir water quality. The following sections outline the general objectives of the management simulations and then describe each of the scenarios and their respective outcomes.

5.1 Goal of management simulations

The ability to develop and simulate management scenarios followed the considerable effort involved in developing and calibrating the SWAT watershed model and the WASP inlake model. This is particularly true of the watershed model development since the revised version of the SWAT model provides for modification to not only the point and nonpoint sources directly but also to the transfers of water around the watershed.

The goal of the management simulations was to investigate management options that could adequately improve the water quality in Barr Lake and Milton Reservoir. The first set of four simulations was largely a model sensitivity analysis, where adjustments were made to each of several management options and the predicted concentrations of nutrients and chlorophyll in Barr Lake and Milton Reservoir were evaluated. The second set of four simulations expanded on the results of the first set of four and capitalized on the predictions of nutrient and chlorophyll from different management schemes.

5.2 Overview of management options

Management options are considered to be any variance from the current conditions within the watershed that can be effectively managed to improve water quality in Barr Lake and Milton Reservoir. While eliminating all nutrient discharges to surface water within the watershed would lead to a substantial improvement inlake water quality, this is an impractical scenario and not a useful consideration. However, substantial reductions in specifically targeted nutrient sources are possible and might achieve the desired levels of lake and reservoir improvement. Additional management scenarios could include a reduction in not only the magnitude of nutrient loads but also the specific sources of the loads and the timing of the discharge or transfer of water within the watershed.

While the complexity of the Barr-Milton Watershed tended to confound the initial setup of the watershed model, the flexibility of water management within the watershed and robustness of the enhanced version of the SWAT model provides for the simulation of a myriad of management options that would otherwise not be possible. Management alternatives are generally grouped into three categories, including:

1. *Point source controls* – This management alternative includes any modification to a discharge of nutrients directly into the South Platte River, tributaries to the South Platte, or any of several canals within the watershed. In general, these modifications would be to any of the WWTP dischargers within the watershed and are designed to be consistent with levels of treatment possible for each individual facility, although by no means simple or inexpensive.
2. *Nonpoint source controls* – This management alternative includes any modifications to a land use type within the watershed to alter runoff quality. For the purposes of this exercise, no distinction is made between piped runoff from areas covered by MS4 permits, which are defined as point sources for regulatory purposes, and other unconfined sources of runoff. Different land uses clearly discharge different levels of nutrients based on the practices occurring on that land use type. For example, more phosphorus is generally exported from agricultural cropland than from natural grasslands. Similarly, more phosphorus is exported from highly developed areas than from natural forested areas.

Watershed modifications to control nonpoint sources of nutrients would generally be to consider changing a land use type from a high nutrient export type to a low export type or applying a Best Management Practice (BMP) suitable for the watershed and land use type. In the case of the Barr-Milton datashed this would generally be the conversion of agricultural land to developed land or a fractional reduction in nutrient loads resulting from the effects of a BMP.

3. Inlake controls – Management alternatives that involve mechanical, chemical, or biological modifications to either Barr Lake or Milton Reservoir directly are considered inlake controls. Such controls are commonly used to improve short term water quality conditions in water bodies, but can be applied in an ongoing fashion where economical to achieve longer term results.

5.3 Alternative management simulations (Scenarios 1 through 4)

Once the watershed and lake models were declared to be acceptably calibrated for use in predicting lake response to watershed controls, several scenarios were devised in an attempt to test the sensitivity of the model and demonstrate opportunities and constraints relating to control of phosphorus loads to the impoundments. Initially, four scenarios were developed to simulate the effects of 1) the reduction of nutrient loads from contributing WWTPs, 2) the timing of reservoir refill, 3) quantification of the effects of nonpoint sources on inlake water quality, and 4) controlling internal loads of phosphorus to the water column. The results of the scenarios are all presented using the same type of box-and-whisker illustration that was used to evaluate the inlake calibration.

The following describes each of the four scenarios that were run during the initial phase of modeling to test management alternatives.

5.3.1 Scenario 1 – wastewater control

The wastewater control scenario involves reducing phosphorus concentrations from the three largest wastewater dischargers in the watershed for the duration of the two-year simulation. The wastewater management scenario requires that the watershed and inlake model be run a total of three times with progressively lower effluent discharge concentrations of dissolved phosphorus from Metro (the discharges to the SPR and the Pump Works), Littleton-Englewood, and the South Adams County Water and Sanitation District (SACWSD). These WWTPs were chosen because they represent the largest inputs to the system. Discharge total phosphorus concentrations of 1.0 mg/L, 0.5 mg/L, and 0.05 mg/L were applied throughout the entire simulation and were uniformly adjusted for each of the three facilities.

5.3.2 Scenario 2 – reservoir management

The reservoir management scenarios are used to evaluate the ability to improve water quality in the reservoirs by altering the timing and source of water for reservoir filling. This simulation involves removing the Pump Works discharge to the Burlington-O'Brian Canal during the 2003-2004 winter and spring fill periods (Nov 1st through May 1st) and redirecting that water to the SPR instead. The entire volume of water redirected during the two infill periods (2003 - 2004) is then be made up by transferring an equivalent additional volume of water from the SPR to the Burlington-O'Brian Canal during June of each respective year. This simulation results in Barr Lake being filled later in the spring but with water reflective of the SPR rather than the nutrient rich water from the Pump Works. This also has a direct effect on the nutrient loads entering Milton Reservoir. Note that most WWTP inputs are downstream of the point at which SPR is redirected into the Burlington-O’Brian Canal and Barr Lake, although water diverted into the South Platte Canal to Milton Reservoir is still impacted by all the WWTP discharges.

5.3.3 Scenario 3 – land use alterations

The land use change scenario is used to evaluate the effect of the agricultural use of water on the water quality in Barr Lake and Milton Reservoir. While the SWAT model can directly simulate the effect of altering land use on the export of nutrients from a subwatershed, these simulations result in a negligible reduction in predicted nutrient loads until point sources of nutrients are brought under control. Rather than simulate these land use changes directly, this simulation involves running two scenarios and then evaluating the difference in predicted inlake water quality between the two scenarios.

The first scenario simulates the 2003 - 2004 period without any WWTP discharges while maintaining the transfers and the agricultural use of water in the lower watershed. The second scenario simulates the 2003 - 2004 period without any WWTP discharge while maintaining the transfers, but without any agricultural use of water in the lower watershed. The difference in Barr Lake and Milton Reservoir water quality between the two scenarios indicates the effect of the removal of water from Barr Lake for agricultural and the return of agricultural groundwater to the Beebe Canal and the Platte Valley Canal on inlake water quality. This is what would be expected if agricultural land was converted to other uses not requiring irrigation use of Barr-Milton water. It is simplistic in that other land uses might require this water for other supply purposes (e.g., domestic supply with urbanization), but provides some indication of the importance of water loss from the reservoirs relating to agriculture.

5.3.4 Scenario 4 – inlake modifications

The reservoir treatment scenarios are used to evaluate the effect of a decreased internal phosphorus load to the reservoirs. The internal load of phosphorus to each reservoirs was determined through model calibration to account for elevated water column phosphorus loads that could not be accounted for by inflows alone. This is a confusing area of study, given past mass balance efforts that assess only net changes. In reality, much of the incoming phosphorus load is incorporated into algae and settles to the bottom in the spring, while release of some of this phosphorus by decay and resuspension as water levels decline increases internal loads over the summer. These internal loads are more significant now than mass balance models indicate, and are expected to dominate once point sources of phosphorus are reduced. Internal loading is evaluated with effluent discharge concentrations of dissolved phosphorus from Metro (the discharge to the SPR and the Pump Works), Littleton-Englewood, and SACWSD set at 0.5 mg/L. Two simulations were run, one at 50% of the calibrated internal phosphorus load and another at 10% of the calibrated internal phosphorus load, to simulate a control of the seasonal phosphorus release from the reservoir sediments at 50 to 90%, a reasonable range for inlake phosphorus inactivation programs.

The effects of the various scenarios on total phosphorus in Barr Lake are illustrated in Figure 5-1, while the effects on total chlorophyll in Barr Lake are illustrated in Figure 5-2. The effects on total phosphorus in Milton Reservoir are illustrated in Figure 5-3 and the effects on total chlorophyll in Milton Reservoir are illustrated in Figure 5-4.

Figure 5-1. Box and whisker plots showing Barr Lake total phosphorus scenario results

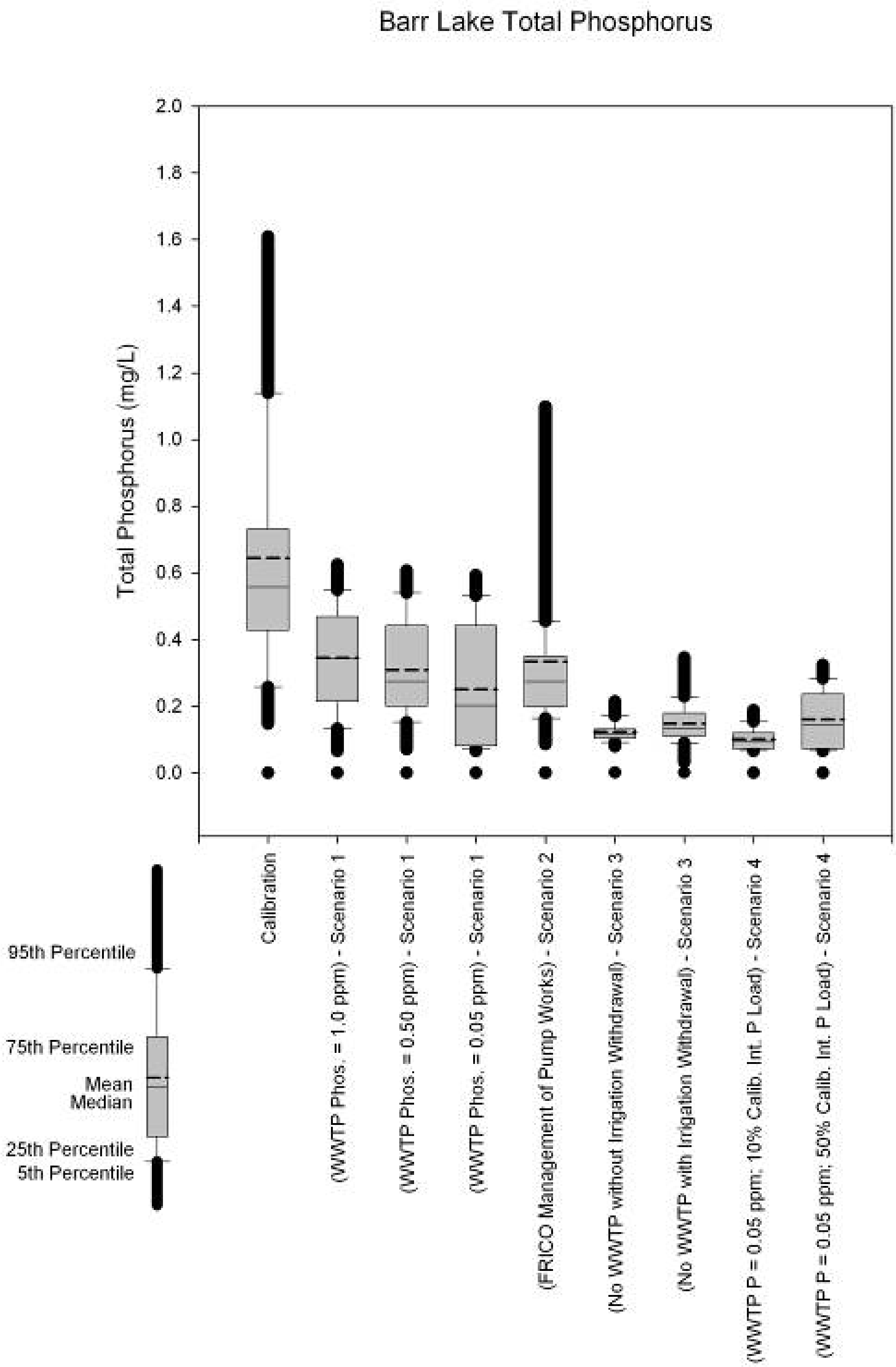


Figure 5-2. Box and whisker plots showing Barr Lake chlorophyll a scenario results

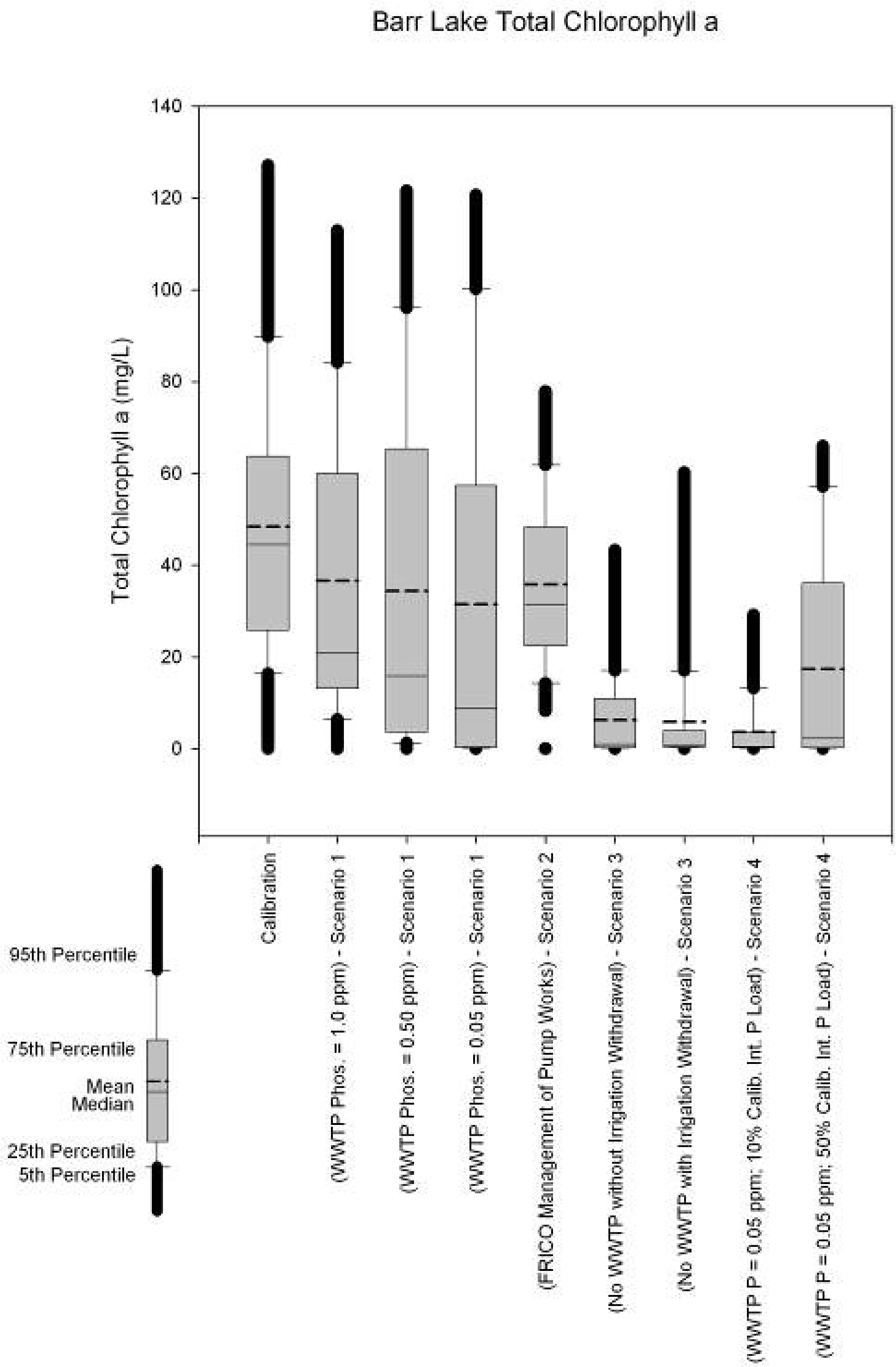


Figure 5-3. Box and whisker plots showing Milton Reservoir total phosphorus scenario results

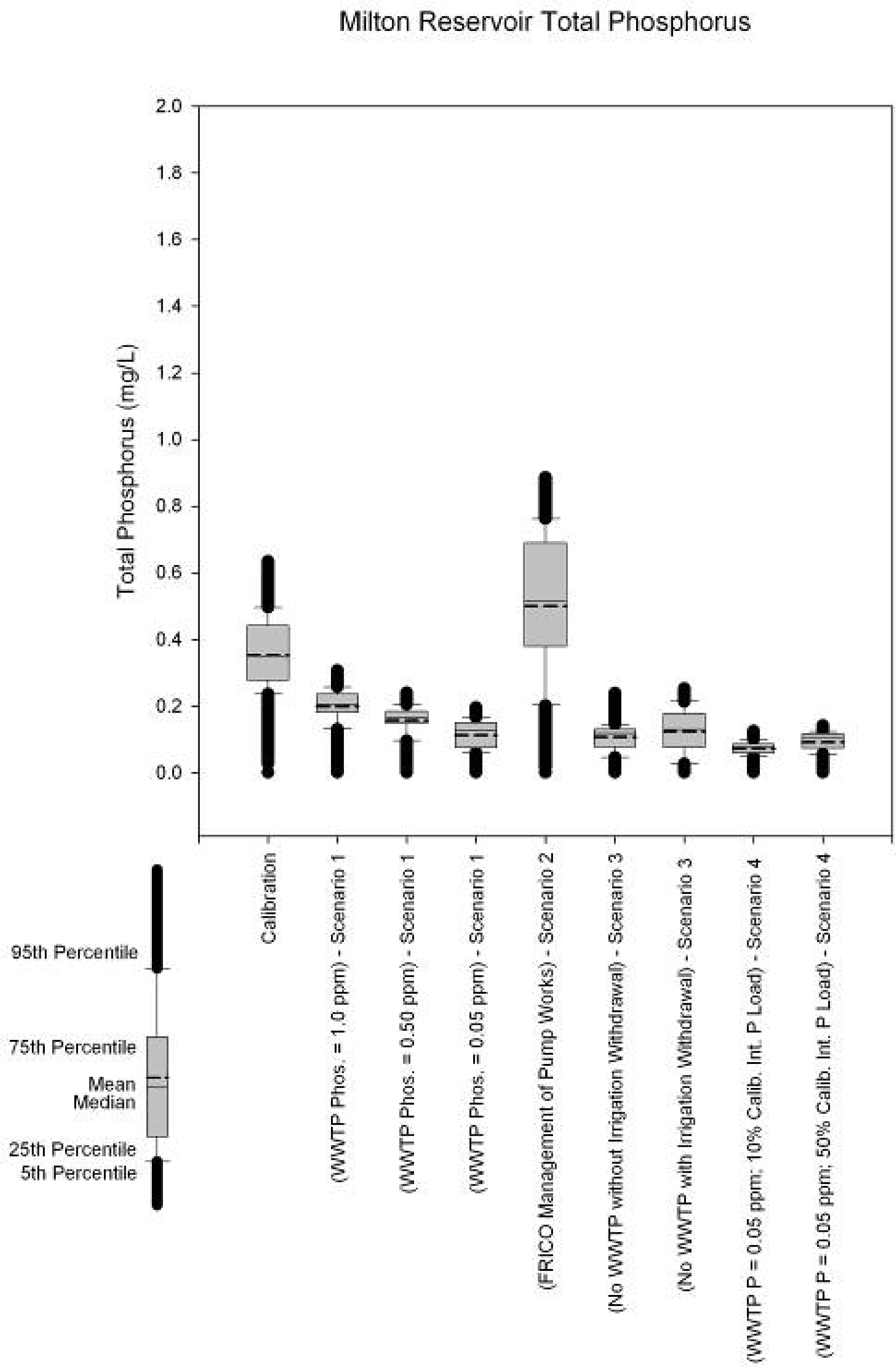
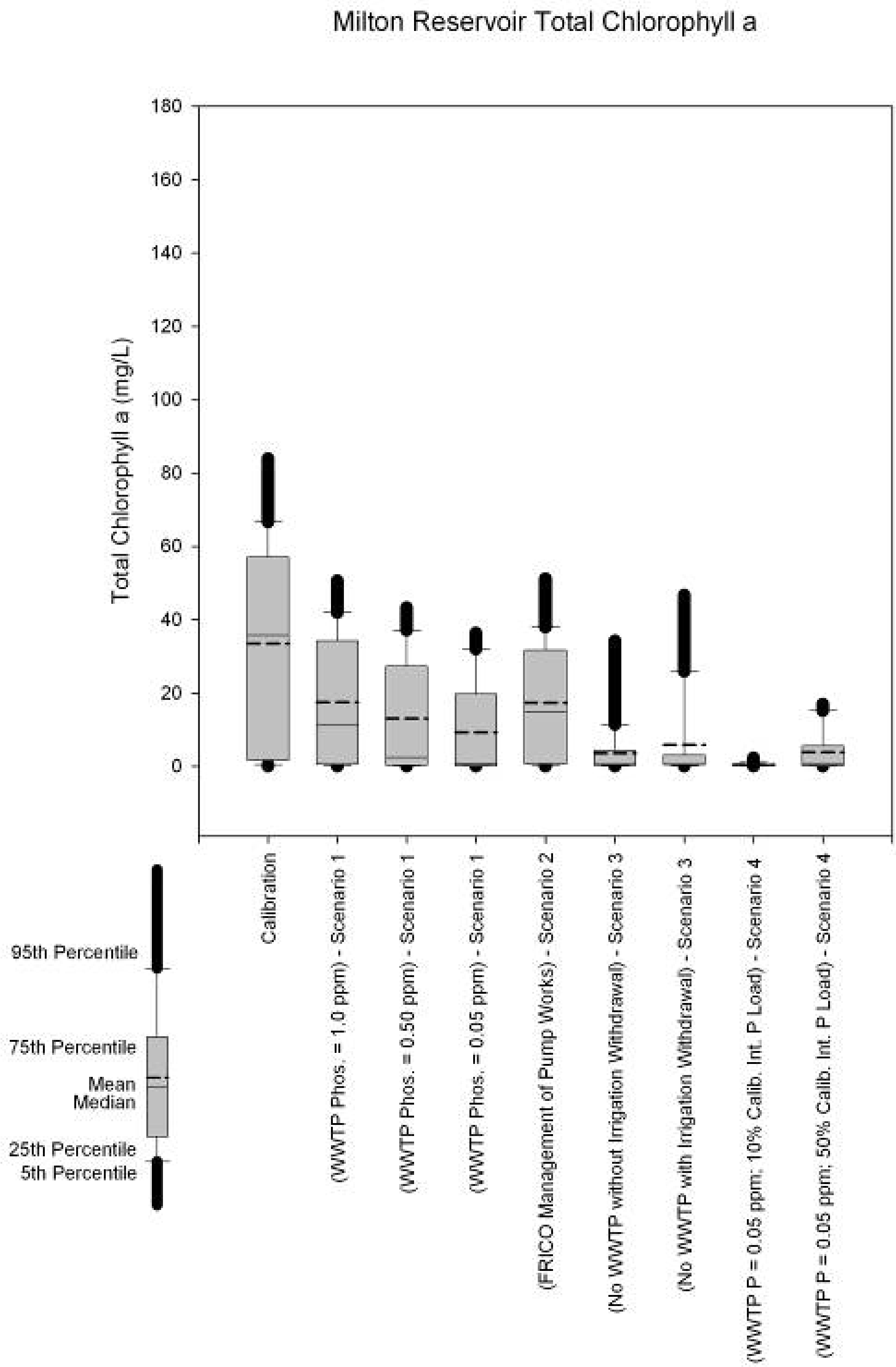


Figure 5-4. Box and whisker plots showing Milton Reservoir chlorophyll a scenario results



5.3.5 Results of management simulations (Scenarios 1 though 4)

The SWAT and WASP model predictions from Scenario 1 indicate that total phosphorus concentrations can be reduced in Barr Lake and Milton Reservoir through reductions in WWTP total phosphorus loads and that internal loading of phosphorus to Barr Lake and Milton Reservoir is significant. Figures 5-1 and 5-3 illustrate that significant reductions in total phosphorus concentrations in the lake and reservoir can be achieved by reducing phosphorus loads from the three largest WWTPs. In both Barr Lake and Milton Reservoir, each statistical measure of the predicted concentration distribution decreases with successive reductions of phosphorus reductions from the plants. There is, however, a point of diminishing returns, as reductions in loading of phosphorus to the reservoirs is counteracted by the internal load of phosphorus. The results of Scenario 1 also indicated distinct reductions in predicted chlorophyll concentrations in Barr Lake and Milton Reservoir, coincident with the predicted reductions in phosphorus, but this distribution is much clearer in the Milton Reservoir predictions (Figure 5-2) than in the Barr Lake predictions (Figure 5-3). The results from Scenario 1 indicate that significant reductions can be made to phosphorus and chlorophyll concentrations in Barr Lake and Milton Reservoir with reductions in phosphorus loads from each of the three major WWTPs but that the overall reduction becomes limited because of the competing effect of the simulated internal phosphorus load.

The Scenario 2 simulation required a modification to the timing of the discharge from the Pump Works and the transfer of water from the South Platte River to the Burlington-O'Brian Canal and took full advantage of the capabilities added to the SWAT model as a result of this investigation. The results of this simulation indicate that while total phosphorus and chlorophyll concentrations in Barr Lake are reduced by replacing wastewater discharged through the Pump Works with water from the South Platte River, the concentrations of each tend to increase in Milton Reservoir. This increase is a direct result of the elevated nutrient loads available in the South Platte River, due to the simulated alternative upstream management (more Metro wastewater enters the South Platte River), and a greater availability of nutrients in the river during the downstream transfer form the South Platte River to the Platte Valley Canal. The results from Scenario 2 indicate that while alternative management in the form of altered water transfers can be used to improve water quality in Barr Lake, it may be at the expense of water quality in Milton Reservoir.

The Scenario 3 simulation was designed to gain some insight into the effects of nonpoint sources of nutrients from agricultural activities and the influence of water movement for agricultural purposes. If agricultural use of land and water decreases, so will these influences. As WWTP inputs are dominant, these were removed to facilitate a more direct analysis of agricultural influences. But given that there are no WWTPs included in the simulation, it is clearly not a realistic management alternative on its own. The results of this simulation indicate, not surprisingly, that removing all WWTP discharge of phosphorus from the watershed substantially reduced total phosphorus predictions in Barr Lake and Milton Reservoir. With regard to the influence of agricultural practices, the simulation illustrates a minimal additional change in the total phosphorus concentrations linked to nonpoint sources and the concentrating effect that irrigation withdrawal has on the lakes. This simulation highlights the fact that the water quality problems in Barr Lake and Milton Reservoir are largely the result of point source discharges.

The Scenario 4 simulation was used to quantify the relative magnitude of the effect of an internal load of phosphorus on the total phosphorus and chlorophyll concentrations in Barr Lake and Milton Reservoir. This simulation was run using the lowest WWTP load of total phosphorus applied in Scenario 1. The results of Scenario 4 indicated that total phosphorus and chlorophyll can be substantially reduced in the lake and reservoir if the internal load is reduced to 10% of its calibrated rate, but that at 50% of its calibrated rate the chlorophyll concentrations in Barr Lake, while being reduced, may still remain relatively elevated. The effect is not so striking in Milton Reservoir, but as conditions in Milton Reservoir are largely dependent on conditions in Barr Lake, there is greater uncertainty surrounding predictions for Milton Reservoir. The many years of accumulated P reserves in these lakes provides a reserve that can counter decreased external loading for many years; experience elsewhere suggests that internal load would remain a factor for two to three decades.

The results of the first four simulations indicated that the model responds in an intuitive fashion and that the relative magnitude and direction of the changes make sense. The results indicate that the water quality problems in these two reservoirs are largely point source problems and that internal loading is significant. Also, the simulations indicate that altering the timing of discharge to the lake and reservoir can have a significant effect on inlake concentrations in Barr Lake.

5.4 Alternative management simulations (Scenarios 5 through 8)

The development and execution of the second set of four alternative management scenarios followed a detailed review of the results from the first four scenarios. AECOM worked with the BMW Association to develop this second set of additional scenarios to refine the model predictions and take advantage of what was learned during the first round of simulations.

The refinements made to the first four scenarios and applied to the second set 1) evaluated the effects of additional water treatment from different combinations of wastewater dischargers, 2) looked at both constant and seasonal modifications to treatment of wastewater, 3) looked at the effects of reducing runoff-derived nutrient loads from MS4 permitted and non-permitted watersheds, and 4) incorporated a reduction of internal loads into the other load reduction scenarios. The scenarios expanded the understanding of model response and will be used to further refine the management alternatives which may ultimately be included in the TMDL.

The following describes each of the four scenarios that were run during the second phase of modeling to test management alternatives.

5.4.1 Scenario 5 – detailed wastewater control

The detailed wastewater control scenario was designed to determine the effect of a reduction in total phosphorus from each of several WWTPs to 1 mg/L and 100 µg/L. These values bracket the range of phosphorus effluent limits commonly applied by the USEPA and state agencies when renewing permits, although higher and lower limits have certainly been imposed. Phosphorus reductions were made to both the Littleton-Englewood and the Metro WWTP, then the Centennial WWTP was included, and finally reductions were made to all WWTPs included in the SWAT model. The Centennial WWTP was addressed before the South Adams WWTP in this scenario as a function of its position in the watershed and potential impact on Barr Lake. Since it has been determined that the bulk of the phosphorus enters Barr Lake and Milton Reservoir during the spring refill period, a seasonal component was also added to these simulations and reductions were only made during the late fall and early spring.(Nov 1 to Apr 1). To account for additional treatment, which is either already in place or expected to occur in the near future, total nitrogen from the Metro WWTP, including the Pump Works discharge, was reduced by 75% and total nitrogen from the Littleton-Englewood WWTP was reduced by 30%.

5.4.2 Scenario 6 – reductions from permitted areas

The simulation to investigate the effect of nonpoint source reductions from the MS4 permitted areas was developed to highlight the reduction in total phosphorus and chlorophyll in Barr Lake and Milton Reservoir that could be achieved through runoff management in developed areas served by municipal separate storm sewer systems (MS4). The reduction was not expected to be significant, given the results from Scenario 3, but quantifying the potential reduction was considered important to overall planning. In this simulation the total phosphorus concentration from all the WWTPs was fixed at 100 µg/L and the total phosphorus loads from the MS4 areas was reduced by 25%. Similar to Scenario 5, total nitrogen from the Metro WWTP, including the Pump Works discharge, was reduced by 75% and total nitrogen from the Littleton-Englewood WWTP was reduced by 30%.

5.4.3 Scenario 7 – reductions from permitted and non-permitted areas

This simulation to investigate the effect of nonpoint source reductions from non-regulated areas was developed to highlight the reduction in total phosphorus and chlorophyll in Barr Lake and Milton Reservoir that could be achieved by runoff management in both permitted (MS4) and non-permitted areas. This simulation was very similar to the previous scenario except that both MS4 and non-regulated areas were lumped together and assigned a reduction of P inputs of 25%. In this simulation the total phosphorus concentration from all the WWTPs was fixed at 100 µg/L. Similar to Scenario 6, total nitrogen from the Metro WWTP, including the Pump Works discharge, was reduced by 75% and total nitrogen from the Littleton-Englewood WWTP was reduced by 30%.

5.4.4 Scenario 8 – modified reductions to internal loads

This simulation is an expanded version of Scenario 5, with an additional reduction in the internal load of phosphorus. The total phosphorus concentrations from all WWTPs are set at 100 µg/L. Total nitrogen from the Metro WWTP, including the Pump Works discharge, was reduced by 75% and total nitrogen from the Littleton-Englewood WWTP was reduced by 30%. The internal load of phosphorus in both Barr Lake and Milton Reservoir has been reduced by 70%, which represents a realistic goal if phosphorus inactivation is used as an inlake management alternative.

The effects of the various scenarios on total phosphorus in Barr Lake are illustrated in Figure 5-5, while the effects on total chlorophyll in Barr Lake are illustrated in Figure 5-6. The effects on total phosphorus in Milton Reservoir are illustrated in Figure 5-7, and the effects on total chlorophyll in Milton Reservoir are illustrated in Figure 5-8.

5.4.5 Results of management simulations (Scenarios 5 though 8)

The result of the SWAT and WASP simulations from the second set of four scenarios expands the knowledge gained from the first set of four scenarios. Scenario 5 encompasses several similar but different management alternatives. The first three simulations from Scenario 5, where the WWTP loads were set to 1 mg/L, and the second three simulations from the same scenario, where the WWTP loads were set to 100 µg/L, indicated that the reductions from WWTPs other than the Metro and Littleton-Englewood WWTPs have little effect on inlake phosphorus and chlorophyll concentrations. The loads from the Metro WWTP and the Littleton-Englewood WWTP are so large as to overwhelm any other point source in the system, making it likely that major reductions in those two sources, at least initially, will result in the biggest decrease in phosphorus concentrations in Barr Lake and Milton Reservoir. Of course, as the total phosphorus from these two plants and from other sources in the system are brought under control, the phosphorus loads from the smaller WWTPs will become more important and may also need reduction.

The seasonal treatment simulations in Scenario 5 resulted in slightly higher total phosphorus and chlorophyll predictions in Barr Lake and Milton Reservoir, presumably because the prescribed season did not encompass the entire period when wastewater discharge was being incorporated into the reservoirs for refilling. With refinement, this alternative might reduce phosphorus and chlorophyll in the reservoirs, but only if the period of infill and seasonal treatment were coincident. The complications of water rights and timing of water availability for refill increase the complexity and uncertainty of this approach, and it may not be as reliable as some other options. Any change in the magnitude and timing of water routing would be subject to scrutiny under the Colorado water rights administration system.

Figure 5-5. Box and whisker plots showing Barr Lake total phosphorus scenario results

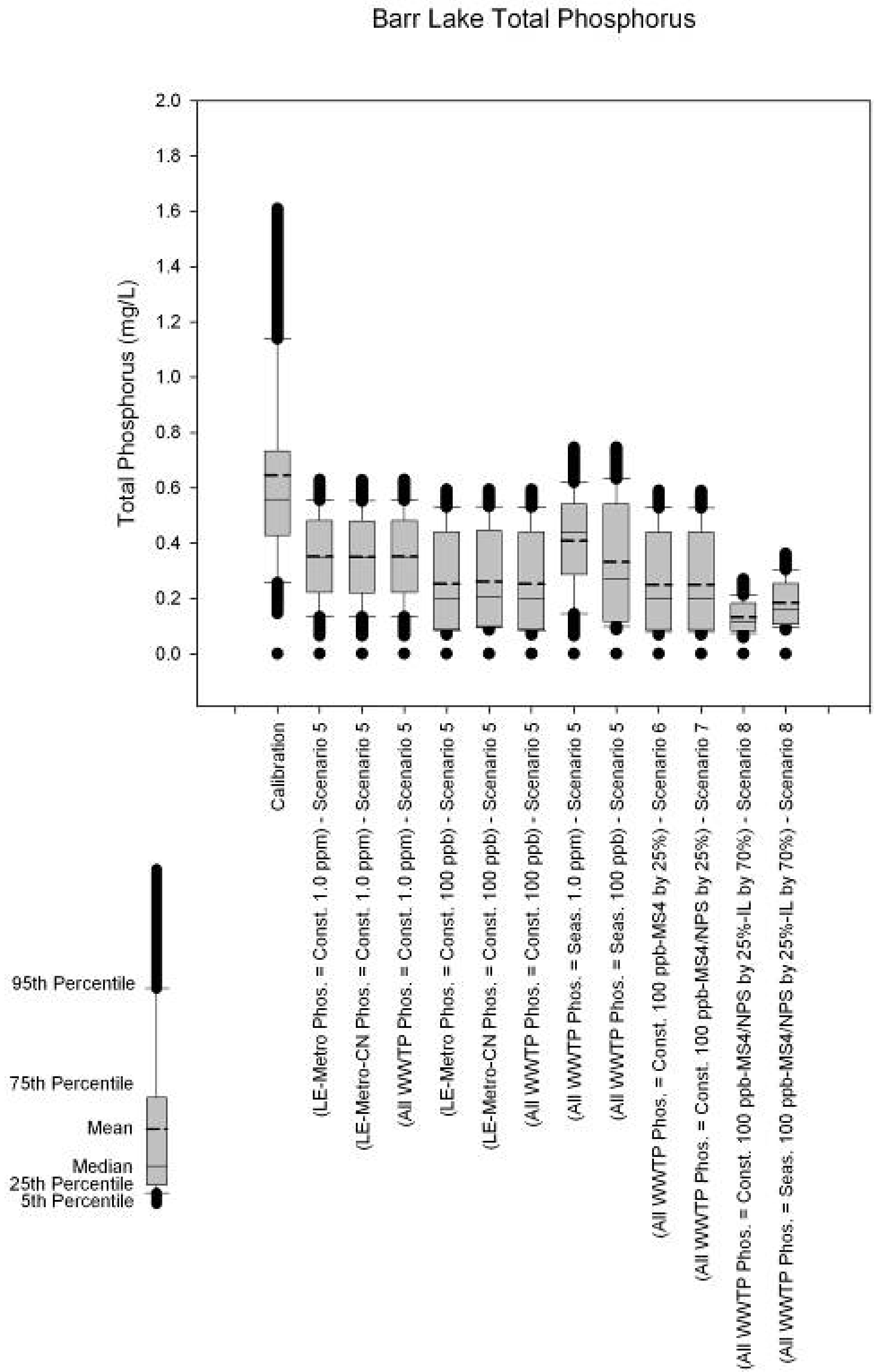


Figure 5-6. Box and whisker plots showing Barr Lake chlorophyll a scenario results

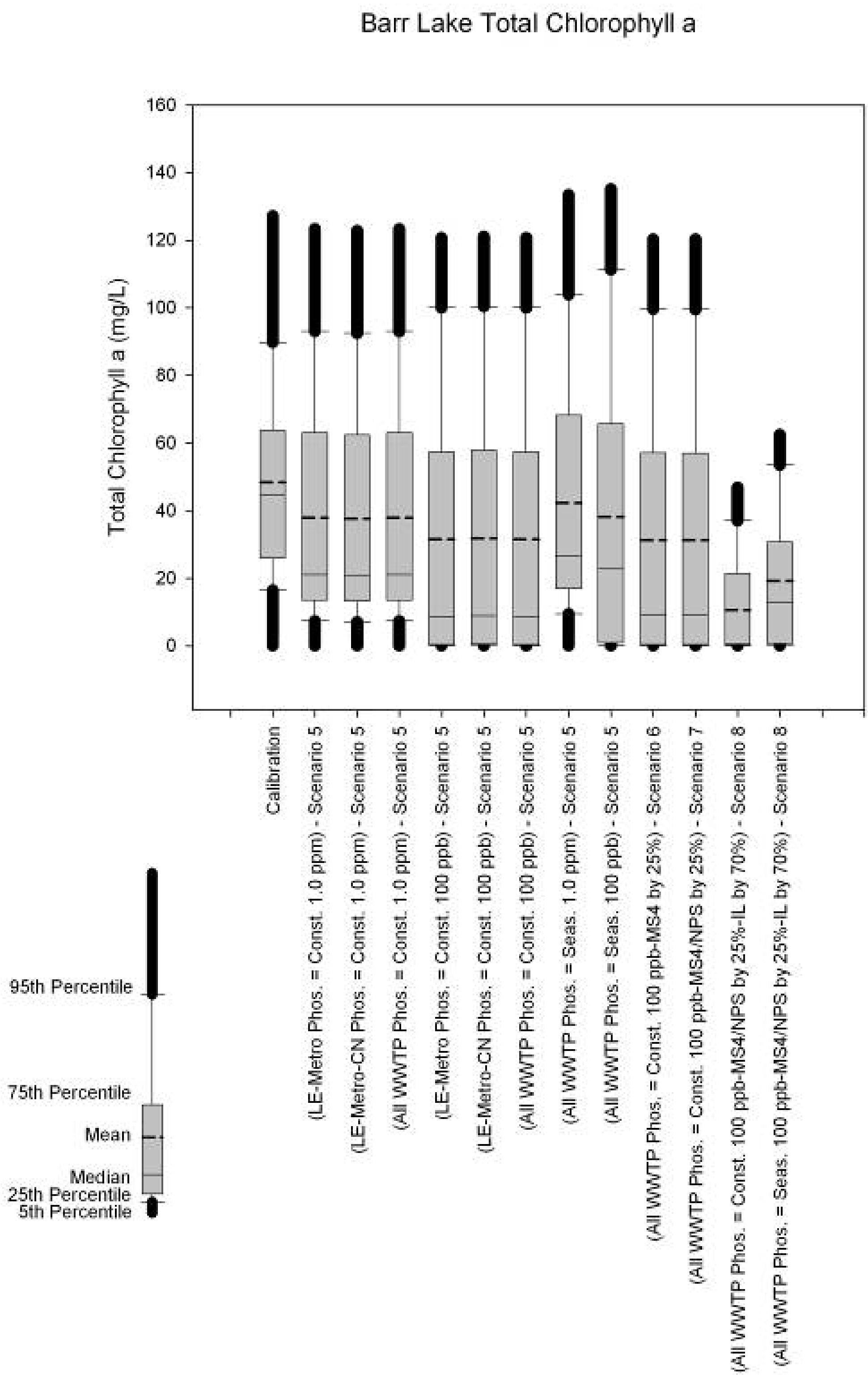


Figure 5-7. Box and whisker plots showing Milton Reservoir total phosphorus scenario results

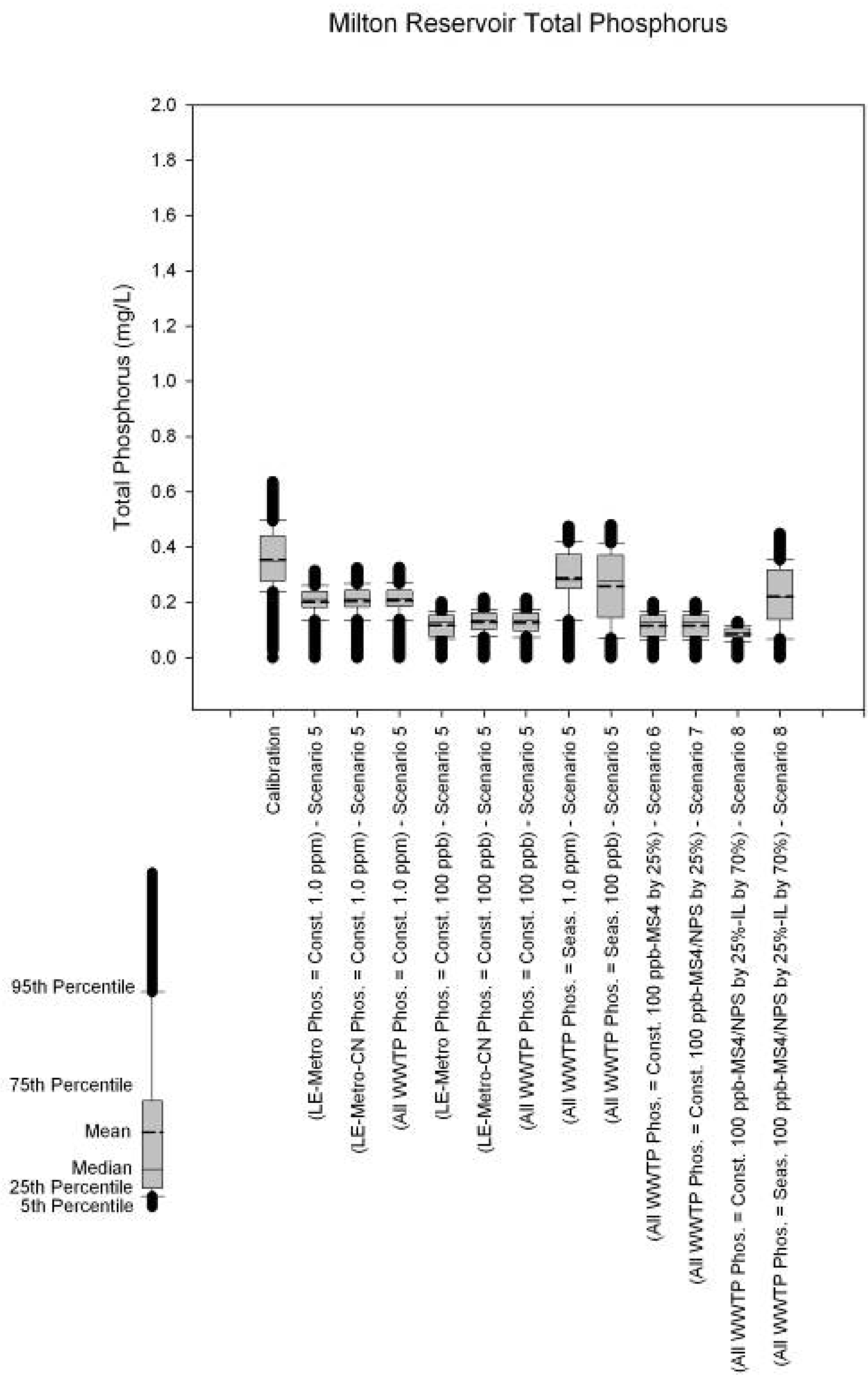
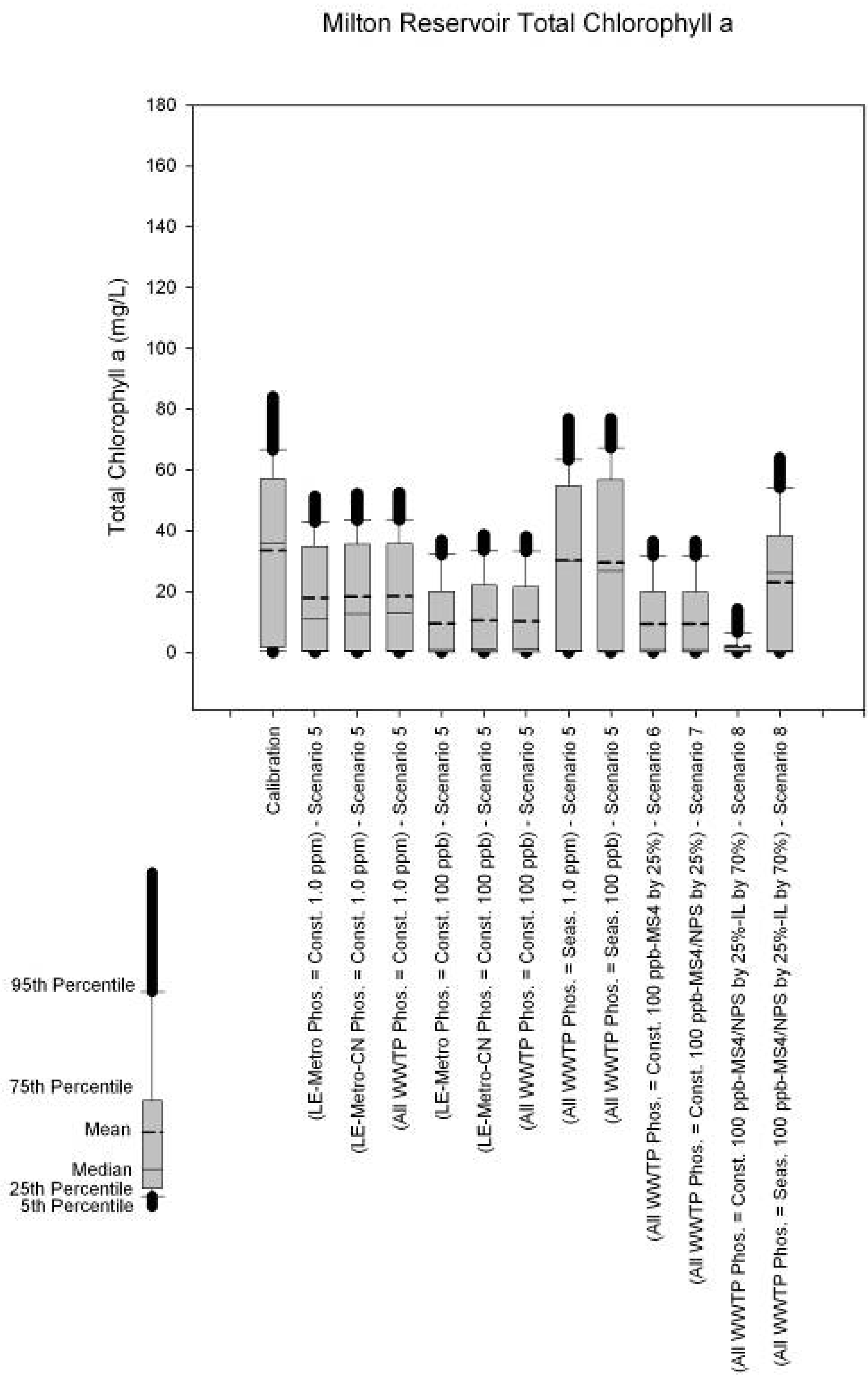


Figure 5-8. Box and whisker plots showing Milton Reservoir chlorophyll a scenario results



The results of Scenario 6 and Scenario 7 lead to the same conclusion as the results of Scenario 3. That is, under the current circumstances controlling nonpoint sources of phosphorus does little to reduce the total phosphorus and chlorophyll concentrations in Barr Lake and Milton Reservoir. This is not to say that nonpoint sources of nutrients are irrelevant, but that currently they are dwarfed by the loads introduced to the lake and reservoir from point sources. If in the future point sources are reduced significantly, then nonpoint source loads could become important and a noticeable benefit might be seen by their reduction through BMPs. There is little to be gained, however, by nonpoint source controls without point source controls at this time.

Finally, the results of Scenario 8 highlight two of the most significant factors controlling total phosphorus concentrations in Barr Lake and Milton Reservoir. A constant reduction in the concentration of total phosphorus discharged from the Metro WWTP and the Littleton-Englewood WWTP, combined with a significant reduction in the internal load of phosphorus by inactivation, would result in a substantial reduction in the concentration of total phosphorus and chlorophyll in Barr Lake and Milton Reservoir. However, even the 100 µg/L limit may not be stringent enough to guarantee compliance with the pH standard.

5.5 Discussion of management alternative simulation results

The first four management scenario simulations demonstrated varying reductions in both phosphorus and chlorophyll concentrations in Barr Lake and Milton Reservoir, depending on the scenario evaluated. These simulations highlighted the importance of point source control, particularly from the largest WWTPs in the system, and the importance of internal phosphorus loading. Also, the first set of simulations indicated that at the current levels of phosphorus being discharged to the surface waters in the Barr-Milton datashed, nonpoint sources comprise a relatively small amount of the overall load. Therefore, under current conditions, controlling only the nonpoint source load of phosphorus to the system will have little impact on the concentrations of total phosphorus and chlorophyll in the lake and reservoir under current loading by point sources.

The results of the second set of four management scenario simulations demonstrated much the same influences, but the refinements facilitated a more detailed evaluation of how to best address the problem. The simulations again highlight that the currently elevated total phosphorus concentrations in Barr Lake and Milton Reservoir are primarily the result of the two largest WWTPs in the watershed and that when phosphorus is treated to 100 µg/L from these sources and internal loading is minimized, a significant reduction in reservoir phosphorus and chlorophyll can be achieved. This reduction may still not be enough to achieve pH compliance, but appears essential if progress toward that goal is to be made through external load control.

6.0 TMDL development and implementation considerations

The development of the watershed model for the proximal portion of the Barr-Milton system, called the datashed, along with the accompanying inlake models for Barr Lake and Milton Reservoir, facilitated an evaluation of management alternatives that might be applied to meet the pH standard and overall reservoir condition goals. The potential management scenarios developed by the BMW Association and AECOM resulted in a better understanding of the nutrient loads from the watershed and of inlake dynamics.

Evaluating the potential for point source nutrient controls, nonpoint source nutrient controls, water transfer management, and inlake controls provided indications of which approaches would be the most beneficial. Each has some utility in achieving pH compliance, but based on the SWAT and WASP model simulations and the results of the eight alternative management scenarios presented previously in the report, point sources and internal recycling will require attention if desired conditions are to be achieved.

6.1 Target concentrations and loads

Exactly what constitutes desired conditions relates mainly to the state standard for pH, but incorporates reductions in algal blooms believed responsible for the elevated pH values that exceed the standard of 9.0 for no more than 15% of the time. While the primary focus of this modeling effort was to adequately characterize existing conditions with public domain models and evaluate management scenarios for possible application to meet the pH standard, it is necessary to link pH to chlorophyll and total phosphorus through the models to make predictions. As a result, possible targets for total phosphorus and chlorophyll have been derived (Section 3).

While there is room for debate over which possible target value is most appropriate and the role of the TMDL process in moving toward desired conditions, it is clear that a major reduction in phosphorus loading is needed to gain control over algal growth and related chlorophyll levels. The associated productivity removes carbon dioxide and increases the pH. While it is possible to have a high chlorophyll value with relatively little activity and hence a pH not higher than 9.0, development of that high chlorophyll value will necessitate active production and probable pH standard exceedences. Likewise, there have been exceedences of the pH standard at low chlorophyll levels, but as the natural background pH is <8.0 Standard Units (SU) in this area (probably close to 7.6 SU, based on data from area reservoirs); elevated productivity must be occurring somewhere in order to raise the pH. Control of algae in the Barr-Milton system can achieve compliance with the pH standard.

Control of algal production can be achieved in numerous ways, some of which will be discussed in this section of the report. But in terms of nutrient limitation, phosphorus is invariably the best management choice from a scientific perspective. Nitrogen can limit production, and in situations where phosphorus concentrations are high, nitrogen often is more limiting that phosphorus. However, certain forms of algae, specifically certain types of blue-green algae or cyanobacteria, can utilize dissolved nitrogen gas, and with so much of the atmosphere comprised of nitrogen gas, equilibrium chemistry dictates that this source will not be controllable in the aquatic environment. Nitrogen limitation will typically foster cyanobacterial dominance. These algae are effective users of bicarbonate, the primary carbon source at higher pH levels, can form surface scums, and are linked to taste, odor and toxicity episodes in aquatic systems. Removing nitrogen is not an invalid strategy, but is unlikely to produce the sustainable results desired in algal control programs without complementary phosphorus removal. Phosphorus can be made to be the limiting nutrient, and while that is not always a practical option, it remains the first choice of management in the planning stages.

The highest chlorophyll target that can be justified for the Barr-Milton system is about 77 μg/L, but the confidence interval surrounding that number is too high to be reliable for TMDL development. More believable values of 18 to 25 μg/l are derived from multiple lines of reasoning using actual data for these or other nearby reservoirs (see Section 3). Temperature plays an important role in the types of algae present, the activity level of chlorophyll and resulting pH change, such that it is possible that higher winter chlorophyll levels could be sustained without contravention of the pH standard. At the same time, the conditioning of Milton Reservoir water by passage through Barr Lake suggests that Milton Reservoir will require a lower chlorophyll target level if Barr Lake is not concurrently improved.

Translation of chlorophyll levels into total phosphorus concentrations is subject to considerable uncertainty, as phosphorus levels are routinely so high in these reservoirs that predictions in the lower range of the phosphorus and chlorophyll scale are not very reliable. The highest total phosphorus level that might achieve the pH standard appears to be between 0.16 and 0.17 mg/L, but several lines of reasoning lead to the conclusion that a total phosphorus concentration on the order of 0.10 mg/L will be necessary. A value as low as 0.05 mg/L might be needed, but that would be an extreme starting point in the TMDL process, which is meant to iteratively approach its goals in complex situations such as this. As a preliminary inlake target total phosphorus level that could achieve the desired summer chlorophyll level and keep the pH below 9.0 SU for at least 85% of the time, 0.10 mg/L appears to be the most appropriate choice at this time. It is important to bear in mind that reduced mean values may be less important that lowered peak values, as these are likely responsible for elevated pH that is then sustained by high alkalinity; it may be possible to achieve pH compliance by a change in phosphorus of chlorophyll distribution that does not involve an extreme lowering of the mean.

The load that will achieve any target inlake total phosphorus concentration can be derived iteratively through the model, mainly by changing the loads in key SWAT segments. The loads entering Barr Lake via the Burlington-O'Brian Canal and Milton Reservoir via both the Platte Valley Canal and Beebe Canal are the dominant inputs from outside the reservoirs. The internal load must also be addressed, however, as it has been predicted to have the potential to maintain algal blooms and undesirable conditions in each reservoir even with reduced external loads. Combinations of external and internal load reductions can be applied, yielding predicted inlake phosphorus concentrations that can be compared to any chosen target level.

Table 6-1 provides the results from iterative model runs, combining internal load reductions of 0, 70, 90 and 100% with external load reductions of 0, 50, 70, 90, 95, 97 and 99 or 100%. Resultant inlake TP levels when these reductions are applied to 2003 or 2004 annual or summer conditions are predicted. Lightly shaded cells with blue typeface indicate achievement of an inlake TP level of 0.10 mg/L, while more heavily shaded cells with red typeface indicate achievement of the most stringent target conceivable, 0.05 mg/L. It is readily apparent that even with major internal loading reductions of 70 to 90%, it will be necessary to reduce the external load by more than 90% to achieve an inlake TP concentration <0.10 mg/L. A target level of 0.10 mg/L is not achievable without an extreme reduction in both the external and internal loads; the best combination tested is a 97% reduction in external load with a 90% reduction in internal load. Because the internal load is an important summer phenomenon, achieving the 0.10 mg/L target level for TP requires a greater reduction in the internal load if considering summer conditions only, compared with conditions on an annual level.

Note that the zero load reduction scenario in Table 6-1 (upper left corner) represents current conditions; actual TP in the reservoirs is underpredicted, but the magnitude (very large) is correct. The 100% loading reduction scenario (lower right corner), while completely improbable, is a check on the model, as this scenario should yield a minimal TP level, leaving only atmospheric deposition and some direct seepage to supply phosphorus; TP values are indeed very low. Yet even a 99% reduction in external loading and a 90% reduction in internal loading will not achieve the 0.10 mg/L TP concentration in both reservoirs during the range of summer conditions tested; guaranteeing compliance with the pH standard under all assumed model conditions requires what appears to be a very unrealistic total phosphorus load reduction. The necessary load reduction as derived from this exercise explains why nearly all of the tested management scenarios failed to achieve a low enough TP level to meet the presumed need (Figures 5-1 through 5-8). Only part of scenario 4 (WWTP effluent set at 0.05 mg P/L and 90% reduction of internal load) yields input reductions commensurate with the needs as derived from the iterative load reduction exercise summarized in Table 6-1.

Table 6-1. Inlake TP concentrations resulting from various combinations of external and internal load reduction for Barr Lake and Milton Reservoir

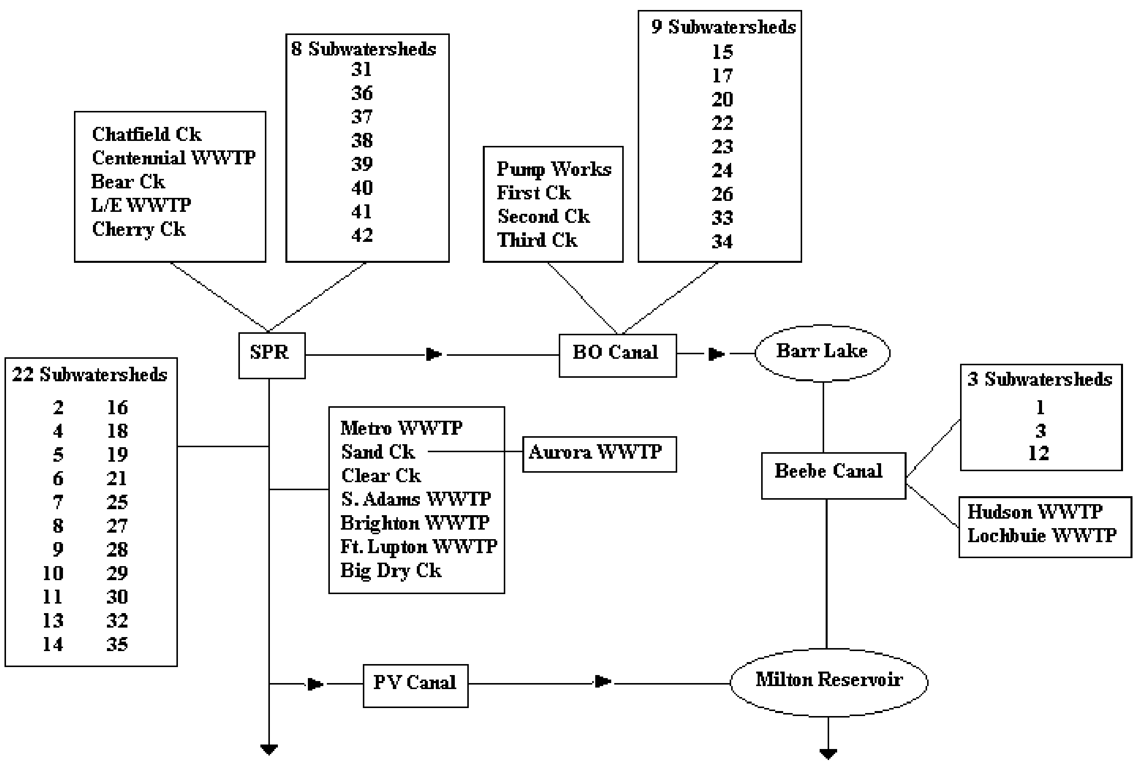
External Load Reduction	Average in-lake TP concentration with no reduction in internal load			Average in-lake TP concentration with 70% reduction in internal load			Average in-lake TP concentration with 90% reduction in internal load			Average in-lake TP concentration with 100% reduction in internal load		
External Load Reduction = 0%		Barr	Milton		Barr	Milton		Barr	Milton		Barr	Milton
	2003	0.694	0.313	2003	0.576	0.275	2003	0.555	0.266	2003	0.550	0.261
	2004	0.595	0.394	2004	0.411	0.354	2004	0.365	0.348	2004	0.346	0.346
	summer 2003	0.430	0.302	summer 2003	0.226	0.237	summer 2003	0.169	0.219	summer 2003	0.140	0.211
	summer 2004	0.597	0.309	summer 2004	0.233	0.232	summer 2004	0.171	0.217	summer 2004	0.145	0.210
External Load Reduction = 50%		Barr	Milton		Barr	Milton		Barr	Milton		Barr	Milton
	2003	0.419	0.221	2003	0.308	0.189	2003	0.292	0.184	2003	0.282	0.183
	2004	0.404	0.278	2004	0.231	0.243	2004	0.198	0.239	2004	0.195	0.238
	summer 2003	0.414	0.231	summer 2003	0.204	0.166	summer 2003	0.145	0.149	summer 2003	0.112	0.143
	summer 2004	0.573	0.233	summer 2004	0.202	0.163	summer 2004	0.147	0.148	summer 2004	0.116	0.142
External Load Reduction = 70%		Barr	Milton		Barr	Milton		Barr	Milton		Barr	Milton
	2003	0.317	0.179	2003	0.225	0.159	2003	0.206	0.153	2003	0.187	0.154
	2004	0.351	0.222	2004	0.184	0.200	2004	0.159	0.200	2004	0.146	0.205
	summer 2003	0.372	0.197	summer 2003	0.199	0.136	summer 2003	0.146	0.123	summer 2003	0.102	0.117
	summer 2004	0.548	0.200	summer 2004	0.199	0.134	summer 2004	0.132	0.123	summer 2004	0.096	0.121
External Load Reduction = 90%		Barr	Milton		Barr	Milton		Barr	Milton		Barr	Milton
	2003	0.225	0.133	2003	0.155	0.101	2003	0.124	0.097	2003	0.083	0.084
	2004	0.331	0.160	2004	0.166	0.126	2004	0.138	0.119	2004	0.103	0.106
	summer 2003	0.293	0.163	summer 2003	0.196	0.116	summer 2003	0.125	0.116	summer 2003	0.046	0.095
	summer 2004	0.536	0.174	summer 2004	0.175	0.106	summer 2004	0.108	0.093	summer 2004	0.056	0.073
External Load Reduction = 95%					Barr	Milton		Barr	Milton		Barr	Milton
				2003	0.133	0.086	2003	0.103	0.074	2003	0.058	0.049
				2004	0.133	0.097	2004	0.102	0.088	2004	0.058	0.069
				summer 2003	0.194	0.124	summer 2003	0.119	0.094	summer 2003	0.038	0.056
				summer 2004	0.175	0.107	summer 2004	0.110	0.096	summer 2004	0.041	0.069
External Load Reduction = 97%					Barr	Milton		Barr	Milton		Barr	Milton
				2003	0.116	0.076	2003	0.083	0.058	2003	0.036	0.031
				2004	0.119	0.082	2004	0.086	0.069	2004	0.036	0.044
				summer 2003	0.189	0.118	summer 2003	0.106	0.075	summer 2003	0.024	0.036
				summer 2004	0.175	0.106	summer 2004	0.110	0.084	summer 2004	0.026	0.044
External Load Reduction = 99-100%	**100% external load reduction**			**99% external load reduction**			**99% external load reduction**			**100% external load reduction**		
		Barr	Milton		Barr	Milton		Barr	Milton		Barr	Milton
	2003	0.181	0.100	2003	0.098	0.063	2003	0.061	0.040	2003	0.001	0.002
	2004	0.271	0.104	2004	0.104	0.064	2004	0.070	0.044	2004	0.001	0.002
	summer 2003	0.328	0.155	summer 2003	0.183	0.106	summer 2003	0.092	0.054	summer 2003	0.002	0.002
	summer 2004	0.527	0.168	summer 2004	0.176	0.099	summer 2004	0.111	0.063	summer 2004	0.002	0.002

6.2 Load partitioning

One of the major benefits of the model constructed in this project is the ability to partition loads among identified sources. Tracking a load through the watershed with mass balance methods is extremely difficult in this system, given the spatial and temporal variability in inputs, withdrawals and transfers. Available monitoring data, while extensive is not adequate to assess inputs for more than a few sources. A separate project involving considerable effort was undertaken by Lewis and McCutchan (2009) to estimate just the portion of the TP and TN loads to Barr and Milton Reservoirs from the Metro WWTP. With many more sources identified in this watershed, a model such as that constructed by AECOM is necessary to estimate the relative contributions of those sources.

To partition the load of phosphorus, nitrogen and water, each identified source was “zeroed out” of the model, one at a time, and the difference in resulting inlake concentration (or volume in the case of water load) was taken as the contribution of the corresponding source. The overall schematic for loading to Barr Lake and Milton Reservoir (Figure 4-6) can be simplified for easier comprehension of the juxtaposition of sources as shown in Figure 6-1, where SPR represents the South Platte River and numbered subwatersheds represent corresponding drainage areas from the SWAT model. All other inputs should be self-evident from previous description and notation.

Figure 6-1. Simplified schematic of the Barr-Milton Watershed



Summarizing the results of this analysis for total phosphorus loading to Barr Lake and Milton Reservoir (Table 6-2), the dominant sources to Barr Lake are the Littleton/Englewood WWTP and the pump works, which discharges Metro WWTP effluent to the Burlington-O'Brian Canal. The Metro WWTP, via its discharge to the South Platte River, is the dominant source of phosphorus to Milton Reservoir. Contributions vary somewhat when the internal load is included, but overall, the Littleton/Englewood WWTP contributes 35 to 52% of the total phosphorus in Barr Lake, while the pump works contributes 24 to 41%. Together these two wastewater sources account for 88 to 91% of the external phosphorus load to Barr Lake. This total declines to 59 to 69% if the substantial internal load is considered (24 to 33%), but much of the internal load is recycled inputs from the major external sources. Conversion of phosphorus inputs to particulates with substantial settling over the winter and spring is followed by a combination of resuspension of particulates and solubilization of phosphorus from bottom sediments during summer.

For Milton Reservoir, the Metro WWTP is the dominant source of total phosphorus, contributing 71 to 80% of the estimated total. Littleton/Englewood WWTP, South Adams WWTP, Big Dry Creek, and Clear Creek are the next most important sources, all between 1.4 and 6.6% of the total phosphorus load. The only other identified source with a contribution greater than 2% at any time is the internal load from Barr Lake as a source for Milton Reservoir via the Beebe Canal, at 3.3 to 4.1%. Again, this load is largely a function of recycled external loads from the Barr Lake watershed, with the pump works and Littleton/Englewood WWTP inputs at the dominant sources.

Note that the total contributions do not add up to precisely 100% in each case. This is related to rounding error and model inefficiency. Scaling all contributions to achieve exactly 100% does not appreciably change the results, and it was felt that it was better to show the actual results and allow error to be transparent. Variability among years and with or without internal load included is greater than the discrepancy from the 100% total.

Table 6-2. Partitioning of phosphorus load among sources for Barr Lake and Milton Reservoir

Relative Portion of External and Internal Loads

Source	Barr Load 2003	Barr Load 2004	Milton Load 2003	Milton Load 2004
External Total P Load (kg)	92,100	62,200	73,500	108,000
Internal Total P Load (kg)	28,300	30,600	3,700	-5,600
Point Sources:				
Lochbuie WWTP	NA	NA	0.01%	0.01%
Hudson WWTP	NA	NA	0.01%	0.01%
Fort Lupton WWTP	NA	NA	0.3%	0.3%
Brighton WWTP	NA	NA	0.3%	0.3%
South Adams WWTP	NA	NA	2.2%	3.5%
Metro WWTP	NA	NA	71%	80%
Aurora WWTP	NA	NA	0.1%	0.1%
Centennial WWTP	0.9%	1.4%	0.1%	0.2%
Pump Works (from Metro)	31%	24%	0.2%	0.1%
Littleton-Englewood WWTP	38%	35%	2.9%	6.4%
Subwatersheds:				
Clear Creek	NA	NA	3.8%	1.5%
Big Dry Creek	NA	NA	6.3%	6.5%
Cherry Creek Reservoir	0.6%	0.7%	0.1%	0.2%
Bear Creek Reservoir	1.2%	1.2%	0.2%	0.2%
Chatfield Reservoir	1.6%	1.3%	0.3%	0.3%
All other subwatersheds	2.7%	2.4%	1.7%	1.2%
Benthic P Load from Barr	24%	33%	3.9%	3.5%
Benthic P Load from Milton	NA	NA	4.8%	-5.5%
TOTAL	**100%**	**99%**	**98%**	**99%**

NA indicates Not Applicable - source is downstream of point of interest.

Relative Portion of External Loads Only

Source	Barr Load 2003	Barr Load 2004	Milton Load 2003	Milton Load 2004
External Total P Load (kg)	92,100	62,200	73,500	108,000
Internal P Load excluded				
Point Sources:				
Lochbuie WWTP	NA	NA	0.01%	0.00%
Hudson WWTP	NA	NA	0.01%	0.01%
Fort Lupton WWTP	NA	NA	0.3%	0.3%
Brighton WWTP	NA	NA	0.3%	0.3%
South Adams WWTP	NA	NA	2.3%	3.3%
Metro WWTP	NA	NA	75%	76%
Aurora WWTP	NA	NA	0.1%	0.1%
Centennial WWTP	1.2%	2.1%	0.1%	0.2%
Pump Works (from Metro)	41%	36%	0.2%	0.1%
Littleton-Englewood WWTP	50%	52%	3.0%	6.1%
Inlets:				
Clear Creek	NA	NA	4.0%	1.4%
Big Dry Creek	NA	NA	6.6%	6.2%
Cherry Creek Reservoir	0.8%	1.1%	0.1%	0.2%
Bear Creek Reservoir	1.6%	1.7%	0.2%	0.2%
Chatfield Reservoir	2.1%	1.9%	0.3%	0.3%
All other subwatersheds	3.6%	3.6%	1.8%	1.1%
Benthic P Load from Barr	NA	NA	4.1%	3.3%
TOTAL	**100%**	**99%**	**98%**	**99%**

The same partitioning exercise conducted for total phosphorus was performed for total nitrogen loading to Barr Lake and Milton Reservoir (Table 6-3). Without considering internal load other than the contribution from Barr Lake to Milton Reservoir, the dominant source of nitrogen to Barr Lake is the Littleton/Englewood WWTP at 59 to 61% of the total, followed by the pump works at 26 to 28%. For Milton Reservoir, Metro WWTP contributes 67 to 69% of the total nitrogen load to that waterbody, while Littleton/Englewood WWTP contributes 6 to 9% and all other sources represent <5% of the total load. The overall portion of the nitrogen load contributed by the two largest WWTPs (Metro and Littleton/Englewood) is about 87% for Barr Lake and 74 to 78% for Milton Reservoir, similar to the importance of these two major sources of phosphorus to these reservoirs.

Table 6-3. Partitioning of nitrogen load among sources for Barr Lake and Milton Reservoir

Relative Portion of External Loads to Barr and Milton Reservoirs				
Source	**Barr Load 2003**	**Barr Load 2004**	**Milton Load 2003**	**Milton Load 2004**
External Total N Load (kg)	815,427	510,946	390,496	599,932
Internal N Load excluded				
Point Sources:				
Lochbuie WWTP	NA	NA	0.0%	0.0%
Hudson WWTP	NA	NA	0.0%	0.0%
Fort Lupton WWTP	NA	NA	0.8%	0.9%
Brighton WWTP	NA	NA	1.1%	1.2%
South Adams WWTP	NA	NA	1.7%	2.0%
Metro WWTP	NA	NA	67.4%	69.0%
Aurora WWTP	NA	NA	0.7%	1.0%
Centennial WWTP	3.3%	6.2%	0.4%	0.6%
Pump Works (from Metro)	27.9%	25.8%	0.4%	0.0%
Littleton-Englewood WWTP	59.0%	61.1%	6.3%	9.2%
Inlets:				
Clear Creek	NA	NA	4.2%	1.7%
Big Dry Creek	NA	NA	8.4%	8.4%
Cherry Creek Reservoir	0.0%	0.1%	0.0%	0.1%
Bear Creek Reservoir	1.6%	0.6%	0.5%	0.1%
Chatfield Reservoir	0.3%	0.5%	0.2%	0.1%
All other subwatersheds	7.0%	5.2%	4.9%	3.4%
Benthic P Load from Barr	NA	NA	4.9%	2.7%
TOTAL	**99%**	**99%**	**102%**	**100%**
NA indicates Not Applicable - source is downstream of point of interest.				

For purposes of understanding system hydrology under current conditions, and how that hydrology affects loading and lake condition now and potentially in the future, estimates of the water contribution from identified sources have been derived using the model. Table 6-4 provides estimates of daily and annual flows from sources in the watershed, with a total flow through the watershed and an estimate of the portion diverted into each of Barr Lake and Milton Reservoir.

This accounting of system hydrology does help explain of some of the loading results, especially coupled with knowledge of nutrient concentrations in various discharges. For example, the dominance of the flows from Metro WWTP is apparent. Coupled with relatively high concentrations of phosphorus and nitrogen in the Metro effluent, these flows explain the importance of this source in nutrient loading to Milton Reservoir via the South Platte River and to a lesser extent to Barr Lake via the pump works into the Burlington-O'Brian Canal. The Littleton/Englewood WWTP discharge, while smaller than that from several reservoirs discharging from the larger watershed into the datashed, exhibits much higher nutrient concentrations, explaining its importance to Barr Lake as a function of diversion of South Platte River water into the Burlington-O'Brian Canal upstream of the Metro WWTP discharges to the South Platte River. The relatively small contribution from runoff in the datashed is consistent with the inability of management actions involving associated nonpoint source inputs to make an appreciable difference in water quality in the reservoirs. Only a fraction of the water passing through the watershed is diverted to Barr Lake and Milton Reservoir, with the sources, magnitude and timing of those diversions having a distinct impact on water quality in the reservoirs (Table 6-4, Figures 6-2 and 6-3).

Table 6-4. Flows from identified sources in the Barr Lake and Milton Reservoir Watershed

	2003		2004	
Water Sources	**m3/day**	**Million m3/yr**	**m3/day**	**Million m3/yr**
Point Sources:				
Lochbuie WWTP	2,838	1.0	2,838	1.0
Hudson WWTP	3,785	1.4	3,785	1.4
Fort Lupton WWTP	7,806	2.8	7,806	2.8
Brighton WWTP	7,410	2.7	7,410	2.7
South Adams WWTP	9,832	3.6	11,845	4.3
Metro WWTP	462,270	168.7	438,452	160.0
Aurora WWTP	11,980	4.4	13,146	4.8
Centennial WWTP	20,074	7.3	20,194	7.4
Pump Works (from Metro)	43,639	15.9	42,029	15.3
Littleton-Englewood WWTP	84,826	31.0	84,517	30.8
Subwatersheds entering Datashed:				
Clear Creek	271,579	99.1	131,606	48.0
Big Dry Creek	97,924	35.7	105,974	38.7
Cherry Creek Reservoir	40,623	14.8	48,827	17.8
Bear Creek Reservoir	89,639	32.7	110,211	40.2
Chatfield Reservoir	191,309	69.8	170,367	62.2
Non-Point Runoff in Datashed:	5,962	2.2	5,243	1.9
Total	**1,351,496**	**493.3**	**1,204,250**	**439.6**
Flow entering Barr Lake	**237,582**	**86.7**	**188,067**	**68.6**
Flow entering Milton Reservoir	**179,897**	**65.7**	**208,076**	**75.9**

Figure 6-2. Predicted flow into Barr Lake over the 2003-2004 model period

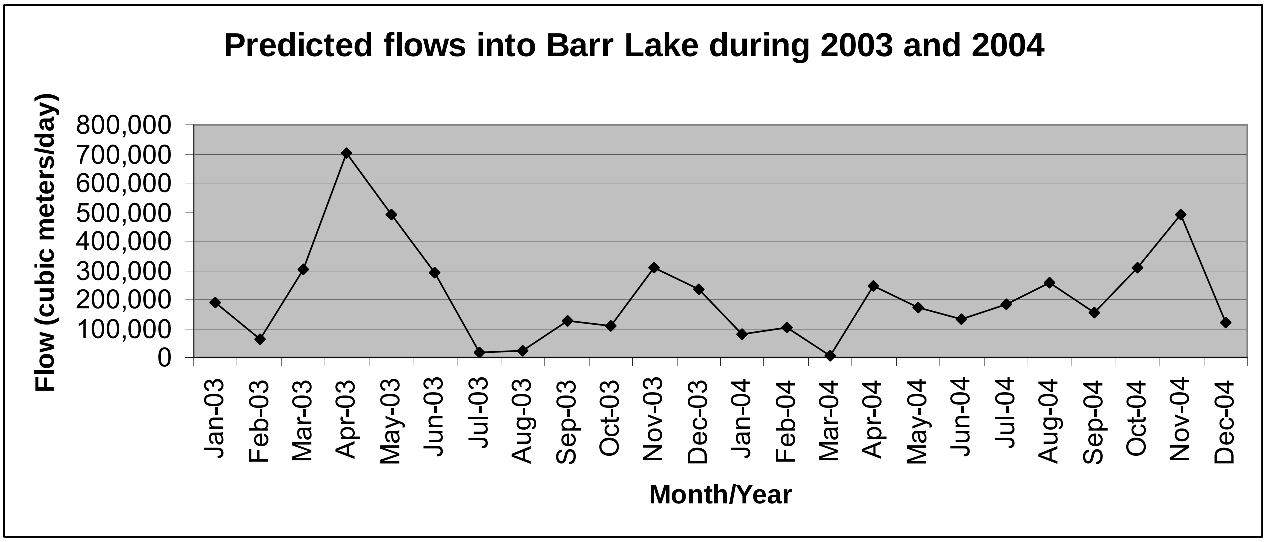
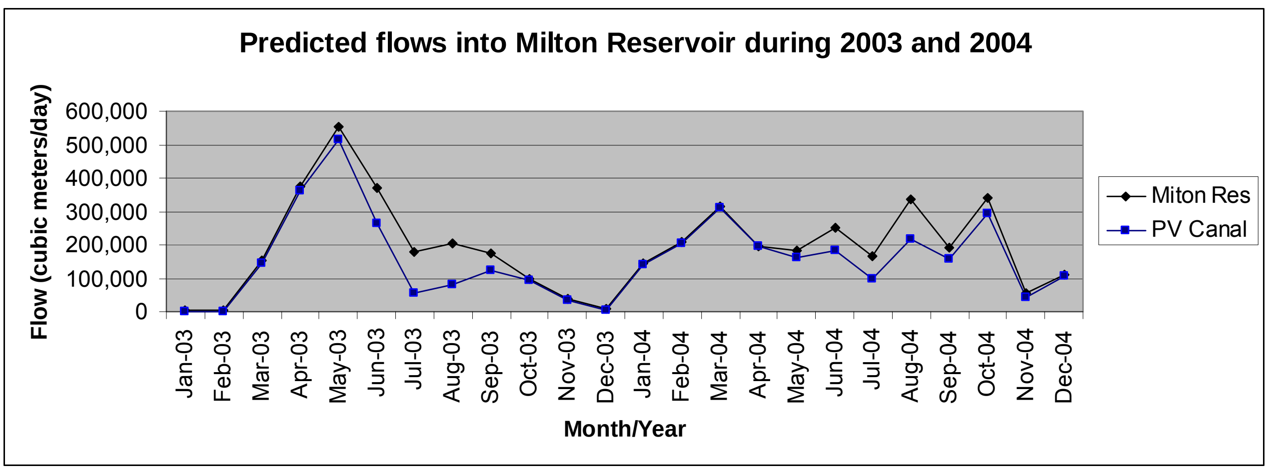


Figure 6-3. Predicted flow into Milton Reservoir over the 2003-2004 model period



6.3 Internal loading assessment

Internal loading to Barr Lake and Milton Reservoir is a complicated aspect of nutrient dynamics in these reservoirs. External loads are high, and almost half the incoming phosphorus is retained in the sediments (AMEC 2008a, 2008b), creating the potential for very high internal recycling. At the same time, high water column phosphorus levels have the potential to suppress soluble release from sediments (Reddy et al. 2007). The precise phosphorus level at which equilibrium will be achieved is not a constant and is not easy to predict, but recent and as yet unpublished work (William James, USACE, pers. comm. 2009) suggests that with P-rich sediments the value will be higher than 0.1 mg/L and able to support algal blooms. Work by AECOM staff on impoundments of Hop Brook in Massachusetts (ENSR 2004) demonstrated that if WWTP inputs were reduced, internal loading of phosphorus increased markedly. Consequently, there is little doubt that internal loading will be an important factor in future algal blooms in Barr Lake and Milton Reservoir if external inputs are reduced.

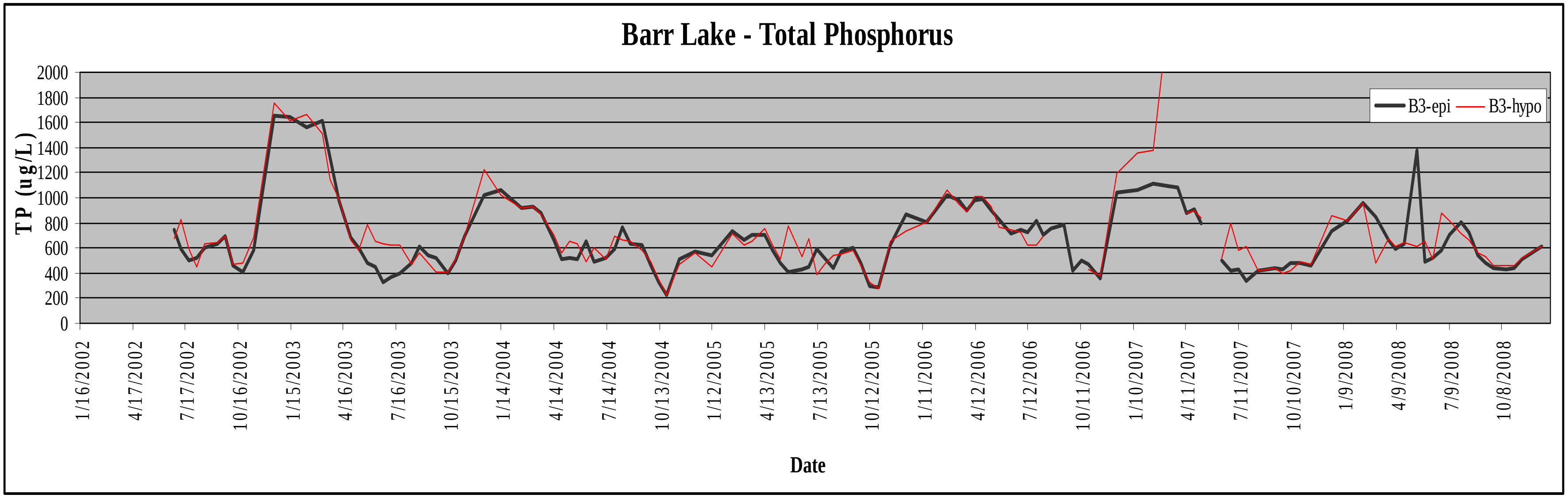
How much phosphorus is currently available in bottom sediments is unknown, and AECOM has recommended that testing be performed in accordance with the approach of Rydin and Welch (1998, 1999) to determine the potential for internal loading. In the absence of such data for the sediment reserves of phosphorus, Estimates have been derived from deep water accumulation during brief periods of stratification or simply by difference between measured inputs and inlake mass balance (AMEC 2008a, 2008b). Neither approach is especially reliable in a quantitative fashion, but it is evident from the pattern of water column concentrations (Figure 6-4) that there is a rise in summer phosphorus levels in Barr Lake and to a lesser extent in Milton Reservoir that cannot be explained by external inputs at that time. Estimates that look only at net change will underestimate internal loading, and it appears that the internal load to at least Barr Lake is substantially larger than suggested in the AMEC evaluations. However, this internal load has been facilitated by excessive external loads, and its control will not provide significant relief from algal blooms and elevated pH without a major reduction in the external load.

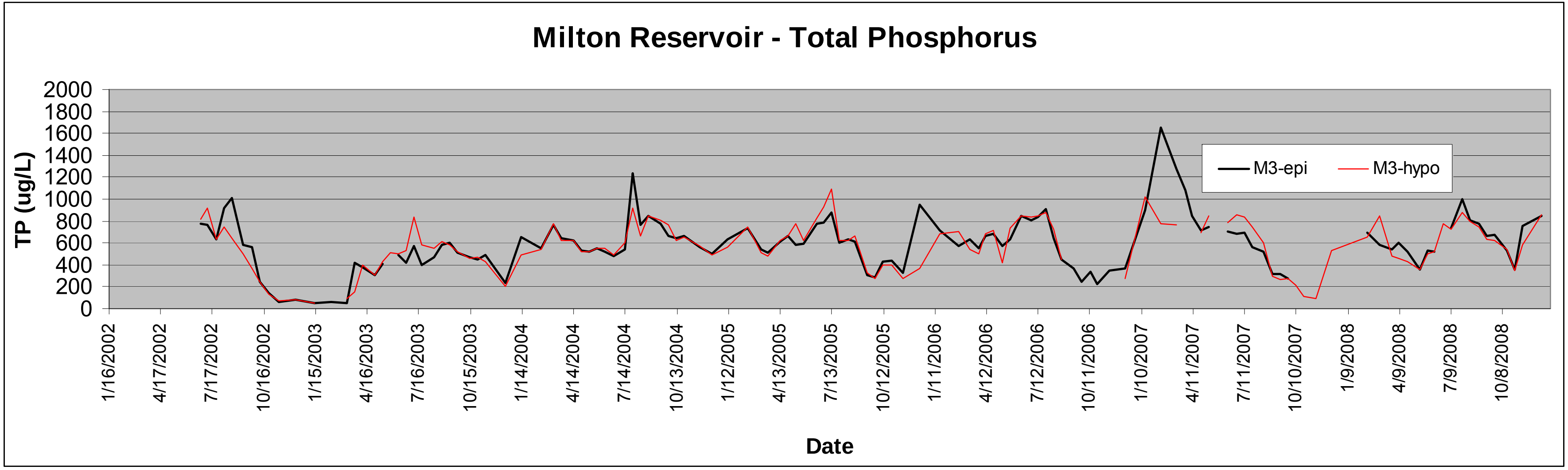
Internal loading can occur by several means: soluble release from bottom sediments; desorption from resuspended sediments; and release from rooted aquatic plants. As aquatic plant growths are negligible in these reservoirs, only release from bottom sediments, either from the bottom or after resuspension by wind or bottom-feeding fish (e.g., carp), are viable mechanisms in these reservoirs, but both are likely active routes of transfer. To get the inlake spring phosphorus concentrations to match observed values in the Barr Lake WASP model, a high settling rate for phosphorus had to be applied in the spring, and was not altered for the summer. To continue the reasonable match of predicted and observed concentrations through the summer, the internal loading rate had to be increased to near 100 mg/m^2/day, a very high value. It is likely that no more than half of this and probably no more than a third is soluble release, with the remainder linked to resuspended sediments, but no testing has been done to verify rates or mechanisms of release. The AMEC reports cited release rates up to about 43 mg/m^2/day, and applied rates of 12 mg/m^2/day for soluble release.

The actual mass of phosphorus input attributed to internal loading by AMEC is 6% for Barr Lake and 1% for Milton Reservoir. The AECOM evaluation by combined SWAT and WASP models suggests that for 2003-2004, the internal phosphorus load is 24 to 33% for Barr Lake and 4.8 to -5.5% for Milton Reservoir (Table 6-2). Furthermore, the portion of the Barr Lake internal load that is passed downstream to Milton Reservoir may represent 3 to 4% of the Milton Reservoir phosphorus load. Again, the internal Barr Lake load is predominantly a function of excessive external loads, but if external loading was greatly reduced, the internal load would continue for many years if not addressed, and is large enough to support problem algal blooms. For Milton Reservoir, the internal load appears to be much lower, and there are no data to aid interpretation of this apparent situation. However, increased phosphorus loading in the event of decreased external loading would be expected for Milton Reservoir as well.

Less is known of nitrogen releases, but these usually equal or exceed phosphorus releases in AECOM experience, sometimes by a factor of 20 or more, but usually by a factor of 3 to 5. The internal loading rate applied by AMEC was only 19 mg/m^2/day. Aside from solubilization and desorption, nitrogen fixation by certain cyanobacteria is likely, and has not been quantified for these reservoirs. No site-specific testing has been done to evaluate potentially influential sources of nitrogen within these reservoirs, although analysis of the South Platte River and the canals suggests both losses and gains over space and time (Lewis and McCutchan 2009). Losses of aqueous nitrogen through denitrification is very likely in these reservoirs at times, so a very dynamic system of internal increases and decreases is to be expected. The model attempts to take this into consideration, but data limitations prevent any real testing of assumptions.

Figure 6-4. Observed total phosphorus concentrations in Barr Lake and Milton Reservoir, 2002-2008





6.4 Effects of uncertainty in the TMDL process

No data have been provided from any QA/QC program that would allow an assessment of the potential error in modeling or comparisons with real data attributable to sampling or laboratory error. It is assumed that the data provided are largely reliable, and that any error induced by sampling and lab operations is minor. Of greater concern, however, is the reliance on one or a few samples over time periods of a month to represent each reservoir or inlet point. Variability over space is rarely characterized by current sampling programs directed at the Barr-Milton system, and variability over time is limited to monthly to seasonal time steps. Chlorophyll variation is of particular concern, as the vertical and horizontal distribution of algae in the reservoirs is not expected to be uniform. A program is currently underway to evaluate this variability, and its results will be factored into TMDL development in the next phase of this project.

Variation in pH at lower phosphorus levels is unknown for these reservoirs, as phosphorus concentrations <0.25 mg/L are very rarely encountered. However, the variation at higher phosphorus levels, where no change in phosphorus concentration is expected to have a significant impact on pH, appears to be on the order of $\pm$0.9 SU for Barr Lake and $\pm$0.7 SU for Milton Reservoir for summer conditions (Figure 3-7). To keep the pH <9.0 SU for 85% of the summer, based on these data only, a logical target for the mean pH would be about 8.5 or 8.6 SU in each reservoir. This does not consider any change in variation with reduced mean pH, and in biologically influenced systems, that variation tends to decline, so a slightly higher mean pH could be tolerated. At the same time, this also does not consider the influence of high alkalinity, which tends to hold elevated pH values longer and will require a lower mean pH to ensure compliance unless all algal blooms can be prevented.

Uncertainty associated with model predictions can be derived by comparing observed with predicted values. However, this comparison is limited by the amount and frequency of observed data compared to the short time steps employed by the model, and by the single point nature of observed values compared to the systemwide averaging of the model. In general, the model tends to overpredict phosphorus and underpredict chlorophyll. Since it is not expected that phosphorus will be a reliable predictor of chlorophyll at such high phosphorus concentrations, any quantification of model error is probably best focused on differences in observed and predicted phosphorus levels. For Barr Lake, the difference averages about 8%, while for Milton Reservoir it is about 24%.

What these levels of uncertainty suggest depends on the TMDL philosophy applied. If one takes the position that the TMDL should guarantee compliance, uncertainty must be factored in as a margin of safety (MOS) either explicitly or implicitly, lowering the recommended TMDL for wasteloads (point sources) and nonpoint source loads. On the other hand, if one assumes that conditions might be better than predicted, or that the initial TMDL need not account for uncertainty, the MOS would need only to reflect potential future loads that are to be accommodated. In either case, a monitoring program is strongly recommended to track progress and allow iterative adjustment of both the TMDL and implementation program to achieve compliance.

Additional assessment of uncertainty will be incorporated into the next phase of TMDL development. Some discussion of the preferred approach and inclusion of data from the assessment of spatial variability of chlorophyll in the reservoirs is desirable in that phase.

6.5 Watershed options for improving lake water quality

The SWAT watershed modeling scenarios were integral to the evaluation of long term water quality improvement in Barr Lake and Milton Reservoir because the nutrient loads to the lakes are ultimately a function of watershed activities. The applied watershed management scenarios investigated:

1. Point nutrient reductions from WWTPs (Scenarios 1, 3, 4, 5, 6, 7, and 8)
2. Nonpoint nutrient reductions from MS4 permitted and non-permitted areas (Scenarios 3, 6, and 7)

3. Alternative management of water during the infill period (Scenario 2)

Given that there are two major point sources (Metro WWTP and Littleton-Englewood WWTP) continually discharging wastewater to the upstream portion of the datashed at average total phosphorus concentrations of 2.5 to 3.0 mg/L, in addition to several smaller WWTPs discharging wastewater throughout the datashed, it was expected that a reduction in these sources would have a positive impact on water quality in Barr Lake and Milton Reservoir. The results of the point source reduction scenarios indicate that reducing nutrient loads from the two largest point sources has a significant impact on the predicted total phosphorus and chlorophyll concentrations in both Barr Lake and Milton Reservoir.

However, reductions in nutrient loads from the remaining point sources does not have an appreciable effect on its own, as these loads are much smaller and occur at points where they have less effect on at least Barr Lake. It may indeed be beneficial to reduce these nutrient loads, but unless the loads from Metro WWTP and Littleton-Englewood WWTP are reduced, reductions from other WWTP would not result in a significant improvement of inlake and reservoir water quality. The simulation results suggest that any reduction in point sources must include Metro and Littleton-Englewood WWTPs, since they comprise about 90% of the phosphorus load to Barr Lake and 80% of the load to Milton Reservoir (Table 6-2).

Chlorophyll concentrations predicted in Barr Lake and Milton Reservoir are expected to be directly related to concentrations of phosphorus below a threshold that occurs between 100 and 200 ug/L, but as current levels are much higher, the existing link between phosphorus and chlorophyll in these reservoirs is weak. Likewise, the link between pH and chlorophyll is expected to be relevant to management below a threshold that appears to be somewhere near 30 ug/L, but higher chlorophyll levels are routinely experienced now. Additionally, high alkalinity allows high pH to be sustained for an extended period of time once it occurs. Watershed management to achieve pH compliance must therefore be sufficient to lower phosphorus and chlorophyll far enough below the relevant thresholds to prevent high pH from developing.

The scenarios that evaluated the benefit of controlling nonpoint nutrient sources resulted in only a small predicted reduction in total phosphorus concentrations in Barr Lake and Milton Reservoir, regardless of whether the reductions were from MS4 permitted areas or non-permitted areas. The point loads from the WWTPs, particularly from Metro and Littleton-Englewood, are sufficient to create a nutrient overload without any influence from nonpoint sources. Controlling nonpoint nutrient sources would lead to reductions in some instream phosphorus levels, but no meaningful reduction in reservoir phosphorus concentrations, and hence inlake chlorophyll concentrations and pH values would remain elevated until the point source inputs were significantly reduced.

The alternative management option of controlling the source of refill water to Barr Lake has the potential to improve water quality in Barr Lake, but only at the expense of the water quality in Milton Reservoir. This is because any waste water discharged to the South Platte River, as opposed to discharging it directly to the Burlington-O'Brian Canal, is available for transfer to Milton Reservoir through the Platte Valley Canal. Raising the waste water component of the South Platte River during the time of Milton Reservoir refill will result in higher nutrient levels. Additionally, the risk of not reaching full level in Barr Lake in the spring increases as a consequence of dependence on river flows, and therefore snowmelt, for refill. This management option could be explored further since there may be other ways in which to fill Barr Lake and Milton Reservoir while minimizing the percentage of wastewater in the fill water. However, careful scrutiny of unintended consequences and consistency with existing water rights will be needed for any management approach that alters flow patterns. Altered flow scenarios might include:

1. Transferring additional water from the South Platte River to Barr Lake and then filling Milton Reservoir through Barr Lake rather than through the Platte Valley Canal. This further increases the risk of not reaching full level by the time irrigation water is needed, but would improve water quality.
2. Increasing control of the transfer of water to optimize the water quality in both reservoirs at the expense of water quality in the South Platte River. This would involve tracking water quality at key

transfer points and only diverting the best quality water to the reservoirs, most likely during spring snowmelt. This also increases the risk of not achieving full water level before irrigation water is needed.

Alternative flow management scenarios could optimize water quality in Barr Lake and Milton Reservoir, thereby reducing total phosphorus and total chlorophyll concentrations and moving toward pH compliance. However, given the results of all the model simulations, this approach alone is not likely to improve water quality enough to meet the pH requirements of the TMDL. The influence of wastewater on the entire system is simply too great. Adding the overarching water rights considerations, such options appear to be of limited utility, but may warrant additional discussion.

Actual methods for reducing nutrient inputs from watershed sources are well known (Holdren et al. 2001, Mattson et al. 2004, Cooke et al. 2005). Nonpoint source control needs and options for urban and agricultural areas are well known (WI Dept Agric 1989, NH DES 1994, Sharpley et al. 1994, USEPA 1999, Center for Watershed Protection 2003), and many techniques are applicable within the watershed of Barr Lake and Milton Reservoir. However, the greatest need for Barr Lake and Milton Reservoir is reduced point source phosphorus inputs, specifically major reductions from the Metro and Littleton-Englewood WWTP. Current discharge concentrations average between 2.5 and 3.0 mg/L. Concentrations of 0.5 to 1.0 mg/L are achievable through chemical additions during secondary treatment. Concentrations consistently <0.5 mg/L would require a more dedicated tertiary treatment system, typically with either flocculation and filtration or a dissolved air flotation system. Some biological treatment systems can achieve low phosphorus levels, but the extended treatment time taxes holding capacity. The complexity and cost of meeting low phosphorus limits in a large WWTP discharge should not be ignored in the overall TMDL process, although they may have no bearing on the calculated load reduction needs.

One way to utilize combined physical, chemical and biological treatment systems without a direct burden on the treatment facility grounds is to establish downstream treatment wetlands, an approach that has been successful elsewhere (Kadlec and Knight 1996). These would have to be extensive and well designed, and it is possible that there could be complications relating to water rights if too much water was lost to groundwater or evapotranspiration. However, creation of properly designed and sufficiently sized treatment wetlands somewhere along the Beebe Canal and Platte Valley Canal could greatly reduce the phosphorus levels entering Barr Lake and Milton Reservoir. The models utilized in this investigation could be used to project the necessary level of phosphorus reduction in treatment wetlands with input on watershed and especially WWTP input levels. As a general rule, the wetland area will need to be between 2 and 7% of the area it serves, depending on local conditions and forms of treatment provided (e.g., detention, filtration, subsurface flow). Areas totaling on the order of 11,000 to 38,000 acres would be needed to address the portion of the watershed defined as the datashed. However, the steady flow of wastewater could support such treatment wetlands.

Whatever combination of techniques are applied, there are two aspects of the scenario results that should be kept in mind: the expected average and median values and the distribution of all values. In many cases the mean or median do not decline as much as might be intuitively expected, but the range is decreased and the distribution of values is compressed. This reduction in high values for total phosphorus and/or chlorophyll may be even more influential than any change in the mean or median, as the intent is to reduce the incidence of high pH. A decrease in the mean and median will result as well, but the change in high end distribution may be more important to achieving compliance with the pH standard.

6.6 Alternatives for controlling internal phosphorus loads and algal populations

The WASP model simulations of inlake eutrophication indicated that while external reductions in total phosphorus are critical to reducing total chlorophyll concentrations in Barr Lake and Milton Reservoir, these reductions must be accompanied by concurrent reductions in the internal load of phosphorus. The lake management scenarios were largely related to a percent reduction in the summer seasonal load of phosphorus to each waterbody.

Scenarios 4 and 8 clearly indicate the additional reduction in total phosphorus and total chlorophyll that can be achieved by reducing internal phosphorus loading rates. The long history of nutrient load to the lake and reservoir and the removal of particulate phosphorus that was hypothesized and demonstrated during the calibration phase of this investigation suggest that an accumulation of phosphorus in the bottom sediments is a reasonable assumption. The SWAT and WASP simulations indicate that internal loads of phosphorus will probably need to be reduced by at least 70%, in addition to major reductions in phosphorus loads from upstream discharges, for there to be the magnitude of total phosphorus and total chlorophyll reductions in the lake and reservoir necessary to achieve compliance with the pH standard.

Current internal loading appears more significant than originally presumed, at least for Barr Lake, and would be expected to become a major influence as external inputs decline. Not enough is known of the sediment chemistry and forms of phosphorus in those sediments, but it is highly likely that phosphorus releases would be sufficient to fuel algal blooms and contravene the pH standard for many years after major watershed loading reductions; this has been the experience elsewhere (Godfrey et al. 2004, Cooke et al. 2005). Based on reasonable modeling assumptions, a minimum of a 70% reduction in internal loading would be desirable in conjunction with external loading controls, and this would be addressed through inlake methods.

There are multiple alternatives for reducing internal phosphorus loads and for reducing populations of algae. The methods range from physical alterations of the lake to the addition of some chemical or biological component that would fundamentally change inlake processes and dramatically effect eutrophication or its symptoms. Table 6-5 provides a brief summary of some of the alternatives available and highlights the advantages and disadvantages of each method, with accompanying discussion adapted from Wagner (2004). These methods all require different levels of effort and have varying potential outcomes depending upon the details of application. The more applicable methods for Barr Lake and Milton Reservoir are discussed below.

6.6.1 Mixing

Whole lake artificial circulation is also referred to as destratification or whole lake mixing. It may be accomplished through aeration, but can also be done mechanically. Circulation affects mixing and the uniformity of lake conditions. Thermal stratification and features of lake-morphometry such as coves create stagnant zones that may be subject to loss of oxygen, accumulation of sediment, or algal blooms. Artificial circulation minimizes stagnation and can eliminate thermal stratification or prevent its formation. Movement of air or water is normally used to create the desired circulation pattern in shallow (<20 ft) lakes, and this has been accomplished with surface aerators, bottom diffusers, and water pumps. Algae may simply be mixed more evenly in the available volume of water in many cases, but turbulence, changing light regime and altered water chemistry can cause shifts in algal types. At the very least, increased contact with the atmosphere tends to minimize pH extremes and could help meet the pH standard in the Barr-Milton system. Proper mixing does not disturb sediments.

6.6.2 Aeration

Aeration puts air into the aquatic system, increasing oxygen concentration by transfer from gas to liquid and generating a controlled mixing force. The oxygen transfer function is used to prevent anoxia near the bottom of the lake. By keeping the water from becoming anoxic, aeration should minimize the release of phosphorus, iron, manganese and sulfides from deep bottom sediments and decrease the build-up of undecomposed organic matter and oxygen-demanding compounds (e.g., ammonium). Hypolimnetic aeration can also increase the volume of water suitable for habitation by zooplankton and fish. Pure oxygen can be used in place of air to maximize oxygen transfer at an increased cost. Proper aeration/oxygenation does not disturb sediments. The combined functions of mixing and limitation of phosphorus release from bottom sediments could help achieve pH compliance in the Barr-Milton system.

Table 6-5. Management alternatives to control algae

OPTION	MODE OF ACTION	ADVANTAGES	DISADVANTAGES
Mixing	♦ Use of water or air to keep water in motion ♦ Intended to prevent or break stratification ♦ Generally driven by mechanical or pneumatic force	♦ Reduces surface build-up of algal scums ♦ May disrupt growth of blue-green algae ♦ Counteraction of anoxia improves habitat for fish/invertebrates ♦ Can eliminate localized problems without obvious impact on whole lake	♦ May spread localized impacts ♦ May lower oxygen levels in shallow water ♦ May promote downstream impacts ♦ Some mixers may create surface obstructions to boating
Aeration or Oxygenation	♦ Addition of air or oxygen at varying depth provides oxic conditions ♦ May maintain or break stratification ♦ Can also withdraw water, oxygenate, then replace	♦ Oxic conditions promote binding/sedimentation of phosphorus ♦ Counteraction of anoxia improves habitat for fish/invertebrates ♦ Build-up of dissolved iron, manganese, ammonia and phosphorus reduced	♦ May disrupt thermal layers important to fish community ♦ Theoretically promotes supersaturation with gases harmful to fish ♦ May be difficult to achieve desirable oxygen levels at sediment-water interface
Phosphorus inactivation	♦ Typically salts of aluminum, iron or calcium are added to the lake, as liquid or powder ♦ Phosphorus in the treated water column is complexed and settled to the bottom of the lake ♦ Phosphorus in upper sediment layer is complexed, reducing release from sediment ♦ Permanence of binding varies by binder in relation to redox potential and pH	♦ Can provide rapid, major decrease in phosphorus concentration in water column ♦ Can minimize release of phosphorus from sediment ♦ May remove other nutrients and contaminants as well as phosphorus ♦ Flexible with regard to depth of application and speed of improvement	♦ Possible toxicity to fish and invertebrates, especially by aluminum at low or high pH ♦ Possible release of phosphorus under anoxia or extreme pH ♦ Possible resuspension of floc in shallow areas ♦ Adds to bottom sediment, but typically an insignificant amount ♦ Results limited with continuing high external loading
Algaecides	♦ Liquid or pelletized algaecides applied to target area ♦ Algae killed by direct toxicity or metabolic interference ♦ Typically requires application at least once/yr, often more frequently	♦ Rapid elimination of algae from water column , normally with increased water clarity ♦ May result in net movement of nutrients to bottom of lake	♦ Possible toxicity to non-target species ♦ Restrictions on water use for varying time after treatment ♦ Increased oxygen demand and possible toxicity ♦ Possible recycling of nutrients
Sonication	♦ Sound waves disrupt algal cells	♦ Supposedly affects only algae (new technique) ♦ Applicable in localized areas	♦ Unknown effects on non-target organisms ♦ May release cellular toxins or other undesirable contents into water column

OPTION	MODE OF ACTION	ADVANTAGES	DISADVANTAGES
Dredging	♦ Sediment is physically removed by wet or dry excavation, with deposition in a containment area for dewatering ♦ Dredging can be applied on a limited basis, but is most often a major restructuring of a severely impacted system ♦ Nutrient reserves are removed and algal growth can be limited by nutrient availability	♦ Can control algae if internal recycling is main nutrient source ♦ Increases water depth ♦ Can reduce pollutant reserves ♦ Can reduce sediment oxygen demand ♦ Can improve spawning habitat for many fish species ♦ Allows complete renovation of aquatic ecosystem	♦ Temporarily removes benthic invertebrates ♦ May create turbidity ♦ May eliminate fish community (complete dry dredging only) ♦ Possible impacts from containment area discharge ♦ Possible impacts from dredged material disposal ♦ Interference with recreation or other uses during dredging
Dyes	♦ Creates light limitation	♦ Creates light limit on algal growth without high turbidity or great depth ♦ May achieve some control of rooted plants as well	♦ May cause thermal stratification in shallow ponds ♦ May facilitate anoxia at sediment interface with water
Bio-manipulation	♦ Manipulation of biological components of system to achieve grazing control over algae ♦ Typically involves alteration of fish community to promote growth of large herbivorous zooplankton, or stocking with phytophagous fish	♦ May increase water clarity by changes in algal biomass or cell size distribution without reduction of nutrient levels ♦ Can convert unwanted biomass into desirable form (fish) ♦ Harnesses natural processes to produce desired conditions	♦ May involve introduction of exotic species ♦ Effects may not be controllable or lasting ♦ May foster shifts in algal composition to even less desirable forms

6.6.3 Phosphorus inactivation

The release of phosphorus stored inlake sediments can be so extensive in some lakes and reservoirs that algal blooms persist long after incoming phosphorus has been significantly lowered. Phosphorus precipitation by chemical complexing removes phosphorus from the water column and reactions in surficial sediments can prevent the release of phosphorus from that sediment. Such inactivation can control algal abundance until the phosphorus supply is replenished. In the absence of external input control in the Barr-Milton system, benefits would be short-lived, but inactivation may be necessary after external inputs are reduced to maintain low phosphorus availability in these reservoirs. Phosphorus inactivation typically involves addition of binders, with aluminum compounds being the most common and iron and calcium formulations also used under certain circumstances. It is essentially an “anti-fertilizer” addition.

Such binders are commonly used in water and wastewater treatment as coagulants to remove impurities and contaminants prior to use or discharge (Cooke et al. 2005, Holdren et al. 2001). Use in WWTPs is for control of solids, bacteria, phosphorus, and other compounds that can be settled more efficiently after addition of a coagulant. Out in the environment, these binders perform the same function, with the reservoir typically used as the settling basin after treatment. Such environmental applications have been focused on inactivation of phosphorus in sediments over the last 30 years, but more recently have included inactivation of phosphorus in the water column or incoming waters in cases where upstream control was infeasible. Coagulated material, including much phosphorus, settles to the bottom and is incorporated into the sediment. Release from sediment depends on the binder and water/sediment chemistry, but a properly planned program provides for permanent sequestration of the phosphorus. Water column treatments are often combined with mixing systems, and where iron is used as a binder, adequate oxygen must be maintained to keep the phosphorus bound.

Binders are applied to the surface or subsurface, in either solid or liquid form, normally from a boat or barge. These compounds dissolve and form hydroxides, $Al(OH)_3$, $Fe(OH)_3$, or in the case of calcium, carbonates such as calcite ($CaCO_3$). These minerals form a floc that can remove particulates, including algae, from the water column within minutes to hours and precipitate reactive phosphates. Because aluminum and iron added as sulfates or chlorides dissolve to form acid anions along with the formation of the desired hydroxide precipitates, the pH will tend to decrease in low alkalinity waters unless basic salts such as sodium aluminate or lime are also added. Conversely, calcium is usually added as carbonates or hydroxides that tend to raise pH. The pH is likely to be very stable in Barr Lake and Milton Reservoir, necessitating no buffer addition.

The binders form a floc that settles on the sediment surface, gradually mixes with the upper few centimeters of sediment, reacts with available phosphorus, and prevents the release of phosphorus back into the water column. The resulting nutrient limitation in the surface waters prevents algal blooms from forming. The various floc minerals behave very differently under high or low dissolved oxygen and they also differ in their response to changes in pH. Because of its ability to continue to bind phosphorus under the widest range of pH and oxygen levels, aluminum is usually the preferred phosphorus inactivator. Other binders are applied under specific conditions that favor their use, but not as commonly as aluminum.

Aside from the benefits and drawbacks of inactivation listed in Table 6-4, the situation at Barr Lake and Milton Reservoir presents too additional challenges. First, the CDPHE currently does not allow the use of inactivators in environmental treatments, preferring that nutrient overloads be addressed at the source. If upstream sources are controlled, however, leaving internal recycling as the main phosphorus source, this position might be reconsidered. Secondly, the large swings in water level caused by use of reservoir water for irrigation over the summer will lead to exposure of considerable sediment that could be a source of phosphorus and might be treated. The ability of those sediments to retain the phosphorus upon inactivation is unknown, and would require further investigation if this approach was considered for implementation.

6.6.4 Algaecides

Algaecides are chemicals used to kill algae. They are much like herbicides, having various formulations meant to enhance effectiveness and/or minimize damage to non-target organisms, but focused on directly killing the target organisms by disruption of cellular processes. However, as algae grow in the water column, move with water masses, and are an integral part of virtually every natural aquatic system, elimination is not a realistic or desirable goal. The purpose of proper algaecide use is to either prevent algal growth from becoming excessive where conditions favoring such growth exist, or to alter the composition of the algal flora in a way that favors more desirable species, preferably those that are processed more readily in the food web. Algae depend mainly on sunlight and nutrients for sustenance; we have limited control over light, so control of nutrients is the most effective long-term approach to controlling algae. However, some algae can make use of dissolved or particulate organic material to grow, and pulses of nutrient inputs are nearly impossible to prevent, so additional means of control may be needed where recreation or water supply are threatened.

A wide range of chemicals have been used for algae control historically, but there are only three active ingredients commercially manufactured at this time: copper, peroxides and endothall. Copper is by far the most common and versatile, with many formulations, common use in recreational and drinking water supply lakes, and very little evidence of long-term negative impacts. In the short-term, however, toxicity to non-target organisms is a concern, release of cell contents is perceived as undesirable, and effectiveness is not certain by any means. Peroxides have been used in some form for many years with varied results, but recent advances have produced products that appear more effective and have less risk than copper formulations. Endothall tends to be a special use herbicide, applied to control green algal mats that are resistant to other algaecides and many other means of control.

On a regular basis to eliminate blooms in the highly fertile waters of Barr Lake and Milton Reservoir, algicides would be an undesirable approach. As an emergency method for avoiding major ecological and human health problems, algicides can be useful, but require careful tracking of the algal community to know when and how much algicide to apply.

6.6.5 Dredging

Dredging is perhaps best known for maintaining navigation channels in rivers, harbors and ports or for underwater mining of sand and gravel, but dredging can also be an effective lake management technique for the control of excessive algae and invasive growth of macrophytes. The management objectives of a sediment removal project are usually to deepen a shallow lake for boating and fishing, or to remove nutrient rich sediments that can cause algal blooms or support dense growths of rooted macrophytes. Dredging is discussed here in its role as a nutrient control strategy.

The release of algae stimulating nutrients from lake sediments can be controlled by removing layers of enriched materials. This may produce significantly lower inlake nutrient concentrations and less algal production, assuming that there has been adequate diversion or treatment of incoming nutrient, organic and sediment loads from external sources. Even where incoming nutrient loads are high, dredging can reduce benthic mat formation and related problems with filamentous green and blue-green algae, as these forms may initially depend on nutrient-rich substrates for nutrition. Dredging also removes the accumulated resting cysts deposited by a variety of algae. Although recolonization would be expected to be rapid, changes in algal composition can result.

For Barr Lake and Milton Reservoir, dredging would be a highly desirable means for removing nutrient-rich sediment and limiting internal loading. With the water level drawn down by irrigation at the end of most summers, conventional excavation is possible around the edge of these reservoirs, but removing the critical nutrient reserves in the deeper areas would have to be done hydraulically. We do not have adequate information for calculating the amount of sediment that should be removed, but if a 2 ft layer was removed over half the area of either reservoir (about 950 acres), that would be approximately 3 million cubic yards.

6.6.6 Biomanipulation

Biomanipulation to improve lake transparency includes elimination of fish such as the common carp or bullheads that are bottom browsers and can release significant amounts of sediment and nutrients to the water column as these fish feed and digest food. Harvesting these fish has resulted in increased clarity in some cases. It has been suggested that alternative stable equilibria exist for lakes, based on biological structure, and removal of bottom feeding fish could shift the balance. Removing such fish, however desirable, can be very difficult since they tolerate very low levels of dissolved oxygen and high doses of fish poisons. Labor intensive programs appear necessary to achieve substantial reductions in bottom-feeding fish populations, unless the entire fish population can be sacrificed.

Beyond bottom feeder removal, it is also possible to enhance algal control by altering fish community structure. In many lakes an abundance of algae is believed to be caused by a lack of zooplankton that graze on the algae. The lack of zooplankton in turn is thought to be a result of an overabundance of small fish that prey on zooplankton. By introducing or augmenting fish such as largemouth bass that eat the small fish, those planktivorous fish are reduced in numbers and the populations of large-bodied zooplankton can increase and graze on the algae, thus clearing the water. However, simply adding bass to a pond will not solve the algae problem as many ponds already are at carrying capacity for these predators. Biomanipulation has not been very successful at high phosphorus levels; it is suggested that concentrations be reduced below 0.1 mg/L before a significant long-term impact from biomanipulation can be expected (Sondergaard et al. 2008). Consequently, biomanipulation is a follow up technique for the Barr-Milton system, not a central focus prior to nutrient input reduction.

6.7 Implementation choices for compliance

A phosphorus loading limit that will control algae to an extent that prevents contravention of the pH standard can be set and is the primary thrust of TMDL development. However, achieving the commensurate reduction from current loading is likely to be a daunting task, and setting such a TMDL without consideration of alternative means for meeting the standard may not be in the best interest of all parties. The reason to develop a TMDL is to set in motion a management program that will result in compliance with a state water quality standard, and when the TMDL is directly related to the standard being violated, there may be few choices. However, where the TMDL is indirectly linked to the violation, as with phosphorus and pH in Barr Lake and Milton Reservoirs, alternative measures for achieving compliance might be considered.

There is no doubt that reduced nutrient loading is desirable for the uses of these reservoirs. There is no question that loads are currently excessive, and that the load from two point sources dominates water quality in these reservoirs. However, there is considerable doubt that an implementation program that achieves compliance with the state standard by reducing phosphorus loading can be practically achieved in even one to two decades. The use of alternative means, including aeration/mixing, inlake chemical treatments, or even dredging to control summer algal blooms, is entirely consistent with management for designated uses. It is true that by themselves these are maintenance measures, not true restoration, but the reservoirs could be managed to achieve pH compliance without the stringent loading reductions indicated by the modeling analysis. The target pH would remain the same (9.0 SU no more than 15% of the time, and probably on the order of 8.5 as a mean value to provide a margin of safety), but the phosphorus concentration might not have to be reduced so drastically to meet this goal.

The development of a TMDL for phosphorus in these reservoirs remains a valid exercise, but its implementation will foster considerable debate. Since there are options for supporting designated uses and achieving pH compliance that would not require such stringent reductions, the implementation of an approved TMDL for Barr Lake and Milton Reservoir might be modified to reflect the synergy of combined approaches to achieving compliance. This will involve economic and sociopolitical elements of the process not covered in this scientific effort.

7.0 Conclusions

A large quantity of data for watershed and reservoir features was examined in this project. The watershed and lake modeling investigation documented in this report provides a framework to facilitate the development of a TMDL for pH in Barr Lake and Milton Reservoir. The modified version of the SWAT watershed model and the multi-species WASP eutrophication model represent advancements in each model that, when combined and applied to the Barr-Milton system, allowed simulation of current conditions and a diverse set of alternative management scenarios representing potential options for improving water quality in the reservoirs. This relatively complex modeling investigation relied on incorporating the measured and estimated point loads and water transfers, consumptive use, and lake water management to facilitate the numerical representation of the lake and reservoir during the period of 2003-2004. Evaluation of available data and model results yields the following conclusions:

1. Analysis of relationships between phosphorus, chlorophyll and pH suggests that the highest total phosphorus value that could be reasonably expected to support achievement of the pH standard is 0.1 mg/L in each lake, although a lack of data for conditions in the reservoirs at phosphorus levels <0.25 mg/L adds uncertainty. The corresponding target mean chlorophyll *a* concentration would be 20 to 25 µg/L. Based on current variability, a mean pH near 8.5 SU is predicted to result in a pH distribution that meets the standard.
2. Nutrient loading to Barr Lake and Milton Reservoir is excessive. As phosphorus levels rise above 0.1 mg/L, there is a diminishing linkage with productivity measures as other factors become more important in controlling algae growth. Phosphorus concentrations in these two reservoirs are rarely <0.25 mg/L.
3. Currently, point sources of nutrients dominate the nutrient loads to the reservoirs. Nonpoint sources are much smaller in comparison. Water entering the datashed is of generally acceptable quality, but becomes overloaded with nutrients through sequential discharges to the South Platte River prior to diversion into Barr Lake and Milton Reservoir.
4. The Metro WWTP and Littleton-Englewood WWTP are the largest dischargers of phosphorus to the system, providing approximately 90% of the load to Barr Lake and 80% of the load to Milton Reservoir. Of these two sources, Littleton/Englewood WWTP is slightly more influential on Barr Lake and Metro WWTP is much more influential on Milton Reservoir.
5. Internal loading is difficult to quantify with existing data, but the model indicates that internal loading of phosphorus may be an important input source in at least Barr Lake now. Internal loading in both reservoirs is sufficient to support algal blooms and contravene the pH standard, and is expected to increase substantially if external loading is decreased. Additional investigation into this compensatory mechanism has been recommended.
6. The SWAT model tends to overpredict nutrient loading while the WASP model underpredicts resultant inlake phosphorus concentrations. Important processes appear adequately simulated, however, and predictions of the direction and magnitude of change in response to possible management actions are considered useful for TMDL development.
7. It is not possible to achieve a meaningful reduction in phosphorus loading without addressing the dominant point sources and the internal load. More than a 90% reduction in each is needed, and it may take a 99% reduction in the external load to achieve phosphorus concentrations believed to correspond to compliance with the pH standard. This would require major reductions from many sources in the watershed, not just the dominant point sources.
8. Management of water transfers in the watershed offers potential to improve water quality in Barr Lake, but potentially at the expense of the water quality in Milton Reservoir, and not enough to meet the pH standard. Water transfer management that will benefit both reservoirs may be possible, but would

involve water rights issues and is likely to reduce certainty of summer water supply from the reservoirs.

9. Additional inlake approaches for minimizing algal production and moving toward pH compliance are available, but a watershed-based effort may be necessary to consistently achieve water quality goals. TMDL development is based on reducing phosphorus loading and inlake concentrations to a point at which algal growth will be limited and high pH will be minimized. Still, with the extreme effort necessary to reduce external loads to the necessary level, inlake actions that could achieve pH compliance bear further scrutiny.

10. Almost all scenarios examined in this exercise do not result in mean phosphorus and/or chlorophyll levels as low as may seem desirable from the evaluation of possible target values. However, it appears more important to avoid high values than to lower the mean or median by an extreme amount, and it may be easier to change the shape of the distribution of values than to shift the entire distribution to a lower level. Implementation should consider how to achieve compliance with the pH standard and support of designated uses, not simply how to drastically reduce phosphorus levels in this wastewater dominated system.

8.0 References

AECOM. 2008. Lake Waco Comprehensive Lake Management Study. City of Waco, TX.

Ambrose, R.B., Wool, T.A., and Martin, J.L., 1993. The Water Quality Analysis Simulation Program, WASP5 Part A: Model Documentation. Environmental Research Laboratory. U.S. Environmental Protection Agency. Athens, GA.

Ambrose, R.B., Wool, T.A., Martin, J.L., Connolly, J.P., and Schanz, R.W., undated. WASP4, A Hydrodynamic and Water Quality Model - Model Theory, User's Manual, and Programmer's Guide. Environmental Research Laboratory. Office of Research and Development. U.S. Environmental Protection Agency. Athens, GA.

AMEC. 2008a. Barr Lake: Reservoir Water Quality Assessment, Adams County, Colorado. Barr-Milton Watershed Association, Denver, CO.

AMEC. 2008b. Milton Reservoir: Reservoir Water Quality Assessment, Weld County, Colorado. Barr-Milton Watershed Association, Denver, CO.

BMW (Barr-Milton Watershed Association) 2008. Barr Lake and Milton Reservoir Watershed Management Plan. Prepared by Watershed Plan Writing Committee of the Barr Lake and Milton Reservoir Watershed Association. October 2008.

Bradford, M.E. and R.H. Peters. 1987. The relationship between chemically analyzed phosphorus fractions and bioavailable phosphorus. Limnol. Oceanogr. 32:1124-1137.

Carlson, R. 1977. A trophic state index for lakes. Limnol. Oceanogr. 22:361-369.

Center for Watershed Protection. 2003. Impacts of Impervious Cover on Aquatic Systems. Watershed Protection Research Monograph #1, CWP, Ellicot City, MD.

CDPHE (Colorado Department of Public Health and Environment). 2004. Status of Water Quality in Colorado. CDPHE, Water Quality Control Division, Denver, CO.

CDPHE (Colorado Department of Public Health and Environment). 2008. Status of Water Quality in Colorado. CDPHE, Water Quality Control Division, Denver, CO.

Chapra, S.C., 1997. Surface Water Quality Modeling. McGraw-Hill Companies, Inc. 844 pages.

Cooke, G.D., E.B. Welch, S.A., Peterson and S.A. Nichols. 2005. Restoration and Management of Lakes and Reservoirs. Third Edition. Taylor & Francis, Boca Raton, FL.

Dillon, P.J. and F.H. Rigler. 1974. The phosphorus-chlorophyll relationship in lakes. Limnol. Oceanogr. 19:767-773.

Dodds, W.K., E. Carney and R.T. Angelo. 2006. Determining ecoregional reference conditions for nutrients, Secchi depth and chlorophyll a in Kansas lakes and reservoirs. Lake and Reserv. Manage. 22:151-159.

Dodds, W.K., K.R. Johnson and J.C. Priscu. 1989. Simultaneous nitrogen and phosphorus deficiency in natural phytoplankton assemblages: theory, empirical evidence and implications for lake management. Lake Reserv. Manage. 5:21-26.

ENSR. 2004. Supplemental Loading Evaluation of Hop Brook. Prepared for the MA DEP and New England District USACE. Westford, MA.

Ernst, M. and J. Owens. Development and application of a WASP model on a large Texas reservoir to assess eutrophication control. Lake Reserv. Manage. 25:136-148.

Godfrey, P., R. Kortmann, S. Souza and K. Wagner. 2004. Recommendations for the Management of Neponset Reservoir for Control of Excessive Nutrients, Algae, and Macrophytes. NRRC, Foxborough, MA.

Hargreaves and Sumani, 1982. Estimating potential evapotranspiration Tec. Not., J. Irrig. And Drain. Engr. 108(3):225-230.

Holdren, G.C., W. Jones and J. Taggart. (Editors). 2001. Managing Lake and Reservoirs. USEPA/NALMS, Madison, WI.

Jones, J. and R. Bachmann. 1976. Prediction of phosphorus and chlorophyll levels in lakes. JWPCF 48:2176-2184.

Jones, A., W. Rast and G.F. Lee. 1979. Relationship between summer mean and maximum chlorophyll-a concentrations in lakes. Environ. Sci. & Technol. 13:869-70.

Kadlec, R. and R. Knight. 1996. Treatment Wetlands. CRC Press, Boca Raton, FL.

Kirchner, W. and P. Dillon. 1975. An empirical method of estimating the retention of phosphorus in lakes. Water Resourc. Res. 11:182-183.

Larsen, D. and H. Mercier. 1976. Phosphorus retention capacity of lakes. J. Fish. Res. Bd. Can. 33:1742-1750.

Lewis, W.M. Jr. and J.H.McCutchan, Jr. 2009. Modeling of the Contribution of Metro District Effluent to Total Phosphorus andNitrogen Loading of Barr Lake and Milton Reservoir. Prepared for Metro, Denver, CO.

Mattson, M.D., P.J. Godfrey, R.A. Barletta and A. Aiello. 2004. Eutrophication and Aquatic Plant Management in Massachusetts. Final Generic Environmental Report. Edited by Kenneth J. Wagner. Department of Environmental Protection and Department of Conservation and Recreation, EOEA Commonwealth of Massachusetts.

Mountain River Associates, 2004. Barr Lake Water Quality Data Summary Report Water Years 1995-2004.

Neitsch, S.L., J.G. Arnold, J.R. Kiniry, and J.R. Williams, (2005a). Soil and Water Assessment Tool Theoretical Documentation, Version 2005.

Neitsch, S.L., J.G. Arnold, J.R. Kiniry, and J.R. Williams, (2005b). Soil and Water Assessment Tool User Manual, Version 2005.

New Hampshire Department of Environmental Services. 1994. Best Management Practices to Control Nonpoint Source Pollution: A Guide for Citizens and Town Officials. NHDES-WSPCD – 94-2, NHDES, Concord, NH.

Oglesby, R.T. and W.R. Schaffner. 1978. Phosphorus loadings to lakes and some of their responses. Part 2. Regression models of summer phytoplankton standing crops, winter total phosphorus, and transparency of New York lakes with phosphorus loadings. Limnol. Oceanogr. 23:135-145.

Penman, H.L., 1956. Evaporation: An Introductory survey. Netherlands Journal of Agricultural Science 4:7-29.

Priestley, C.B.H. and R.J. Taylor, 1972. On the assessment of Surface Heat Flux and evaporation using large-scale parameters. Mon. Weather Rev. 100:81-92.

Reckhow, K.H. 1977. Phosphorus Models for Lake Management. Ph.D. Dissertation, Harvard University, Cambridge, MA.

Robertson, D.M., H.S. Garn and W.J. Rose. 2007. Response of calcareous Nagawicka Lake, Wisconsin, to changes in phosphorus loading. Lake and Reserv. Manage. 23:298-312.

Rosenberg, N. J., D. L. Epstein, D. Wang, L. Vail, R. Srinivasan, and J. G. Arnold. 1999. Possible impacts of global warming on the hydrology of the Ogallala aquifer region. Clim. Change 42(4): 677□692.

Reddy, K.R., M.M. Fisher, Y. Wang, J.R. White and R.T. James. 2007. Potential effects of sediment dredging on internal phosphorus loading in a shallow, subtropical lake. Lake Reserv. Manage. 23:207-228.

Rydin, E. and E.B. Welch. 1998. Aluminum dose required to inactivate phosphate in lake sediments. Wat. Res. 32:2969-2976.

Rydin, E. and E.B. Welch. 1999. Dosing alum to Wisconsin lake sediments based on in vitro formation of aluminum bound phosphate. Lake Reserv. Manage. 15:324-331.

Santhi, C., J. G. Arnold, J. R. Williams, W. A. Dugas, R. Srinivasan, L. M. Hauck, 2007. Validation of the SWAT model on a large river basin with point and nonpoint sources. Journal of the American Water Resources Association. Volume 37, Issue 5, Date: October 2001, Pages: 1169-1188

Sharpley, A.N., S.C. Chapra, R. Wedpohl, J.T. Sims, T.C. Daniel, and K.R. Reddy, 1994. Managing Agricultural Phosphorus for Protection of Surface Waters: Issues and Options. J. Environ. Qual. 23:437-451.

Smith, V. 1983. Low nitrogen to phosphorus ratios favor dominance by blue-green algae in lake phytoplankton. Science 221:669-671.

Sondergaard, M., L.. Liboriussen, A. Pedersen and E. Jeppesen. 2008. Lake restoration by fish removal: Short- and long-term effects in 36 Danish lakes. Ecosystems 11:1291-1305.

Srinivasan, R., J.G. Arnold, T.S. Ramanarayanan, and S.T. Bednarz. 2000. Modeling Wister lake watershed with the soil and water assessment tool (SWAT) J. American Water Resources Association (in review)

Smith, V., F. deNoyelles, D.W. Graham, and S.J. Randtke. 2001. A Comparative Water Quality Study of Cheney Reservoir, Kansas. Final Report of the City of Wichita Water and Sewer Department, Lawrence, KS.

USEPA, 1985. Rates, Constants, and Kinetics Forumlations in Surface Water Quality Modleing (Second Edition). EPA/600/3-85/040. June 1985.

USEPA, 1987. The Enhanced Stream Water Quality Models QUAL2E and QUAL2E-UNCAS: Documentation and User's Manual. EPA/600/3-87/007. May 1987.USEPA. 1999. Preliminary Data Summary of Urban Storm Water Best Management Practices. EPA-821-R-99-012. USEPA, Washington, DC.

Vollenweider, R. 1975. Input-output models with special reference to the phosphorus loading concept in limnology. Schweiz. Z. Hydrol. 37:53-62.

Vollenweider, R. 1982. Eutrophication of Waters: Monitoring, Assessment and Control. OECD, Paris.

Wagner, K.J. 2004. The Practical Guide to Lake Management. MA DCR/DEP, Boston, MA.

Walker, W.W. 1984. Statistical bases for mean chlorophyll-a criteria. pp. 57-62 in Lake and Reservoir Management - Practical Applications, Proc. 4th Annual Conference, North American Lake Management Society, McAfee, New Jersey, October 1984.

Watson, S.B., McCauley, E. and Downing, J.A. 1997. Patterns in phytoplankton taxonomic composition across temperate lakes of differing nutrient status. Limnol. Oceanogr. 42:487-495.

Wisconsin Department of Agriculture and Trade and Consumer Protection. 1989. Best Management Practices for Wisconsin Farms. WDATCP, Madison, WI.

Wool, T.A., Ambrose, R.B., Martin, J.L., and Comer, E.A . Undated. Water Quality Analysis Simulation Program (WASP) Version 6.0. Draft: User's Manual.

WQCD. 2009. Development of a Feasibility-based Chlorophyll Standard for Cherry Creek Reservoir. WQCD Exhibit 3, Rebuttal Statement Cherry Creek Reservoir, Denver, CO.

Appendix A

Sources of Model Data

Sources of Input Data for SWAT and WASP Models:

DEM - www.seamless.usgs.gov

Landuse – www.seamless.usgs.gov

Landuse/Irrigation – Colorado's Decision Support Systems http://cdss.state.co.us

National Land Cover Dataset 2001 from MRCL www.mrlc.gov/

Soils – Statsgo from USDA http://datagateway.nrcs.usda.gov

NHD – http://www.epa.gov/waterscience/ftp/basins/gis_data/huc/10190003

Meteorological data: http://www.ncdc.noaa.gov/oa/ncdc.html

Stations: Denver International Airport, Denver Stapleton, Castle Rock, Greeley UNC, Fort Lupton

Barr and Milton sampling stations and corresponding data – Hydrosphere database and AMEC 2008a, 2008b

Model Flows/Loads

Generally: Flows and WQ - Hydrosphere Database, Data provided directly from WWTPs, Data provided from FRICO, State of Colorado

Big Dry Creek – USGS gage 06720800

Brantner Ditch – state engineer's office, CDSS, Hydrosphere

Clear Creek – USGS gage 06714100 – old gage 1914-1982

Bear Creek – state engineer's office, CDSS, Hydrosphere

Platte Valley Canal outflow – state engineer's office, CDSS, Hydrosphere, FRICO spreadsheet

Latham Reservoir (Gilmore Ditch) – FRICO spreadsheet

Fulton Ditch – state engineer's office, CDSS, Hydrosphere

Beebe Drain – FRICO spreadsheet, loss to irrigation w. vac. house, Speer/Wess

Denver Hudson Canal – FRICO spreadsheet

Cherry Creek – USGS gage 06713000

O'Brian Canal – Removal and into Barr – FRICO spreadsheet

Barr and Milton flows - FRICO