Little Rock Creek Watershed

Total Maximum Daily Load Report: Dissolved Oxygen, Nitrate, Temperature and Fish Bioassessment Impairments

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Little Rock Creek Watershed Total Maximum Daily Load Report: Dissolved Oxygen, Nitrate, Temperature and Fish Bioassessment Impairments

Prepared for
Benton County Soil and Water Conservation District
Minnesota Pollution Control Agency

December 2015

CLEAN
WATER
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AMENDMENT

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List of Acronyms/Abbreviations

ac	acre
AUID	assessment unit identification number
BEHI	Bank Erosion Hazard Index
BMP(s)	best management practice(s)
BWSR	Board of Water and Soil Resources
°C	degrees Celsius
CAFO(s)	Concentrated Animal Feeding Operation(s)
CBOD	carbon oxygen demand
CDL	Crop Data Layer
Chl-a	Chlorophyll-a
Cr	Creek
CPPE	Conservation Practice Physical Effects
DEM	Digital Elevation Model
DM	Daily Maximum
DO	dissolved oxygen
°F	degrees Fahrenheit
GJ	gigajoules
HRU	hydrologic response unit
IBI	Index of Biotic Integrity
in	inches
kg	kilograms
km	kilometers
LA	load allocation
m	meter
mi	mile
mg/L	milligrams per liter
MDA	Minnesota Department of Agriculture
MDNR	Minnesota Department of Natural Resources
MODFLOW	modular finite-difference flow model
MOS	margin of safety
MPCA	Minnesota Pollution Control Agency
MS4	Municipal Separate Storm Sewer Systems
MWAT	Maximum Weekly Average Temperature

NASS	National Agricultural Statistics Service
NBOD	nitrogenous oxygen demand
NBS	near-bank stress
NCDC	National Climatic Data Center
NRCS	Natural Resources Conservation Service
NLCD	National Land Cover Database
NO_3	nitrate
NPDES/SDS	National Pollutant Discharge Elimination System/State Disposal System
NSE	Nash-Sutcliffe Efficiency
Obwell(s)	observation well(s)
PDI	Palmer Drought Index
PEST	Parameter EStimation Software
POM	particulate organic matter
QUAL2K	2000 Enhanced Stream Water Quality Model
RC	Reserve Capacity
s	seconds
SSURGO	Soil Survey Geographic Database
SWAT	Soil and Water Assessment Tool
SWCD	Soil and Water Conservation District
SWUDS	State Water Use Data System
SOD	sediment oxygen demand
TMDL	total maximum daily load
UMN	University of Minnesota
USDA	United States Department of Agriculture
USEPA	United States Environmental Protection Agency
USGS	United States Geological Survey
VRI	variable rate irrigation
WLA	wasteload allocation
WMA	Wildlife Management Area
yr	year

Glossary

Assessment Unit Identifier (AUID): The unique water body identifier for each river reach comprised of the USGS eight-digit HUC plus a three-character code unique within each HUC.

Aquatic life impairment: The presence and vitality of aquatic life is indicative of the overall water quality of a stream. A stream is considered impaired for impacts to aquatic life if the fish Index of Biotic Integrity (IBI), macroinvertebrate IBI, dissolved oxygen, temperature, or certain chemical standards are not met.

Cold water fish assemblage: Refers to a healthy community of cold water sport or commercial fish and associated aquatic life.

Connectivity: Refers to the flow, exchange, and pathways that move organisms, energy, and matter through creek systems. Barriers to movement or exclusion from habitat will limit connectivity.

Hydrologic Unit Code (HUC): A Hydrologic Unit Code (HUC) is assigned by the USGS for each watershed. HUCs are organized in a nested hierarchy by size. For example, the Minnesota River Basin is assigned a HUC-4 of 0702 and the Pomme de Terre River Watershed is assigned a HUC-8 of 07020002.

Impairment: Water bodies are listed as impaired if water quality standards are not met for designated uses including: aquatic life, aquatic recreation, and aquatic consumption.

Index of Biotic integrity (IBI): A method for describing water quality using characteristics of aquatic communities, such as the types of fish and invertebrates found in the waterbody. It is expressed as a numerical value between 0 (lowest quality) to 100 (highest quality).

Lithophils: Fish species that exhibit burying behavior and construction of nests that are dependent on clean rocky substrates to spawn.

Piscivores: Fish species that are strictly dependent on fish for food.

Sensitive Individuals: Species with the highest degree of susceptibility to perturbation.

Source (or Pollutant Source): This term is distinguished from ‘stressor’ to mean only those actions, places or entities that deliver/discharge pollutants (e.g., sediment, phosphorus, nitrogen).

Stressor (or Biological Stressor): This is a broad term that includes both pollutant sources and non-pollutant sources or factors (e.g., altered hydrology, dams preventing fish passage) that adversely impact aquatic life.

Total Maximum Daily Load (TMDL): A calculation of the maximum amount of a pollutant that may be introduced into a surface water and still ensure that applicable water quality standards for that water are met. A TMDL is the sum of the wasteload allocation for point sources, a load allocation for nonpoint sources and natural background, an allocation for future growth (i.e., reserve capacity), and a margin of safety as defined in the Code of Federal Regulations.

TMDL SUMMARY

<table>
<tr><th>USEPA/MPCA Required Elements</th><th>Summary</th><th>TMDL Page #</th></tr>
<tr><td>Location</td><td>Little Rock Creek watershed; Central Minnesota; Benton and Morrison Counties; Upper Mississippi River Basin</td><td>3</td></tr>
<tr><td>303(d) Listing Information</td><td>1 listing for dissolved oxygen, 2 listings for nitrate and 1 listing for Fish bioassessments; *see Table 1.1*</td><td>2</td></tr>
<tr><td>Applicable Water Quality Standards/ Numeric Targets</td><td>*See Section 2.0*</td><td>19</td></tr>
<tr><td>Loading Capacity (expressed as daily load)</td><td>*See Section 3*</td><td>21</td></tr>
<tr><td>Wasteload Allocation</td><td>*See Section 3*; The following Concentrated Animal Feeding Operation (CAFO, over 1,000 animal units) is a permitted source in the Little Rock Creek watershed:
<table>
<tr><td>CAFO PERMIT NUMBER</td><td>PERMITTED LOAD AMOUNT</td></tr>
<tr><td>MNG441098</td><td>0</td></tr>
</table></td><td>21</td></tr>
<tr><td>Load Allocation</td><td>*See Section 3*</td><td>21</td></tr>
<tr><td>Margin of Safety</td><td>*See Section 3.3.2*</td><td>25</td></tr>
<tr><td>Seasonal Variation</td><td>Load duration curve methodology accounts for seasonal variation and water quality modeling was calibrated for critical conditions; *see Section 3.2*</td><td>23</td></tr>
<tr><td>Reasonable Assurance</td><td>NPDES permits provide assurance for permitted sources to comply with WLAs. *see Section 6.0.*</td><td>49</td></tr>
<tr><td>Monitoring</td><td>A general overview of follow-up monitoring is included; *see Section 4.0.*</td><td>38</td></tr>
<tr><td>Implementation</td><td>A discussion of factors to consider for implementation is provided, as well as recommended BMPs to achieve the TMDL. (A separate, more detailed implementation plan will be developed at a later date.) *See Section 5.0.*</td><td>41</td></tr>
<tr><td>Public Participation</td><td>Various stakeholder, technical advisory, public participation and outreach efforts were conducted; *see Section 7.0.*
The public notice comment period took place from February 4, 2013 –March 6, 2013</td><td>51</td></tr>
</table>

Executive Summary

The Clean Water Act, Section 303(d), requires that every two years states publish a list of waters that do not meet water quality standards and do not support their designated uses. These waters are then considered to be "impaired". Once a waterbody is placed on the impaired waters list, a Total Maximum Daily Load (TMDL) must be developed. The TMDL provides a calculation of the maximum amount of a pollutant that a waterbody can receive and still meet water quality standards. It is the sum of the individual wasteload allocations (WLAs) for point or permitted sources, load allocations (LAs) for nonpoint or nonpermitted sources and natural background, plus a margin of safety (MOS). This TMDL report applies to Little Rock Creek which is impaired due to a lack of coldwater fish assemblage and includes impaired waters listings for dissolved oxygen and nitrates. Bunker Hill Creek, a tributary to Little Rock Creek, is also listed for nitrates.

The Little Rock Creek Watershed is 44,229 acres and is divided between Benton (12,590 acres) and Morrison (31,639 acres) counties. The main stream segment of Little Rock Creek is perennial, whereas, a majority of the tributaries to the creek are intermittent or have been converted to drainage ditches. Little Rock Creek flows south through Little Rock Lake and ultimately discharges to the Mississippi River via the Harris Channel. The drainage area for Little Rock Creek has been further defined by linked surface water and groundwater modeling developed for this study. The groundwater model domain area for the Little Rock Creek Watershed is 215,701 acres, and was selected because groundwater purturbations outside of the surface watershed area will affect the groundwater drainage area, along with climatic variations and variations in groundwater pumping. Groundwater flows west through the Little Rock Creek watershed, discharging both to the creek and to the Mississippi River (south and west of the watershed).

The Little Rock Creek Stressor Identification report (Benton SWCD, 2009) cites lower groundwater levels as a possible contributor to the impairments for dissolved oxygen and temperature. The data show that the dry weather and associated low flow conditions from the TMDL monitoring period (2006 through 2008) were not as severe at the 1988 drought, but the persistence of dry conditions resulted in above average pumping rates for agricultural irrigation (normalized to the drought index) for six consecutive years that may have exacerbated the flow conditions for Little Rock Creek.

This study used a variety of methods to evaluate the current loading and contributions from the various pollutant sources, as well as the allowable pollutant loading capacity of the impaired reaches. The load duration curve approach was used to develop allocations for reaches impaired by nitrate and temperature and the 2000 Enhanced Stream Water Quality Model (QUAL2K) water quality modeling was used to develop the pollutant loading capacity and allocations for dissolved oxygen, as well as simulations of the effect of potential mitigation options on dissolved oxygen, nitrate and temperature levels throughout Little Rock Creek.

Overall, a 52% reduction in total oxygen demand is necessary to ensure that the DO standard is met throughout Little Rock Creek under the critical flow conditions. Reductions in nitrate load of 47% and 29% are necessary to ensure that the standard is met in Little Rock Creek under the dry and low flow conditions, respectively. Reductions in nitrate load of 33% and 19% are necessary to ensure that the standard is met in Bunker Hill Creek under the moist and mid-range flow conditions, respectively. Overall, a 1% reduction in thermal loading across all thermal sources is needed in the Station 13 section of Little Rock Creek to meet the Maximum Weekly Average Temperature (MWAT) criteria.

The calibrated water quality modeling was used to simulate three mitigation scenarios: removal of the man-made impoundment, doubling the groundwater flow into the system while maintaining the same chemical loads, and a combination of the first two mitigation scenarios. The results of this modeling showed that a combination of both types of mitigation would be required to meet the dissolved oxygen standard and the temperature criteria, while an increase in groundwater flow would be necessary to meet the drinking water standard for nitrate in Little Rock Creek. The ideal combination of implementation strategies, or combinations of Best Management Practices (BMPs), would provide some or all of the following:

- Reductions in groundwater use will be necessary to improve conditions in the stream. A variety of potential options to reduce groundwater use should be explored, including: limits on total appropriations, improved irrigation efficiency, scheduling and technologies, identifying alternative sources, timing, proximity to the stream and other options not yet identified
- Nutrient and organic constituent reductions
- Creating more of a free flowing system, while incorporating current Wildlife Management Area (WMA) management strategies, to improve connectivity and temperature issues during the critical conditions described in this report

Implementation strategies intended to restore the connectivity and thermal regime of the stream, as well as nonpoint source-related actions that address all of the impairments are provided in this report and more specific implementation planning will be developed and made available, separately. It is expected that groundwater and hydrology management will improve the loading capacity and water quality toward meeting the State water quality standards and temperature criteria over a long period, while helping to restore biological integrity in Little Rock Creek. Nonpoint contributions are not regulated and, therefore, reductions will need to proceed on a voluntary basis. Allowable loadings from future permitted point sources of construction and industrial activities related to the TMDLs are described in this report. These will be addressed through the MPCA’s National Pollutant Discharge Elimination System (NPDES) permit programs.

1.0 Background

1.1 303(d) Listings

Section 303(d) of the Clean Water Act provides authority for completing Total Maximum Daily Loads (TMDLs) to achieve state water quality standards and designated uses.

A TMDL is a calculation of the maximum amount of pollutant that a waterbody can receive and still meet water quality standards and designated uses. It is the sum of the loads of a single pollutant from all contributing point and nonpoint sources. TMDLs are approved by the U.S. Environmental Protection Agency (USEPA) based on the following elements:

1. They are designed to implement applicable water quality criteria;
2. Include a total allowable load as well as individual waste load allocations;
3. Consider the impacts of background pollutant contributions;
4. Consider critical environmental conditions;
5. Consider seasonal environmental variations;
6. Include a margin of safety;
7. Provide opportunity for public participation; and
8. Have a reasonable assurance that the TMDL can be met.

In general, the TMDL is developed according to the following relationship:

$$\mathbf{TMDL = \sum WLA + \sum LA + MOS + RC}$$

Where:

∑WLA = sum of all wasteload allocations; portion of the TMDL allocated to existing or future point sources of the relevant pollutant;

∑LA = sum of all load allocation; portion of the TMDL allocated to existing or future nonpoint sources of the relevant pollutant. The load allocation may also encompass “natural background” contributions;

MOS = margin of safety; an accounting of uncertainty about the relationship between pollutant loads and the quality of the receiving water body. The margin of safety can be provided implicitly through analytical assumptions or explicitly by reserving a portion of loading capacity (USEPA, 1999); and

RC = reserve capacity, an allocation for future growth which accounts for reasonably foreseeable increases in pollutant loads. Reserve capacity was not considered to be applicable for this TMDL.

This TMDL report applies to Little Rock Creek which is impaired due to a lack of coldwater fish assemblage and includes impaired waters listings for dissolved oxygen and nitrates. Bunker Hill Creek, a tributary to Little Rock Creek, is also listed for nitrates. Initially, Little Rock Creek was listed on the 2002 303(d) list for impaired waters based on a 1999 in-stream biological assessment for fish due to a low fish index of biotic integrity (IBI). The fish community at the location on Little Rock Creek was comprised of highly tolerant warmwater species and absent of species indicative of coldwater habitats. Little Rock Creek scored 26 out of 100, based on a warmwater IBI developed for the Upper Mississippi River Basin, triggering the need for a Total Maximum Daily Load (TMDL) study. In 2008, through some revisions to the impaired waters list in previous assessment cycles, Little Rock Creek was listed as impaired for “lack of a coldwater assemblage” rather than the 2002 listing for low fish IBI score (see Table 1-1). Table 1-1 also shows that in 2010, the same stream segment of Little Rock Creek was listed for dissolved oxygen and nitrate impairments and Bunker Hill Creek was included on the impaired waters list for nitrates.

Table 1-1 Little Rock Creek Watershed 303(d) impairments

Reach	Description	Year listed	Assessment Unit ID	Affected Use	Pollutant or Stressor
Little Rock Creek	T39 R30W S27, south line to T38 R31W S28, east line (trout stream)	2002	07010201-548	Aquatic life	Lack of a coldwater assemblage
Little Rock Creek	T39 R30W S22, south line to T38 R31W S28, east line	2010	07010201-548	Drinking Water	Nitrates
Little Rock Creek	T39 R30W S22, south line to T38 R31W S28, east line	2010	07010201-548	Aquatic Life	Dissolved Oxygen
Bunker Hill Creek	T38 R30W S6, north line to Little Rock Cr	2010	07010201-511	Drinking Water	Nitrates

The MPCA projected schedule for Total Maximum Daily Load (TMDL) report completion, as indicated on Minnesota’s 303(d) impaired waters list, implicitly reflects Minnesota’s priority ranking of these TMDLs. The Little Rock Creek Watershed TMDL study was scheduled to begin to address the lack of coldwater assemblage in 2004 and be complete in 2013. The subsequent listings for dissolved oxygen and nitrate target 2015 for the start and 2019 for the completion of the TMDL study. Ranking criteria for scheduling TMDL projects include, but are not limited to: impairment impacts on public health and aquatic life; public value of the impaired water resource; likelihood of completing the TMDL in an expedient manner, including a strong base of existing data and restorability of the water body; technical capability and willingness locally to assist with each TMDL; and appropriate sequencing of TMDLs within a watershed or basin.

This report details the TMDL analyses conducted for Little Rock Creek. The background information relevant to all impairments is provided in this section, followed by the applicable water quality standards and TMDL endpoints in Section 2.0. The TMDL technical elements for each of the impairments are provided in Section 3.0. For follow-up monitoring, implementation, reasonable assurance and public participation all impairments are addressed together in Sections 4.0, 5.0, 6.0 and 7.0. Appendix A details the watershed, groundwater and receiving water modeling analyses.

1.2 Watershed and Stream Characteristics

The Little Rock Creek Watershed is 44,229 acres and is divided between Benton (12,590 acres) and Morrison (31,639 acres) counties (see Figure 1-1). The watershed receives approximately 28 inches of precipitation per year (Benton SWCD, 2009). The average maximum air temperature for the months of May through September is approximately 75 degrees F; average minimum temperature is 55 degrees (Benton SWCD, 2009).

Little Rock Creek is made up of two main stream types, intermittent and perennial. Intermittent streams flow at different times of the year, or seasonally, when there is enough water from rainfall, springs, or other surface sources such as melting snow. Perennial streams flow year round. The main stream segment of Little Rock Creek is perennial, whereas, a majority of the tributaries are intermittent or have been converted to drainage ditches. Little Rock Creek flows south through Little Rock Lake and ultimately discharges to the Mississippi River via the Harris Channel. The elevation ranges from 1,296 feet in the northeast portion of the watershed, to 1,017 feet at the outlet of Little Rock Lake into the Mississippi River. The watershed boundary relates to the basin where surface water drains whereas the groundwater boundary delineates where groundwater discharges. The drainage area for Little Rock Creek has been further defined by a groundwater model developed for this study (see Figure 1-2). The groundwater model domain area for the Little Rock Creek Watershed is 215,701 acres (337 square miles), and was selected because groundwater purturbations outside of the surface watershed area will affect the groundwater drainage area, along with climatic variations and variations in groundwater pumping.

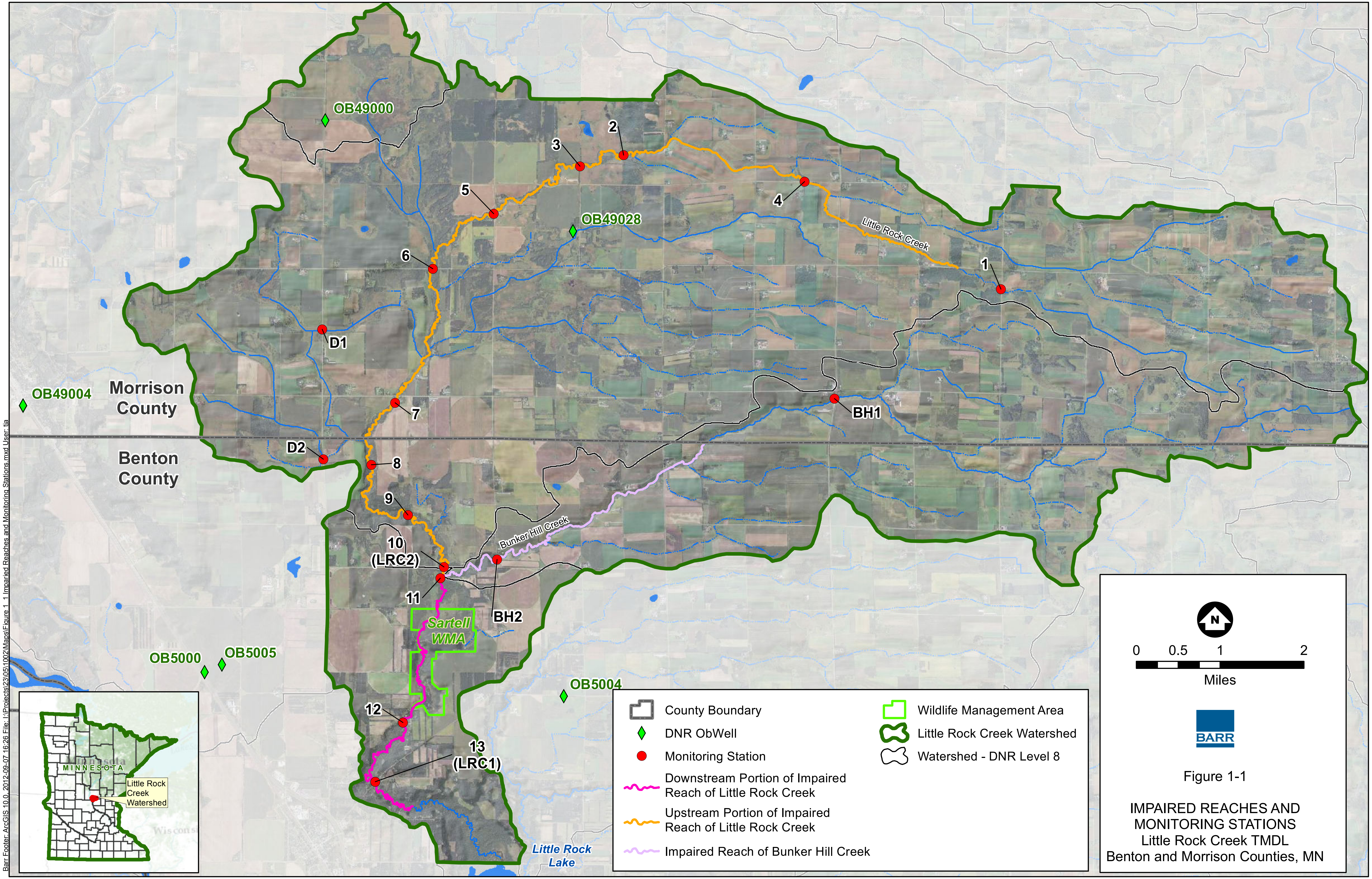


Figure 1-1

IMPAIRED REACHES AND
MONITORING STATIONS
Little Rock Creek TMDL
Benton and Morrison Counties, MN

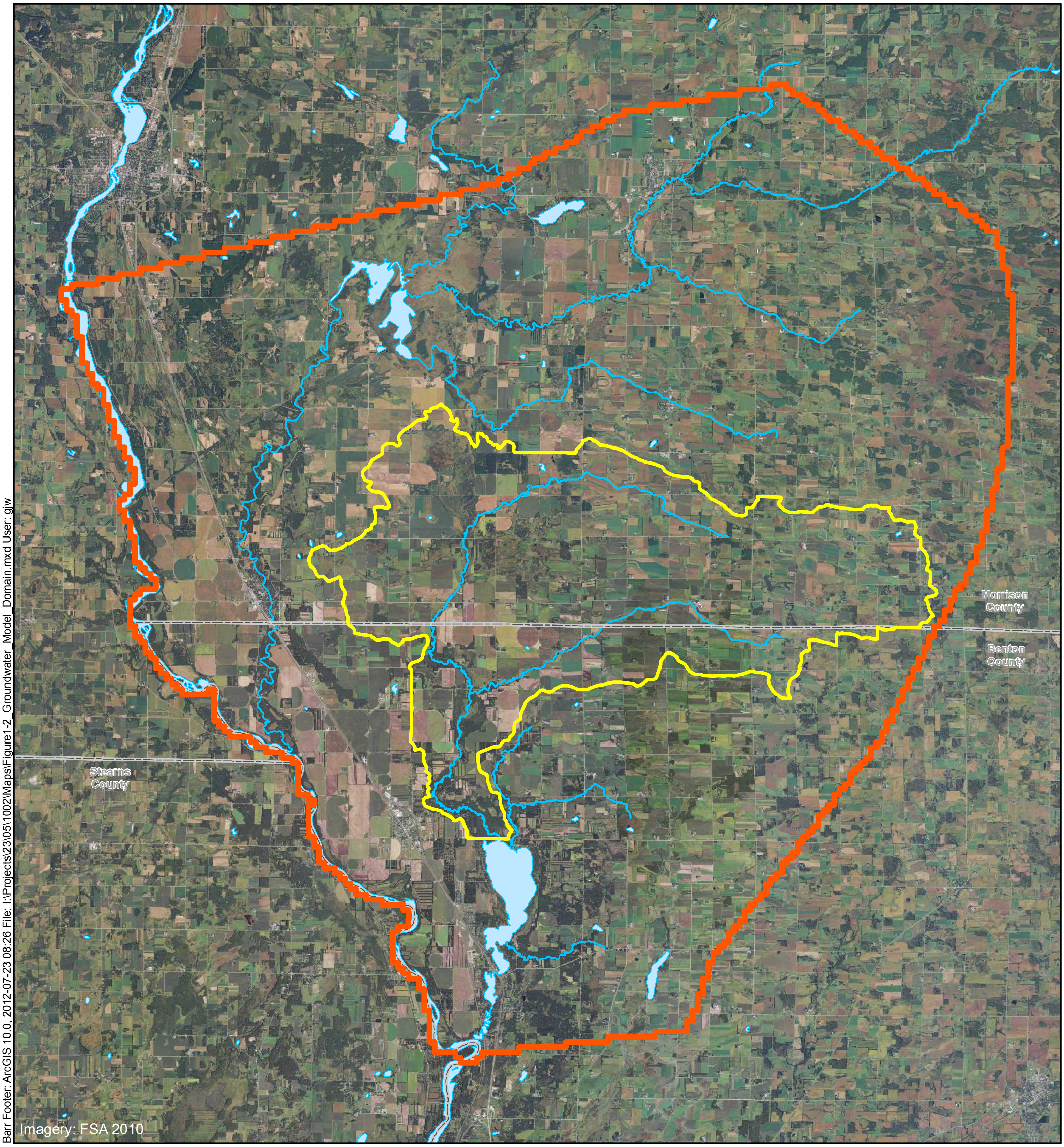


Figure 1-2
Groundwater Model Domain
Little Rock Creek TMDL
Benton and Morrison Counties, MN

According to the National Agricultural Statistical Service, in 2009 the land use in the watershed consisted of 50% crops, 14% woodland, 22% grass/pasture, 13% water/wetlands and less than 1% residential development. Due to the predominance of sandy soils in the watershed, many croplands are irrigated. Channelization is not prevalent on the main stem of Little Rock Creek although many tributaries in the upper watershed have been ditched and straightened (Benton SWCD, 2009).

The watershed has alluvial soils made up predominantly of fine sands. The topography is flat to gently rolling. Most of the watershed is in the Agram Sand Plain and the Pierz Drumlin Plain (Benton SWCD, 2009).

The USEPA defines ecoregions for Minnesota based on areas of relative homogeneity for land use, soils, landform, and potential natural vegetation (Omernik, 1987). The Little Rock Creek watershed is located within the North Central Hardwood Forest Ecoregion. This ecoregion is an area of transition between the forested areas to the north and east and the agricultural areas to the south and west. The terrain varies from rolling hills to smaller plains. Upland areas are forested by hardwoods and conifers. Plains include livestock pastures, hay fields and row crops such as potatoes, beans, peas and corn.

Stream habitat in Little Rock Creek changes throughout its course. The upstream portion (from the headwaters to Station 5) is slow, marshy and warmer than downstream sections. From Station 5 (see Figure 1-1) in Morrison County and downstream, the creek picks up groundwater from springs and the temperature drops. The MDNR trout stream designation (Minnesota Rules 6264.0050 Subp. 4 EE(3); Minnesota Rules 6264 Subp. 4 D(2)) begins at Station 1 and extends downstream to Station 13 (see Figure 1-1). Substrates in the trout stream section change from sand and silt in the vicinity of Station 5 to boulder, rock, gravel and sand near Station 7. Coarse substrates persist from Station 7 downstream approximately 1.5 river miles, to where the stream slows and becomes more meandering. Sand and silt substrates dominate throughout the remainder of the stream. Riffle, pool and undercut bank type habitat components do not appear to be limiting factors on brown trout abundance (Benton SWCD, 2009).

Little Rock Creek has supported a wild brown trout population since they were introduced into Little Rock Lake in 1908 (Benton SWCD, 2009). Brown trout were present in routine stream assessments through the late 1980’s. The population assessment done in 1992, however, failed to document the presence of brown trout suggesting that population may have become critically low during the drought years of the late 1980’s and early 1990’s. The stream contains a diverse fish community with 28 species sampled in a prior assessment (1992). White sucker, blacknose dace, Johnny darter and creek chub were the most common species sampled. In an effort to reestablish a self-sustaining brown trout population in Little Rock Creek, wild brown trout were stocked in the springs of 1995, 1996, 1997 and 1998.

Natural recruitment of brown trout in Little Rock Creek has been low to nonexistent since the 1980's. Ten naturally produced fingerlings were captured in 1999, one in 1998, and none were seen in fall assessments from 1995 through 1997. Sexually mature trout have been present since 1996.

1.3 Stressor Identification Summary and Supplementary Analyses

Before the development of this TMDL a stressor identification analysis report (Benton SWCD, 2009) was completed to analyze the specific physical and/or chemical factors causing the biological impairment to Little Rock Creek. This analysis identified stressors in the Little Rock Creek Watershed using a series of logical steps based on the United States Environmental Protection Agency (USEPA) Stressor Identification Guidance Document and the Minnesota Pollution Control Agency Biota TMDL Protocols and Submittal Requirement documents (Jasperson, 2009). Impairments were evaluated, candidate causes of impairment were described, relationships between causes, stressors, and biotic conditions were assessed, and probable stressors were identified based on strength of evidence from all available data. The report can be found at: http://www.pca.state.mn.us/index.php/view-document.html?gid=7968.

Strength of evidence analyses provided in the stressor identification report revealed that several candidate stressors may be contributing to the biological impairment of Little Rock Creek. Based on the evidence available, it is probable that altered flow, temperature, sediment, dissolved oxygen, and nitrates may be causing a biological impairment in Little Rock Creek. It was concluded that altered flow is a dominant stressor as it serves as a step in the causal pathways of several other stressors. Evidence regarding predation on trout by pike and other warmwater piscivores and connectivity was inconclusive due to insufficient evidence, but suggests that each has the potential to contribute to the biological impairment. Further monitoring could shed light on the potential effects of predation and connectivity as stressors to the biological community of Little Rock Creek (Benton SWCD, 2009).

The following discussion provides specifics about the candidate stressors for biological impairment.

1.3.1 Dissolved Oxygen

Biological organisms depend on dissolved oxygen for life. Low dissolved oxygen (DO) can have detrimental effects on fish communities. Fish, such as brown trout, have been known to avoid areas of water with DO less than 5 mg/L (Raleigh et al., 1986), and the daily minimum DO levels largely impact fish growth rates (Doudoroff and Warren, 1965).

A lack of aeration from minimal instream habitat due to aggradation and the lack of aeration by riffles as well as the higher temperatures measured in Little Rock Creek can lead to decreased DO levels (Benton SWCD, 2009). As temperatures increase the saturation levels of DO decrease, while higher temperature increases the DO needs for fish (Raleigh et al., 1986). Low DO can be an issue in streams with slow currents, excessive temperatures, high biological oxygen demand and high groundwater seepage (Hansen, 1975). Natural sources of oxygen demanding substances include organic material from decaying plants and animal waste (Penn et al., 2013).

The DO levels in Little Rock Creek were below the state standard for Class 2A streams, which is 7.0 mg/L as a daily minimum (as discussed in Section 2.0). These levels show that low DO is a stressor to the biological community. Low levels of DO (as low as 4 mg/L) were measured throughout the creek system under low flow conditions in August, 2008 (Benton SWCD, 2009).

A detailed assessment of DO dynamics in the Little Rock Creek system is presented in Section 3.4 and Appendix B.

1.3.2 Nitrate

Nitrate levels are a plausible stressor causing the lack of coldwater assemblage in Little Rock Creek, considering that levels exceeded the state standard for drinking water of 10 mg/L. Nitrate levels in Little Rock Creek ranged from below 1 mg/L to 18 mg/L. These levels have proven to be detrimental to some invertebrates, fish and amphibians. It is unlikely that the elevated nitrate levels in LRC are due to the geology or other natural sources in the watershed (Benton SWCD, 2009), because the background condition of nitrates in the watershed is below 1 mg/L (shown by samples that were less than 1 mg/L). Natural sources of nitrate inputs include atmospheric deposition, bedrock and decaying organic material (Nolan, 2003).

A detailed assessment of Little Rock Creek nitrate levels is included in Section 3.5 and Appendix B.

1.3.3 Temperature

The 2008 mean daily stream temperatures and flows were combined and shown in Figure 1-3. The number of measurements that were greater than the chronic temperature (19 °C) for trout varied each month for each of the stations, but Station 13 had all of the measurements exceeding the chronic temperature criteria in July. The mean monthly temperatures varied among stations, with Station 13 having the warmest July monthly average at 20.7°C. Station 9 was the coldest location, in July, with a mean temperature of 16.0 °C. Stations 11 and 13 were the only stations to have measurements above the brown trout acute temperature criteria of 24 °C (see Figure 1-3 [re-plotted for this study]).

Temperature in Little Rock Creek exceeds chronic and at times acute temperatures for brown trout. The data strongly suggest that the increased temperatures in the stream are a stressor to the biological community. Natural sources of thermal inputs include high air temperature, surface runoff and solar radiation, combined with a lack of shade. The strength of evidence shows that the impoundment and groundwater withdrawal are likely causing increased stream temperatures (Benton SWCD, 2009).

A detailed assessment of Little Rock Creek temperature is included in Section 3.6 and Appendix B.

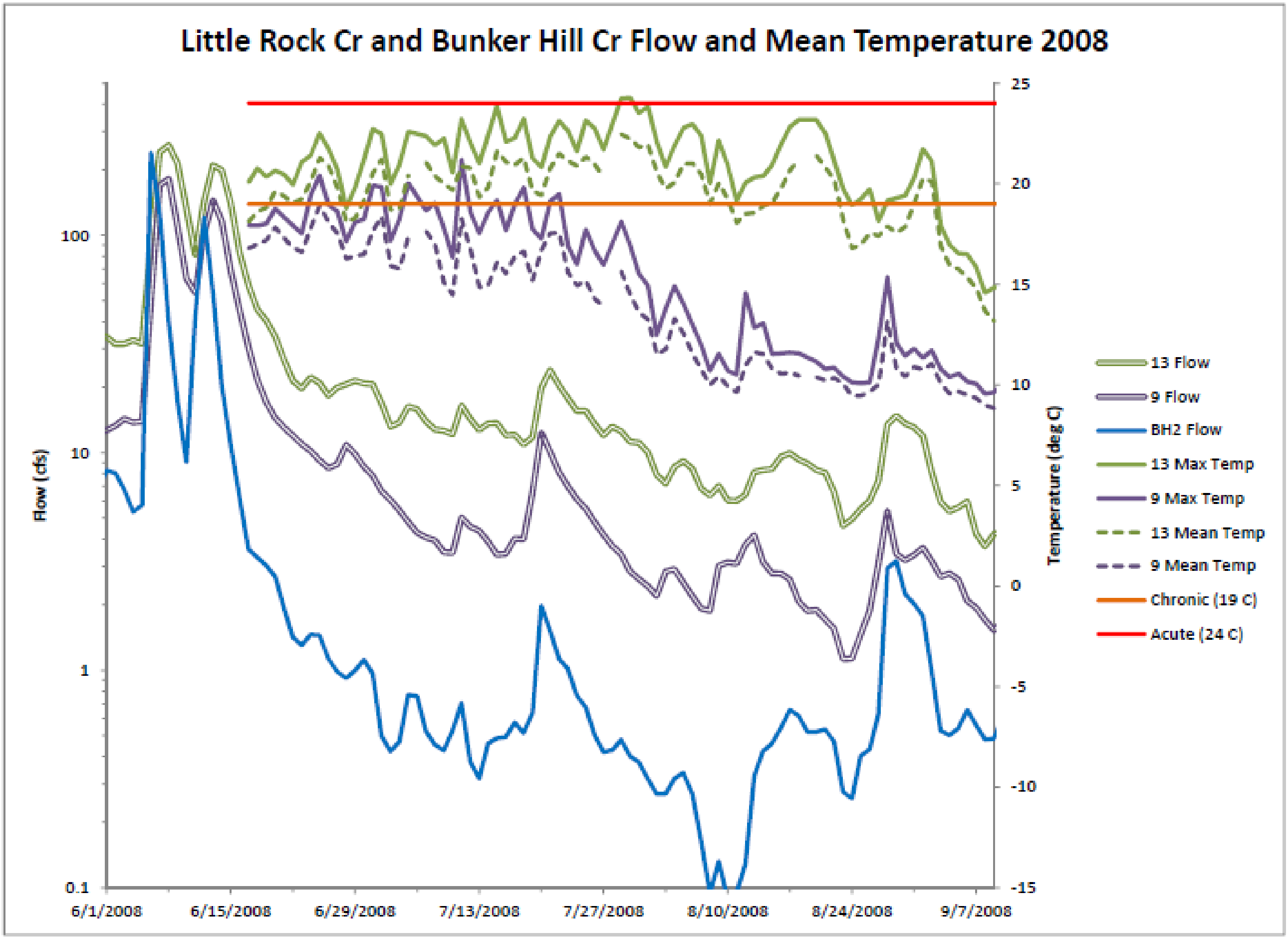


Figure 1-3 Temperature and Flow Data for Little Rock Creek and Bunker Hill Creek

1.3.4 Bedded Sediment

There are two types of sediment that may affect stream biota: suspended sediment and deposited/bedded sediment. Sediment transport can be separated into two primary categories based on the mechanism by which sediment moves through the system; suspended or bedload. Suspended sediment was not determined to be a stressor in Little Rock Creek.

Bedded sediment in Little Rock Creek is a plausible stressor causing the lack of coldwater assemblage. The highest percentage of simple lithophils and sensitive individuals in Little Rock Creek were found at Station 7, which had the lowest amount of fine substrates. Greater numbers of mayflies and larval riffle beetles were found at Station 7, which had greater amounts of coarse substrate. The macroinvertebrate community, as measured by several metrics (Tricoptera, scrapers, EPT taxa), responds positively to sites having more flow and more exposed rocky substrate, especially pebbles. The source(s) of the bedded sediment is uncertain, but altered flow was provided as a potential reason for the problem.

More detailed assessment of flow impacts on bedded sediment in the Little Rock Creek system is presented in Section 1.4.

1.3.5 Flow Alteration

Flow alteration refers to modification of flow characteristics, relative to reference or natural conditions. For the purposes of this case study, altered flow regime refers to a decrease in base discharge (or baseflow). Decreases in baseflow may result in decreased aquatic habitat availability in terms of wetted channel width or depth and decreased habitat quality in terms of flow heterogeneity. Reductions in baseflow may also significantly alter other habitat variables (e.g., DO, temperature).

The next two sections respectively summarize the evaluation of flow alteration in Little Rock Creek from the Stressor Identification analysis (Benton SWCD, 2009) as well as supplementary analyses to support the modeling completed as a part of this study.

1.3.5.1 Evaluation of Flow Alteration from Stressor Identification Analysis

One hypothesis for impaired biota in Little Rock Creek is that increased pumping of groundwater near the creek has intercepted water that would otherwise have discharged into the creek. Less water in the creek raises temperatures and reduces habitat. A first step toward testing this and related hypotheses involved analyzing all relevant hydrologic datasets for patterns or trends that would explain the change in the condition of the creek (Benton SWCD, 2009).

Historically, agricultural producers in Minnesota have used groundwater for irrigation since the late 1800’s. But it wasn’t until 1969 that the Department of Natural Resources began regulating large volume groundwater appropriations through permits. The MDNR regulates the use of groundwater in amounts over 10,000 gallons a day, or 1 million gallons a year (Minn. Stat. §103G.271, 2011). Most of the MDNR pumping permits issued in the Little Rock Creek watershed are for crop irrigation.

Because surface water and groundwater are connected, it is important to recognize the cumulative effects of groundwater pumping. Streams either gain water from inflow of groundwater or lose water by outflow to groundwater. A pumping well can change the quantity and direction of flow between an aquifer and stream in response to different rates of pumping. The adjustments to pumping of a hydrologic system may take place over many years, depending upon the physical characteristics of the aquifer, degree of hydraulic connection between the stream and aquifer, and locations and pumping history of wells. Reductions of streamflow as a result of groundwater pumping are likely to be of greatest concern during periods of low flow, particularly when the reliability of surface water supplies is threatened by drought.

Figure 1-4 shows that there is a statistically significant ($p \leq 0.01$) increasing trend in groundwater pumping volumes in the Little Rock Creek watershed. Since 1944, MDNR Waters has managed a statewide network of water level observation wells (obwells). MDNR obwell hydrographs display groundwater surface elevation changes with time. The Stressor Identification report (Benton SWCD, 2009) established that there was not a statistically significant trend in the supply of water to the system from precipitation, based on local gage data, but the volume of groundwater removed from the system through irrigation pumping has increased significantly. Measurement of groundwater levels can provide information that can be used to understand how these two important parameters interact. Figure 1-5 (which was re-plotted) shows a statistically significant ($p<0.1$) decreasing trend between 2002 and 2008 in the MDNR obwell levels for locations in close proximity (see Figure 1-1) to Little Rock Creek that correspond to the dry periods used for this TMDL study (Benton SWCD, 2009).

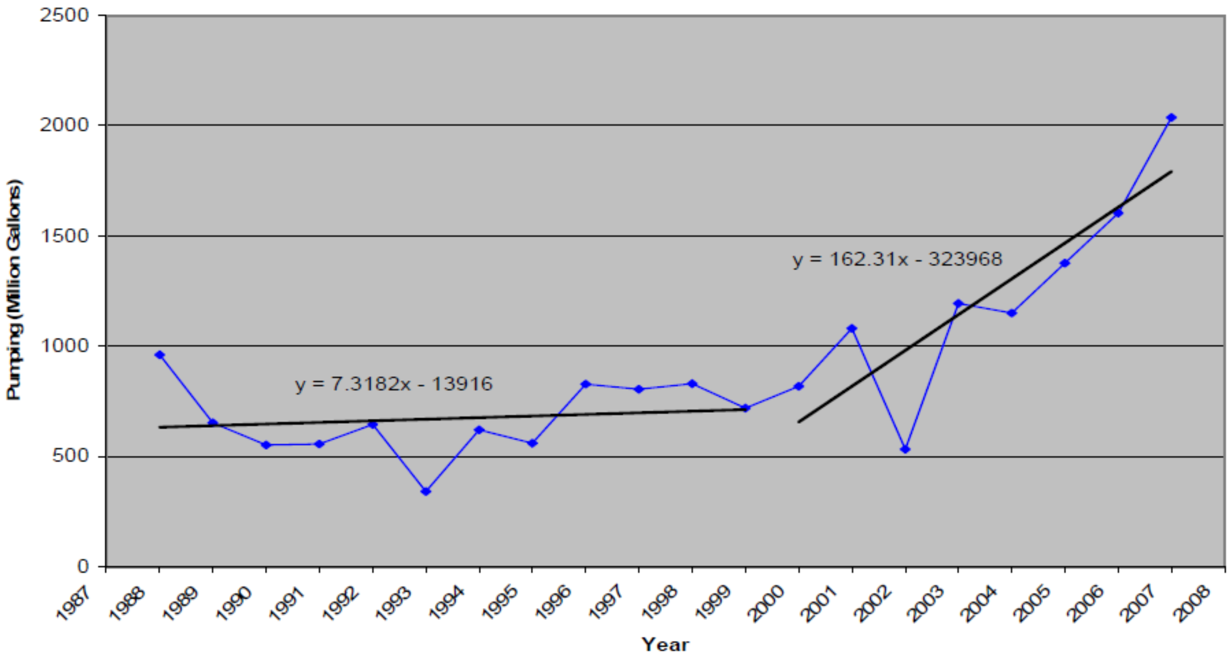
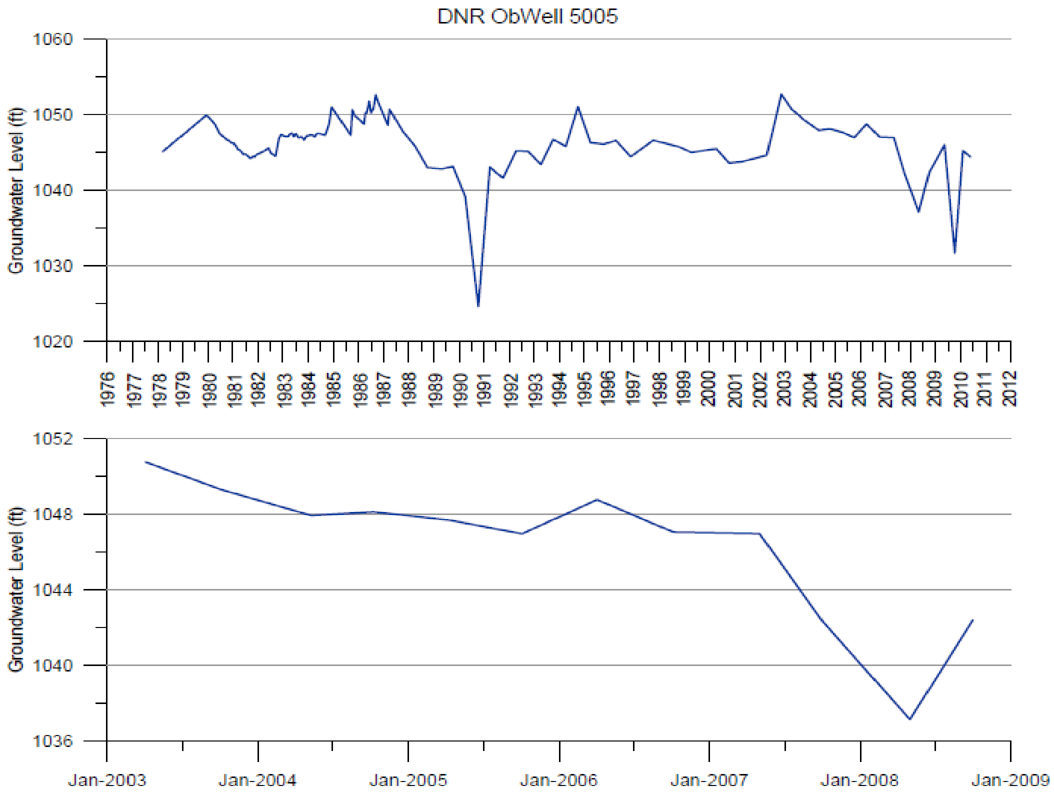
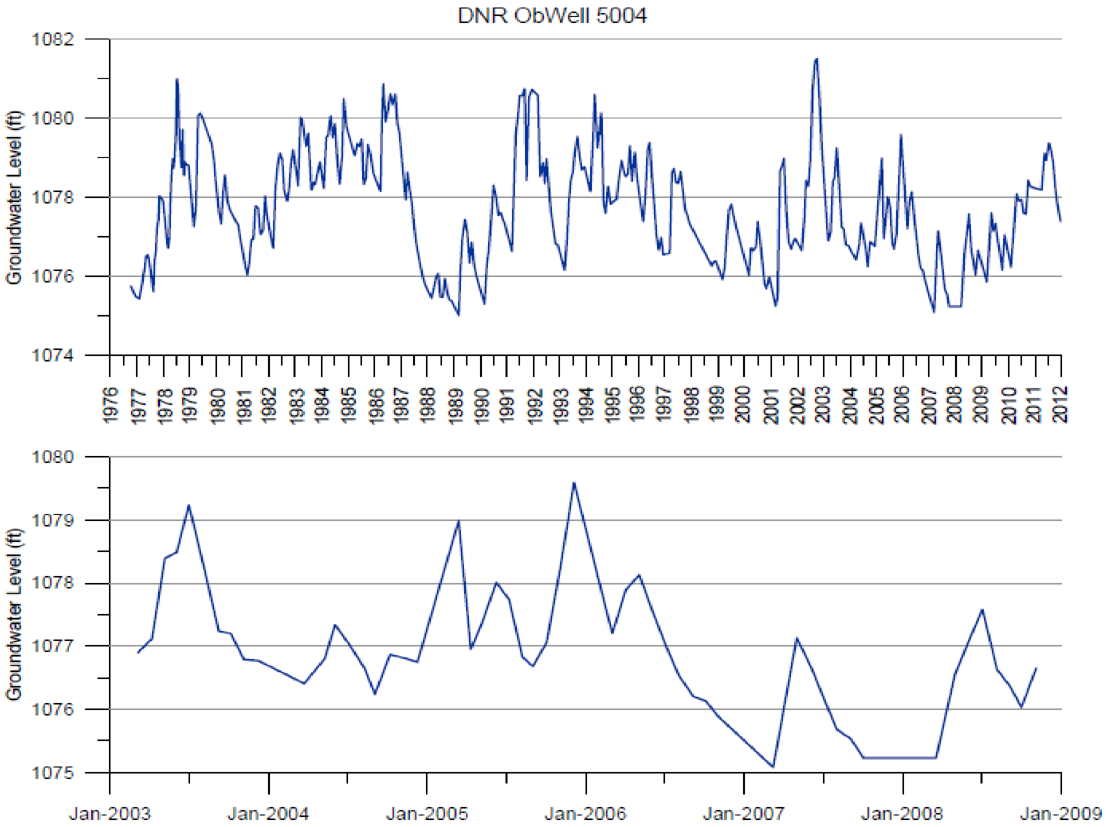


Figure 1-4 Groundwater Pumping Trend for Little Rock Creek Watershed



DNR ObWell 5005



DNR ObWell 5004

Figure 1-5 MDNR Obwell Data Trends for Locations Near Little Rock Creek

Stream flow hydrographs quantify stream volume discharge changes. Stream discharge was measured at Stations 6, 7, 9, 11 and 13 on Little Rock Creek in 2008 (shown in Figure 1-6). The change in discharge was examined between pumping and non-pumping seasons. Stream discharge for each sampling period was compared against all other sampling periods with the t-test (or the Mann-Whitney Rank Sum where the datasets are non-normal) to identify statistical differences in datasets (Benton SWCD, 2009). The statistical tests show that the creek discharges measured in the summer pumping season are different from non-pumping season values. The cause is most likely a combination of increased evapotranspiration and the diversion of groundwater from the creek to irrigation during the growing season.

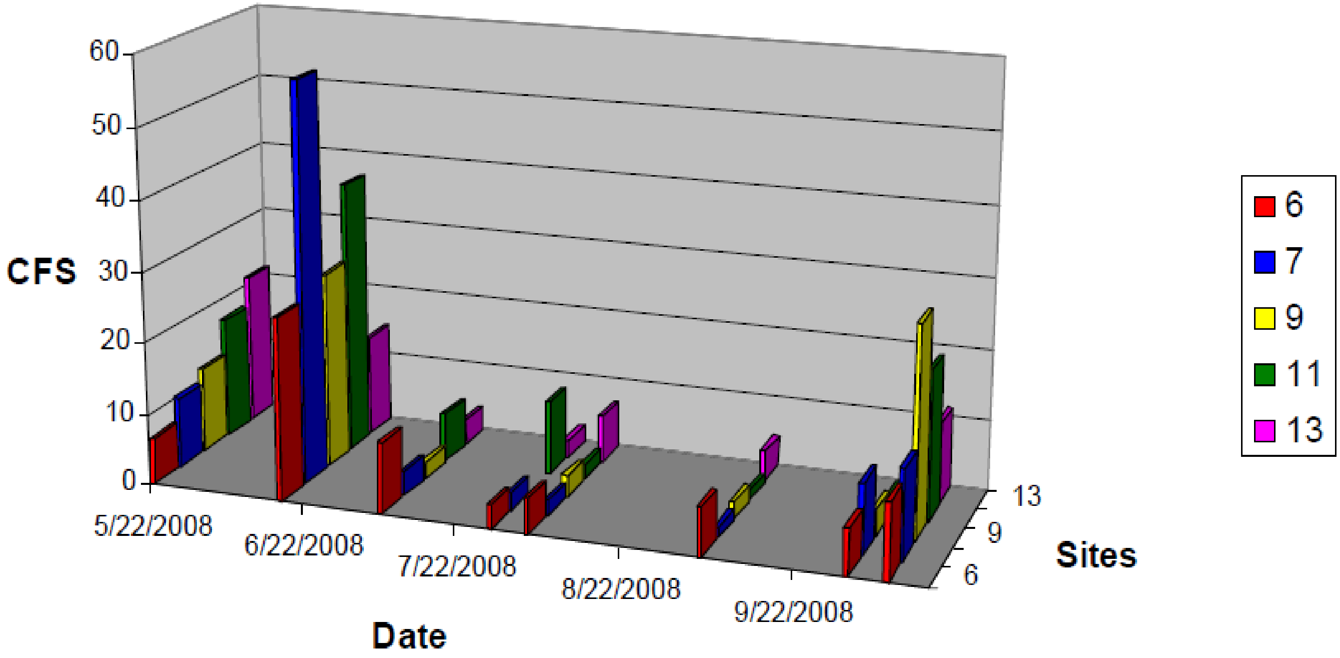


Figure 1-6 Temporal and Spatial Variations in 2008 Flows in Little Rock Creek

1.3.5.2 Supplementary Analyses of Flow Alteration

Figure 1-7 shows that the increasing trend in groundwater pumping (see Figure 1-4) is primarily related to increasing acreage that has been irrigated over the last 15 years. Since irrigation volumes were also expected to correlate with soil moisture, the monthly Palmer Drought Index (PDI) Z-values were weighted by monthly crop water needs during the growing season to show how soil moisture departs from normal (higher negative values correspond to a higher degree of drought, while higher positive values correspond to the degree of moisture excess). Comparing the annual unit volumes of irrigation (total irrigation volume divided by total irrigated crop area) to the weighted PDI Z-values (shown in Figure 1-7) it is evident that groundwater pumping volumes will also vary based on the severity and persistence of drought-like conditions. This is further evidenced by the statistical relationship between the annual unit irrigation volumes and the weighted PDI Z values shown in Figure 1-8.

The data shown in Figures 1-7 and 1-8 indicate that the dry weather and associated low flow conditions from 2006 through 2008 were not as severe as the 1988 drought, but the persistence of dry conditions resulted in above average pumping rates (normalized to the drought index) for six consecutive years that may have exacerbated the flow conditions for Little Rock Creek.

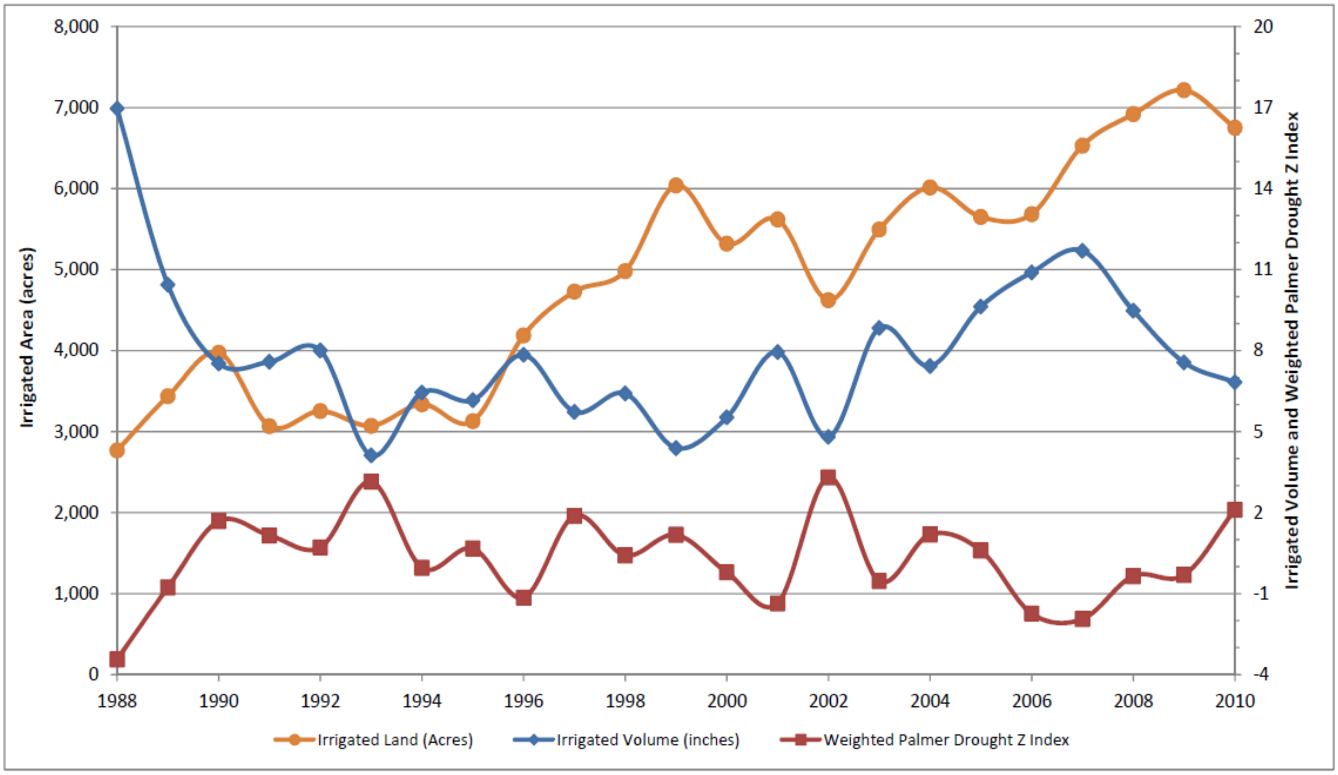


Figure 1-7 **Trends in Irrigated Cropland, Unit Volume Irrigated and Palmer Drought Index Values for Little Rock Creek Watershed**

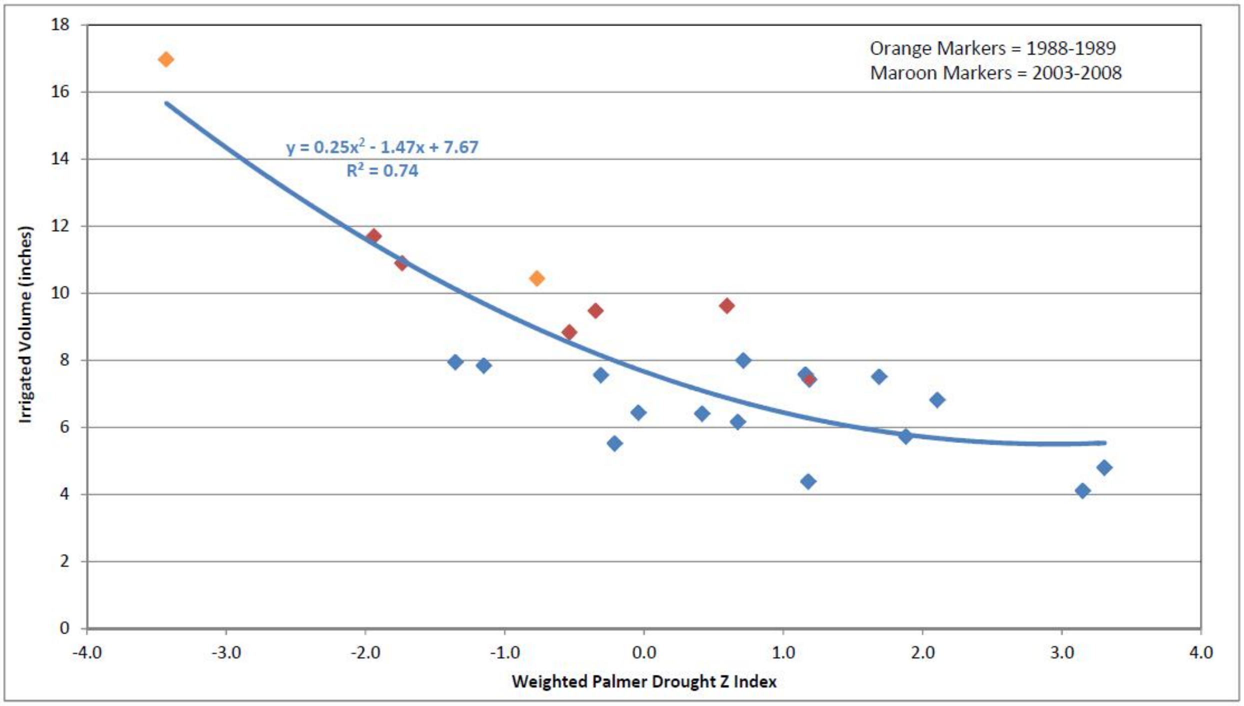


Figure 1-8 Unit Irrigation Volume and Weighted Palmer Drought Z Index Relationship for Little Rock Creek Watershed

Rivord (2012) included an evaluation of 2010 synoptic water levels of pumping wells which indicated that two shallow supra- and sub-Emerald buried aquifer units are likely connected to the surface enough to fluctuate with seasonal precipitation. Water levels in groundwater and surface waters are typically greatest after a winter of minimal consumptive use and a pulse of spring recharge from snowmelt. The first frame in Figure 1-9 shows that as the growing season progresses, evapotranspiration and consumptive use decrease groundwater levels in the leaky, combined aquifer system. With decreases in groundwater levels, the groundwater system provides diminished baseflow to local surface waters. Without adequate precipitation throughout the year and continued or increasing groundwater demand, this watershed and groundwater system will potentially show decreasing water levels in streams and aquifers (Rivord, 2012).

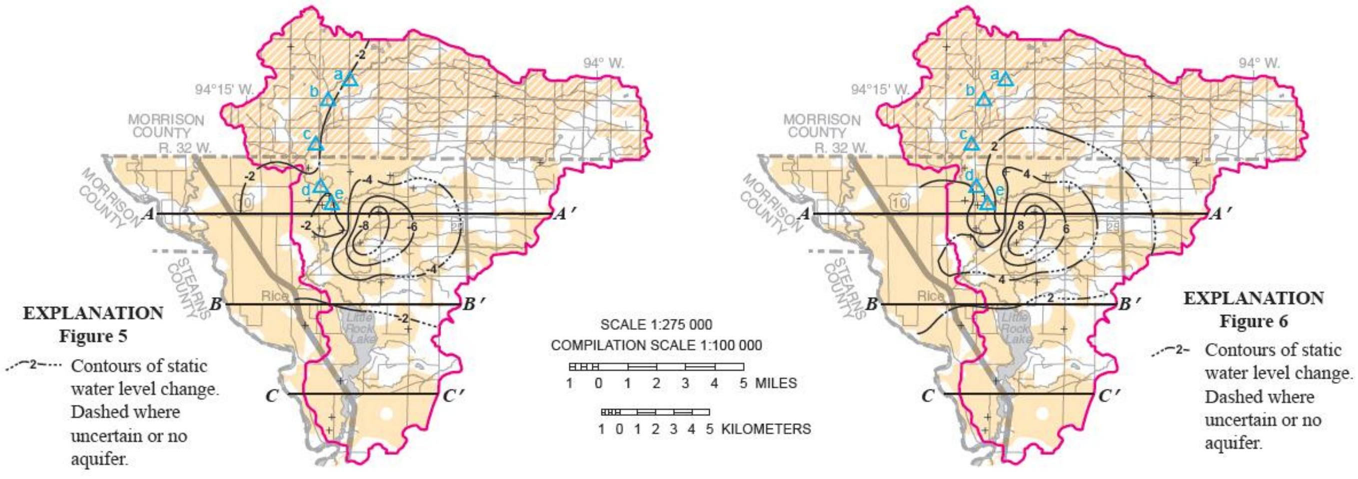


FIGURE 5. *Contours of change in static water levels from April to July in Little Rock Creek watershed for combined se and sb buried sand aquifer units. Negative contour intervals indicate a decrease in water levels between measurements. Locations of streamflow measurements included and referenced in Table 4.*

FIGURE 6. *Contours of change in static water levels from July to September in Little Rock Creek watershed for combined se and sb buried sand aquifer units. Positive contour intervals indicate an increase in water levels between measurements. Locations of streamflow measurements included and referenced in Table 4.*

Figure 1-9 Differences in Static Water Levels Before and After Peak Pumping Season in 2010 (Rivord, 2012)

1.3.6 Connectivity

Four primary longitudinal connectivity stressors for the Little Rock Creek include: Little Rock Lake, Sartell Wildlife Management Area's wetland impoundment, rock-dams, and numerous culvert crossings. Each one of these structures can change the hydrology of the system, as well as larger watershed changes, which can create unintended impacts for both the physical and biological entities of the creek.

Quantifying the negative effects of connectivity in Little Rock Creek is difficult given the lack of data available. Connectivity is interrelated to hydrology in which flow is one of the primary biological stressors for this system. The presence of dams and numerous culverts at a minimum suggest migration barriers, which can have significant biological impacts (Benton SWCD, 2009).

1.3.7 Predation by Warmwater Piscivores

Quantifying the negative effects of warmwater piscivores in Little Rock Creek is difficult given the available data. The presence of northern pike at nearly every biological monitoring station during summer months suggests that trout are subject to direct predation, as well as competition for available habitat and food. The brook and brown trout fingerlings currently used to stock the stream may be especially vulnerable to predation given their smaller size (Benton SWCD, 2009).

1.4 Impairment Assessment

As previously discussed in section 1.3.5.1, although altered flow is a dominant stressor in Little Rock Creek, USEPA does not believe that flow, or lack of flow, is a pollutant as defined by CWA Section 502(6). This is because USEPA interprets section 303(d)(1)(C) to require that TMDLs be established for “pollutants” and does not believe TMDLs are required to address impairments caused solely by lack of adequate flow (USEPA, 2005).

Instead, low flow is a condition of a waterbody (i.e., a reduced volume of water) that when manmade or man-induced would be categorized under the CWA Section 502(19) as pollution, provided it altered the physical, biological, and radiological integrity of the water. Many forms of human activity, including the introduction of pollutants can cause water pollution. Pollutants relevant for TMDL development include “all pollutants under the proper technical conditions”, which refers to the availability of analytical methods, modeling techniques, and the data necessary to make calculations for the TMDL process (Federal Register, 1978).

As discussed in Section 1.3.4, bedded sediment levels in Little Rock Creek was identified as a plausible stressor causing the lack of coldwater assemblage. It was further suggested that altered flow was a potential reason for the problem. As discussed in Appendix A, the calibrated watershed-groundwater modeling developed for this project included modeling of two hypothetical scenarios intended to evaluate the various effects that changes in groundwater pumping would have on stream flows in Little Rock Creek. Each scenario was simulated for the same 22 years (January 1989 to December 2010) of climatic record. The only differences between the two scenarios is the number of pumping wells, the total volume of groundwater pumped (both simulated in the modular finite-difference flow model [MODFLOW]), and the amount of irrigation (simulated in the Soil and Water Assessment Tool [SWAT]). To define the amount of pumping for the low and high pumping conditions, historical pumping data from the state water use data system (SWUDS) database were used. For the low pumping condition, the average monthly pumping for the period of 1997-1999 was used to define the number of wells and pumping volumes. These pumping volumes were then repeated for each of the 22 years in the simulation to measure the effect of pumping for both wet and dry years. For the high pumping condition, the average monthly pumping for 2006-2008 was used. The two periods used to define the high and low pumping scenarios (1997-1999 and 2006-2008) were chosen for several reasons. Most importantly, the differences between the two defined scenarios represents the increase in groundwater pumping that has been observed in the Little Rock Creek watershed and surrounding areas over the past several decades. Also, in the late 1990’s naturally produced trout were observed in Little Rock Creek. Stream flow and temperature data during this time also indicated favorable conditions for trout development. The period of 2006-2008 was used for model calibration and represents a period of increased groundwater pumping and stream conditions that were observed to be unfavorable for trout development—segments of Little Rock Creek went dry in 2006.

The high pumping scenario resulted in more surface runoff (4%) and less baseflow (15%) than the low pumping scenario for the upstream segment of Little Rock Creek (which includes Station 7, shown in Figure 1-1). While the high pumping scenario had eight percent less total flow there were no significant differences in the maximum or bankfull flows, except during growing season where bankfull frequency flowrate is five percent higher. The results of this modeling would indicate that the flow impacts from irrigation would not be expected to significantly change embeddedness in the system. In addition, Section 1.3.4 mentions that the highest percentage of simple lithophils and sensitive individuals in Little Rock Creek were found at Station 7, which had the lowest amount of fine substrates and greater amounts of coarse substrate. In comparing the two modeling scenarios, the results indicate that the groundwater baseflow impacts associated with higher pumping would be most pronounced in the area of Station 7, but the latest stream survey data indicates that this station possesses some of the best habitat for trout and supports the benthic organisms that are most sensitive to sediment embeddedness.

As a result of the Stressor Identification assessments and the inconclusive evidence (based on the analysis presented in this section) of flow alterations on bedded sediment, this TMDL report addresses the need to develop the loading capacities and pollutant allocations for temperature, nitrates, and dissolved oxygen, by calculating the allowable pollutant loads with reference to the existing flow conditions as the basis of each impairment.

The nitrate impairments and two of the biological stressors – dissolved oxygen and temperature – would be addressed by achieving TMDL load reductions through this TMDL report. Two of the stressors – connectivity and altered flow – are not associated with a specific pollutant for which a TMDL can be developed.

2.0 Water Quality Standards and Biological Criteria

A discussion of water classes in Minnesota and the standards for those classes is provided below in order to define the regulatory context and environmental endpoint of the TMDLs addressed in this report.

All waters of Minnesota are assigned classes based on their suitability for the following beneficial uses:

1. Domestic consumption
2. Aquatic life and recreation
3. Industrial consumption
4. Agriculture and wildlife
5. Aesthetic enjoyment and navigation
6. Other uses
7. Limited resource value

Little Rock Creek is listed in the Minn. Rules Ch. 7050.0470 classification as a 1B, 2A, 3B water body. Water quality standards are associated with each of the three classifications, with a 2A classification being the most restrictive. Class 2A waters are defined as:

> **Class 2A waters**. The quality of Class 2A surface waters shall be such as to permit the propagation and maintenance of a healthy community of cold water sport or commercial fish and associated aquatic life, and their habitats. These waters shall be suitable for aquatic recreation of all kinds, including bathing, for which the waters may be usable. This class of surface waters is also protected as a source of drinking water (Class 1B).

Dissolved Oxygen

In class 2A streams, the Minnesota standard for dissolved oxygen is 7.0 mg/L as a daily minimum (MPCA, 2012a). It also requires compliance with the standard 50 percent of the days at which the flow is equal to the 7Q10.

Nitrates

According to Minnesota Rule 7050.0470 Subpart 4 Little Rock Creek is classified as a 1B stream. This classification designates that treated water will meet both the primary and secondary drinking water standards with approved disinfection. When assessing drinking water-protected surface water Classes 1B and 1C, the 24-hour average nitrate concentrations are compared to the 10 mg/L water quality standard (MPCA, 2012a).

Temperature

The temperature standard for Class 2A waters (aquatic life – cold water fishery) is “no material increase,” a narrative standard found in Minnesota Rules, chapter 7050.0222, subpart 2 (MPCA, 2012a). Narrative standards are sometimes called “free forms” because they help keep surface waters free from visible and basic types of water pollution.

In order to quantify and determine a TMDL for Little Rock Creek, a numeric water quality standard had to be selected. This Study uses the values set forth in the USEPA’s *Quality Criteria for Water* (1986), also known as the “Gold Book,” which provides the following numeric criteria for trout:

19 °C (66 °F) = maximum weekly average temperature (MWAT) for growth (chronic)

24 °C (75 °F) = daily maximum (DM) temperature for survival of short term exposure (acute)

The cooler temperature (19 °C) was selected as the standard for two reasons: 1) there were more temperature exceedances to analyze and model at the MWAT, (instead of the DM) and, 2) using an implicit Margin of Safety (MOS) required the use of the more conservative temperature.

Fish Bioassessments

“Lack of Coldwater Assemblage” means that species that favor warmer waters are being found in a stream where we would expect to find species that prefer cold water temperatures, such as in designated trout streams like Little Rock Creek. It could also mean that coldwater species are declining or absent (Brady and Brenneman, 2010). As discussed in Section 1.1, Little Rock Creek was listed on the 2002 303(d) list for impaired waters based on a 1999 in-stream biological assessment for fish due to a low fish index of biotic integrity (IBI), based on a warmwater IBI developed for the Upper Mississippi River Basin. The fish community at the location on Little Rock Creek was comprised of highly tolerant warmwater species and absent of species indicative of coldwater habitats. Few trout were captured in the 1999 MPCA fish survey; there was also an absence of sculpin and burbot. In 2008, through some revisions to the impaired waters list in previous assessment cycles, Little Rock Creek was listed as impaired for “lack of a coldwater assemblage” rather than the 2002 listing for low fish IBI score.

3.0 TMDL Allocations

This section details the process to develop the pollutant loading capacities and associated TMDL allocations, as well as the load reductions needed in the creek to meet the TMDL requirements.

3.1 Watershed Source Assessment and Modeling Approach

There are many individual sources of nitrates, oxygen demanding substances, and thermal inputs spread throughout the Little Rock Creek watershed. Nutrients and carbon occur naturally in soil, animal waste, plant material and the atmosphere, while thermal loadings are exacerbated by the lack of vegetation or shade. Currently, there is not sufficient data to provide a quantifiable watershed source assessment. However, a source assessment based on general knowledge can be provided as follows: Sources of nutrients and oxygen demanding substances include: septic systems, erosion, groundwater, runoff from the developed and agricultural land uses (livestock feedlots, row-crop), as well as practices that might worsen pollutant delivery such as row-crop, tiling, winter manure application, and impervious surfaces. Agricultural land use is dominant in the Little Rock Creek watershed (see Figure 3-1).

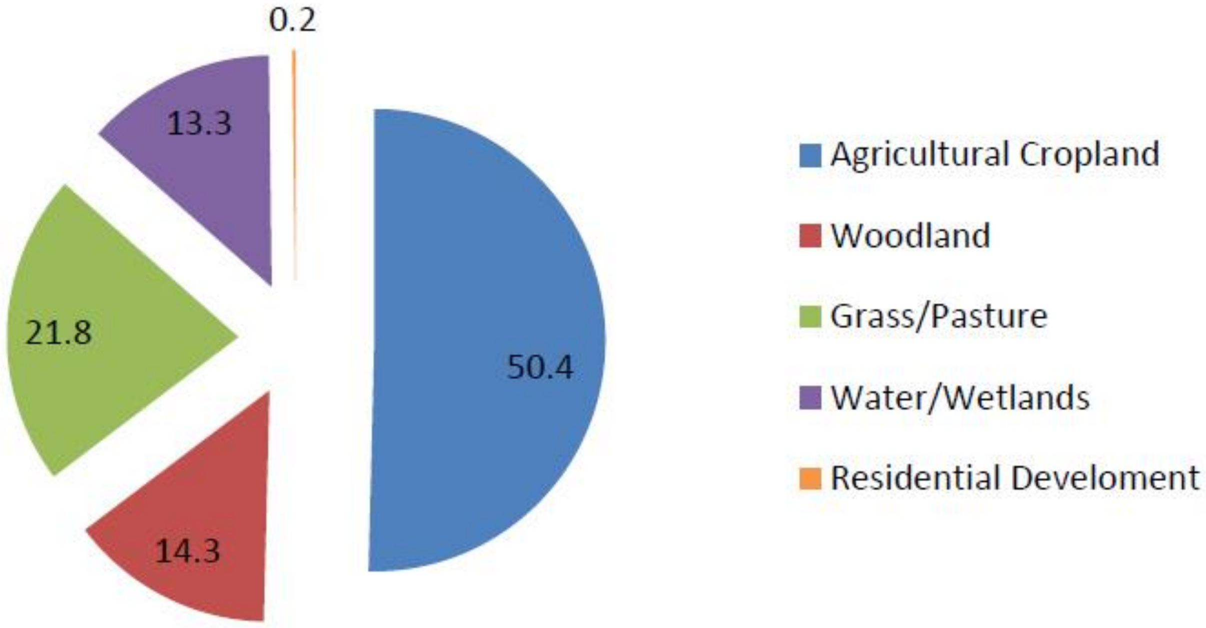


Figure 3-1 Little Rock Creek Land Use Percentages

Animal unit densities are high, based on livestock numbers in proportion to agricultural land area, giving a high rate of manure production per acre. As a result, spring runoff is of more concern in the Little Rock Creek watershed, with higher levels of nutrients and oxygen demanding substances available for runoff to the stream. A portion of this pollutant load would be expected to drop out of suspension as the flow progresses downstream where it could later result in a higher sediment oxygen demand under late-summer, lower flow conditions. It is also expected that another contributor to higher sediment oxygen has been the higher loadings and accumulation of nutrients and organics in the stream channel sediment as a result of past land management practices and riparian use in the watershed.

The relative importance of pollutant sources depends upon location in the watershed and the source, itself. Winter manure application, row-crop, and livestock directly on tributaries and waterways are of a higher concern than the same sources that are buffered or located in the headwaters of the watershed. Groundwater withdrawals result in higher pollutant concentrations (as has been observed with nitrate under low flow conditions) and lower assimilation or pollutant loading capacities in Little Rock Creek, exacerbating the dissolved oxygen and temperature stressors for fish. The Little Rock Creek impoundment at the Sartell Wildlife Management Area also reduces the pollutant loading assimilation capacity of the stream.

The modeling approach developed for this study was designed to assess the relationship between groundwater pumping and stream flow in Little Rock Creek. In order to assess this relationship, a model capable of simulating both surficial hydrologic processes and groundwater flow is necessary. The coupling of two models, SWAT and MODFLOW, was chosen to provide the following:

- A simplified, but robust, representation of the essential hydrologic and hydrogeologic features in the study area
- Simulation of observed hydraulic heads and stream flows consistent with available data
- An assessment of scenarios (i.e. changes in groundwater pumping, or changes in climate) to measure the effects on stream flow and aid in the development of a TMDL and implementation strategies for Little Rock Creek.

The results of the coupled SWAT-MODFLOW flow modeling was, in turn, used to inform the QUAL2K water quality modeling for all of the flowing reaches of Little Rock Creek under the critical seasonal (late-summer) and flow conditions for the biological stressors in need of TMDL allocations, as discussed in Section 1.4. QUAL2K is a stream water quality model that simulates a series of individual reaches, well mixed vertically and laterally, that have constant hydraulic characteristics (e.g., slope, bottom width, etc.). The heat budget, temperatures and all water quality variables are simulated as a function of meteorology on a diurnal time scale. Point and non-point loads and abstractions can be added at any point along the stream. The model also accounts for sediment oxygen demand.

3.2 Critical Conditions and Seasonal Variation

USEPA states that the critical condition *"…can be thought of as the "worst case" scenario of environmental conditions in the waterbody in which the loading expressed in the TMDL for the pollutant of concern will continue to meet water quality standards. Critical conditions are the combination of environmental factors (e.g., flow, temperature, etc.) that results in attaining and maintaining the water quality criterion and has an acceptably low frequency of occurrence"* (USEPA, 1999). Dissolved oxygen levels are generally at their worst following long low-flow periods in the late-summer months. During this time water temperatures are at a maximum, reducing the water saturation concentration of dissolved oxygen, and flow rates are at a minimum, which reduces reaeration rates in the stream. By completing the TMDL under these conditions, DO concentrations will be protected in all other seasons and flow rates, where conditions are more favorable for higher levels of dissolved oxygen. To a lesser extent, conditions for nitrate levels and temperature follow a similar pattern, but can also be exacerbated by runoff events immediately following extended dry periods. Seasonal variation is somewhat more difficult to generalize given reach-specific differences. Regardless, such conditions and variation are fully captured in the duration curve methodology used for nitrate and temperature in this TMDL, as allocations have been developed for five separate segments of the overall flow-duration regime. The QUAL2K modeling was developed to capture the monitoring period that identified the critical stream segment and represented the critical flow condition for dissolved oxygen, based on the best available data for assessing the loading capacity and dynamics associated with oxygen demanding substances. In addition, the QUAL2K modeling provided relational assessments of both nitrate and temperature in the creek system during the same critical flow period (late-August 2008).

3.3 Methodology for Load Allocations, Wasteload Allocations and Margins of Safety

Permitted sources, for the purpose of this TMDL, are those facilities/entities that discharge or potentially discharge pollutants to surface water or otherwise contribute to impairments and require a NPDES permit from the MPCA. Typical point source categories include: wastewater treatment facilities, Concentrated Animal Feeding Operations (CAFOs), construction activities, and municipal and industrial stormwater sources.

The only permitted sources that currently apply to this watershed are one CAFO (NPDES Permit #MNG441098) and construction stormwater sources. No industrial or wastewater treatment plants discharge into Little Rock Creek, and CAFOs are not included in the allocations since the permits must have zero discharge, therefore these categories are not further considered in this analysis.

Regarding construction, the MPCA issues construction permits for any construction activities disturbing: one acre or more of soil; less than one acre of soil if that activity is part of a "larger common plan of development or sale" that is greater than one acre; or less than one acre of soil, but the MPCA determines that the activity poses a risk to water resources. Although stormwater runoff at construction sites that do not have adequate runoff controls can be significant on a per acre basis (MPCA, 2012b), the source currently appears to be a negligible source of pollutants in the Little Rock Creek watershed.

No industrial stormwater sources currently exist in the watershed, but for the purpose of the TMDL this source is lumped with construction stormwater into a categorical WLA to account for any future sources of industrial stormwater sources.

The TMDLs consist of three main components: WLA, LA, and MOS as defined in Section 1.1. The WLA includes a construction plus industrial permitted stormwater category. The LA, reported as a single category, includes the nonpoint sources described in Section 3.3.3. The third component, MOS, is the part of the allocation that accounts for uncertainty that will result in attainment of water quality standards. The three components (WLA, LA, and MOS) were calculated as total daily load of each pollutant.

The duration curve approach was used to derive and express the load components for nitrate and temperature and the QUAL2K modeling was used to develop the individual load components that address the dissolved oxygen impairment for the critical period. For each impaired reach and flow condition, the total loading capacity or "TMDL" was divided into its component WLA, LA, and MOS. It should be noted that these methods implicitly assume that observed stream flows and flow regimes remain constant over time or consistent with the flows used to derive each of the load components. The process for computing each component of the TMDL is described below.

3.3.1 Wasteload Allocation

Watershed scale pollutant load modeling was conducted and load duration curves were developed to establish TMDLs at levels necessary to attain and maintain applicable water quality standards. Federal regulation 40 CFR 130.3 states that *TMDLs can be expressed in terms of either mass per time, toxicity, or other appropriate measure*. Effluent concentrations are appropriate expressions of the applicable wasteload allocations. Thus, according to the nature of the NPDES permits written for the various sub-categories of point source dischargers, appropriate measures for achieving compliance with wasteload allocations are described as follows.

Industrial & Municipal Wastewater Treatment Facilities

No industrial or municipal wastewater treatment facilities are actively discharging into Little Rock Creek.

Construction and Industrial Stormwater: Categorical WLA

Given the transient nature of construction work, these loads are difficult to quantify. The wasteload allocation for stormwater discharges from sites where there is construction activities reflects the number of construction sites ≥ 1 acre expected to be active in the watershed at any one time, and the Best Management Practices (BMPs) and other stormwater control measures that should be implemented at the sites to limit the discharge of pollutants of concern. The BMPs and other stormwater control measures that should be implemented at construction sites are defined in the State's NPDES/SDS General Stormwater Permit for Construction Activity (MNR100001). If a construction site owner/operator obtains coverage under the NPDES/SDS General Stormwater Permit and properly selects, installs and maintains all BMPs required under the permit, including those related to impaired waters discharges and any applicable additional requirements found in Appendix A of the Construction General Permit, the stormwater discharges would be expected to be consistent with the WLAs in this TMDL. It should be noted that all local construction stormwater requirements must also be met.

The wasteload allocation for stormwater discharges from sites where there is industrial activity reflects the number of sites in the watershed for which NPDES industrial stormwater permit coverage is required, and the BMPs and other stormwater control measures that should be implemented at the sites to limit the discharge of pollutants of concern. The BMPs and other stormwater control measures that should be implemented at the industrial sites are defined in the State's NPDES/SDS Industrial Stormwater Multi-Sector General Permit (MNR050000) or NPDES/SDS General Permit for Construction Sand & Gravel, Rock Quarrying and Hot Mix Asphalt Production facilities (MNG490000). If a facility owner/operator obtains coverage under the appropriate NPDES/SDS General Stormwater Permit and properly selects, installs and maintains all BMPs required under the permit, the stormwater discharges would be expected to be consistent with the WLAs in this TMDL. It should be noted that all local stormwater management requirements must also be met.

3.3.2 Margin of Safety

The purpose of the MOS is to account for uncertainty that the allocations will result in attainment of water quality standards. For this TMDL an explicit ten percent MOS is applied to the allocations for dissolved oxygen and nitrate. This is expected to provide an adequate accounting of uncertainty as the allocations are applied to five separate portions of the flow regime.

An implicit margin of safety is applied to the heat inputs associated with the temperature stressor. The TMDL process allows for an implicit MOS, which is incorporated through conservative assumptions in the analysis and modeling of the data. Our conservative assumptions included the use of the chronic (19 °C) criteria instead of the acute (24 °C) temperature standard for trout in our analysis and estimation of acceptable heat loading to the creek.

3.3.3 Load Allocations

The LA includes nonpoint pollution sources that are not subject to NPDES permit requirements, as well as "natural background" sources.

3.3.4 Calculation Methodology

The methodology for developing the WLAs and LAs was as follows:

- For CAFOs and industrial and municipal wastewater treatment facilities the WLA was set to zero.
- Construction stormwater and industrial stormwater are lumped together into a categorical WLA based on an approximation of the land area covered by those activities. To account for industrial stormwater, as well as reserve capacity (to allow for the potential of higher rates of construction and additional industrial facilities), this TMDL assumes 0.1 percent of the land area for a combined construction and industrial stormwater category. The allocation to this category is made after an explicit MOS (where applicable) is subtracted from the total loading capacity. That remaining capacity is divided up between construction and industrial stormwater and all of the nonpoint sources (the LA) based on the percent land area covered.
- The LAs representing agricultural and natural lands are made after the WLAs are determined and the MOS are subtracted from the total loading capacity. Subtracting the 0.1 percent allocated to construction and industrial stormwater and 10% for MOS results in the other 89.9% of loadings allocated to the LA with the duration curve approach.

3.4 Dissolved Oxygen

The TMDL for dissolved oxygen has been developed to match the loading capacity for oxygen demanding substances that ensures that the dissolved oxygen daily minimum target of 7 mg/l is met across all reaches for the critical, low flow condition in Little Rock Creek. In a waterbody, dissolved oxygen is consumed both in the water column and through the sediment water interface. Three processes were examined as contributing sources to oxygen depletion in Little Rock Creek: sediment oxygen demand (SOD), Nitrogenous biological oxygen demand (NBOD) and carbon biological oxygen demand (CBOD). CBOD represents the amount of oxygen microorganisms require to convert organic carbon to CO_2. It is a representation of the oxygen equivalent of the carbonaceous organic matter in a sample. NBOD represents the oxygen consumption produced through the process of transforming organic nitrogen to ammonia nitrogen and then to nitrate through nitrification. In this TMDL NBOD was calculated by multiplying the sum of organic and ammonia nitrogen by 4.57 which is the stoichiometric ratio between oxygen demand and nitrogen used in the QUAL2K model. Sediment oxygen demand represents the aerobic decay of organic matter in the sediments of a water body. SOD is defined as a rate per unit area of oxygen consumption.

3.4.1 Load Capacity

The QUAL2K model discussed in Appendix B was used to calculate the oxygen loads under existing conditions as well as the loads required to meet the 7 mg/l standard in Little Rock Creek. A sensitivity analysis showed the DO concentration in the creek was most sensitive to SOD concentrations. QUAL2K uses two source of SOD including model predicted SOD and user defined SOD. As discussed in Appendix B user-defined SOD was used to calibrate the model to observed DO levels. The user defined SOD represents a load that is either unknown or which QUAL2K has difficulty modeling. The load capacity of Little Rock Creek was calculated by adjusting the prescribed SOD concentration in all reaches by a uniform percentage until minimum DO concentration through the modeled area were above the 7 mg/l standard. To reach the DO standard, an 80% reduction in the SOD load was required. The resulting target SOD rate of each reach in the model (in g-O_2/m^2/day) was multiplied by the corresponding wetted area to calculate the SOD TMDL load (Table 3-1).

3.4.2 Load Allocations

The load allocations are nonpoint source loads within the stream. For this TMDL, it includes all SOD, CBOD, and NBOD loads. The current SOD loads were calculated using the QUAL2K model integrating both the model-calculated and user-prescribed SOD rates. The rates used in the calibrated existing conditions model were multiplied by the wetted perimeter under low flow conditions for each reach to obtain a daily oxygen consumption load. The TMDL load was calculated by reducing the prescribed SOD rate by a uniform percentage through the stream until dissolved oxygen levels met the 7 mg/l daily minimum standard. The final dissolved oxygen consumption loads were then calculated for this condition. The nonpoint source CBOD and NBOD were calculated by multiplying the total modeled diffuse inflow volumes between stations 6 and 13 by model calibrated diffuse inflow concentrations of CBOD, organic-N and ammonia. Due to the low flow conditions of the modeled period all diffuse inflow are assumed to come from groundwater sources (as described in Appendix B). The sensitivity analysis of the QUAL2K model shown in Figure B-5 shows that the modeled DO concentration in Little Rock Creek is more sensitive to sediment processes than CBOD and NBOD. In addition, the current level of CBOD and NBOD loading sources were not contributing to an impairment under higher flow conditions. As discussed in Section 3.1, it is expected that past land management practices and riparian use in the watershed has contributed to higher loadings and accumulation of nutrients and organics in the stream channel sediment, along with the fact that a portion of the annual pollutant load drops out of suspension and can result in higher sediment oxygen demand under late-summer, lower flow conditions. As a result, no changes were made to CBOD and NBOD loads to meet the TMDL requirements.

3.4.3 Waste Load Allocations

There are no wastewater or industrial dischargers in the Little Rock Creek watershed. From the baseflow modeling, described in Appendix A, groundwater flow between stations 6 and 13 dominated diffuse water sources during the modeling period (described in Appendix B). Therefore, all diffuse runoff is received through nonpoint sources and applied as a load allocation. This TMDL assumes 0.1 percent of the land area for a combined construction and industrial stormwater category therefore 0.1% of the CBOD and NBOD loads are categorized under the WLA.

3.4.4 Margin of Safety

The purpose of the MOS is to account for uncertainty that the allocations will result in attainment of water quality standards. For this TMDL an explicit ten percent MOS is applied. This is expected to provide an adequate accounting of uncertainty in predicting SOD loads, the uncertainty and assumptions in determining channel dimensions and SOD coverage as well as the uncertainty in how the stream may respond to changes in SOD loading.

3.4.5 TMDL for Oxygen Demand

The total maximum daily load is the sum of the load allocations, the waste load allocations and the margin of safety. Table 3-1 illustrates the required loads to meet the TMDL requirements resulting in a minimum DO concentration of 7 mg/l throughout Little Rock Creek. Overall the total oxygen consumption load needs to be reduced from 327.5 kg/day to 155.9 kg/day under low flow conditions.

Table 3-1 Loading capacity and TMDL allocations for Dissolved Oxygen (AUID: 07010201-548)

	Oxygen Demand (kg/day) from:						*Total Oxygen Demand (kg/day)*	
	CBOD		*NBOD*		*SOD*			
Source	*Current*	*TMDL*	*Current*	*TMDL*	*Current*	*TMDL*	*Current*	*TMDL*
Load: Sediments					227.6	40.4	227.6	40.4
Load: Diffuse Sources	54.4	54.4	45.3	45.3			99.7	99.7
Wasteload: Construction/ Industrial Activities	0.1	0.1	0.1	0.1			0.2	0.2
Margin of Safety						15.6		15.6
Total	54.5	54.5	45.4	45.4	227.6	56.0	327.5	155.9

Overall, a 52% reduction in total oxygen demand is necessary to ensure that the DO standard is met throughout Little Rock Creek under the critical flow conditions. Since the watershed land use is expected to remain mostly agricultural, with NPDES permitted activities expected to continue to be a negligible portion of land disturbance, no reductions in current pollutant loading levels would be expected from NPDES permitted construction and industrial activities to meet the TMDL.

3.5 Nitrate

TMDL loading capacities were calculated for two reaches including all of Little Rock Creek and Bunker Hill Creek which is a tributary to Little Rock Creek. Flow data and water quality data collected by the MPCA were used in this load duration curve analysis. Daily average flow data were available at Station 13 and Station BH1 from 2006 through 2008. Water quality sampling data taken at various locations during different flow conditions were used in conjunction with the flow data to develop the water quality and load duration curves.

3.5.1 Loading Capacity and Nitrate TMDL Allocations for Little Rock Creek

The flow rates were divided into five categories: high flows (0-10%), moist conditions (10-40%), mid-range flows (40-60%), dry conditions (60-90%) and low flows (90-100%). The five categories were used to calculate the nitrate loading capacities and allocations for Little Rock Creek (Table 3-2). The total daily loading capacity was calculated using the mid-point flow rates for each of the flow zones and the 10 mg/l nitrate standard concentration. The flow rates of 70.8, 23.2, 13.8, 9.4, 4.4 cfs for the high, moist, mid, dry and low flow zones respectively were calculated using flow data from Station 13 (LRC1). The extent of the impaired waterway extended beyond Station 13 therefore the load capacities were adjusted based on the total watershed area compared to the watershed area up to Station 13. This addition amounted to a 1% increase in the loading capacity. The total daily load capacities for Little Rock Creek were calculated at 1,740, 570, 340, 230 and 110 kg/day for the high, moist, mid, dry and low flow zones respectively. This loading capacity was then divided between MOS, WLA, and LA components. In this analysis MOS, construction and industrial stormwater requirements and LAs from natural and agricultural lands are apportioned. These result in 89.9% of the capacity being allocated to LAs, 0.1% allocated to construction and industrial stormwater and 10% applied to the MOS.

Table 3-2 Loading capacity and Nitrate TMDL allocations for Little Rock Creek (AUID: 07010201-548)

	Flow Zone				
	High (95%)	Moist (75%)	Mid (50%)	Dry (25%)	Low (5%)
	kg/day				
TOTAL DAILY LOADING CAPACITY	1,740	570	340	230	110
Wasteload Allocation					
Construction/Industrial Stormwater	2	0.6	0.3	0.2	0.1
Load Allocation	1,564	512.4	305.7	206.8	98.9
Margin of Safety	174	57	34	23	11
	Percent of total daily loading capacity				
Wasteload Allocation					
Construction/Industrial Stormwater	0.1%	0.1%	0.1%	0.1%	0.1%
Load Allocation	89.9%	89.9%	89.9%	89.9%	89.9%
Margin of Safety	10%	10%	10%	10%	10%

3.5.2 Loading Capacity and Nitrate TMDL Allocations for Bunker Hill Creek

The total daily loading capacity for Bunker Hill Creek was calculated using the same methods in the Little Rock Creek calculation described in the previous section (Table 3-3). The flow rates of 18.1, 2.87, 0.84, 0.34, 0.003 cfs for the high, moist, mid, dry and low flow zones respectively were calculated using flow data from Station 13 (LRC1). The total daily load capacities for Bunker Hill Creek were calculated at 442.5, 70.4, 20.6, 8.4 and 0.07 kg/day for the high, moist, mid, dry and low flow zones respectively. This loading capacity was then divided between MOS, WLA, and LA components. In this analysis MOS, construction and industrial stormwater requirements and LAs from natural and agricultural lands are apportioned. These result in 89.9% of the capacity being allocated to LAs, 0.1% allocated to construction and industrial stormwater and 10% applied to the MOS.

Table 3-3 Loading capacity and Nitrate TMDL allocations for Bunker Hill Creek (AUID: 07010201-511)

	Flow Zone				
	High (95%)	Moist (75%)	Mid (50%)	Dry (25%)	Low (5%)
	kg/day				
TOTAL DAILY LOADING CAPACITY	442.5	70.4	20.6	8.4	0.07
Wasteload Allocation					
Construction/Industrial Stormwater	0.4	0.1	<0.1	<0.1	<0.01
Load Allocation	397.8	63.3	18.5	7.6	0.06
Margin of Safety	44.3	7.0	2.1	0.8	0.01
	Percent of total daily loading capacity				
Wasteload Allocation					
Construction/Industrial Stormwater	0.1%	0.1%	0.1%	0.1%	0.1%
Load Allocation	89.9%	89.9%	89.9%	89.9%	89.9%
Margin of Safety	10%	10%	10%	10%	10%

3.5.3 Load Duration Curves

Load duration curves for nitrate in Little Rock Creek and Bunker Hill Creek were developed as shown in Figures 3-2 and 3-3. Each duration curve includes a line representing the TMDL loading capacity of nitrates for the respective streams and individual sample loads for each flow category. Individual sampling points in the Little Rock Creek duration curve are further sub-divided by the various sampling locations. The loads were calculated using the flow rates at Station 13 and concentrations recorded at various locations throughout the stream. Exceedances of the 10 mg/l standard were observed only under dry or low flow conditions at Stations 4 and 10 (see Figure 3-2). It is noted that 10 mg/L is a single target concentration and that reducing the highest concentration would be the most effective method for estimating necessary load reductions. The highest percentage load difference above the corresponding TMDL load allocation for each part of the flow regime was used to determine the loading reductions that would be required to ensure that the nitrate loading capacity is always met. Reductions in nitrate load of 47% and 29% are necessary to ensure that the standard is met in Little Rock Creek under the dry and low flow conditions, respectively.

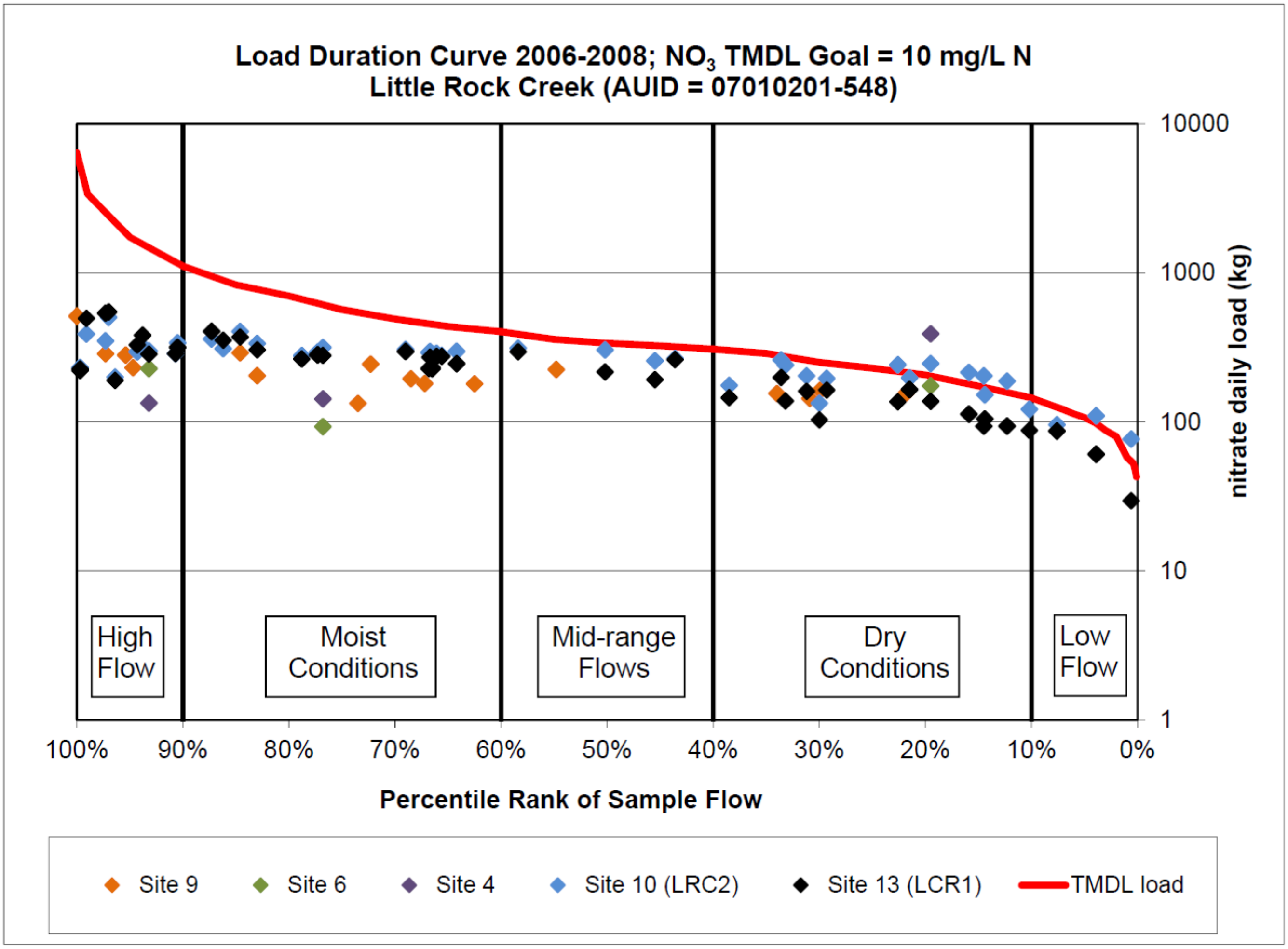


Figure 3-2 Load duration curve Little Rock Creek (AUID: 07010201-548)

In Bunker Hill Creek, based on flow and sampling data from Station BH1, exceedances of the 10 mg/l standard occurred under both moist and mid-range flow conditions (Figure 3-3). No samples were taken under low flow conditions at this location. Reductions in nitrate load of 33% and 19% are necessary to ensure that the standard is met in Bunker Hill Creek under the moist and mid-range flow conditions, respectively.

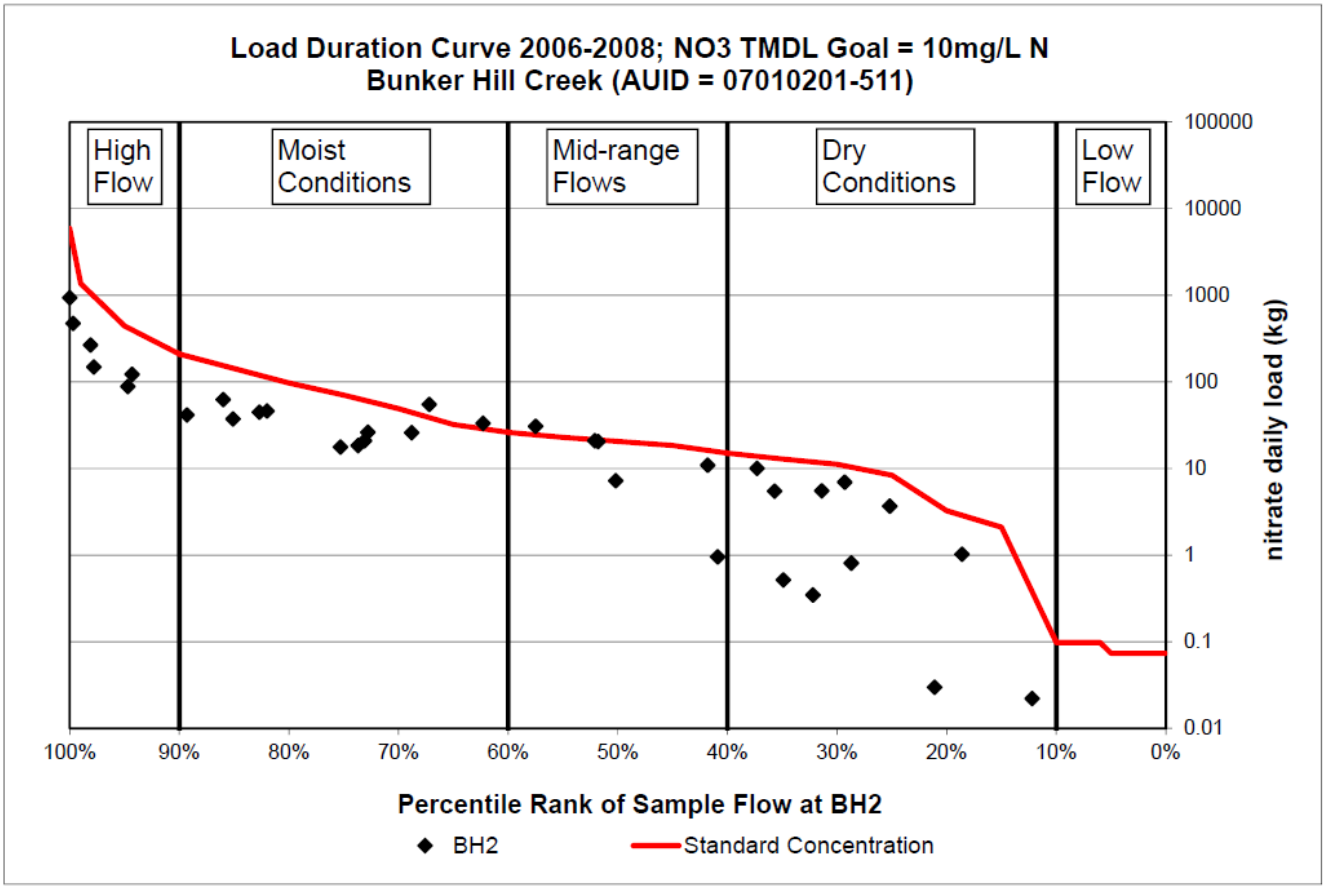


Figure 3-3 Load duration curve Bunker Hill Creek (AUID: 07010201-511)

3.6 Temperature

3.6.1 Daily Loading Capacity and Allocations

As discussed in Section 2.0, the maximum weekly average temperature (MWAT) provides chronic temperature criteria for trout growth of 19°C (66°F), while the daily maximum (DM) temperature of 24°C (75°F) provides acute criteria for survival of short term exposure. Continuous temperature monitoring was conducted throughout the Little Rock Creek system during the 2008 growing season (June 17-September 23), which included 95 average daily temperature readings that represented a conservatively warm and dry period for comparison with the temperature criteria. As shown in Table 3-4, exceedances of the MWAT temperature criteria were more common than exceedances of DM criteria for each of the monitoring stations in the Little Rock Creek system. The DM criteria were exceeded twice at both Stations 11 and 13 (by less than 0.5 °F), while the MWAT criteria were exceeded several times at Stations 5, 7, 8 and 13. As a result, the MWAT criteria have been used to develop the daily loading capacity and heat input allocations.

Table 3-4 Comparison of Little Rock Creek Temperature Monitoring with Criteria

	Station 5	Station 6	Station 7	Station 8	Station 9	Station 11	Station 13
MWAT	19.1	18.5	19.7	19.5	17.6	17.8	21.6
# Exceedances of 19°C	5	0	9	10	0	0	60
Largest MWAT Exceedance (deg. F) =	0.2	--	1.2	1.0	--	--	4.7
# Exceedances of 24°C	0	0	0	0	0	2	2

This study establishes a TMDL for temperature in Little Rock Creek that is divided among five portions of the flow regime: High, Moist, Mid-range, Dry and Low flow conditions. Heat input exceedances at Little Rock Creek monitoring stations occurred under varying parts of the flow duration range, usually exacerbated in response to runoff events that followed extended dry periods at the monitoring stations upstream of the Sartell Wildlife Management Area (WMA) impoundment. The data clearly indicate that Station 13, which is the only monitoring station downstream of the WMA impoundment, should be the focus of heat loading mitigation activities for achieving the water quality targets of this study, as 63 percent of the MWAT readings exceeded the criteria while the exceedance percentages were approximately 10 percent or less at the remaining monitoring stations.

3.6.2 Daily Heat Input Allocations

The TMDL loading capacity and allocations were calculated in terms of the gigajoules per day of heat that the stream can assimilate and still maintain water temperatures below the 19°C MWAT, the numeric standard used for this TMDL, based on the same observed flow rates corresponding to the available 2008 growing season daily temperature readings. Because of the complexity associated with presenting allowable “loads” of temperature, this TMDL utilizes the part of USEPA’s regulations that allow TMDLs to be expressed “in terms of either mass per time, toxicity, or other appropriate measures” (40 C.F.R. § 130.2(i) of the Clean Water Act [Federal Register, 2002]). In this case, an energy-based allocation (expressed in gigajoules per day) is used in order to express temperature as a load-based TMDL, based on the flow and temperature monitoring data at Station 13. Gigajoules (GJ) is a metric term for available energy (1 GJ of electricity will keep a 60-watt bulb lit continuously for six months). The portion of the impaired waterway extended beyond Station 13 therefore the load capacities were adjusted based on the total watershed area compared to the watershed area tributary to Station 13. This addition amounted to a 1% increase in the loading capacity.

Construction stormwater permits are primarily related to sediment (turbidity), not temperature. According to MPCA guidance, construction stormwater should receive a categorical WLA if the impairment is for: turbidity, dissolved oxygen, nutrient/eutrophication biological indicators, or bioassessments. The impairment for Little Rock Creek is for temperature/lack of coldwater assemblage, which is not one of the above listed impairments requiring a WLA. Therefore, construction stormwater is not assigned a WLA. Appendix A of the NPDES General Permit for Construction Stormwater (MPCA, 2012b) does require permittees to take steps to protect impaired waters with enhanced Best Management Practices. Temperature controls for trout streams are also explicity listed under Section C5 of Appendix A of the permit (MPCA, 2012b).

Temperature is not a benchmark pollutant for any permitted industries within the watershed, because there aren’t any permitted industries in the watershed, therefore industrial stormwater does not receive a WLA. Similarly, this would apply to future construction activities in the watershed unless the permitted activity is deemed to include temperature as a benchmark pollutant. In this case, the permitted activity would necessitate a transfer from the load allocation as prescribed in item #5 of Section 3.8.

The flow rates were divided into five categories: high flows (0-10%), moist conditions (10-40%), mid-range flows (40-60%), dry conditions (60-90%) and low flows (90-100%). The five categories were used to calculate the total heat input loading capacities and allocations for Little Rock Creek (Table 3-5). The total daily loading capacity was calculated using the mid-point flow rate for each of the flow zones and the MWAT criteria of 19°C. This loading capacity was then completely allocated to the LA component since there is an implicit margin of safety and there are no NPDES permittees subjected to temperature mitigation requirements.

Table 3-5   Temperature loading capacities and allocations (AUID: 07010201-548)

	Flow Zone				
	High (5%)	**Moist (25%)**	**Mid (50%)**	**Dry (75%)**	**Low (95%)**
	GJ/day				
TOTAL DAILY LOADING CAPACITY	73.1	45.8	33.5	22.9	14.8
Load Allocation	73.1	45.8	33.5	22.9	14.8

Overall, a 1% reduction in thermal loading across all thermal sources is needed in the Station 13 section of Little Rock Creek to meet the MWAT criteria, based on a comparison to the observed 2008 growing season maximum weekly average temperature readings.

3.7 Impacts of Future Growth on TMDL Allocations

As discussed in Section 1.3.5, altered flow was identified as a dominant stressor in the Little Rock Creek watershed. Low flow is a condition of a waterbody (i.e., a reduced volume of water) that when manmade or man-induced would be categorized under the CWA as pollution, provided it altered the physical, biological, and radiological integrity of the water. Since surface water and groundwater are connected and streams either gain water from inflow of groundwater or lose water by outflow to groundwater, reductions of streamflow as a result of increases in groundwater pumping are the greatest concern for meeting the water quality and biological standards in Little Rock Creek.

Figure 3-4 shows that there has been a significantly increasing trend (approximately 192 acres per year) in the irrigated cropland acreage within the Little Rock Creek watershed. It is expected that future growth in appropriations for irrigating additional cropland will be limited by aquifer storage in the Agram Sand Plain portion of the watershed while the Pierz Drumlin Plain portion of the watershed will not support significant water appropriations. It should be noted that the methods in this TMDL study implicitly assume that observed stream flows and flow regimes remain constant over time or consistent with the flows used to derive each of the load components. As a result, no reserve capacity is included in the TMDL allocations for the Little Rock Creek watershed and the associated groundwater-shed. Future water appropriations permitting changes affecting Little Rock Creek will need to occur within the allocated load for each pollutant and will be subject to a water allocation planning process to account for any changes to the TMDL loading capacities.

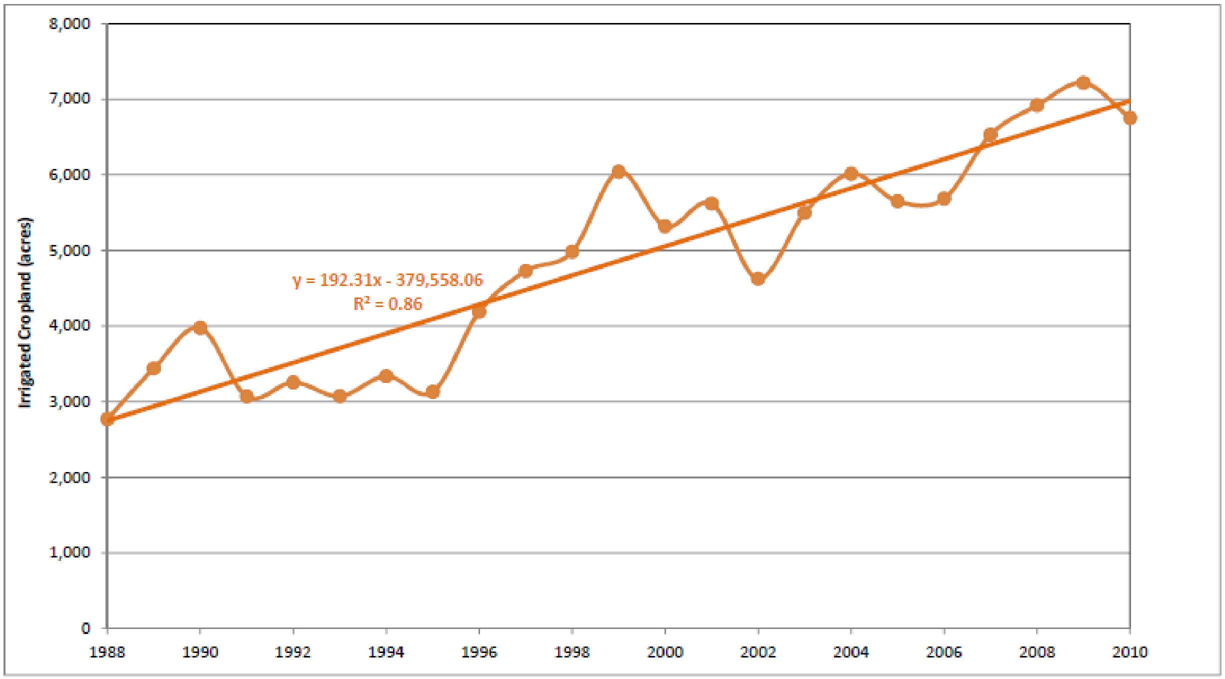


Figure 3-4 Trend in Irrigated Cropland for Little Rock Creek Watershed

3.8 Future Transfer of TMDL Allocations

There are currently no permitted MS4 permittees in the Little Rock Creek watershed. Future transfer of loads in this TMDL may be necessary if any of the following scenarios occur within the Little Rock Creek watershed:

1. New development occurs within a regulated MS4. Newly developed areas that are not already included in the WLA must be given additional WLA to accommodate the growth.
2. One regulated MS4 acquires land from another regulated MS4. Examples include annexation or highway expansions. In these cases, the transfer is WLA to WLA.
3. One or more non-regulated MS4s become regulated. If this has not been accounted for in the WLA, then a transfer must occur from the LA.
4. Expansion of an urban area encompasses new regulated areas for existing permittees. An example is existing state highways that were outside an Urban Area at the time the TMDL was completed, but are now inside a newly expanded urban area. This will require either a WLA to WLA transfer or a LA to WLA transfer.
5. A new MS4 or other stormwater-related point source is identified and is covered under a NPDES permit. In this situation, a transfer must occur from the LA.

Load transfers will be based on methods consistent with those used in setting the allocations in this TMDL. In cases where WLA is transferred from or to a regulated MS4, the permittees will be notified of the transfer.

4.0 Monitoring Plan

The goals of follow-up monitoring are to both evaluate progress toward the water quality targets provided in the TMDL and to inform and guide implementation activities. The impaired water body will remain listed until water quality standards are met. More specific monitoring plan(s) will be developed as part of implementation efforts.

4.1 Water Quality and Biological Monitoring

At a minimum, water quality monitoring will occur in the Little Rock Creek watershed for assessment/study purposes as a part of the next MPCA monitoring cycle. This monitoring should include:

- Ongoing continuous monitoring for flow, temperature and routine water quality sampling—key monitoring sites include Stations 6, 9, BH2, 11 and 13 (shown in Figure 1-1)
- Compliance monitoring (or every 10 years):
    - Conduct longitudinal (am/pm) surveys during critical low-flow and a range of higher flow conditions, including measurements of temperature, DO, flow rate, nitrate, ammonia, CBOD, particulate organic matter (POM) and chlorophyll-a (Chl-a). Add continuous DO meters where possible.
    - Chemical composition, DO and temperature measurements from shallow groundwater sources; time of travel survey

Evidence regarding predation on trout by pike and other warmwater piscivores and connectivity was inconclusive due to insufficient evidence, but suggests that each has the potential to contribute to the biological impairment. Further monitoring could shed light on the potential effects of predation and connectivity as stressors to the biological community of Little Rock Creek.

Future data collection/analysis needs include:

- Document any changes in temperature above and below water control structures and culverts
- Determine at what flows, if any, culverts and beaver dams become fish or other biotic community migration barriers and/or sediment barriers
- Determine if the biotic sampling results indicate barrier issues
- Finalize an index of biotic integrity (IBI) for cold and cool water fish assemblage and incorporation of the MDNR fisheries monitoring into the various components of the IBI;

incorporate the future development of a tiered-aquatic life use (TALU) framework to clarify the attainable use for Little Rock Creek

- Overall, determine how mobile the bedload is and where is aggradation/degradation occurring within the watershed
- Conduct surveys of watershed producers to document crop rotations, tillage, conservation and nutrient management practices

4.2 Groundwater Monitoring

Groundwater observation well monitoring and tracking of appropriations will be continued in the Little Rock Creek watershed for assessment/study purposes as well as a part of the conditions of appropriations permits. This monitoring should include:

- Pumping volume audits to verify the accuracy of the SWUDS data
    - Methods used to track pumping volumes range from electric timers on pumps to more accurate in-line flow meters. In many cases an assumed pumping capacity is used and simply multiplied by how long the pump was on. Specific capacities likely decrease throughout the year and particularly as the well ages, hence volumes may actually be overestimated. Currently all data are self-reported and it is unknown how accurate the data are.
    - Pumping volumes are currently reported on a monthly basis and compiled annually by the MDNR. Compiling pumping volumes more often (e.g., weekly) and publicly sharing this data regularly enables the ability to find areas where increased irrigation efficiency may be achieved
- Pumping tests (ideally involving most sensitive wells) intended to:
    - Target well open to water table aquifer and well open to deeper buried sand and gravel aquifer
    - Monitor both upper and lower aquifer during test to gain better understanding of the connection
- Continued synoptic water level measurements
- Pressure transducers and data loggers in select monitoring wells

4.3 Geomorphology

Little Rock Creek contains numerous segments that show evidence of aggradation, mostly of fine sand material. This aggradation of sediments have altered the channel pattern, profile and dimension in many segments. Evidence on a smaller scale can be found at the road crossings, where sediment is building up on the upstream side and large scour pools downstream. The riparian corridor is pretty well in tact with perennial vegetation, so it is reasonable to assume that the origin of the sediment was historical and could have been a catastrophic event, such as wildfire, widescale removal of perennial riparian vegetation, major flooding, etc or cummulative effects related to landuse change.

An analysis of the watershed history is needed to provide context for both the TMDL and Implementation reports. In addition, repeat and additional geomorphic survey sites should be completed, organized by valley type, stream type and Pfankuch stability rating (good/fair & poor). Each combination of these metrics should have a representative survey completed. The surveys should include a longitudinal profile, cross-sections (riffle, pool, run and glide), pebble counts and streambank erosion estimates (Bank Erosion Hazard Index [BEHI], Near-Bank Stress [NBS]) and validation (bank pins). The potential products and outcomes from these assessments will include an evalution of stream channel succession, i.e. how close the stream channel is to reaching a stable state, how the channel is dealing with the legacy sediment, accurate streambank erosion rates and prioritized implementation strategies.

Monitoring Stations 2, 5, 6, 7, 8, 9, 11, 12 and 13 (see Figure 1-1), as was done for the Stressor Identification project (Benton SWCD, 2009), over a period of years will provide a better picture of whether there are active erosion sites contributing to bedded sediment. A more detailed investigation of local sources of runoff to the stream channels should be performed to determine if upland best management practices can be implemented to reduce the rate and volume of runoff, as well as the likelihood of streambank erosion or increases to the allocated pollutant loadings.

5.0 Implementation

Regarding the nonpoint sources of pollutants, a more detailed implementation plan addressing those sources will be developed following approval of this TMDL study. Since oxygen demanding substances and nutrients have several sources and delivery pathways in common it will make sense to address implementation efforts together. The potential for biological stress associated with temperature increases was more evident in response to runoff events that followed extended dry periods, with the highest temperature exceedances occurring downstream of the Sartell WMA impoundment. Since the Station 13 data exceeded the temperature criteria approximately two-thirds of the time, the WMA impoundment area will need to be the focus of heat loading mitigation activities. The QUAL2K modeling (discussed in Appendix B) was used to evaluate what effect the removal of impounded water at the WMA would have on the water quality results.

The data analyzed for this study show that the dry weather and associated low flow conditions from 2006 through 2008 were not as severe as the 1988 drought, but the persistence of dry conditions resulted in above average pumping rates (normalized to the drought index) for six consecutive years that may have exacerbated the flow conditions for Little Rock Creek. The Little Rock Creek Stressor Identification report (Benton SWCD, 2009) cites lower groundwater levels as a possible contributor to the impairments for dissolved oxygen and temperature. To assess this claim a water quality modeling scenario was simulated with twice the groundwater inflow into the creek (see Appendix B), which was conservatively lower than the groundwater modeling results of the low pumping condition scenario (described in the Pumping Scenarios section of Appendix A), since a comparison of the low and high pumping condition modeling results showed that a 40% reduction in annual pumping volumes resulted in 2.34 times more flow during the critical QUAL2K calibration period of August, 2008. Under this scenario the amount of groundwater entering from each of the stream segments were doubled, with the groundwater source in the upstream segment extended to the boundary condition, which allowed for the whole system to experience increased groundwater flow. The chemical loads were held constant, resulting in a halving of the chemical constituent concentrations, assuming that the groundwater system has reached chemical equilibrium.

Sections 5.1 through 5.3 provide a summary of the potential approaches (mentioned above) for meeting the TMDL allocations, and their applicability for each of the three types of impairments (or important stressors), in the Little Rock Creek watershed. The calibrated model was used to simulate three mitigation scenarios: removal of the man-made impoundment, doubling the groundwater flow into the system while maintaining the same chemical loads, and a combination of the first two mitigation scenarios. This information assists in considering the types of Best Management Practice (BMP) strategies that might be needed for future implementation, depending on the levels of mitigation that can be provided to address altered flow and effect of the WMA impoundment.

5.1 Results of Implementation Scenarios for Dissolved Oxygen

Figure 5-1 shows the minimum DO concentrations simulated for each of the three mitigation scenarios relative to Little Rock Creek under existing conditions. The lowest dissolved oxygen concentrations were modeled in the impoundment under existing conditions. By removing the impoundment, there is a small increase in the DO concentrations near the impoundment. No other change is evident at any other location in the creek due to the removal of the impoundment. Increased dissolved oxygen levels are estimated throughout the creek when the groundwater flow is doubled. The minimum DO concentrations are elevated above 7 mg/l except in the impoundment where minimum concentrations still dip to 6.5 mg/l. When the impoundment is removed, along with the doubling of groundwater flow, all concentrations are elevated above the 7 mg/l standard.

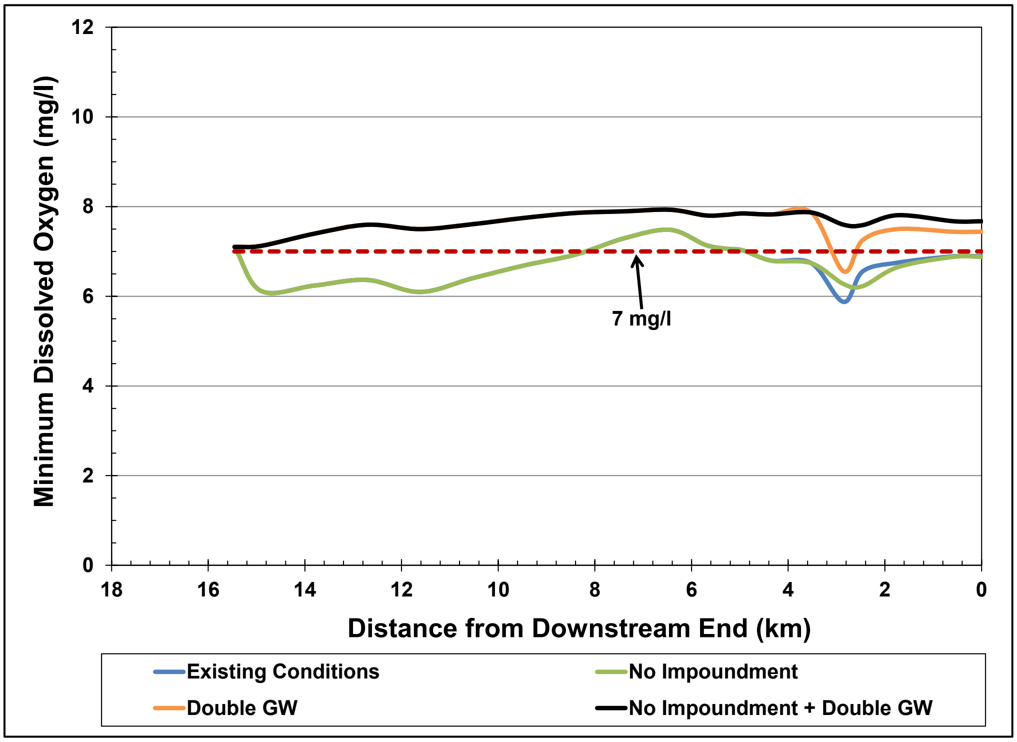


Figure 5-1 Minimum Dissolved Oxygen Concentrations for Simulated Mitigation Scenarios

5.2 Results of Implementation Scenarios for Nitrate

Average nitrate levels are shown in Figure 5-2 for all four model mitigation scenarios. Removing the impoundment did not affect the nitrate concentrations in Little Rock Creek, while doubling groundwater flow rates results in reduced nitrate concentrations. This reduction is caused by the lower nitrate concentrations in the groundwater.

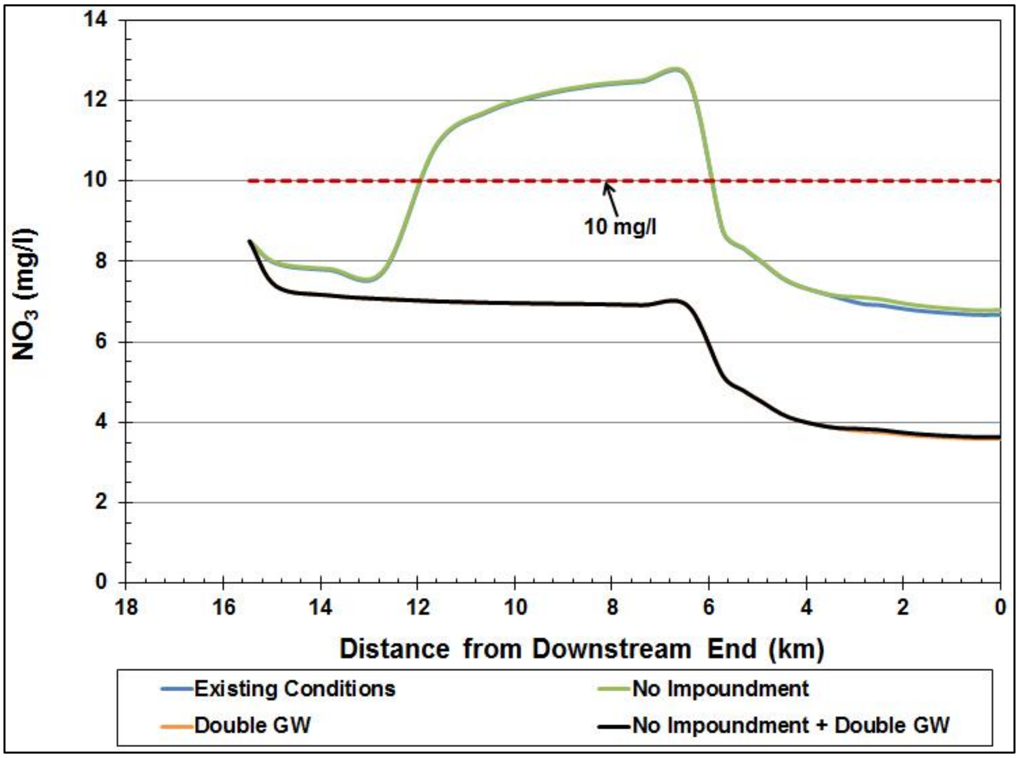


Figure 5-2 Average Nitrate Concentrations for Simulated Mitigation Scenarios

5.3 Results of Implementation Scenarios for Temperature

The average temperatures in Little Rock Creek under existing conditions and each mitigation scenario are shown in Figure 5-3. By removing the impoundment, downstream temperatures are decreased, but are still close to the chronic criteria. By removing the impoundment, the water residence time in areas with low shade coverage is reduced resulting in lower temperatures downstream of where the impoundment was located. Doubling the groundwater flows into the creek results in reduced temperatures throughout the creek. The temperature of the groundwater flow was calibrated to 10 ^{o}C because it provided the best fit to the monitoring data throughout the modeled system. Increasing groundwater flow results in significant reductions in the average temperature throughout the system. Combining both mitigation measures creates the lowest temperature regime throughout the entire creek system.

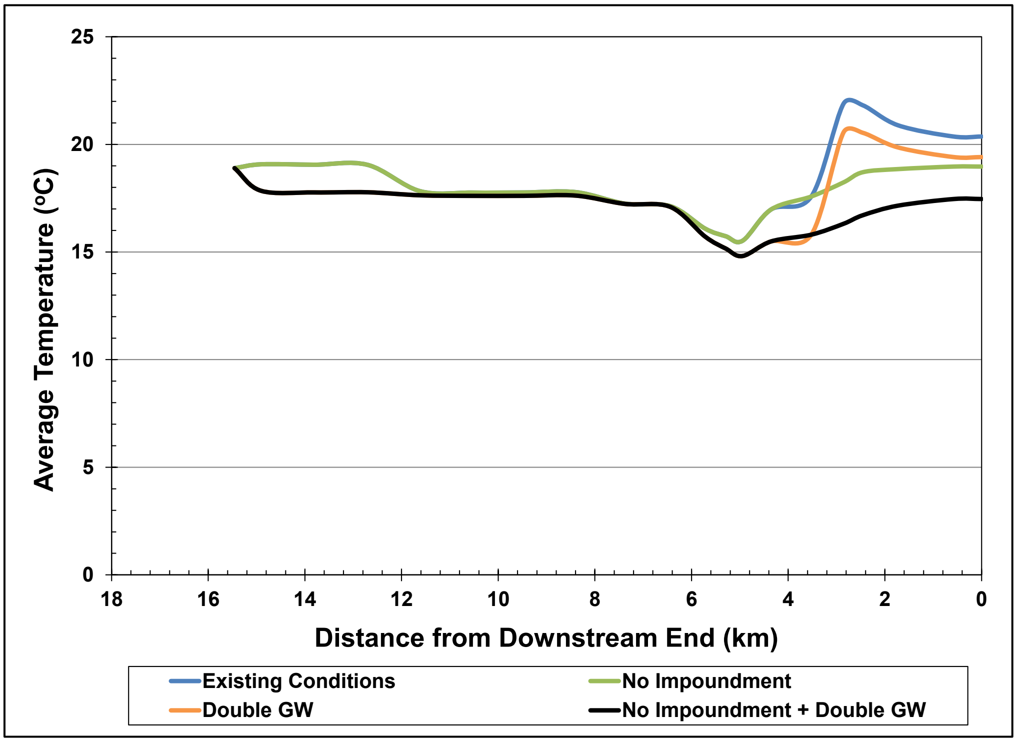


Figure 5-3 Average Creek Temperatures for Simulated Mitigation Scenarios

5.4 Summary of Implementation Strategies

As indicated in the previous sections the ideal combination of implementation strategies would combine restoration of groundwater flow, reductions in nutrient and organic contributions to the stream and a free-flowing system at the WMA impoundment to minimize thermal impacts. More specifically, these implementation strategies, or combinations of BMPs, would provide some or all of the following:

- Reductions in groundwater use will be necessary to improve conditions in the stream. A variety of potential options to reduce groundwater use should be explored, including: limits on total appropriations, improved irrigation efficiency, scheduling and technologies, identifying alternative sources, timing, proximity to the stream and other options not yet identified
- Nutrient and organic constituent reductions

- Creating more of a free flowing system, while incorporating current WMA management strategies, to improve connectivity and temperature issues during the critical conditions described in this report

An examination of Figures 1-6, 1-9, A-14 and B-3 indicates that the largest impacts on groundwater levels and baseflow, and thus the priority focus areas for implementing groundwater flow restoration, primarily exist between Station 7 and the Sartell WMA (shown in Figure 1-1), especially east of the Little Rock Creek.

When identifying implementation practices, it is important to consider a range of attributes and information from a variety of sources for each geographic area. It is important to consider: magnitude of pollutant source or sources, severity of impairment, groundwater and surface water hydrology, system connectivity, soils, slope, topography, geology, precipitation, land use, land cover, ownership, water chemistry, biota, demographics, local interest and capacity, and economics among other factors. Table 5-1 provides an excerpt of the USDA-NRCS Minnesota (2002) matrix that provides guidance on the expected physical effects associated with implementation of a selection of conservation practices that are expected to be pertinent to the Little Rock Creek watershed.

Cost-share funding eligibility for irrigation water management may be limited for some of the appropriations, so other methods may require consideration to restore groundwater flow during the critical flow conditions. Irrigation scheduling is an important strategy for growers to minimize the amount of excess water applied to a field and more closely monitor irrigation water applications. Keeping a close record of rainfall, irrigation, crop evapotranspiration and soil moisture allows for optimum scheduling. Where personal scheduling assistance from a technician is not available (or practical), in-field soil moisture monitoring equipment may be able to provide the soil moisture record that is needed to effectively schedule irrigation water applications. Allowable soil water depletion is an important component of irrigation water scheduling. Instead of managing the field for a consistent soil moisture level throughout the year, this is the practice of varying the soil moisture levels within a field dependent on the crop type and growth stage throughout the growing season to improve water use efficiency.

Table 5-1 NRCS Conservation Practice Physical Effects (CPPE) Matrix

NRCS Standard #	Conservation Practice	Water Quantity—Inefficient Water Use on Irrigated Land	Surface Water Pollution—Nutrients and Organics	Water Quality—Harmful Temperatures in Surface Water	Surface Water Pollution—Low Dissolved Oxygen
327	Conservation Cover	N	SMD	N	SMD
328	Conservation Crop Rotation		SMD		SMD
332	Contour Buffer Strips		SMD		SLD
585	Contour Stripcropping	SMD	SMD	SLD	SMD
393	Filter Strip		SLD	N	SLD
528A	Prescribed Grazing	SLD	SMD	SLD	SMD
449	Irrigation Water Management	SD	SMD	N	SSD
329A	Residue Management	SMI	MD	SLD	SMD
590b	Nutrient Management	N	SD	N	SD

N—Negligible
SD—Significant Decrease
SMD—Slight to Moderate Decrease
SLD—Slight Decrease
SSD—Slight to Significant Decrease
MD—Moderate Decrease
SMI—Slight to Moderate Increase

Precision irrigation technologies, such as variable rate irrigation (VRI), also warrant strong consideration for implementation. VRI matches the water application rate of the irrigation system to the specific field conditions by incorporating crop and yield data, topography, soil type mapping and other variables to optimize the various irrigation prescription zones.

It is especially important to properly manage nitrogen use on the coarse textured soils prevalent in the Little Rock Creek watershed. UMN Extension provides two guidance publications for fertilizer applications to crops for this situation (Best Management Practices for Nitrogen on Course Textured Soils [UMN Extension, 2008a] and Fertilizer Guidelines for Agronomic Crops in Minnesota [UMN Extension, 2011]). Irrigation water management under these conditions also require consideration of irrigation scheduling, available water in the root zone, soil water deficit, allowable soil water depletion, irrigation water depth and crop water use (Irrigation Water Management Considerations for Sandy Soils in Minnesota [UMN Extension, 2008b]).

Sub-Irrigation, which combines drainage and irrigation, could be considered in strategic locations, based on cost-benefit and room for water storage. It is usually done in conjunction with pump(s) and wetland and/or other water storage and offers increased irrigation and fertilization efficiency and reduces appropriations, less nitrification/nitrate/total dissolved phosphorus loads, uniformly high crop yields and more efficient use of land. Drip irrigation could also be implemented in strategic locations, or used instead of sub-irrigation if drainage is not needed, as it offers many of the same benefits.

Additional actions to address the nutrient loadings include upgrading of noncompliant septic systems and correction of feedlots with runoff problems. Current programs/efforts should be further reviewed during the implementation planning process.

Creating more of a free flowing system at the Sartell WMA would likely entail the construction of a diversion channel around the WMA impoundment area, while maintaining the current WMA impoundment and seasonal management, to improve the conditions for connectivity and temperature.

The wasteload allocation for stormwater discharges from sites where there is construction activities reflects the number of construction sites $\geq$ 1 acre expected to be active in the watershed at any one time, and the Best Management Practices (BMPs) and other stormwater control measures that should be implemented at the sites to limit the discharge of pollutants of concern. The BMPs and other stormwater control measures that should be implemented at construction sites are defined in the State's NPDES/SDS General Stormwater Permit for Construction Activity (MNR100001). If a construction site owner/operator obtains coverage under the NPDES/SDS General Stormwater Permit and properly selects, installs and maintains all BMPs required under the permit, including those related to impaired waters discharges and any applicable additional requirements found in Appendix A of the Construction General Permit, the stormwater discharges would be expected to be consistent with the WLAs in this TMDL. It should be noted that all local construction stormwater requirements must also be met.

The wasteload allocation for stormwater discharges from sites where there is industrial activity reflects the number of sites in the watershed for which NPDES industrial stormwater permit coverage is required, and the BMPs and other stormwater control measures that should be implemented at the sites to limit the discharge of pollutants of concern. The BMPs and other stormwater control measures that should be implemented at the industrial sites are defined in the State's NPDES/SDS Industrial Stormwater Multi-Sector General Permit (MNR050000) or NPDES/SDS General Permit for Construction Sand & Gravel, Rock Quarrying and Hot Mix Asphalt Production facilities (MNG490000). If a facility owner/operator obtains coverage under the appropriate NPDES/SDS General Stormwater Permit and properly selects, installs and maintains all BMPs required under the permit, the stormwater discharges would be expected to be consistent with the WLAs in this TMDL. It should be noted that all local stormwater management requirements must also be met.

The Clean Water Legacy Act requires that a TMDL include an overall approximation ("…a range of estimates") of the cost to implement a TMDL [Minn. Statutes 2007, section 114D.25]. Based on cost estimates made in 2004 by a state-level interagency working group which assessed restoration costs for several TMDLs, the initial estimate for implementing the Little Rock Creek TMDL ranges from approximately $10 to $20 million. This estimate will be refined when the detailed implementation plan is developed, following approval of the TMDL study.

6.0 Reasonable Assurances

When establishing a TMDL, reasonable assurances must be provided demonstrating the ability to reach and maintain water quality endpoints. Several factors control reasonable assurances including a thorough knowledge of the ability to implement BMPs, the state and local authority to implement, as well as the overall effectiveness of the BMPs. The explicit margin of safety applied to these TMDLs, at the critical seasonal conditions and all portions of the flow regime, also provides reasonable assurance that the standards will be met with the allocated loadings.

Within one year of the approval of the TMDL Report by the USEPA, a Final Implementation Plan will be released. This Implementation Plan will identify the responsible entities and actions that it will take to incorporate TMDL results into local management activities. The ultimate goal of the Implementation Plan is to achieve the identified load reductions in Little Rock Creek needed to reach the State Standards for dissolved oxygen, nitrate and temperature. Additional reasonable assurance that implementation will be targeted and result in pollutant load reductions in the listed waters toward meeting the designated uses will result from the monitoring plan and tracking progress to guide the proper adjustments for implementation.

The Minnesota Department of Natural Resources regulates the use of groundwater appropriations in amounts over 10,000 gallons a day, or 1 million gallons a year (Minn. Stat. §103G.271) through permits. Most of the MDNR pumping permits issued in the Little Rock Creek watershed are for crop irrigation. The MDNR will provide reasonable assurance that future changes to water appropriations permitting affecting Little Rock Creek will occur within the allocated load for each pollutant and will be subject to a water allocation planning process to account for any changes to the TMDL loading capacities.

Benton and Morrison SWCDs will be critical to providing reasonable assurance that Little Rock Creek can meet the desired water quality and biological endpoints and they have excellent track records in providing the required support. Both SWCDs have a history of successfully installing BMPs in the Little Rock Creek watershed. They have formed many relationships over the years and have continued to build successful relationships with multiple agencies across central Minnesota. Those agencies include, but are not limited to, Benton County officials, Morrison County officials, NRCS, MPCA, MDA, MDNR Fisheries, MDNR Waters, U.S. Fish and Wildlife Service and BWSR. Benton and Morrison SWCDs strive to connect with the citizens of Little Rock Creek watershed. In 2002, a survey was conducted to identify changes citizens have noticed in the watershed, identify citizens' concerns and to identify what landowners would be willing to do to improve water quality.

The SWCDs continue to build existing and new relationships with residents of the Little Rock Creek Watershed.

Benton SWCD formed a Little Rock Watershed Stakeholder Committee in 2010. This committee consists of 16 elected members, who live or work in the Little Rock watershed, including one citizen representative from the seven townships within the watershed, a County Commissioner from Benton and Morrison Counties, a SWCD Supervisor from Benton and Morrison County, as well as representatives from the Little Rock Lake Association, Mid-Minnesota Trout Unlimited Association, East Central Irrigation Association, GNP Company and New Heights Dairy. The goal of this committee is to develop and implement management actions in the Little Rock Watershed related to the Little Rock Lake and Little Rock Creek TMDL projects.

Education and outreach initiatives from Benton and Morrison SWCDs also provide strong reasonable assurance. Benton and Morrison SWCDs hold conservation tours demonstrating land use complexities, conservation solutions, controversies, and successes. Both districts provide technical assistance to landowners interested in conservation practices. Education plays a crucial role in protecting the natural resources of Benton and Morrison Counties and will continue to be incorporated to educate residents in the Little Rock Creek watershed about the impairments and necessary improvements.

On November 4, 2008, Minnesota voters approved a proposed Clean Water, Land and Legacy Amendment. Sales tax revenue is deposited in the state General Fund. The Amendment increased the general sales and use tax rate by three-eighths of one percentage point (0.375) to 6.875% and dedicated the additional proceeds to four categories, including a category to protect, enhance, and restore water quality in lakes, rivers, streams, and groundwater, drinking water sources (MDNR). This is just one potential funding source for projects. Others include but are not limited to: Natural Resource Block Grants and State Cost Share through the Board of Soil and Water Resources (BWSR), 319 Grants through Minnesota Pollution Control Agency (MPCA) as well as funding for individual projects through Natural Resources Conservation Service’s (NRCS) multiple programs.

7.0 Stakeholder and Public Participation

The Little Rock Creek TMDL project was scheduled to be completed in three phases. Phase 1 consisted of collecting and organizing existing data into a GIS map project and entered into STORET. The data was reviewed by technical and stakeholder committees. The committees explored watershed information and landscape activities and developed a list of potential stressors. Phase 1 was completed in 2003.

Phase 2 consisted of three main tasks: 1) collect additional physical, chemical, and biological data, 2) general project administration, coordinating, and bookkeeping, 3) Stressor Identification Report compilation. The product of Phase 2 was a Stressor Identification Report that included watershed GIS data, stakeholder meeting comments, technical group meetings and coordination, causal analysis and stressor identification documentation. Phase 2 began in 2006 and was completed in 2010. Public participation was incorporated into the stressor identification and analysis process in order to receive input from stakeholders and to apprise them of the progress made. Public participation for this process was combined with efforts associated with the development of the Little Rock Lake TMDL.

On September 3rd, 2003 a local stakeholder meeting was organized by the Benton SWCD to inform participants of the stream listing, TMDL process and solicit ideas and information. Subsequent meetings and communications with technical advisory committee members comprised of SWCD, Local Water Managers, MPCA, MDNR Division of Waters and Fisheries and MDA staff revealed a need to gather and organize existing data in a format that can be more effectively interpreted. A second public meeting was held on September 23, 2007 at the Sauk Rapids Middle School in Sauk Rapids Minnesota to inform the stakeholders about the TMDL process and the stressor identification phase. Project information and related materials were available for public distribution at the meeting. Approximately 30 people attended the meeting. The third public meeting was held September 16, 2009 at the Sauk Rapids Middle School in Sauk Rapids. The findings of the Stressor Identification Report were presented to the stakeholders. Public comment was received. Approximately 36 people attended the meeting.

A Little Rock Watershed Stakeholder Committee was established to develop and implement management actions in the Little Rock Watershed related to the Little Rock Lake and Little Rock Creek Total Maximum Daily Load (TMDL) projects. The Little Rock Watershed Committee consists of 16 members who live or work in the Little Rock Watershed, including one citizen representative from each township within the Little Rock Watershed boundary, a County Commissioner from

Benton and Morrison Counties and one SWCD Supervisor from each county, as well as representatives from the Little Rock Lake Association, Mid-Minnesota Trout Unlimited Association, East Central Irrigation Association and New Heights Dairy. A complete list of members (and their area of representation) is shown below:

- Joe Wollak, Benton County Commissioner
- Don Meyer, Morrison County Commissioner
- Bernie Thole, Benton SWCD Supervisor Board Member
- Marvin Stangl, Morrison SWCD Supervisor Board Member
- Ed Popp, Langola Township – Benton County
- Chuck Popp, Graham Township – Benton County
- Diane Wojtanowicz, Watab Township – Benton County
- Lawrence Thell, Mayhew Lake Township – Benton County
- Ray Sieben, Buckman Township – Morrison County
- Robert Stuckmayer, Morrill Township – Morrison County
- Jeff Tiemann, Bellevue Township – Morrison County
- Guy Spence, Little Rock Lake Association
- Ken Nodo, Trout Unlimited Association
- Rick Schlichting, East Central Irrigation Association
- Brent Czech, New Heights Dairy
- Wayne Sanders, GNP Company

A Technical Advisory Committee (TAC) was created so that interested expert stakeholders could be involved in decisions during the TMDL process. These individuals provided feedback, and input into the project from their individual fields of expertise. The committee as a whole had a broad representation, all coming with different technical backgrounds. A complete list of members (and their affiliated agency) is shown below:

- Adam Birr, Minnesota Department of Agriculture
- Nicola Blake-Bradley, Minnesota Department of Natural Resources
- Glen Champion, Minnesota Department of Natural Resources
- Lance Chisholm, Morrison Soil and Water Conservation District
- Evan Christianson, Barr Engineering
- Evan Drivas, Minnesota Department of Natural Resources

- Mark Evenson, Minnesota Pollution Control Agency
- Pat Gehling, Natural Resource Conservation Service (Benton County)
- Joshua Hanson, Natural Resource Conservation Service (Morrison County)
- Jeff Hrubes, Board of Water and Soil Resources
- Jeffrey Jasperson, Minnesota Pollution Control Agency
- Greg Kruse, Minnesota Department of Natural Resources
- Kimberly Laing, Minnesota Pollution Control Agency
- Dan Lais, Minnesota Department of Natural Resources
- Maggie Leach, Minnesota Pollution Control Agency
- Beau Liddell, Minnesota Department of Natural Resources
- Gerry Maciej, Benton Soil and Water Conservation District
- Joe Magner, Minnesota Pollution Control Agency
- Steve Marod, Minnesota Department of Natural Resources
- Helen McLennan, Morrison Soil and Water Conservation District
- Nick Proulx, Minnesota Department of Natural Resources
- John Sandberg, Minnesota Pollution Control Agency
- Lori Stevenson, United States Fish and Wildlife Service
- Andrew Streitz, Minnesota Pollution Control Agency
- Kevin Stroom, Minnesota Pollution Control Agency
- Luke Stuewe, Minnesota Department of Agriculture
- Stephen Thompson, Minnesota Pollution Control Agency
- Greg Wilson, Barr Engineering
- Katie Winkelman, Benton Soil and Water Conservation District

During Phase III of the Little Rock Creek TMDL project the Technical Advisory Committee met three times. The public notice period occurred from February 4, 2013 to march 6, 2013. Nine (9) comment letters were received during the public notice period. Two contested case hearing request letters with multiple signatures were received March 6, 2013. As a result of the comment letters, minor clarifications were made to the study as appropriate.

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Appendices

Appendix A

Watershed and Groundwater Modeling

Watershed-Groundwater Modeling Background

Groundwater pumping within and around the Little Rock Creek watershed has been steadily increasing over the last several decades. Since the year 2000, groundwater pumping has increased 162% in the Little Rock Creek watershed (Benton SWCD, 2009). Over this same period, water levels in nearby long-term observation wells have steadily declined, while the average precipitation trend has been positive. The decline in water levels has been attributed to the increase in groundwater pumping (Benton SWCD, 2009). Initial work by Streitz (2009) indicated the increase in groundwater pumping likely resulted in a decrease in baseflow to portions of Little Rock Creek. Altered flow in Little Rock Creek was identified as a dominant stressor in Phase II of the TMDL process. While not considered a pollutant by the USEPA as part of the TMDL process, low-flow conditions do exacerbate impairing effects of pollutants and are therefore dealt with in the TMDL process by allocating total pollutant loads while considering variation in stream flow (Benton SWCD, 2009).

The modeling conducted for this study was designed to assess the relationship between groundwater pumping and stream flow in Little Rock Creek. In order to assess this relationship, a model capable of simulating both surficial hydrologic processes and groundwater flow is necessary. The coupling of two models, SWAT and MODFLOW, was chosen to accomplish this task. The two models were constructed to:

- Include a simplified, but robust, representation of the essential hydrologic and hydrogeologic features in the study area
- Simulate observed hydraulic heads and stream flows that are consistent with available data
- Allow for assessment of scenarios (i.e. changes in groundwater pumping, or changes in climate) to measure the effects on stream flow and aid in the development of a TMDL and implementation strategies for Little Rock Creek.

Site Geology

The regional geology in the vicinity of the Little Rock Creek watershed consists of a complex series of unconsolidated glacial deposits overlying Archean and Paleoproterozoic crystalline bedrock. This study focuses on groundwater flow within the upper unconsolidated deposits. The permeability of the crystalline bedrock is very low compared to the unconsolidated sediments, with groundwater flow primarily within bedrock fractures. For the purpose of this study the bedrock is considered a regional no-flow boundary and is not simulated in the groundwater flow model.

The unconsolidated Quaternary sediments in the model area are the result of more than a dozen glacial ice advances during the Pleistocene Epoch (Meyer et al., 2010). Each advance and subsequent retreat resulted in both deposition and erosion. The unconsolidated sediments can be simplified into the following; unsorted fine-grained sediment (glacial till) deposited directly from the glacier, fine-grained bedded sediment (lacustrine deposits) deposited in ponded melt water or glacial lakes, and coarser grained sand and gravel deposited by melt water (outwash) streams emanating from the glaciers. The finer grained till and lacustrine deposits comprise confining units that overlie or encompass the coarser grained sand and gravel units that make up the aquifers in the model area. Confining units of till and lacustrine deposits tend to be more laterally continuous than the sand and gravel aquifer units.

The complexity of the aquifer and confining units as mapped by Meyer and Gowman (2010) and Meyer et al. (2010) must be simplified to incorporate into a numerical groundwater flow model. The unconsolidated sediments were broken down into the following for incorporation into the groundwater flow model.

1). **Upper surficial sand and gravel aquifer**

The upper surficial sand and gravel aquifer generally consists of fluvial sand and gravel of the West Campus Formation deposited by early stages of the Mississippi River which acted as an outwash stream for glacial melt water. The deposits are mapped at two terrace levels. The upper Richfield terrace is the more extensive of the two terraces and is the dominant surficial deposit in the western half of the Little Rock Creek watershed. The lower Langdon terrace is less extensive and is only present near the Mississippi River. Alluvial fan deposits consisting of fine-grained sand to gravelly sand, located east of the Richfield terrace deposits, are also considered part of the upper surficial sand and gravel aquifer.

2) **Glacial till confining unit**

The glacial till confining unit consists primarily of sandy till of the Cromwell Formation. This unit generally separates the upper surficial aquifer and the lower sand and gravel aquifer in the western half of the Benton and Morrison counties and is interpreted to act as a leaky confining layer. However, in some areas, particularly near the Mississippi River and near Little Rock Creek, this unit may not be present (Meyer and Gowman, 2010). In the eastern half of the Little Rock Creek watershed this unit is generally present from ground surface to bedrock with some minor sand and gravel units within and below the unit. These smaller sand and gravel units may supply sufficient water to domestic wells; however, it is believed they are not extensive enough to supply high capacity wells for sufficient periods.

3) **Lower sand and gravel aquifer unit.**

The lower sand and gravel aquifer unit is primarily comprised of sand and gravel deposited as part of the St. Croix and Emerald phases of the Superior lobe glaciation along with smaller sand and gravel deposits associated with Pre-Wisconsin Episode glaciations. The most dominate of these sand and gravel units is unit Qsb as mapped by Meyer and Gowman (2010).

Model Selection and Development

Model selection is primarily determined by the purpose and objectives of the model and the availability of data. For this study, the industry standard groundwater flow code MODFLOW (McDonald and Harbaugh 1988; Harbaugh and McDonald 1996; Harbaugh et al. 2000) was used in conjunction with the surface water model code SWAT (Neitsch et al., 2011). MODFLOW is the industry standard finite difference, 3-D, groundwater flow model developed by the USGS. SWAT is a physically based, watershed scale model developed by the USDA to assess the impacts of different land management practices on stream flow along with chemical and sediment loading. These two models were primarily designed to simulate separate spectrums of the hydrologic cycle – SWAT for surface water and MODFLOW for groundwater. SWAT only considers groundwater in a simple “black-box” perfunctory fashion. While in most MODFLOW models, surface water features are used as boundary conditions acting as either a source or sink for groundwater to help maintain an appropriate water balance, and groundwater recharge is typically estimated using inverse modeling methods, or other non-physically based methods. These two models (SWAT and MODFLOW) were used in tandem, allowing for the strengths of each model to substitute for the weaknesses of the other. Essentially, SWAT was used to calculate surface-water runoff and produce recharge values for MODFLOW. MODFLOW was used to simulate groundwater flow in the aquifer, baseflow to the stream, and withdrawal of water from the aquifer via high capacity wells.

MODFLOW Groundwater Model

MODFLOW simulates three-dimensional, steady-state and transient groundwater flow (saturated) using finite-difference approximations of the following differential equation of groundwater flow:

$$\frac{\partial}{\partial x}\left(K_x \frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_y \frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_z \frac{\partial h}{\partial z}\right)-W = S_s \frac{\partial h}{\partial t}$$

where:

K_x, K_y, and K_z are values of hydraulic conductivity along the x, y, and z coordinate axes

W is volumetric flux from water sources and sinks

S_s is specific storage

h is hydraulic head

t is time

MODFLOW was developed by the USGS and is in the public domain. It is widely used and accepted. The graphical user interface Groundwater Vistas (ver. 6.0) (Environmental Simulations, Inc. 2011) was used to help construct the MODFLOW model for this application. The version of MODFLOW used in this study is MODFLOW-2000 (Harbaugh et al., 2000).

Model Domain and Discretization

The groundwater model covers an area of 337 mi^2 (872 km^2) and is shown on Figure A-1. The primary area of interest for this study was the Little Rock Creek watershed, upstream of Little Rock Lake. The size of the model domain was chosen to capture the effect of differing surface water and groundwater watersheds, and to limit the effects of boundary conditions on the area of interest. To the west, the model extends to the Mississippi River. To the east, the model extends to the approximate location of a regional groundwater divide based on interpolation of static water levels from the county well index. The northern and southern boundaries of the model coincide with approximate groundwater flow paths and are located an arbitrary distance from the area of interest to limit the effects of boundary conditions.

The model domain is subdivided into rectilinear grid cells to solve the finite-difference approximations. The model grid consists of 260 rows, 215 columns, and 3 layers, for a total of 167,700 cells, of which 65,429 cells are active during the simulation. The size of the model cells is 200 m x 200 m and is constant throughout the model domain. The length unit of the model is meters and site coordinates are in UTM NAD83, Zone 15N. The X offset of the model grid origin is 391,442 meters and the Y offset of the origin is 5,044,428 meters.

The model is divided into three layers to capture some of the complexity of the Quaternary sediments that make up the aquifers and confining units in the area of interest. A geologic model of Quaternary stratigraphy developed for the Benton County geologic atlas (Meyer and Gowman, 2010) and stratigraphy data from the county well index were used to help define layer elevations roughly corresponding to major lithological contacts (primarily till and sand/gravel; see Section 2.1). Allowing the layer elevation to correspond to major lithological contacts allows for the bulk effective hydraulic conductivity to be used as a parameter rather than the layer transmissivity. Layer transmissivities are calculated internally within the MODFLOW code.

Time is discretized in the model using a unit of days. For model calibration, 61 stress periods were used with daily time steps. The first stress period is steady state. This initial stress period is used to generate initial conditions for a series of month long transient stress periods corresponding to January 2006 to December 2010. Monthly stress periods were chosen as they correspond to the resolution of the reported pumping of high capacity wells. For the initial steady-state stress period, averaging pumping rates from 2005 were used.

Boundary Conditions and Parameters

Boundary conditions establish the sources and sinks of water for a groundwater flow model (e.g. river, lakes, constant-head cells, and no-flow cells). The geologic and hydrogeologic conceptual model aids in the selection of appropriate boundary conditions. Parameter values define aquifer and boundary properties (e.g. hydraulic conductivity, river bed conductance, and recharge) and are either fixed at some defined value or are adjusted within expected ranges during model calibration. Boundary conditions and model parameters are described in the following sections.

Constant Head Boundaries

A constant head boundary was assigned along the western edge of the model domain and represents the Mississippi River, the major groundwater discharge zone in the region (Figure A-2). Elevations for the constant head cells were assigned based on interpolated stream stage elevations from USGS topographic maps.

No-Flow Boundaries

The northern, southern, and eastern boundaries of the model domain were set as no-flow boundaries (Figure A-2). The orientations of these boundaries were determined by interpolating static water levels from the county well index. The northern and southern boundaries are approximately perpendicular to contours of the regional potentiometric surface, or otherwise conceptualized as groundwater flow paths. The eastern no-flow boundary corresponds to a regional groundwater divide. Areas outside the model domain, but within the finite-difference grid, were assigned as no-flow boundary conditions and were not part of the computation process.

Rivers

Rivers and streams within the model domain are represented using the river package (Figure A-2). Stream stage for the smaller rivers and streams were estimated based on interpolated values from a digital elevation model. The stage of these rivers was fixed throughout the model simulation.

Conductance for the river cells was adjusted as an estimated parameter during model calibration and was scaled based on the length and width that each stream intersects a model cell.

Little Rock Lake is also simulated using river cells. As a matter of parsimony the actual width of the lake is not covered by all model cells that intersect the lake area. However, the conductances of the river cells were adjusted to account for this difference. The primary area of interest for this study is north of Little Rock Lake and this simplification is assumed to have little effect on simulated baseflow to the creek.

High-Capacity Wells

Wells with water use permit records maintained by the Minnesota Department of Natural Resources (MDNR) through the State Water Use Data System (SWUDS) within the model domain were included in the groundwater flow model (Figure A-3). The MDNR requires all users withdrawing more than 10,000 gallons per day, or 1 million gallons per year, to obtain a permit and submit water use records. The average pumping for 2005 was included in the first stress period (steady-state) of the model. Monthly pumping records were included for subsequent stress periods (transient) from 2006-2010. Average yearly pumping volumes for wells included in the model are shown for the period of 2006-2008 on Figure A-3.

Recharge

Recharge for the groundwater flow model was derived from output of the SWAT model. In areas of the groundwater flow model that exist outside the domain of the SWAT model, recharge was determined using the inverse method during model calibration.

Hydraulic Conductivity

The different hydrostratigraphic units within the model are represented by hydraulic conductivity zones as shown on Figure A-4. The extent of each hydraulic conductivity zone represents simplified lithological units as described by Meyer (2010), Meyer and Gowan (2010), Meyer and Knaeble (2001), Hobbs and Goebel (1982) and lithology as described in the county well index. The Quaternary sediments in the area of interest are very complex and must be simplified to allow for representation in a finite difference grid that allows for reasonable computational efficiency. Hydraulic conductivity zones in model layer one generally conform to the surficial geology. In the western half of the model domain hydraulic conductivity zones are vertically distributed with a lower permeability zone in layer 2 representing tills below the water table aquifer and a high permeability zone in layer 3 representing lower sand and gravel units. In the eastern half of the model domain layers 1-3 are represented by a single hydraulic conductivity zone representing sandy glacial till.

Storage

Storage parameters are distributed using the same zonation as hydraulic conductivity (Figure A-4). Storage parameters include both specific storage and specific yield. Specific yield is only defined for model layers simulated as unconfined or convertible layers; hence specific yield is not defined for zones 4, 8, and 9 which remain confined. Storage parameters were allowed to vary as an adjustable parameter during model calibration.

Solvers and Convergence Criteria

The preconditioned conjugate-gradient (PCG) Solver was used for this study. The maximum head change during each iteration of the solver was set to 1.0×10^{-4} m. The residual convergence criterion was set at 1×10^{-2} m^3/day. The maximum outer and inner iterations of the PCG solver were both set at 75. Mass balance errors were typically in the range of 0.1 percent, which are deemed to be negligible.

SWAT Surface Water Model

SWAT is a basin-scale continuous distributed water quality simulation model capable of predicting long-term effects of alternative land management practices. Major components of the model include hydrology, erosion, nutrients, pesticides, crop growth, and agricultural management. Hydrologic processes include surface runoff, tile drainage, irrigation, snow-melt runoff, infiltration, lateral flow and plant uptake. The SWAT model classifies precipitation as snow when the average air temperature is less than the snowfall temperature and melts it when the maximum temperature exceeds the snowmelt temperature. Melted snow is treated as rainfall for estimating surface runoff and percolation. Daily average soil temperature is simulated at the soil surface and the center of each soil layer. Soil temperature at the surface is calculated as a function of maximum and minimum air temperature, snow cover, plant cover and residue cover for the day being simulated and the preceding four days. The temperature of the soil layers are calculated as a function of soil surface temperature, mean air temperature and the depth of the soil at which variations in the climatic conditions will not affect the soil temperature. The weather input for SWAT consists of daily values of daily precipitation, and maximum/minimum air temperature. The model has the option of generating the air temperature data if they are not available. Solar radiation, wind speed and relative humidity are also generated by the model.

Landuse

Modeled land cover characteristics for the Little Rock Creek watershed were determined from the 2008 USDA-NASS Crop Data Layer (CDL) coverage in GIS. Most of the watershed is agricultural cropland with various row crop rotations, some of which incorporate alfalfa. There are a number of small wetlands spread throughout the watershed. One class of developed land was included in the land use coverage to ensure that varying amounts of impervious and road surfaces could be modeled. The individual NLCD land use classifications were re-categorized in the ArcSWAT interface to distinguish the following land uses: cultivated cropland, forest, pasture, water/wetlands and residential development.

Soils

A soil map was derived from the Soil Survey Geographic Database SSURGO, a small-scale NRCS soil database. Soil characteristics associated with SSURGO soil map units such as depth of each horizon, particle size distribution, organic matter content, and vertical hydraulic conductivity were developed and pre-processed using a SWAT model database application (SWATioTools), developed at Kansas State.

Topography

Using the statewide hydrography layer to burn in the known streams and associated channel crossings, each watershed was delineated using the available 30-meter digital elevation model (DEM) data, cropped to the boundaries of the Little Rock Creek watershed. Subwatershed divides and slopes were determined in the ArcSWAT interface using the DEM data, but the subwatersheds were not further broken down into separate slope classes in the model. The DEM coverage was used by the ArcSWAT interface to digitally determine the locations of stream and overland channels (flowlines) and the associated morphometric characteristics. The SWAT model had 89 subbasins delineated in ArcSWAT and utilized for further model development.

HRUs / Subwatersheds

Input for the SWAT model was derived at two different scales: the subwatershed and the hydrologic response unit (HRU). HRUs are developed by overlaying soil type, slope and land cover. It is noted that HRUs in the version (2009.93.6, Revision 477) of ArcSWAT used for this project are not defined by a flow direction and the spatial location within each subbasin does not influence pollutant loading to the stream. In addition to the cropland, both with and without irrigation, SWAT was also used to model pasture land, forest land, water and developed land cover HRUs in each subwatershed. The irrigated cropland areas were delineated in GIS using the 2008 aerial photo in the background to ensure that the irrigated cropland area delineated for each SWUDS permit location corresponded with the acreage included in the SWUDS database. The proportions of each of the major crops were distributed across the cropland (and subdivided into corn, soybeans and alfalfa) to maintain consistency with the 2009 NASS data for Benton and Morrison Counties. The following table shows the distribution of the general SWAT model land uses applied to the Little Rock Creek watershed.

Land Use	Percentage of Watershed Area
Row Crops with Irrigation	16.0%
Row Crops without Irrigation	28.5%
Forested	14.3%
Pasture/Meadow/Grassland	21.8%
Alfalfa/Hay	5.9%
Water/Wetlands	13.3%
Residential Development	0.2%

The initial HRUs set up in the ArcSWAT interface were further refined for each subbasin in the watershed to account for the various crops, crop management (discussed below) and irrigation. This resulted in an excessive quantity of HRUs in the watershed, with several of the HRUs resulting from unique combinations of soils and land use that represented negligible areas in each subbasin. As a result, the land use was refined so that each 200 x 200 meter grid cell from the groundwater modeling was represented by the predominant land cover type (row crop, non-row crop, forested, water/wetland and developed). This resulted in 6,360 HRUs regenerated in ArcSWAT and none of the remaining smaller HRU areas were eliminated from the modeling to maintain consistency with the groundwater modeling and provide accurate recharge inputs.

Weather Data

Climatic data such as daily values of precipitation were developed using the available National Weather Service (NWS) station data (MDNR, 2012). Precipitation records from the Rice NWS station were used to develop the rainfall records used in the model simulation between 1989 and 2007. Other climatic data such as average temperature, relative humidity and wind speed was automatically generated as part of the model simulation, based on the nearest National Weather Service weather station location for each subbasin.

Crop Management and Model Parameters

Based on the review of the cultivated cropland in the basin using the 2008 USDA-NASS CDL coverage in GIS, corn and soybeans/dried beans represented most of area, with other crops representing approximately 10% during each of the monitored years. On average, there was an 82% to 18% split between corn and soybeans in the watershed based on the NASS statistics.

Tillage transect surveys were completed in representative areas of Benton County in 2007. The results of the survey data were compiled to evaluate corn and soybean tillage. The survey results indicated that conservation tillage (at least 30% of the soil surface is covered with residue after planting the next crop) was used approximately 30% of the time with both corn and soybeans. As a result, tillage effects were accounted for in the ArcSWAT modeling within the land use refinement for each of the cultivated (both row crops with and without irrigation) land areas (described above).

Irrigation volumes were determined for the three-year monitoring period (2006-2008) based on the Little Rock Creek watershed appropriations permits included in the SWUDS database and the average volumes were scheduled for application to the irrigated cropland HRUs in the SWAT model to correspond to the long-term monthly distributions, such that approximately 25-30 mm of water was applied during each scheduled irrigation event during the course of each growing season that was simulated for the model calibration.

Information on planting, tillage and harvesting dates were utilized from past studies and fertilizer/manure applications were handled in the model by ensuring that enough (28-03-00) fertilizer was applied in the spring of each year to offset nutrient losses from harvesting and leaching/runoff.

Description of Model Linkage

The two models, SWAT and MODFLOW, are linked in a sequential manner. The SWAT model is run first, to completion, calculating surface runoff and groundwater recharge. MODFLOW is then run using groundwater recharge values from SWAT, and calculates aquifer water levels and baseflow to streams. The results of both models are then post processed to combine the surface water runoff from SWAT and the baseflow from MODFLOW. Attempts were made early on to completely couple the two models, passing baseflow and recharge values between the models on a daily time step. However, it was determined that this style of coupling would dramatically increase model run time, and hinder any form of model calibration. The sequentially coupled model as described below took four to five days to complete a model calibration iteration when running in parallel on 20 processors. It is estimated that this would have increased at least five fold if coupled on a daily time step. Running MODFLOW with a daily stress period for a five year simulation period was just not practical, especially when considering that pumping data is only available on a monthly basis.

The following describes how SWAT and MODFLOW were run.

1. SWAT run with standard daily time steps and output summarized by both HRU and sub-basin on a monthly basis

2. Monthly recharge values per HRU were summarized and mapped to MODFLOW grid
3. MODFLOW run with monthly stress period (recharge and groundwater pumping change each stress period)
4. Results from both models were post processed in the following manner
    a. Monthly surface runoff from SWAT was summarized according to contribution to each of three gauging stations
    b. Monthly baseflow from MODFLOW was summarized according to contribution to each of three gauging station locations
    c. Surface runoff and baseflow combined to produce total flow corresponding to each of three gauging station locations

It should be noted that there is no “routing” of water through the watershed using this linking scheme. The total amount of runoff from a given sub-watershed within SWAT is assumed to reach the gauging station in the same day. This simplification is deemed to be insignificant given that monthly flows were used for model calibration, and actual routing of water through the watershed is less than a month.

Model Optimization

The combined SWAT and MODFLOW models were calibrated through a series of automated inverse optimization procedures using the model-independent Parameter ESTimating software (PEST) (Version 12.0) (Watermark Numerical Computing, 2010). Automated inverse optimization is a method for minimizing the differences, or residuals, between simulated results and observations. The sum of the squared weighted residuals for all targets is the objective function that is to be minimized. The square of the residual is used because some residuals are negative and some are positive. Additional independent checks on calibration were made outside of PEST using techniques such as the Nash-Sutcliffe method on time series data of modeled vs. simulated baseflow, surface runoff, and total stream flow.

Using PEST involved making some choices on which parameters (e.g. hydraulic conductivity, river cell conductance, curve numbers, etc.) would be allowed to vary, the maximum and minimum values in which the parameter values could be varied, and initial estimates for the parameter values.

The overall process of the calibration procedure for this study was as follows:

1. The models were constructed
2. Calibration targets were chosen
3. Parameters that were allowed to vary during the optimization process where chosen, as was the range over which the parameters were allowed to vary.
4. The results of the PEST optimization were evaluated and changes were made :
    a. The lower and upper bounds for parameter values were adjusted

b. Insensitive parameters were tied together or fixed
c. The observation weights were adjusted so that one type of observation does not influence the calibration too much, or observations that are less certain don't contribute excessively to the objective function
d. Calibration targets representing periods that the model can't simulate or are not properly constrained to simulate (i.e. snow melt runoff) were reduced in weight or eliminated completely from the optimization.

Calibration Targets

Hydraulic Head

A total of 780 hydraulic head values from the county well index, MDNR observation wells, and synoptic water level measurements taken within the Little Rock Creek watershed were used (Figure A-5). Static water level data from the County Well Index generally represent water levels measured by drilling contractors during the time of well installation. Sources of error in this data include the following:

- Inaccuracy of water level measurement – drilling contractors may not have used precise measuring devices.
- Inaccuracies in well location – many wells are identified only to the nearest quarter-quarter-quarter section (300 to 600 feet location error).
- Inaccuracy in well elevation – well elevations are typically estimated using 7.5 minute topographic maps and are also subject to errors in location
- Water levels may not have stabilized at the time of measurement – water levels are typically collected during or immediately after well installation or development and may not have reached equilibrium with the aquifer.
- Hydrostratigraphic units misidentified or not correctly assigned in the databases – the well may actually be screened in a different unit or multiple units.

Given sources of unavoidable uncertainty in these target values, head targets derived from CWI data are typically assigned a likely error of at least +/- 20 feet (about +/- 6 meters). It is not uncommon to find two nearby targets in the same aquifer with substantially different head values. Geostatistical cross validation techniques and manual review of the CWI data were used to eliminate obvious outliers from the calibration dataset. A total of 105 calibration targets were derived from the County Well Index. Only wells drilled during the period of calibration (2005-2010) were used.

Hydraulic head targets from the MDNR observation well network and the synoptic measurements are more accurate. The location of these wells is accurately known and elevations are typically accurate to less than 0.1 feet. In addition, these observations have a time component to them which helps to constrain aquifer storage parameters and decrease the model predictive uncertainty, particularly in regard to pumping from high capacity wells. As a result, hydraulic head targets from MDNR observation wells and synoptic measurements were given a higher weight in the calibration process compared to targets derived from the CWI. A total of 578 calibration targets were derived from the MDNR observation wells (from 14 locations) and 97 were derived from the synoptic measurements (from 34 locations).

Baseflow

Monthly baseflow at three monitoring locations (Stations 13, 9, and Bunker Hill) were used during model calibration (Figure A-5). Baseflow separation was performed on daily stream flow data using methods of Arnold et al. (1995) and Arnold and Allen (1999). Due to the nature of the baseflow separation technique, the first and last months prior to a gap in data (e.g. winter when stream gauge stations were not active) were not included for calibration. Also, only months with complete records (no missing days) were used. A total of 85 monthly baseflow calibration targets were used; 28 for the station on Bunker Hill Creek, 36 for Little Rock Creek Station 13, and 21 for Little Rock Creek Station 9.

Surface Water Runoff

Monthly surface runoff at three monitoring locations (Stations 13, 9, and Bunker Hill) were used during model calibration (Figure A-5). Surface runoff was derived by subtracting monthly baseflow (see section 3.4.1.2 above) from total stream flow. As with the monthly baseflow, the first and last months prior to a gap in data (e.g. winter when stream gauge stations were not active) were not included for calibration. Also, only months with complete records (no missing days) were used.

Optimization Goals

Model simulated flows were compared to measured flows to determine if the model was adequately calibrated. Both graphical comparisons and quantitative statistical methods were used to evaluate model fit. The primary statistical analysis used to evaluate model fit was the Nash-Sutcliffe efficiency (NSE). NSE is computed as show below (Nash and Sutcliffe, 1970).

$$NSE = 1 - \left[\frac{\sum_{i-1}^{n}(Y_i^{obs} - Y_i^{sim})}{\sum_{i-1}^{n}(Y_i^{obs} - Y^{mean})}\right]$$

Where Y_i^{obs} is the ith observation for the constituent being evaluated, Y_i^{sim} is the ith simulated value for the constituent being evalutated, Y^{mean} is the mean of the observed data for the constituent being evaluated, and n is the total number of observations.

A NSE of 0.5 or above was set at the optimization goal for baseflow, surface runoff, and total stream flow (Moriasi et al., 2007). In addition to stream flow, simulated and measured hydraulic head values were also compared. However, much more emphasis was given to stream flow values compared to hydraulic head.

Optimization Parameters

Parameters that were allowed to vary during the optimization process were:

- MODFLOW
    - Horizontal hydraulic conductivity
    - Anisotropy (Kx/Kz)
    - Riverbed conductance
    - Aquifer storage parameters
    - Regional recharge (outside of SWAT model domain but within MODFLOW model domain)
- SWAT
    - Curve Number (global percent change for all HRUs)
    - Soil evaporation compensation factor
    - Average slope length (global percent change for all HRUs)
    - Groundwater "revap" coefficient (global percent change for all HRUs)
    - Threshold depth of water in the shallow aquifer for "revap" or percolation the deep aquifer to occur (global percent change for all HRUs)
    - Groundwater delay time (time between exiting soil profile and entering the shallow aquifer)

The final optimized MODFLOW parameter values for hydraulic conductivity and storage coefficients are shown on Figure A-4. River cell conductance values are shown on Figure A-6.

The final optimized SWAT parameters were as follows:

- Initial SCS runoff curve number for moisture condition II (CN2) = 5.0% global increase from initial parameter estimates
- Soil evaporation compensation factor (ESCO) = 0.93
- Available water capacity of soil (SOL_AWC) = 2.4 % global increase from initial parameter estimates
- Average slope length (SLSUBBSN) = 30% global decrease from initial parameter estimates
- Groundwater "revap" coefficient (GW_REVAP) = 0.2
- Threshold depth of water in the shallow aquifer (REVAPMN) = 0.16 mm
- Groundwater delay time (GW_DELAY) = 14.4 days
- Baseflow alpha factor (ALPHA_BF) = 0.4 days

Optimization Results

Overall, the final optimized model matched the measured baseflow, surface runoff, total stream flow and hydraulic head values well. While total stream flow (baseflow + surface runoff) was not used as a calibration target by PEST during model optimization it is presented here for completeness. The relative match of simulated total flow to measured total flow was checked after model calibration to verify that one component of the flow, either baseflow or surface runoff, was not dramatically over- or under-contributing to the total stream flow. The final optimized model has the following characteristics with respect to baseflow, surface runoff, and total stream flow.

Monitoring Station	Baseflow NSE	Surface Runoff NSE	Total Flow NSE
Bunker Hill	0.65	0.51	0.68
Little Rock Creek 9	0.42	0.60	0.59
Little Rock Creek 13	0.62	0.68	0.69

Monthly time series plots of measured versus simulated baseflow, surface runoff, and total stream flow are presented in Figure A-7 to Figure A-9.

The final optimized model has the following characteristics with respect to hydraulic head calibration targets:

Group	Mean Residual (ft)	Absolute Residual Mean (ft)	Residual Standard Deviation (ft)
All Targets	0.4	4.5	6.0
CWI	-2.7	12.0	10.5
MDNR Ob Wells	0.7	3.0	3.3
Synoptic	1.6	5.1	6.0

A plot that compares all model simulated heads to measured heads is shown on Figure A-10. A map of head residuals for all heads is shown on Figure A-11. There is a slight spatial bias in the head residuals for some parts of the model domain. The magnitude of spatial bias is slightly less for the more accurate head targets (MDNR ObWells and synoptic head measurements) but is still present in some areas. Correcting spatial bias in a zone based model requires the splitting or changing of zones and potential implementation of additional parameters. In this case there was no justifiable reason to introduce additional zones as there are little data to support additional parameters and the model reasonably mimics the important aspects of the flow system for the objectives of this study.

Over the period of model calibration from 2005-2010, recharge over the Little Rock Creek watershed, as calculated by SWAT and used by MODFLOW, ranged from 5.0 in/yr to 9.5 in/yr with an annual average of 7.7 in/yr (Figure A-12). Most recharge occurs during the spring and fall months. During the winter months most precipitation is locked up in snow, and during the growing season there is a large evapotranspiration demand, both resulting in less recharge compared to spring and fall months (Figure A-12). Simulated regional recharge, outside the SWAT model domain, ranged from 2.0 in/yr on the eastern glacial till plain to 7.8 in/yr on the glacial outwash plain in the western part of the model domain.

Pumping Scenarios

In order to assess the impacts of groundwater pumping on stream flow, two pumping scenarios were simulated; a low pumping condition and a high pumping condition. Each simulation was run for a period of 22 years (January 1989 to December 2010) with measured climatic data used for each simulation. The only differences between the two scenarios is the number of pumping wells, the total volume of groundwater pumped (both simulated in MODFLOW), and the amount of irrigation (simulated in SWAT).

To define the amount of pumping for the low and high pumping conditions, historical pumping data from the SWUDS database were used. For the low pumping condition, the average monthly pumping for the period of 1997-1999 was used to define the number of wells and pumping volumes for twelve monthly stress periods (January to December). These pumping volumes were then repeated for each of the 22 years in the simulation to measure the effect of pumping for both wet and dry years. For the high pumping condition, twelve monthly stress periods were defined in the same manner except the average monthly pumping for 2006-2008 was used. Total monthly pumping for each scenario is shown on Figure A-13. The low pumping condition resulted in 40% less volume (4,305 million gallons per year) than the high pumping condition (7,187 million gallons per year). The spatial distribution of the difference in pumping for the two scenarios is shown on Figure A-14.

The two periods used to define the high and low pumping scenarios (1997-1999 and 2006-2008) were chosen for several reasons. Most importantly, the differences between the two defined scenarios represents the increase in groundwater pumping that has been observed in the Little Rock Creek watershed and surrounding areas over the past several decades. Also, in the late 1990’s naturally produced trout were observed in Little Rock Creek. Stream flow and temperature data during this time also indicated favorable conditions for trout development. The period of 2006-2008 represents a period of increased groundwater pumping and stream conditions that were observed to be unfavorable for trout development—segments of Little Rock Creek went dry in 2006. It is noted that the period of 1997-1999 was a wet period compared to 2006-2008. The average Palmer Drought Index for 1997-1999 was 0.76, compared to -0.94 for 2006-2008. A Palmer Drought Index of zero indicates normal moisture conditions, a negative Palmer Drought index indicates dryer than normal, and a positive index indicates wetter than normal. For example, a value of -2 is a moderate drought and a value of -3 is a severe drought. By simulating the low and high pumping scenarios over 22 years, a wide range of climatic conditions can be compared for both low and high pumping conditions. The Palmer Drought Index over the simulated period of 1989 to 2010 ranged from -1.4 to 3.0.

The simulated baseflow for both the high and low pumping scenarios are shown on Figures A-15 to Figure A-17. The high pumping scenario results in an average reduction in monthly baseflow of 15 percent and 20 percent at monitoring Stations LRC9 and LRC13 respectively, with over 90 percent reduction in baseflow during the mid-summer months of dryer years.

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Figures

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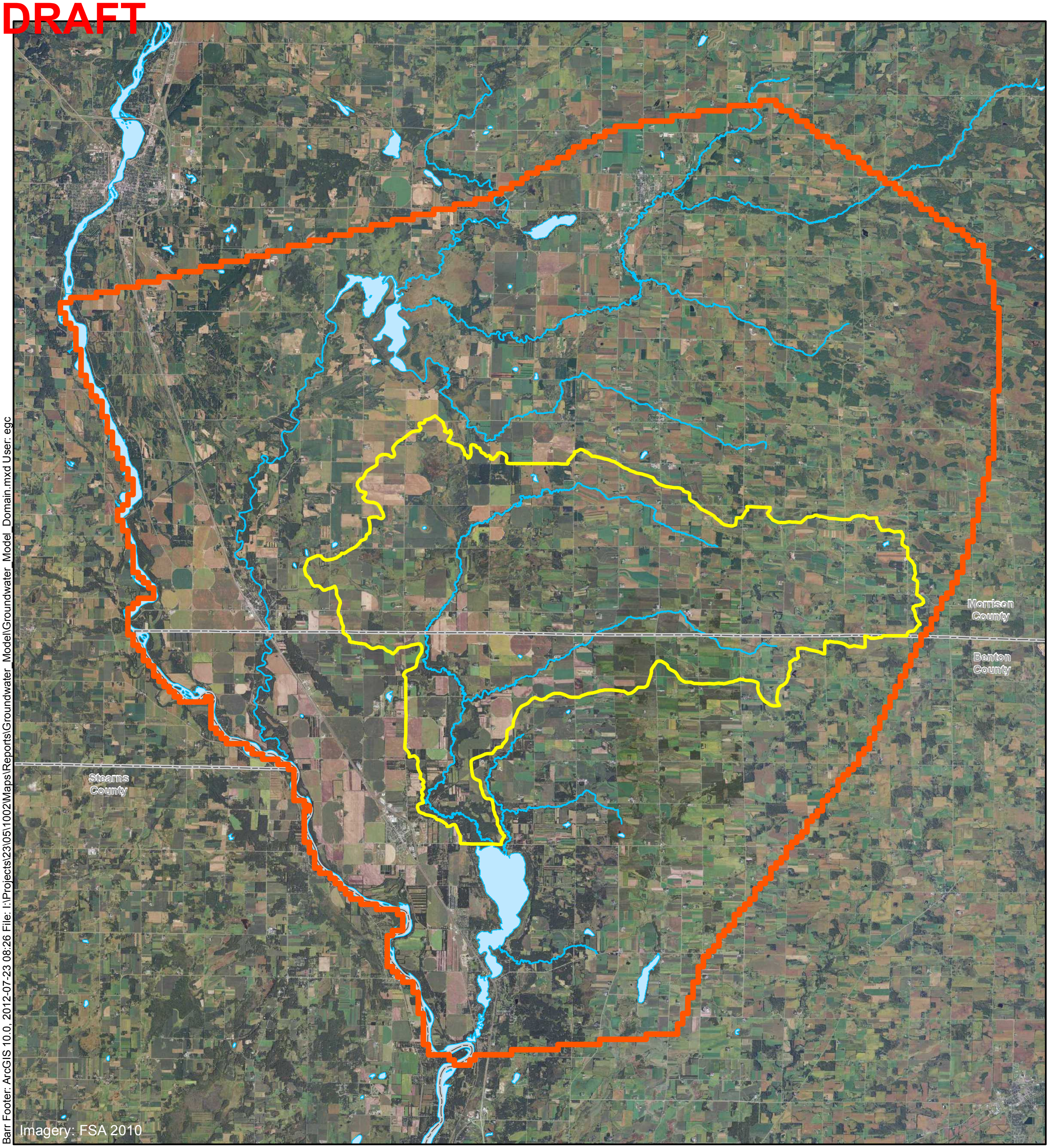

Figure A-1
Groundwater Model Domain
Little Rock Creek TMDL
Benton and Morrison Counties, MN

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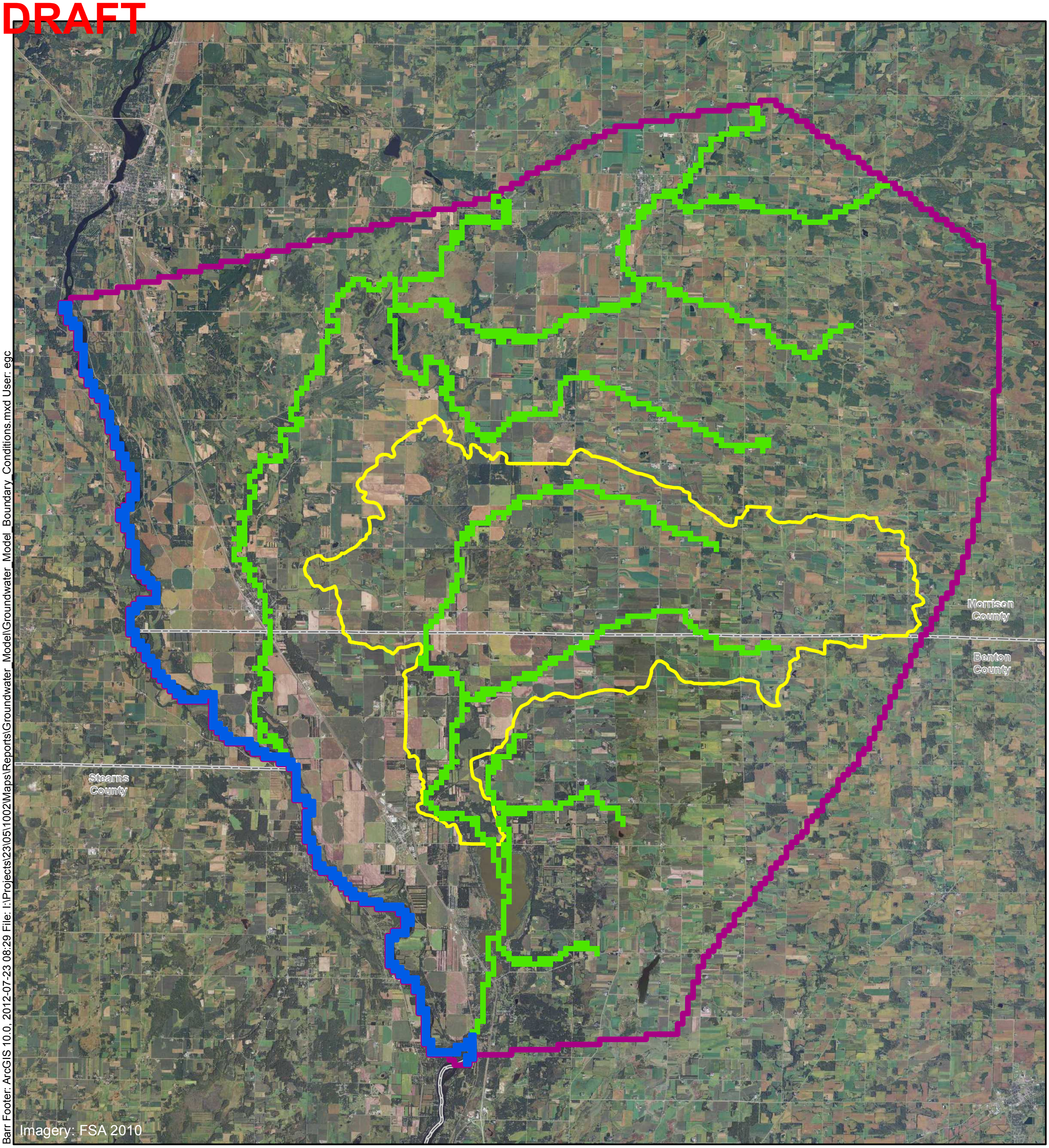

🟦 Constant Head Cells
🟩 River Cells
▭ No-Flow
▭ Little Rock Creek Watershed
▭ County Boundary

Figure A-2
Groundwater Model Boundary Conditions
Little Rock Creek TMDL
Benton and Morrison Counties, MN

N

1 0.5 0 1 2 3 4 5
Miles

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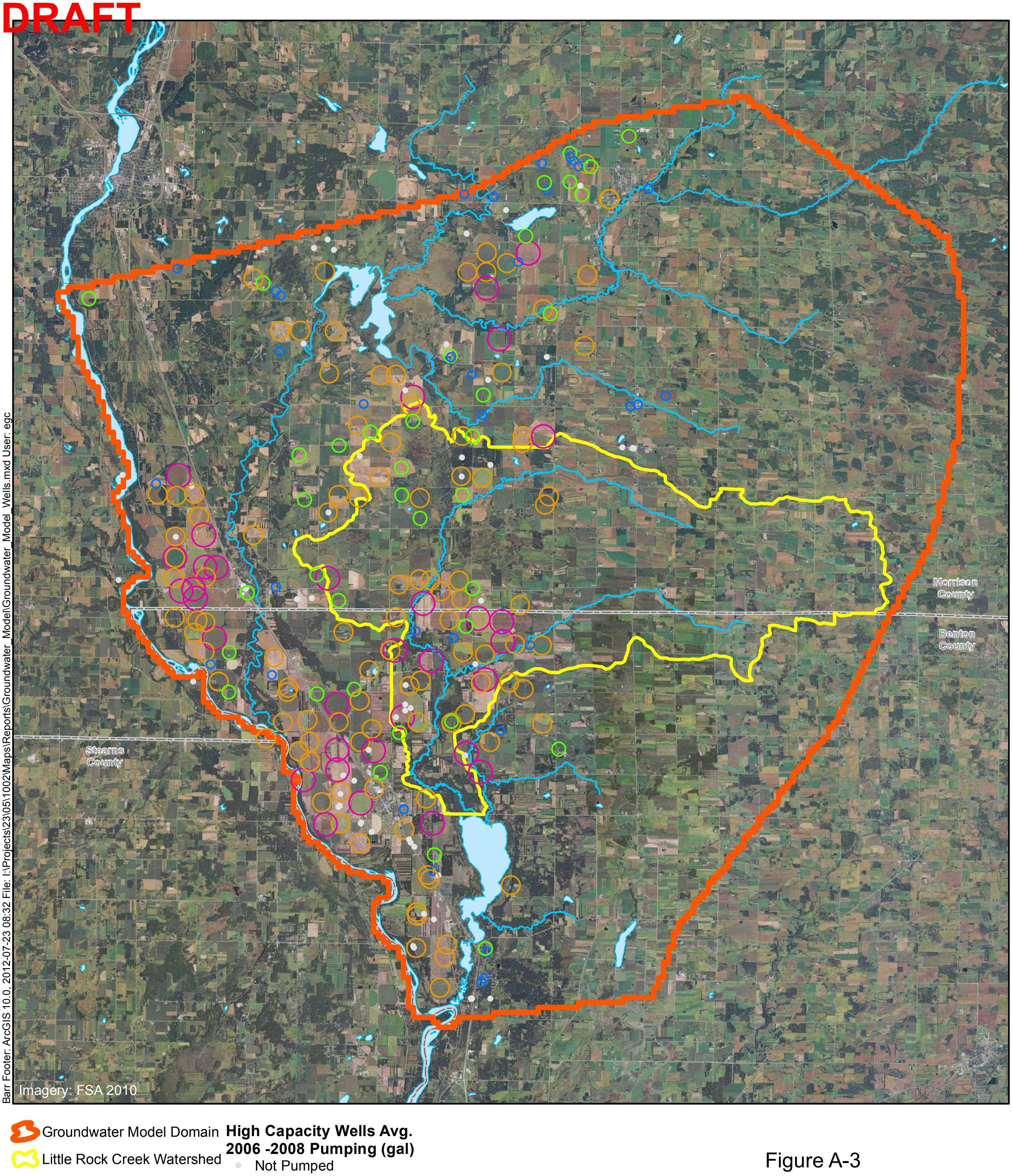
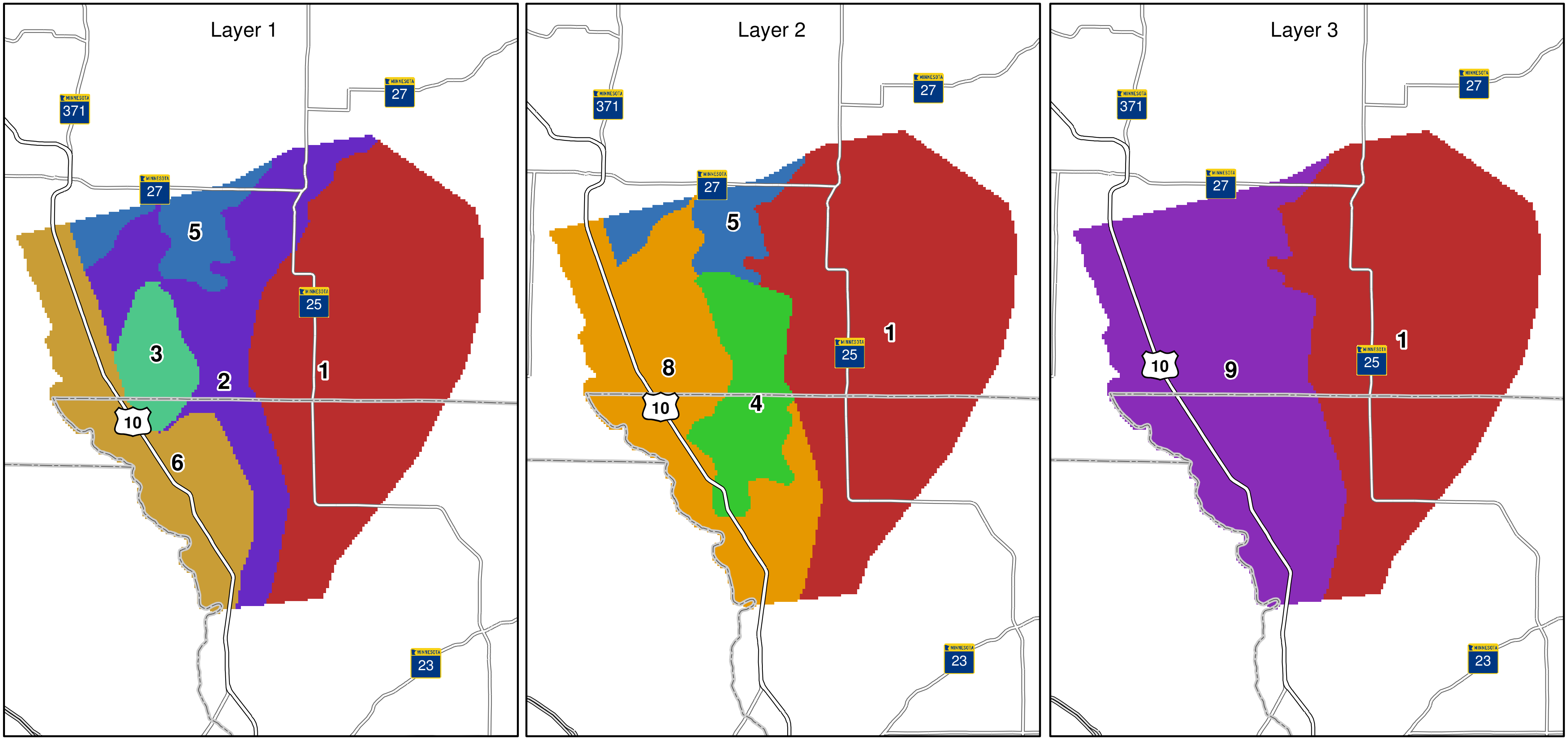


Figure A-3
High Capacity Wells
Little Rock Creek TMDL
Benton and Morrison Counties, MN



Zone #	Description	Kx (m/d)	Kz (m/d)	Ss (m^{-1})	Sy
1	Sandy till with intermixed sand lenses	24	8.6	3.7E-05	0.10
2	Sandy outwash	30	0.3	1.6E-05	0.10
3	Sandy till with intermixed sand lenses	1.5	0.75	2.6E-06	0.18
4	Sandy till (burried, confined)	0.1	0.03	1.0E-05	NA
5	Till and peat	1.0	0.1	1.0E-05	0.20
6	Terrace sands and intermixed sandy till	13	1.3	1.0E-05	0.10
8	Sandy till	0.05	0.005	1.0E-05	NA
9	Sand and gravel (burried, confined)	15.8	0.16	2.1E-06	NA

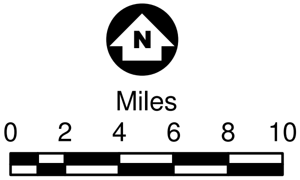


Figure A-4
Groundwater Model
Hydraulic Conductivity and Storage Zones
Little Rock Creek TMDL
Benton and Morrison Counties, MN

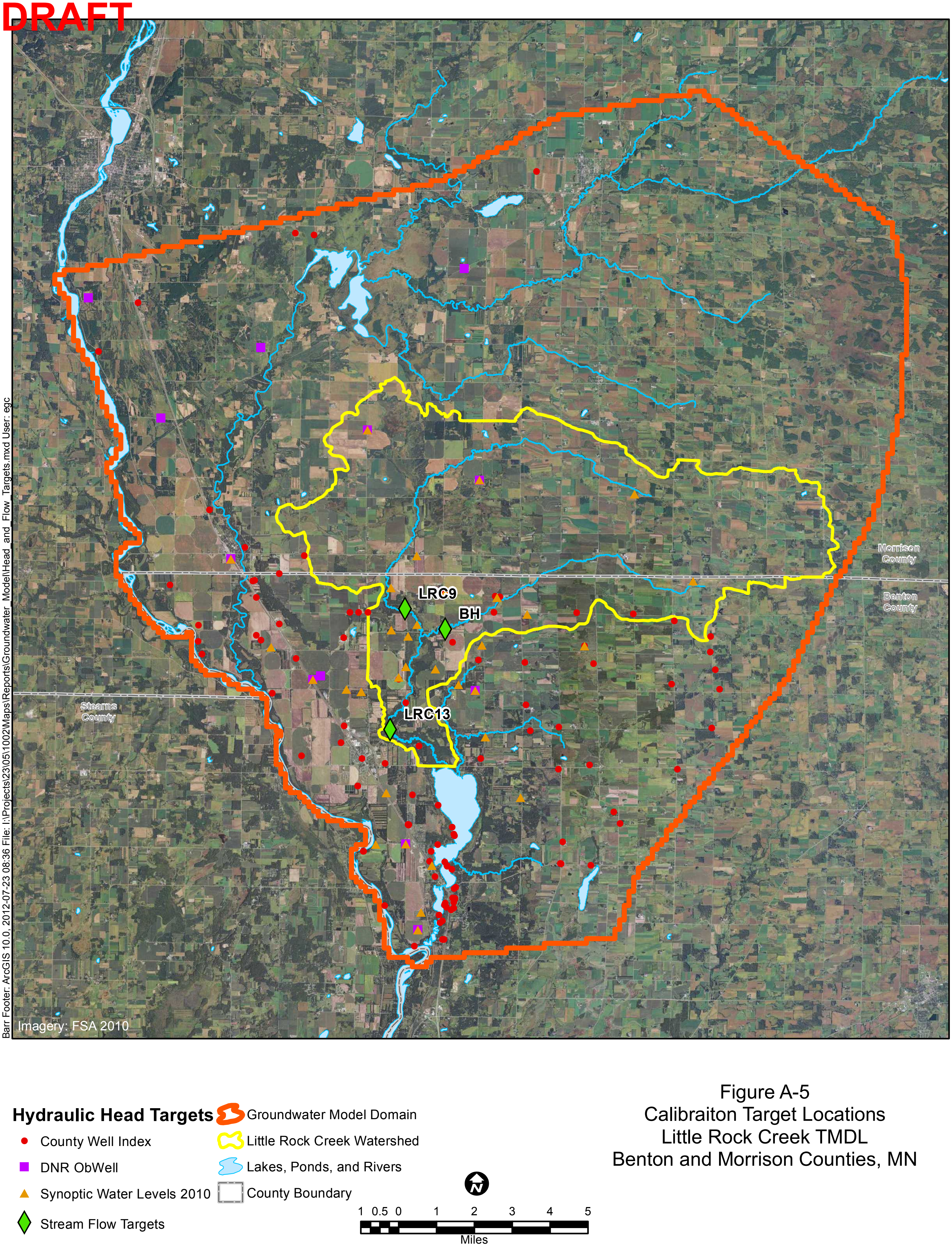


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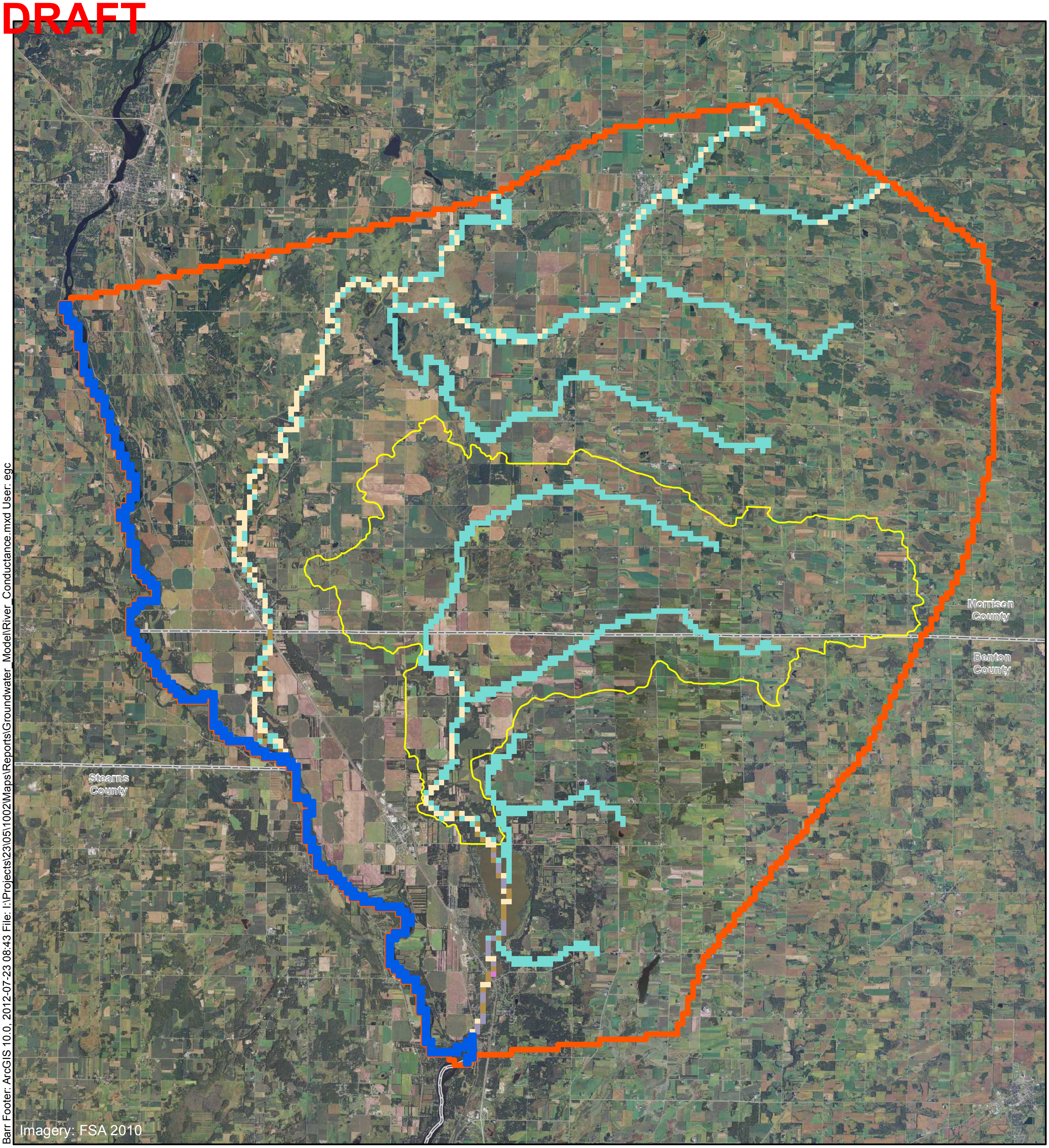
Figure A-5
Calibraiton Target Locations
Little Rock Creek TMDL
Benton and Morrison Counties, MN



River Cell Conductance (m3/day)

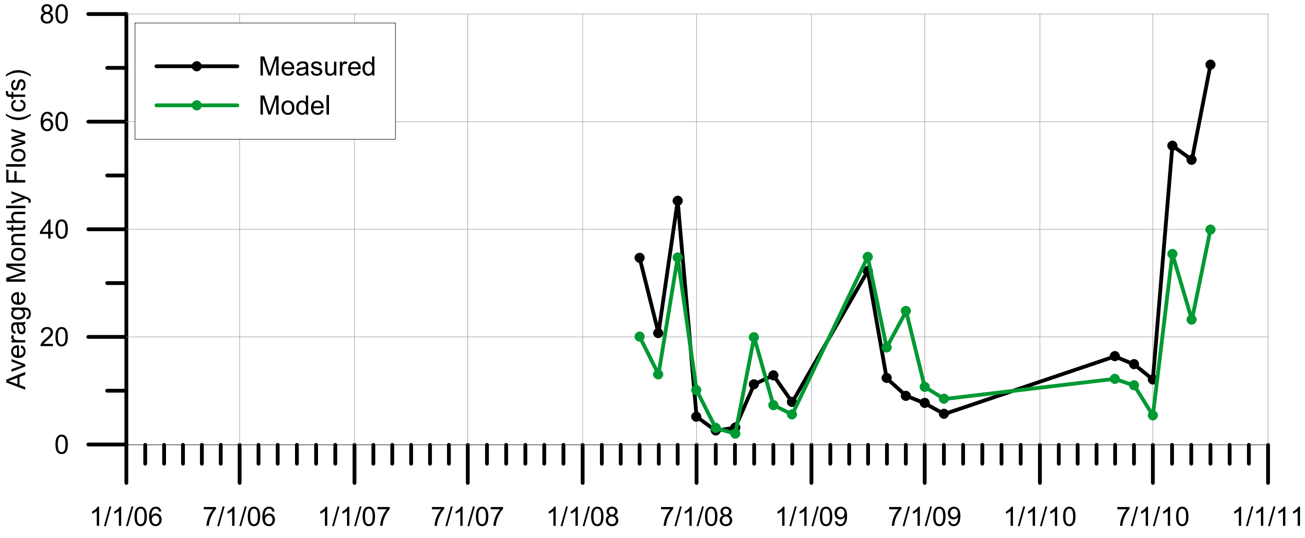
- 🟦 5-5,000
- 🟨 5,001-1,000
- 🟫 10,001-15,000
- 🟪 15,001-20,000
- 🟪 20,001-25000

- 🟦 Constant Head Cells
- 🟧 Groundwater Model Domain
- 🟨 Little Rock Creek Watershed
- ☐ County Boundary

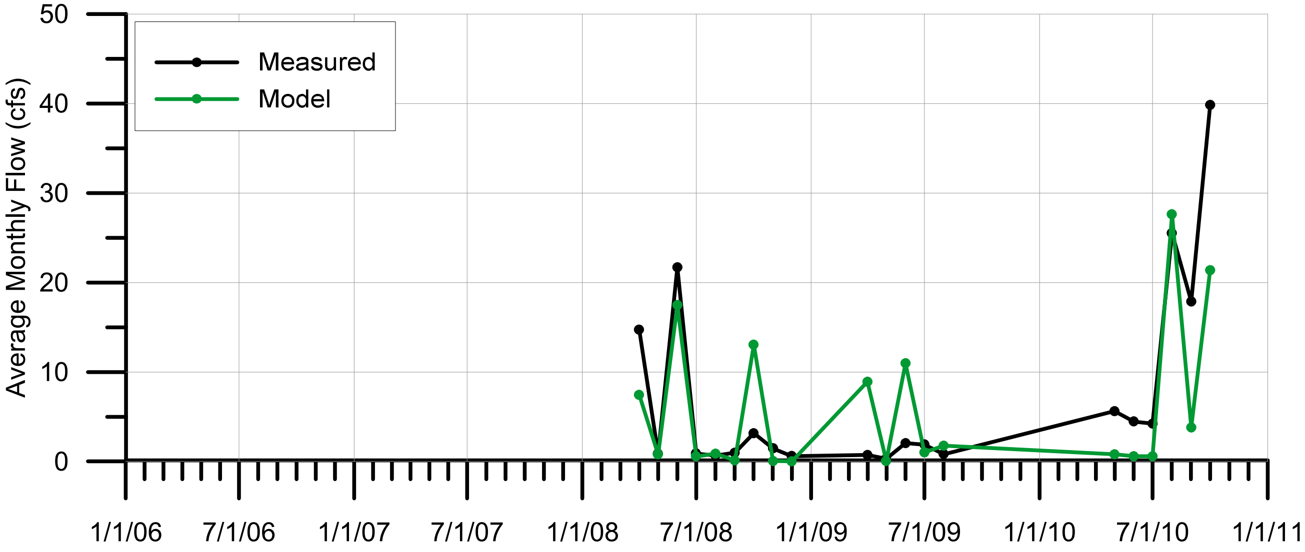
Figure A-6
River Cell Conductance
Little Rock Creek TMDL
Benton and Morrison Counties, MN

DRAFT

LRC9 Total Flow



LRC9 Surface Runoff



LRC9 Baseflow

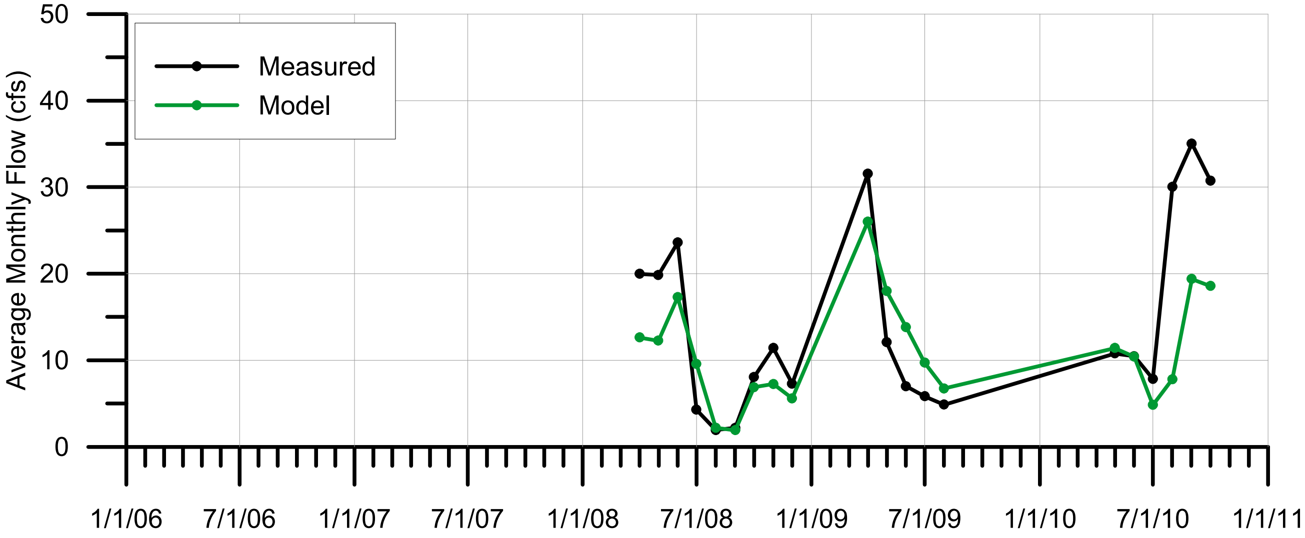


Figure A-7
Model Simulated and Measured Averge Monthly Flow
Monitoring Station LRC9
Little Rock Creek TMDL
Benton and Morrison Counties, MN

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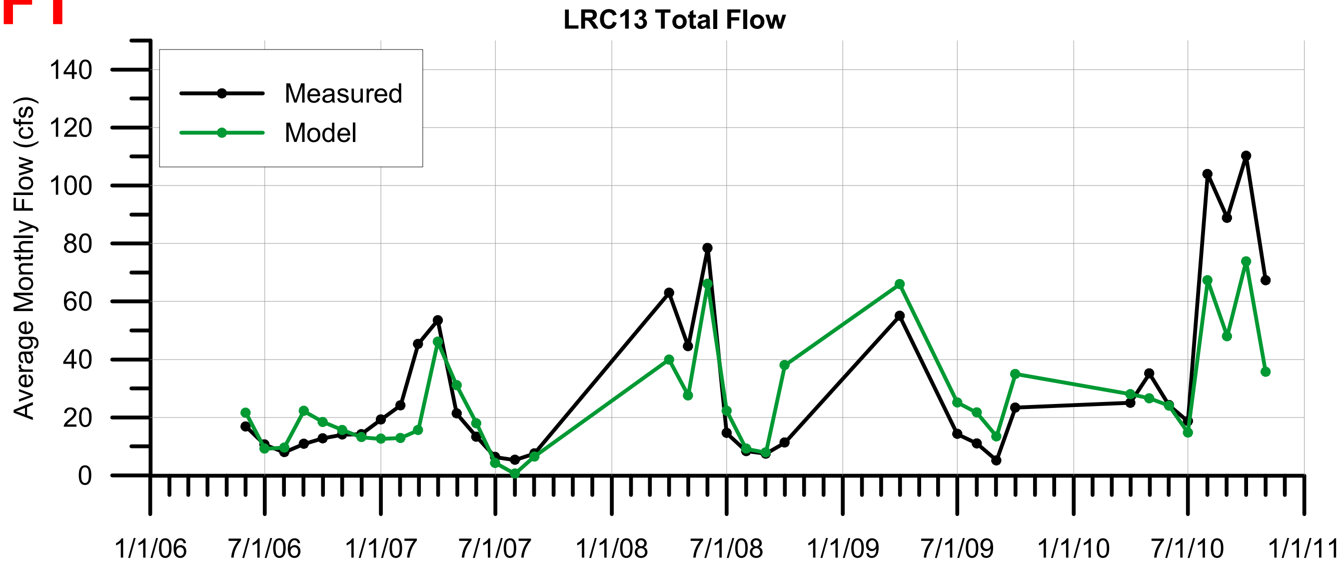

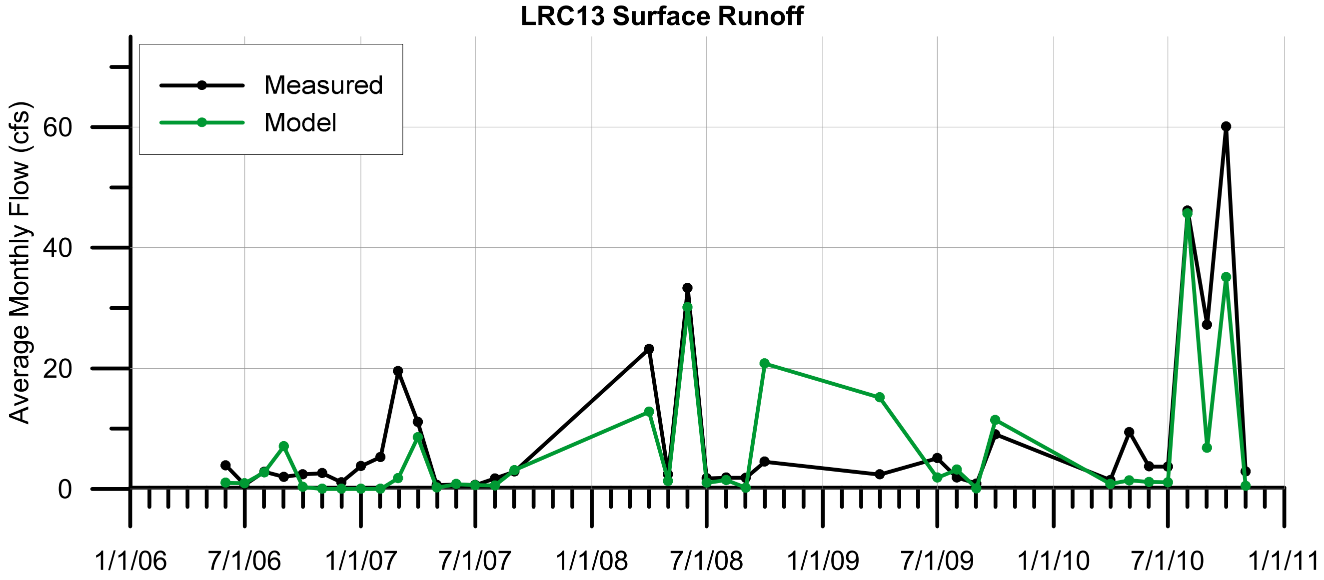

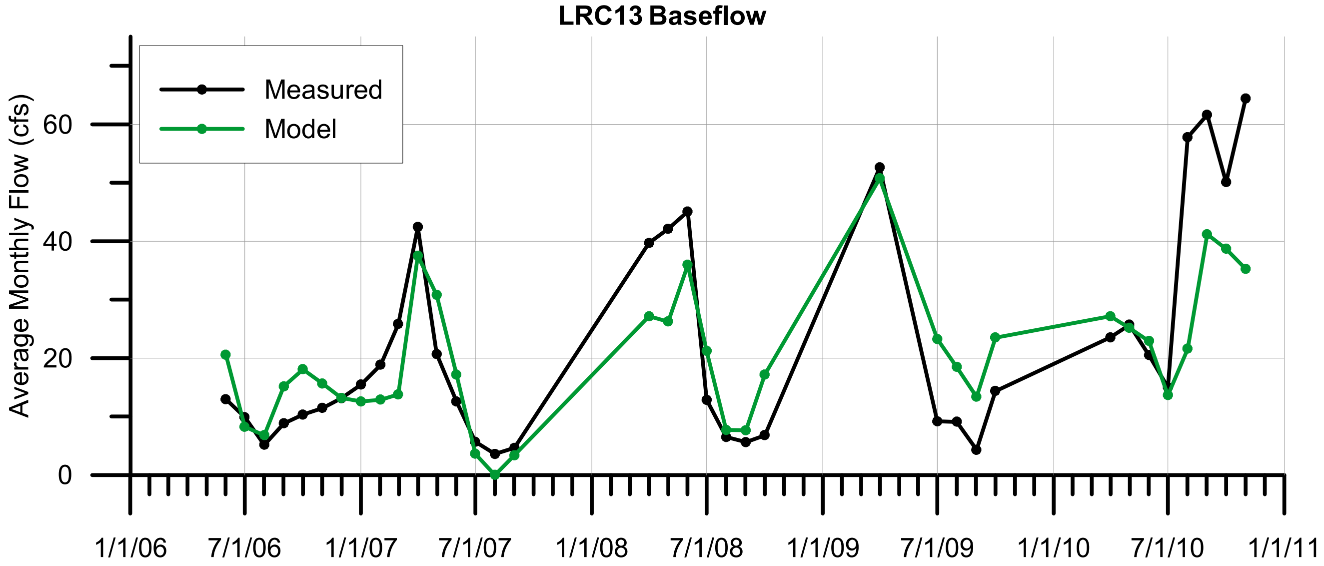

Figure A-8
Model Simulated and Measured Averge Monthly Flow
Monitoring Station LRC13
Little Rock Creek TMDL
Benton and Morrison Counties, MN

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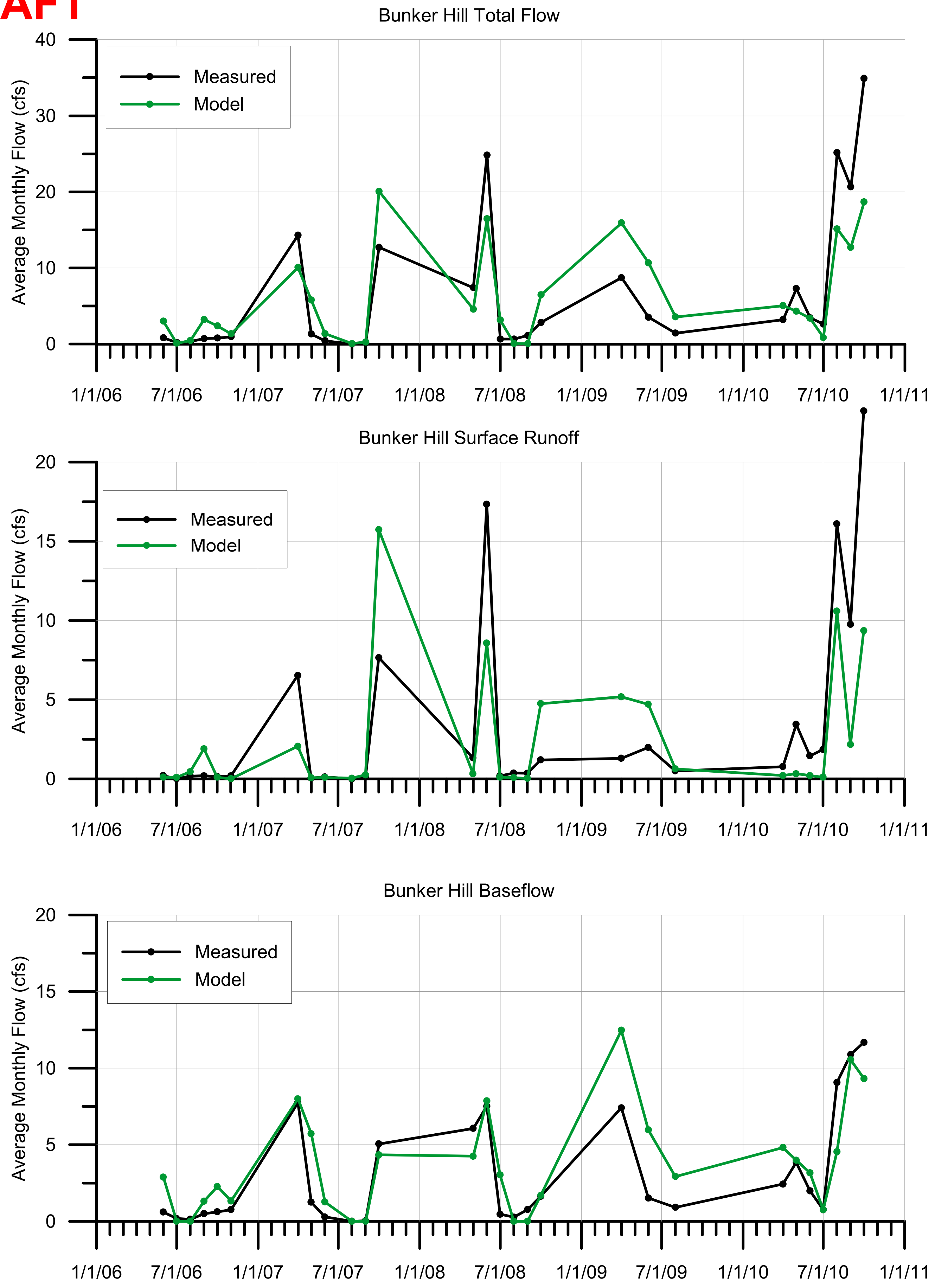
Bunker Hill Total Flow

Bunker Hill Surface Runoff

Bunker Hill Baseflow

Figure A-9
Model Simulated and Measured Averge Monthly Flow
Monitoring Station Bunker Hill
Little Rock Creek TMDL
Benton and Morrison Counties, MN

V:\23\05\1002\Post_Processing\Plots\For_Report\BH Monthly cfs.grf

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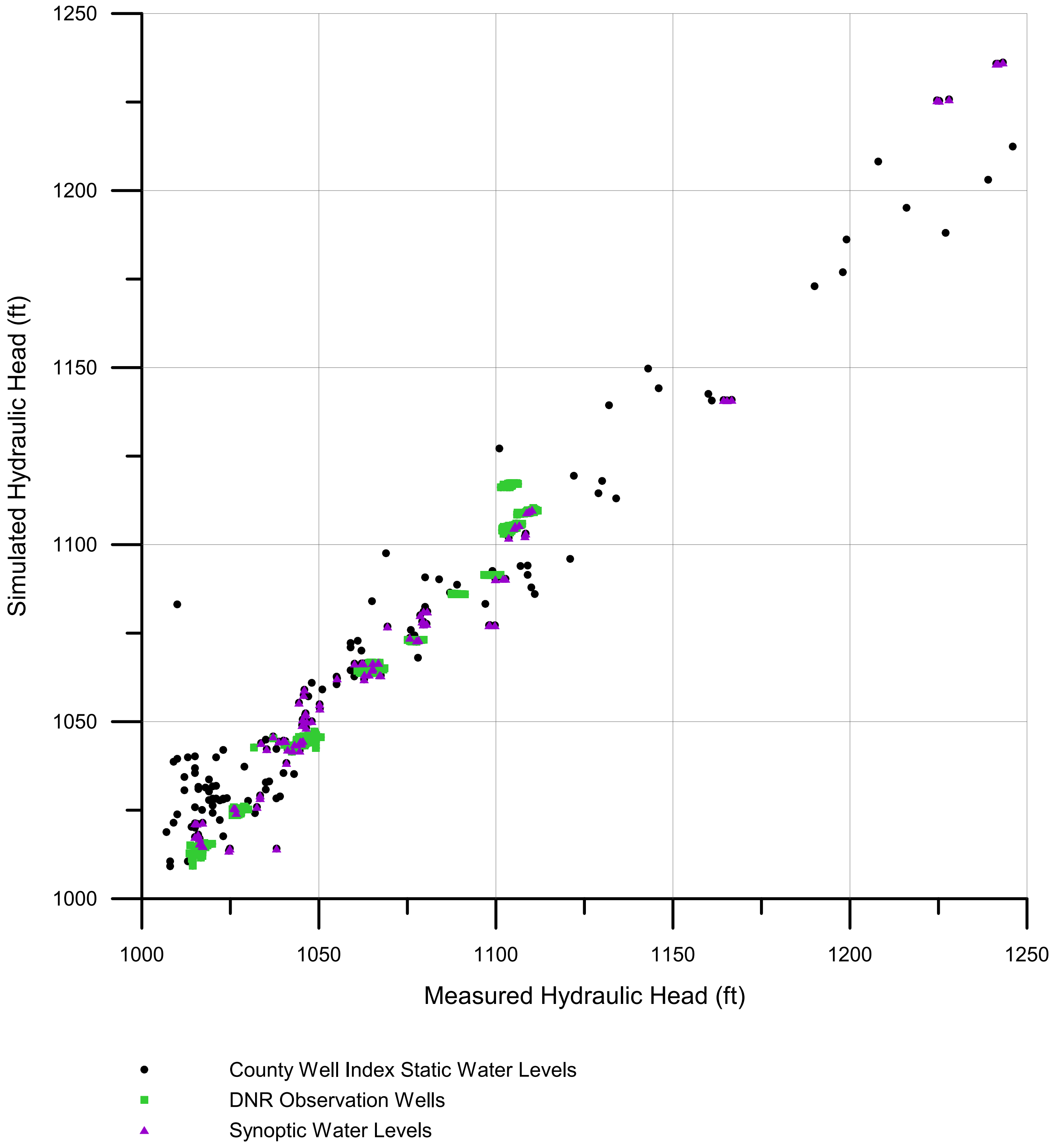

Figure A-10
Measured Versus Simulated Hydraulic Head
Little Rock Creek TMDL
Benton and Morrison Counties, MN

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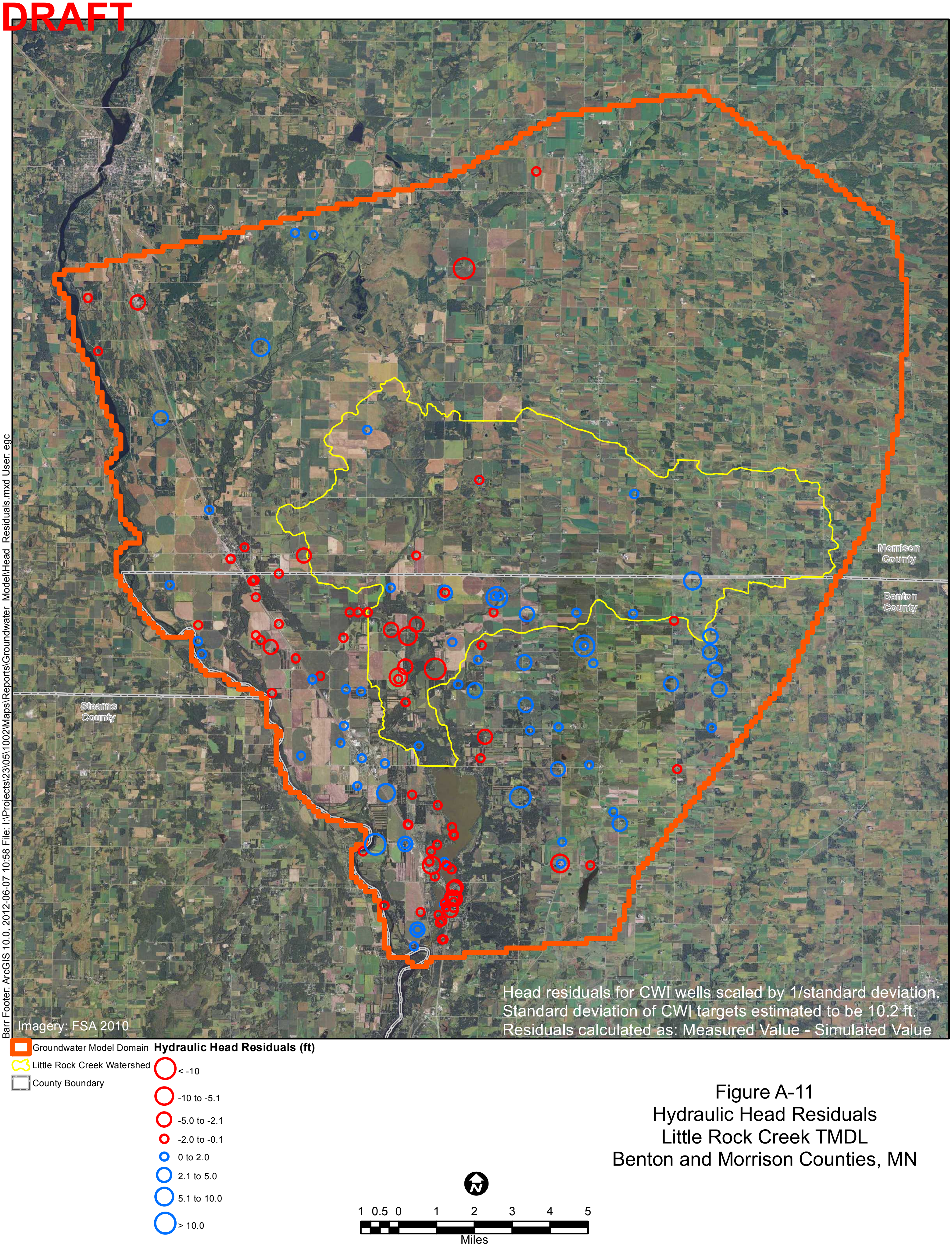

Head residuals for CWI wells scaled by 1/standard deviation.
Standard deviation of CWI targets estimated to be 10.2 ft.
Residuals calculated as: Measured Value - Simulated Value

Imagery: FSA 2010

Barr Footer: ArcGIS 10.0, 2012-06-07 10:58 File: I:\Projects\23\05\1002\Maps\Reports\Groundwater_Model\Head_Residuals.mxd User: egc

Figure A-11
Hydraulic Head Residuals
Little Rock Creek TMDL
Benton and Morrison Counties, MN

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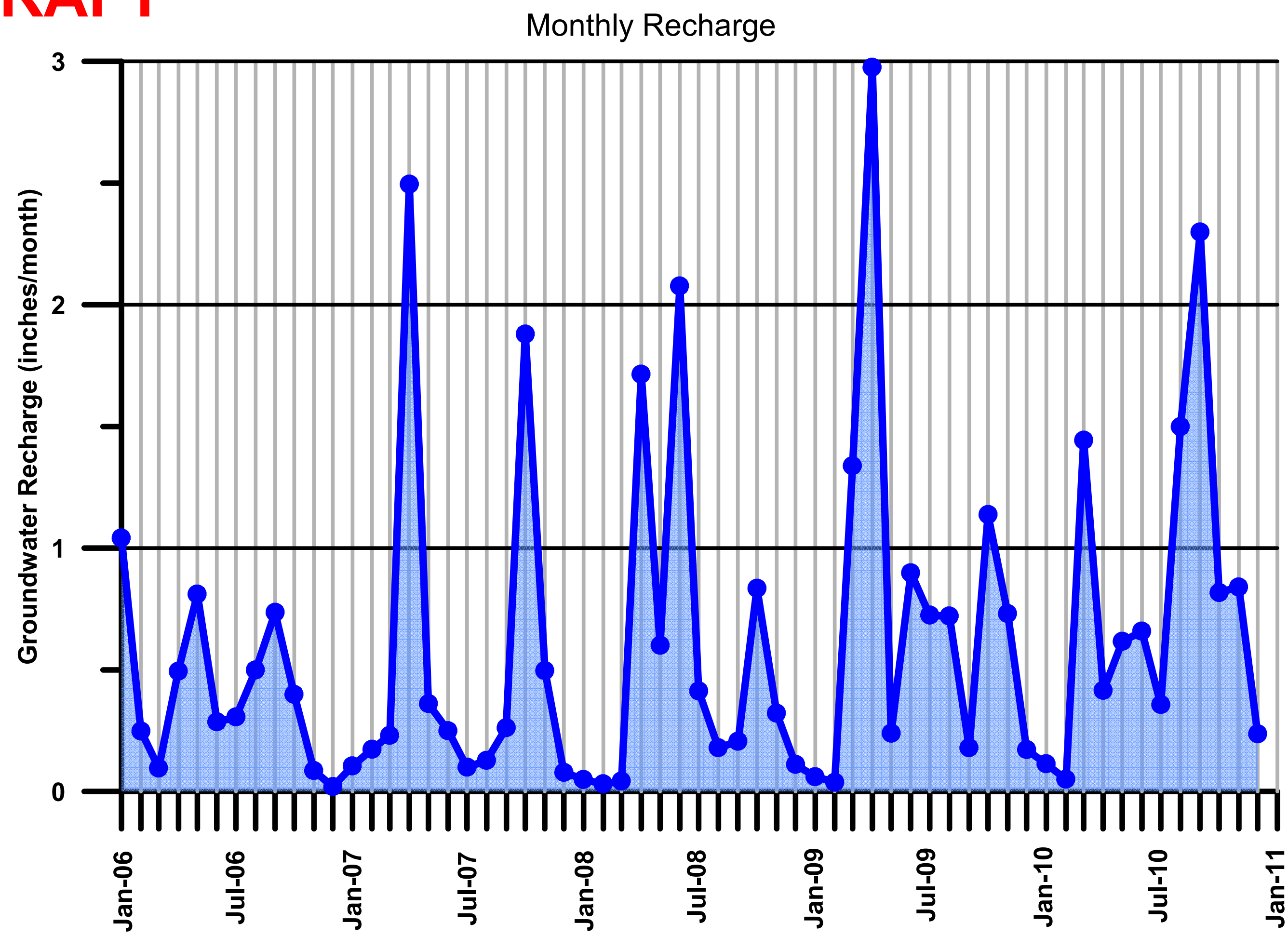

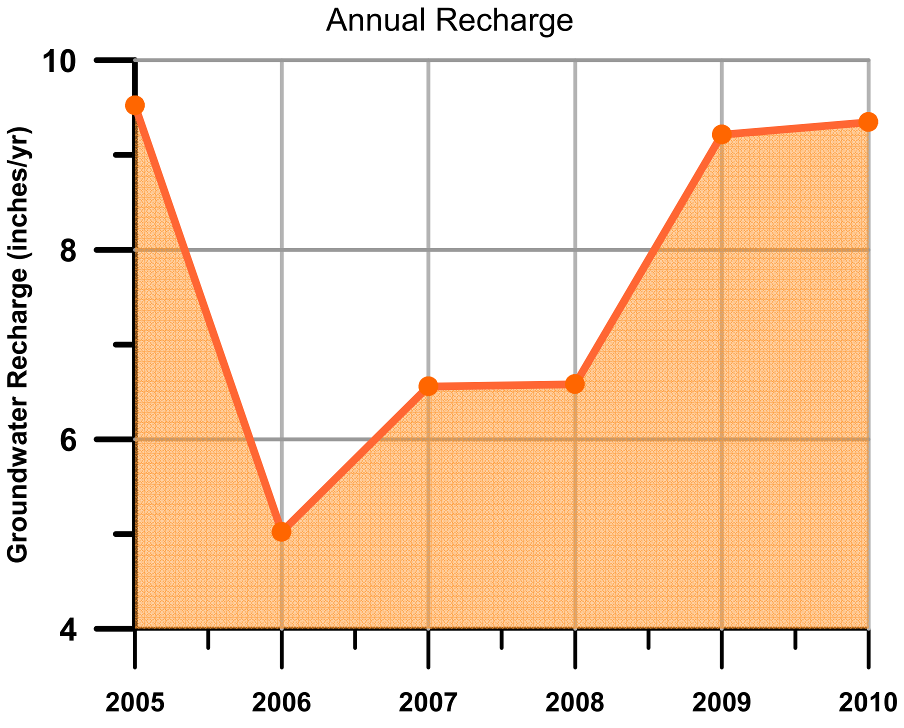

Figure A-12
Simulated Recharge
Little Rock Creek Watershed
Litte Rock Creek TMDL
Benton and Morrison Counties, MN

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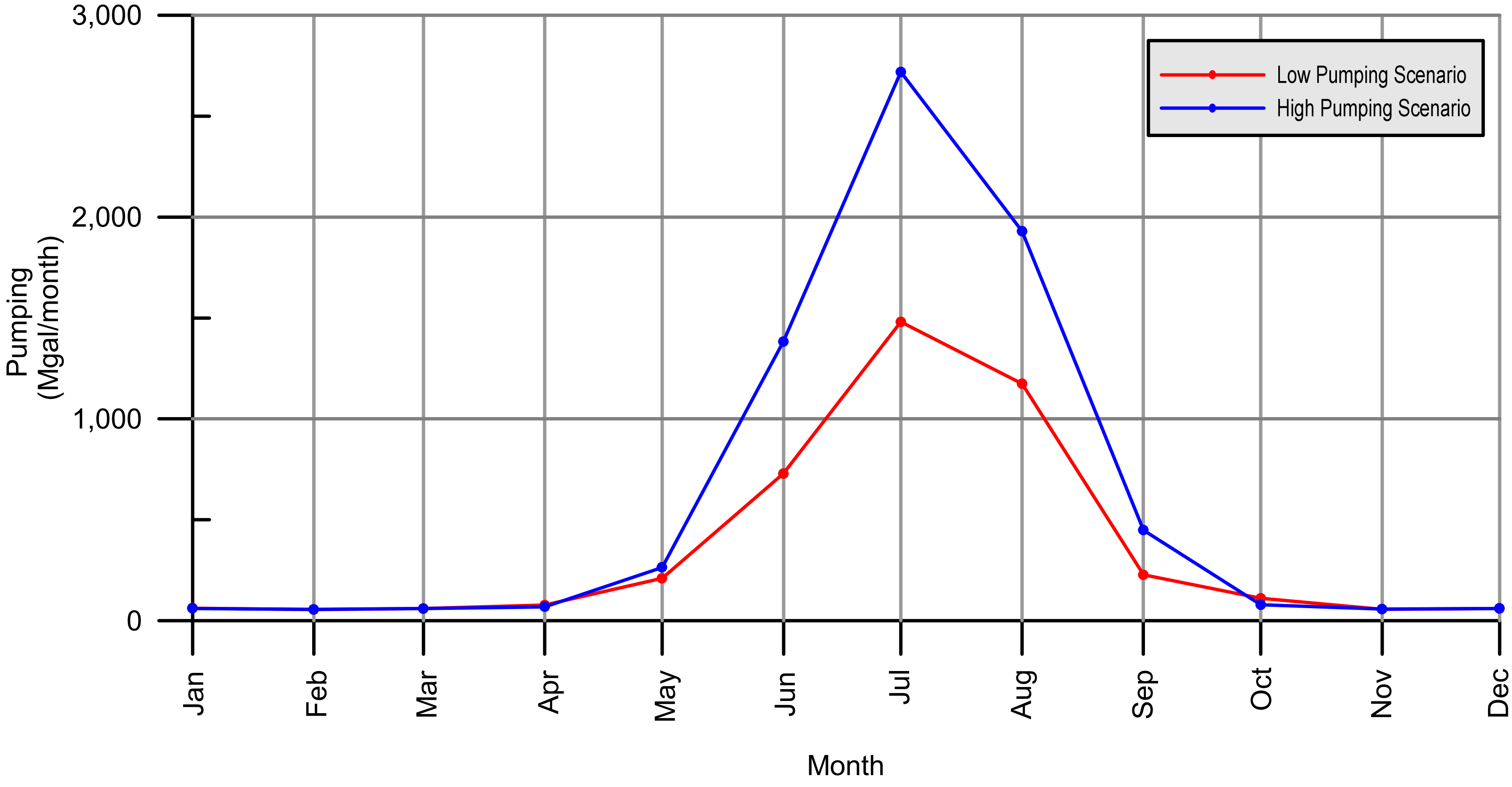

Figure A-13
High and Low Pumping Scenarios
Little Rock Creek TMDL
Benton and Morrison Counties, MN

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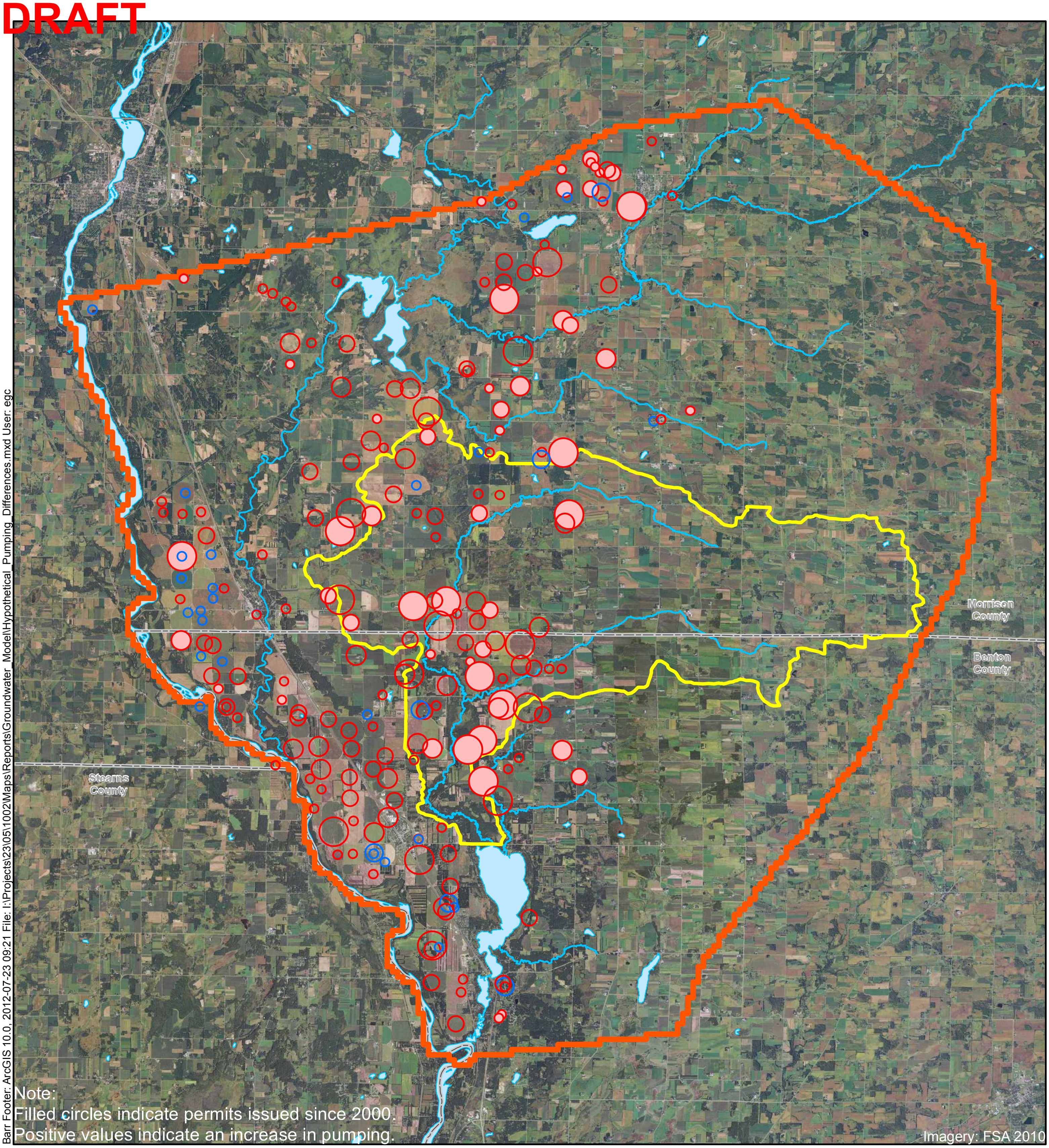

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Groundwater Model Domain
Little Rock Creek Watershed
Lakes, Ponds, and Rivers
County Boundary

Difference in Pumping (gal/yr)
○ < -10,000,000
○ -10,000,000 to 0
○ 0 to 10,000,000
○ 10,000,000 to 20,000,000
○ 20,000,000 to 30,000,000
○ > 30,000,000

N
1 0.5 0 1 2 3
Miles

Figure A-14
High and Low Pumping Scenarios
Difference of Low Pumping Scenario
Compared to High Pumping Scenario
Little Rock Creek TMDL
Benton and Morrison Counties, MN

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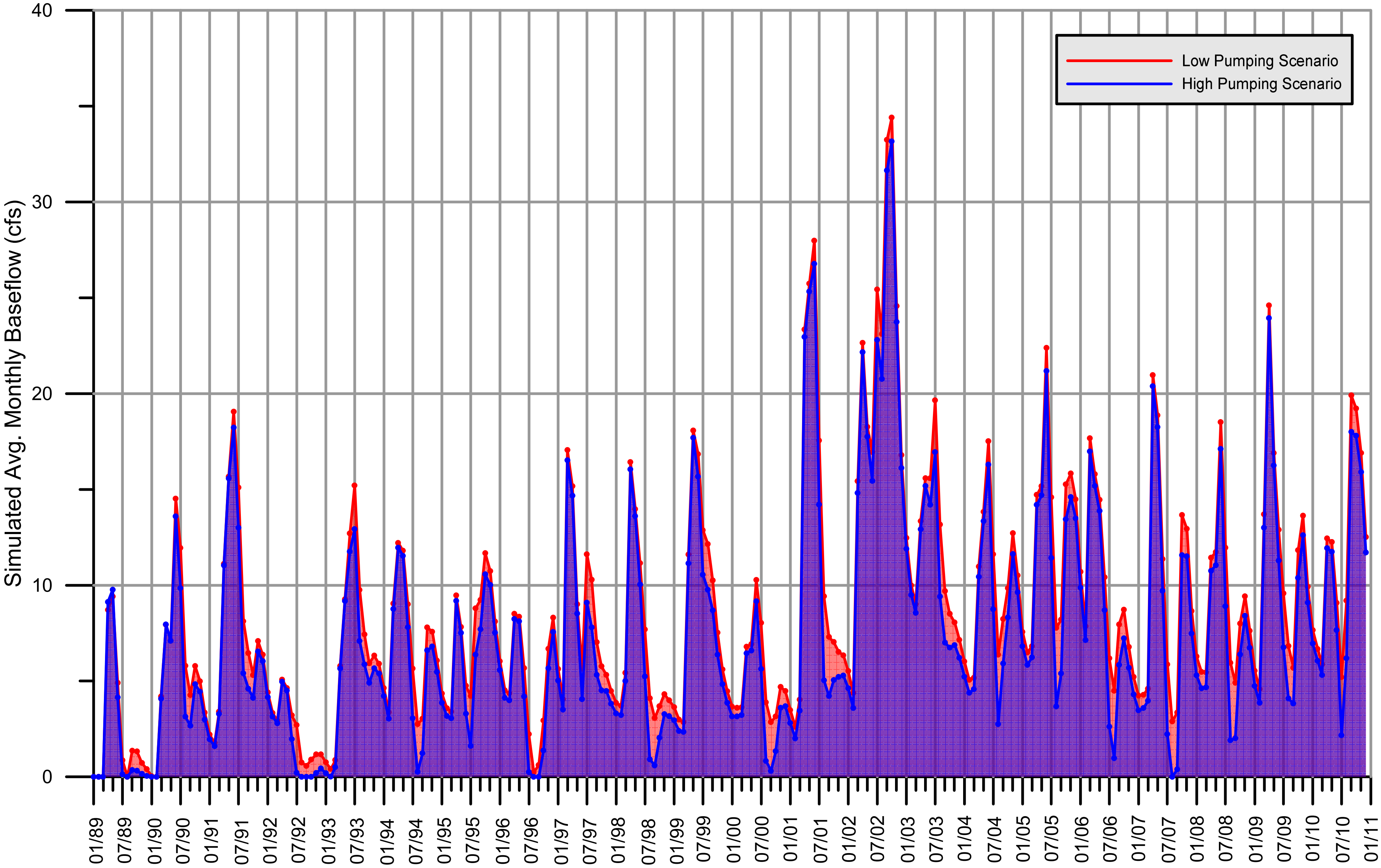

Figure A-15
Simulated Baseflow for High and Low Pumping Scenarios
Monitoring Station LRC9
Little Rock Creek TMDL
Benton and Morrison Counties, MN

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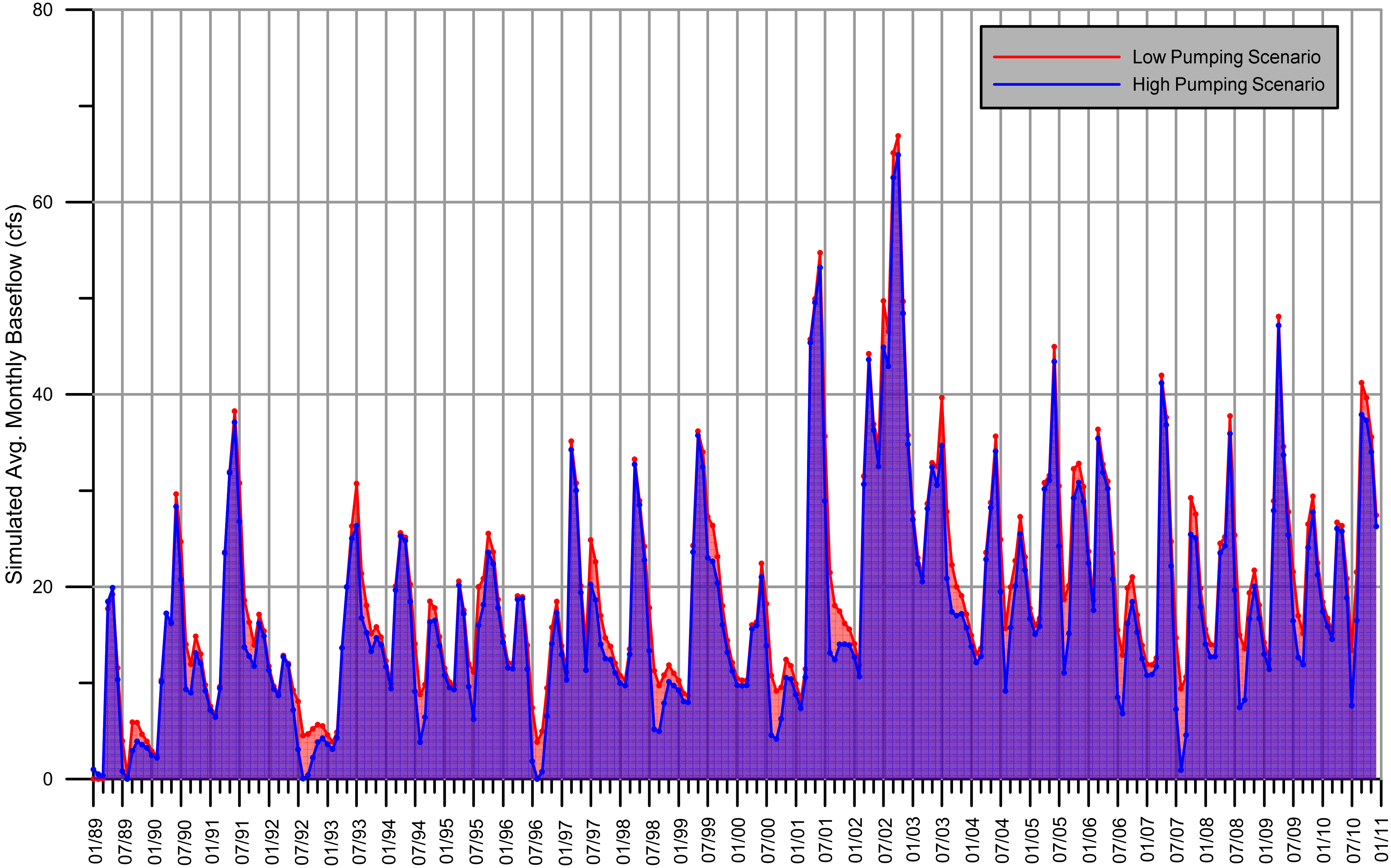

Figure A-16
Simulated Baseflow for High and Low Pumping Scenarios
Monitoring Station LRC13
Little Rock Creek TMDL
Benton and Morrison Counties

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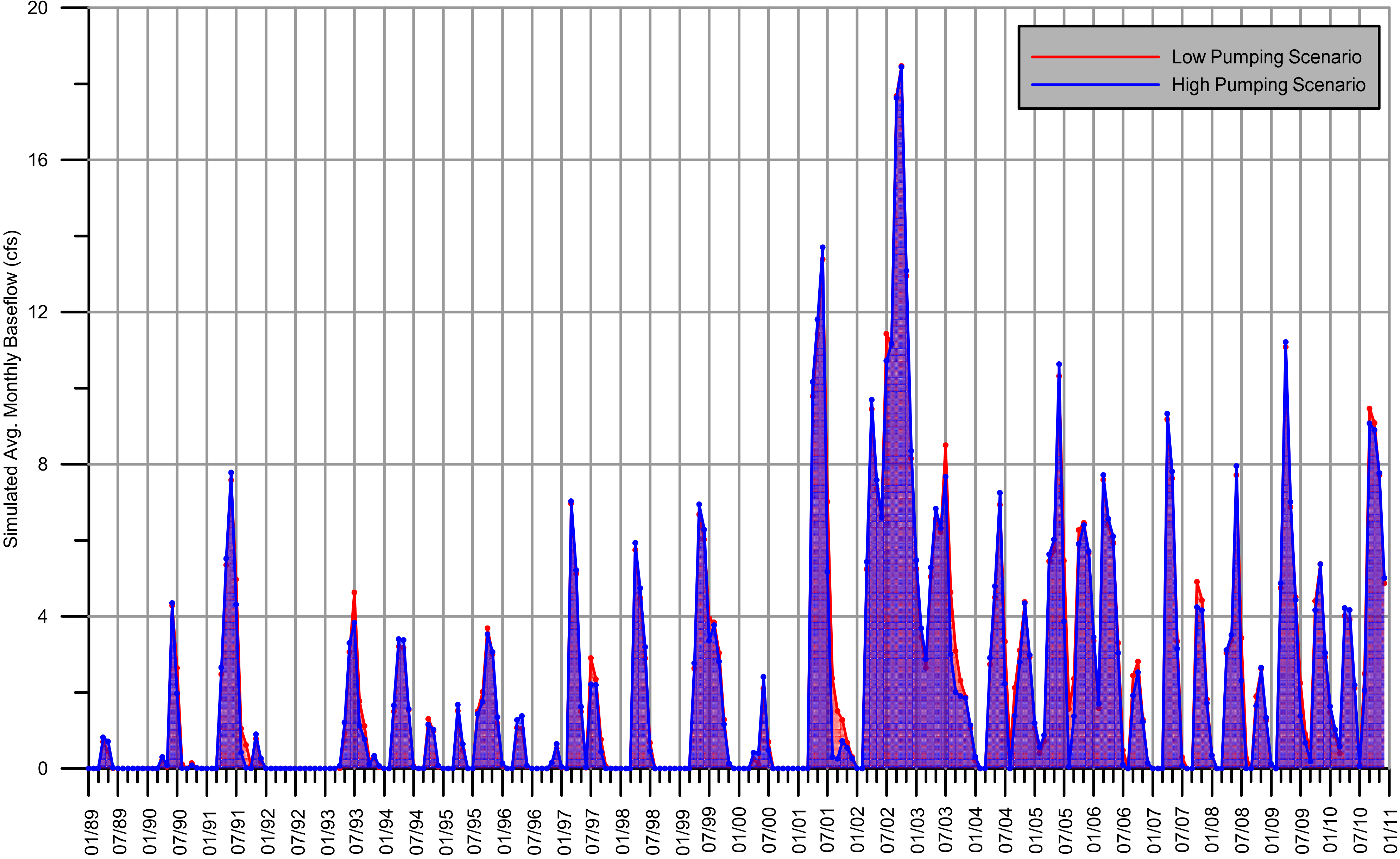

Figure A-17
Simulated Baseflow for High and Low Pumping Scenarios
Bunker Hill Creek
Little Rock Creek TMDL
Benton and Morrison Counties, MN

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Appendix B

Receiving Water Quality Modeling

Model Selection

QUAL2K is a river and stream water quality model developed for the United States Environmental Protection Agency (USEPA) by Dr. Steven Chapra with Tufts University and Greg Pelletier with Washington State (Chapra et al., 2008). It is a one-dimensional model using steady state hydraulics. The model represents a river as a series of reaches, well mixed vertically and laterally, that have constant hydraulic characteristics (e.g., slope, bottom width, etc.). The heat budget and temperatures are simulated as a function of meteorology on a diurnal time scale. All water quality variables are simulated on a diurnal time scale. Point and non-point loads and abstractions can be added at any point along the stream.

Model Overview

Barr created a QUAL2K model to simulate Little Rock Creek under low flow condition with DO impairment present. August 20, 2008 was selected as the simulation date for the critical condition. This date also included the best available water quality monitoring data, the presence of low DO concentrations, and the incidence of low flow conditions. The model simulates the stream from Stations 6 to 13 (Figure B-1) representing areas where sufficient amount of data was present for model calibration.

Water Quality Data Sources

Water quality data collected at various stations throughout Little Rock Creek (Figure B-1) by the Minnesota Pollution Control Agency (MPCA) Watershed Unit, the Benton Soil and Water Conservation District (SWCD) and United States Geological Survey (USGS) was used for this analysis. The MPCA conducted a diurnal dissolved oxygen survey recording average measurements of temperature, specific conductance, pH, turbidity and dissolved oxygen every 15 minutes at Stations 7, 11 and 13 from 11:30 am on 8/19/2008 to 7:45 am on 8/21/2008. A longitudinal dissolved oxygen survey was also conducted on Stations 3-7, 9, 10, 12 and 13, starting at the most upstream station in late afternoon/early evening on 8/20/2008 and then repeated at sunrise on 8/21/2008. The goal was to collect dissolved oxygen levels at approximately the peaks of the diurnal sine wave, i.e. both the highest and lowest levels, throughout the creek. The water quality data collected at all locations on 8/20/2008 included alkalinity, ammonia, chloride, color, Kjeldahl nitrogen, nitrite+nitrate nitrogen, orthophosphorus, total phosphorus, turbidity, and total suspended solids. Finally, the USGS collected water quality data only at Station 13. This data was used to fill in needed information such as CBODfast, phytoplankton (entered as chlorophyll-a concentration) and detritus. These values were assumed to be constant throughout the reach.

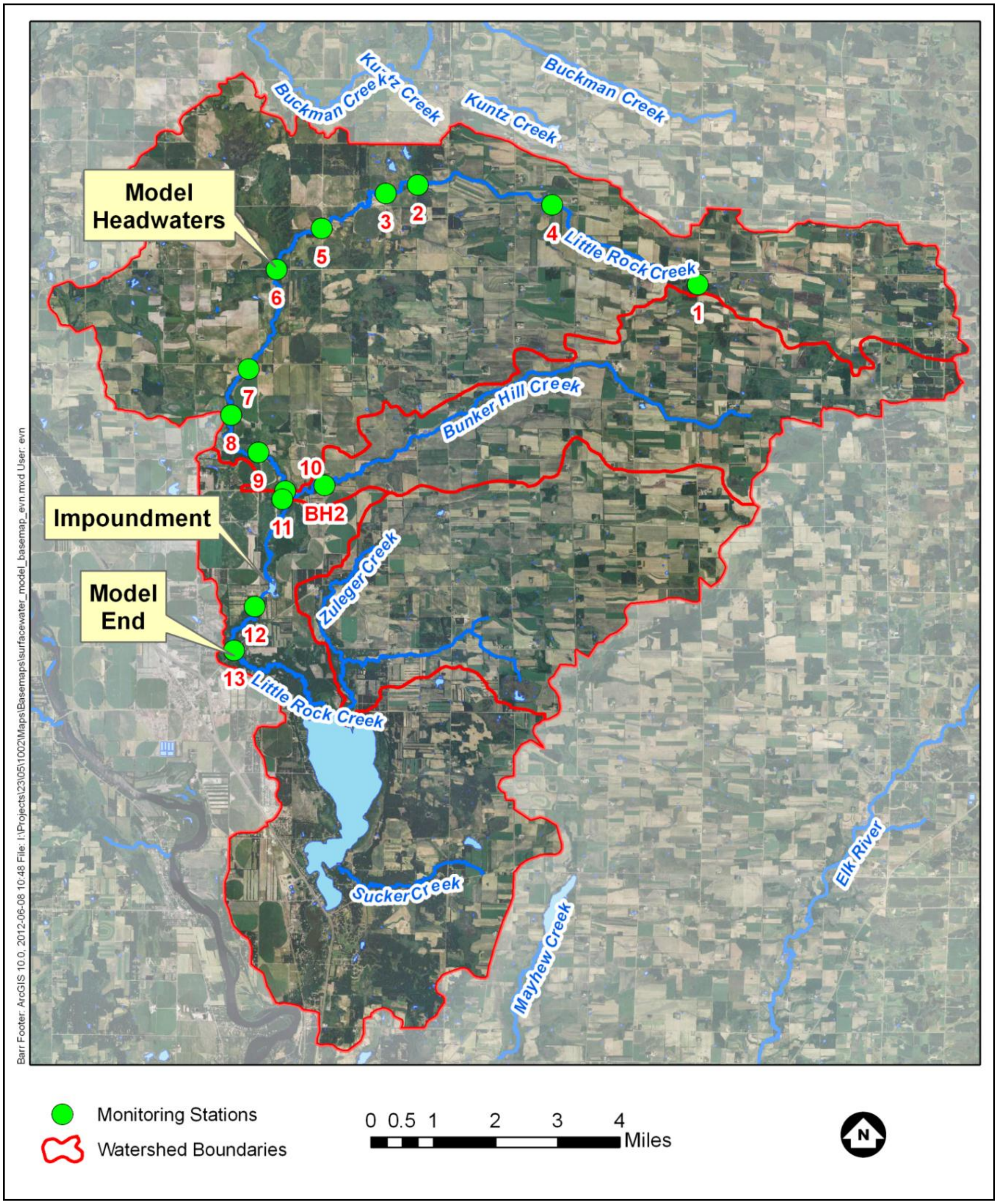

Figure B-1 Little Rock Creek QUAL2K Model Overview

Flow Data Sources

The MPCA measured daily flow data at three stations on Little Rock Creek during the modeling period. Those locations included Station 10, on Little Rock Creek upstream of the confluence with Bunker Hills Creek; Station BH2, located on Bunker Hill Creek before it enters Little Rock Creek; and Station 13, used as the outflow station in our modeling efforts. These three flow measurements defined the boundary conditions for the model. The headwater flow in the model is located at Station 6. No flow measurements were taken at this location with the closest flow station being Station 10. We estimated the flow rates at Station 6 using results from the baseflow modeling discussed in Appendix A. The difference between the estimated flow at Station 6 and the recorded value at Station 10 was entered into the model as a diffusive source. This diffusive source simulated added groundwater flow into the system between Station 6 and 10. The difference in recorded flow at Station 13 and Station 10 minus the flow rate coming in from Bunker Hills Creek (Station BH2) was also added to the model as a diffusive source. This diffusive source represents groundwater flow into the system between Stations 10 and 13.

Model Setup

Headwaters

QUAL2K requires water quality information to be entered at the headwaters of the model as an initial boundary condition. The headwater boundary condition of the model is located at Station 6, while the downstream end of the model is at Station 13 (Figure B-1). Water quality information from the MPCA, USGS (Brightbill and Frankforter, 2010), and the Benton SWCD were used in the model. Diurnal measurements of temperature and dissolved oxygen were entered into the model at the headwaters. Station 6 was not sampled diurnally by the MPCA therefore a representative sinusoidal wave was calculated using the longitudinal survey measurements conducted in the late afternoon on 8/20/2008 and in the early morning on 8/21/2008. The two measurements were treated as the maximum and minimum DO and temperature measurements in the sinusoidal wave. The other water quality parameters were assigned as constant values. The water quality values and sources entered into the model are shown in Table B-1. All measurements were made on 8/20/2008 except for the minimum DO and temperature measurements which were made on 8/21/2008.

Table B-1 Headwaters (Station 6) Water Quality Input Parameters

Parameter	*Value*	*Units*	*Source*
DO PM 8/20/2008	8.33	mg/l	MPCA
DO AM 8/21/2008	7.10	mg/l	MPCA
Temp PM 8/20/2008	21.48	(^oC)	MPCA
Temp AM 8/21/2008	16.68	(^oC)	MPCA
Conductivity	402	umhos	MPCA
CBODfast	3.02	mgO_2/L	(Brightbill and Frankforter, 2010)
Organic Nitrogen	540	ugN/L	Benton SWCD
NH4-Nitrogen	10	ugN/L	Benton SWCD
NO3-Nitrogen	8500	ugN/L	Benton SWCD
Organic Phosphorus	63	ugP/L	Benton SWCD
Inorganic Phosphorus (SRP)	28	ugP/L	Benton SWCD
Phytoplankton	20	ugA/L	(Brightbill and Frankforter, 2010)
Detritus (POM)	0.32	mgD/L	(Brightbill and Frankforter, 2010)
Alkalinity	120	mgCaCO3/L	Benton SWCD
pH	8.33	s.u.	MPCA
Rate	0.006	(m^3/s)	Baseflow model
Channel Slope	0.0018		Estimated from DEM grid
Manning n	0.04		Assumed
Bottom Width	9.74	*m*	(Benton SWCD 2009)

Reaches

The modeled section of Little Rock Creek is approximately 15.5 km long. This section was divided into 9 individual reaches (Table B-2). Each reach ends at a sampling station using the number of that sampling station as the reach name. The section of the creek between Stations 11 and 12 was further divided into four individual reaches. The first reach after Station 11 (Station 12 (Shade)) represents a shaded section of the creek between Station 11 and 12. The next reach section (Station 12 (No Shade) ends at a manmade impoundment and represents an area of the creek that has low shade cover. The third reach section (Station 12 (Impoundment)) ends at the outflow of the impoundment (modeled as a weir with a width 1m and a height of 0.5m) and represents the impoundment area. The final section (Station 12) ends at Station 12.

Physical characteristics are entered into the model for each reach. These characteristics include downstream elevation, channel slope, Manning's n, and bottom width. The channel slope and bottom width were obtained from the Stressor Identification report (Benton SWCD, 2009) for all reaches except for Station 12 (Impoundment). The impoundment section width was estimated using 2010 aerial photography. The average width was estimated by estimating the impoundment area and dividing by the impoundment length. Length and elevations were estimated using ArcGIS and the DEM raster for the area. A Manning's n value of 0.04 was entered for all reaches of the creek representing a natural minor stream that is clean, winding with some pools and shoals.

Water quality parameters such as percent shade coverage, percent bottom algae coverage, reaeration rates, and prescribed SOD were also assigned to each reach. Bottom Algae coverage, percent shade coverage and prescribed SOD were used to calibrate the model to match the dissolved oxygen and temperature levels in the creek. These parameters are discussed further in the Model Calibration Section. Reaeration rates in QUAL2K can be assigned by the user or calculated by the mode. The Tsivoglou-Neal model was selected as the appropriate aeration calculation for this creek because it is better able to predict reaeration rates for flow below 10 cfs (Tsivoglou and Neal, 1972, Thomann and Mueller, 1987). The Tsivolglou-Neal formula is shown below.

$$K_a = 1.8 x V x S$$

Where K_a is the reaeration rate coefficient at 20oC (day-1), *V* is the average velocity (ft/s) and *S* is the slop of the energy gradient (ft/mile). All parameters assigned to each individual reach are summarized in Table B-2.

Table B-2 Reach Parameters

Reach Name	*Reach length (km)*	*Downstream Distance (km)*	*Downstream Elevation (m)*	*Channel Slope (m/m)*	*Bottom Width (m)*
Station 7	3.30	12.157	329.2	0.0012	6.04
Station 9	4.31	7.852	319.5	0.0023	7.73
Station10	1.88	5.968	318.5	0.0005	9.53
Station 11	0.50	5.468	318.0	0.0010	9.53
Station 12 (Shade)	0.70	4.768	317.5	0.0008	10.24
Station 12 (No Shade)	1.66	3.106	316.0	0.0008	10.24
Station 12 (Impoundment)	0.50	2.606	315.9	0.0002	150.00
Station 12	0.30	2.306	315.1	0.0010	13.85
Station13	2.31	0.000	314.2	0.0010	13.85

Climate Data

QUAL2K uses hourly weather data to model water quality parameters. Hourly weather data were obtained from the National Climatic Data Center (NCDC). The St. Cloud, MN airport was the closest station located approximately 20 miles south of Little Rock Creek. Hourly dewpoint and air temperatures along with wind speeds shown in Figure B-2 were collected from this station for 8/20/2008.

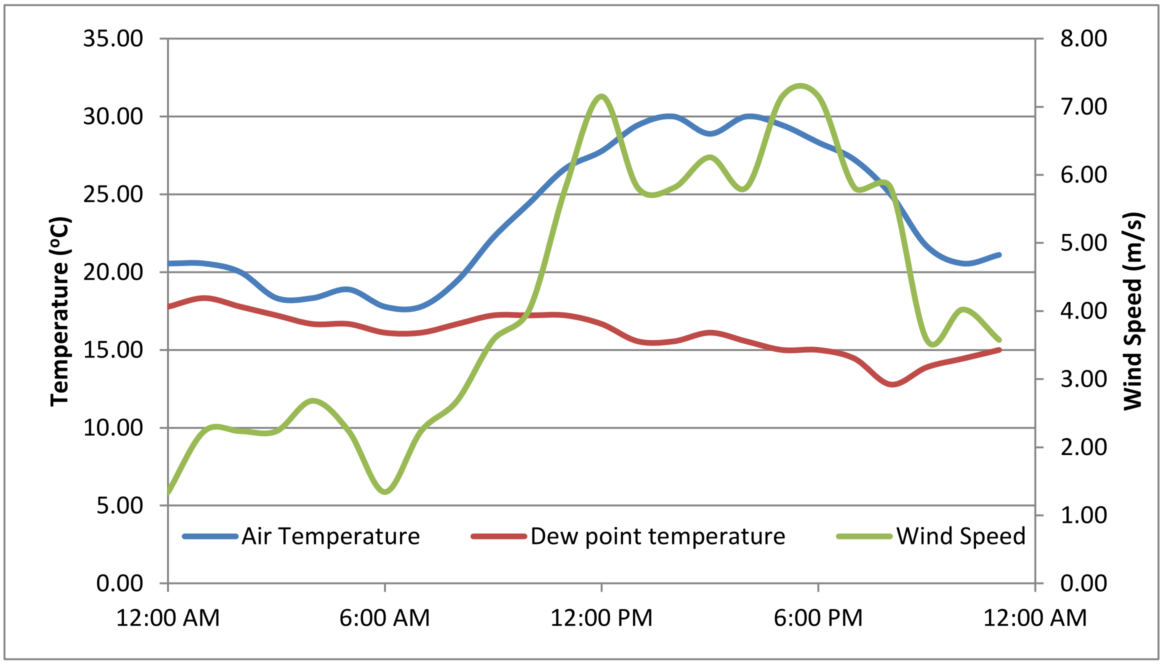

Figure B-2 Hourly Climate Data from St. Cloud Airport on 8/20/2008

Diffuse and point source data

QUAL2K allows diffusive and point sources to be added to the model at any location in the model. It was assumed that all water added to the model on 8/20/2008 was through groundwater sources. These sources were entered into the model as diffusive. Data from the three flow stations were used to estimate groundwater flow rates. Baseflow modeling discussed in Appendix A was used to estimate how the additional flow rates were proportioned throughout the reach.

Three sections of groundwater flow were added as diffusive sources in the model. The first section runs from Station 7 to Station 10. The Baseflow modeling showed no groundwater inflow between Station 6 and 7 therefore the difference in estimated flow at Station 6 of 0.2 cfs (0.006 m^3/s) and the monitored flow at Station 10 of 1.71 cfs (0.0483 m^3/s) was added to the model as a groundwater source between Stations 7 and 10. The additional flow between the monitored flow at Station 10 and the monitored flow at Station 13, which was 8.12 cfs (0.23 m^3/s) minus the flow coming in from Bunker Hill Creek of 0.53 cfs (0.015 m^3/s) was added to the model as two diffuse sources. According to the Baseflow modeling 70% of the groundwater between these two stations is added to the system before the impoundment. Therefore, of the 5.89 cfs (0.1667 m^3/s) added between Stations 11 and 13, 4.12 cfs (0.1166 m^3/s) was added before the impoundment while the other 1.766 cfs (0.05 m^3/s) was added after the impoundment. Figure B-3 shows the flow rates used in the model.

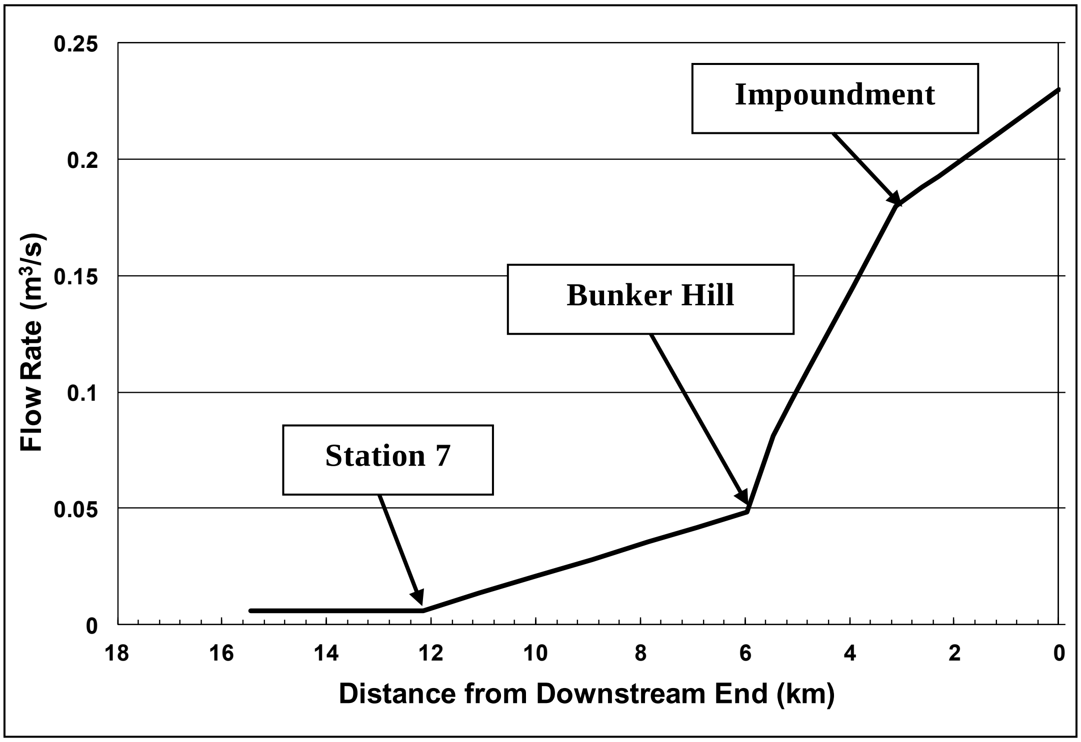

Figure B-3 Flow Rates for Little Rock Creek

All water quality parameters except for nitrate remained constant among all three groundwater sources. Temperature, Dissolved Oxygen and Nitrate were used to calibrate the model. Nitrate was only used to calibrate the nitrate concentration with observed values. Temperature and Dissolved oxygen were used to calibrate the model with corresponding creek values. The resulting dissolved oxygen level of 9 mg/l matched dissolved oxygen level in shallow groundwater recorded by the MPCA near Station 4 on 8/20/2008. All other water quality parameters remained consistent with the values entered at the headwaters of the model.

Table B-3 Diffuse Sources Water Quality Data

Parameter	*Units*	*Station 7 to Station 10*	*Station 11 to Impoundment*	*Impoundment to Station 13*
Upstream location	km	12.16	5.9	3.11
Downstream location	km	5.97	3.11	0.00
Total Inflow	**m^3/s**	**0.0423**	**0.1166**	**0.05**
Temperature	C	10	10	10
Dissolved Oxygen	mg/L	9	9	9
CBOD fast	mgO_2/L	3.02	3.02	3.02
Organic N	ugN/L	540	540	540
Ammonia	ugN/L	10	10	10
Nitrate	ugN/L	14000	6100	6100
Organic P	ugP/L	63	63	63
In Organic P	ugP/L	28	28	28
Phytoplankton	ug/L	20	20	20
Detritus	mgD/L	0.32	0.32	0.32

Bunker Hill Creek was added to the model as a point source between Station 10 and 11 with a flow rate of 0.53 cfs (0.015 m^3/s). Water quality data recorded by the Benton SWCD at location BH1 were used for the water source. Dissolved oxygen recorded as 8.74 mg/l and an average temperature of 16 ^oC were applied to the model.

Model Calibration

The model was calibrated to match temperature, dissolved oxygen and nitrate measurements made at the various sampling locations. Parameters for the individual reaches as well as concentration coming into the system from groundwater sources were used to calibrate the model. Bottom algae coverage and prescribed SOD were assigned for each individual reach to calibrate for dissolved oxygen concentrations. By increasing the amount of bottom algae coverage for a particular reach the range between the minimum and maximum concentration increased while also raising the average concentration. By increasing the prescribed SOD the average dissolved oxygen concentration decreased. SOD is modeled through the delivery and breakdown of particulate organic matter in the water column. QUAL2K allows for SOD to be both calculated by the model and prescribed by the user. The calculated SOD from the model was not sufficient for calibration therefore a prescribed SOD concentration was needed. The final reach parameters used to calibrate the model was percent shade coverage. This value was used to match the recorded temperatures in the creek and was verified using 2010 aerial photography. The values assigned to each individual reach after calibration are shown in Table B-4. Calibration was also conducted using groundwater nitrate concentrations and temperatures.

Table B-4 Reach Calibration Parameters

Reach Name	*Algae Coverage (%)*	*Prescribed SOD ($gO_2/m^2/d$)*	*Shade Cover (%)*
Station 7	0%	1.00	60%
Station 9	0%	1.50	70%
Station10	2%	0.50	90%
Station 11	12%	1.50	90%
Station 12 (Shade)	4%	1.50	90%
Station 12 (No Shade)	4%	1.50	0%
Station 12 (Impoundment)	4%	1.50	0%
Station 12	4%	1.50	0%
Station13	4%	0.75	40%

Model Results

Existing Conditions

The model was calibrated to existing conditions for the date of 8/20/2008. Through model calibration temperature, dissolved oxygen and nitrate levels were reproduced using the QUAL2K model. The following figures show the model fit for temperature (Figure B-4), Dissolved Oxygen (Figure B-5), and Nitrate (Figure B-6). The points represent values collected in the field and the dashed and solid lines represent modeled values. DO concentrations at Station 7, 11 and 12 were recorded below the recommended level of 7.0 mg/l. The model results produced match the low concentrations as well as the peak concentration for the various locations along the creek. Temperatures are shown to decrease until after Station11. At this point the creek enters an area with very little shading. The water also enters a man-made impoundment that increases the travel time by three days (Figure B-7).

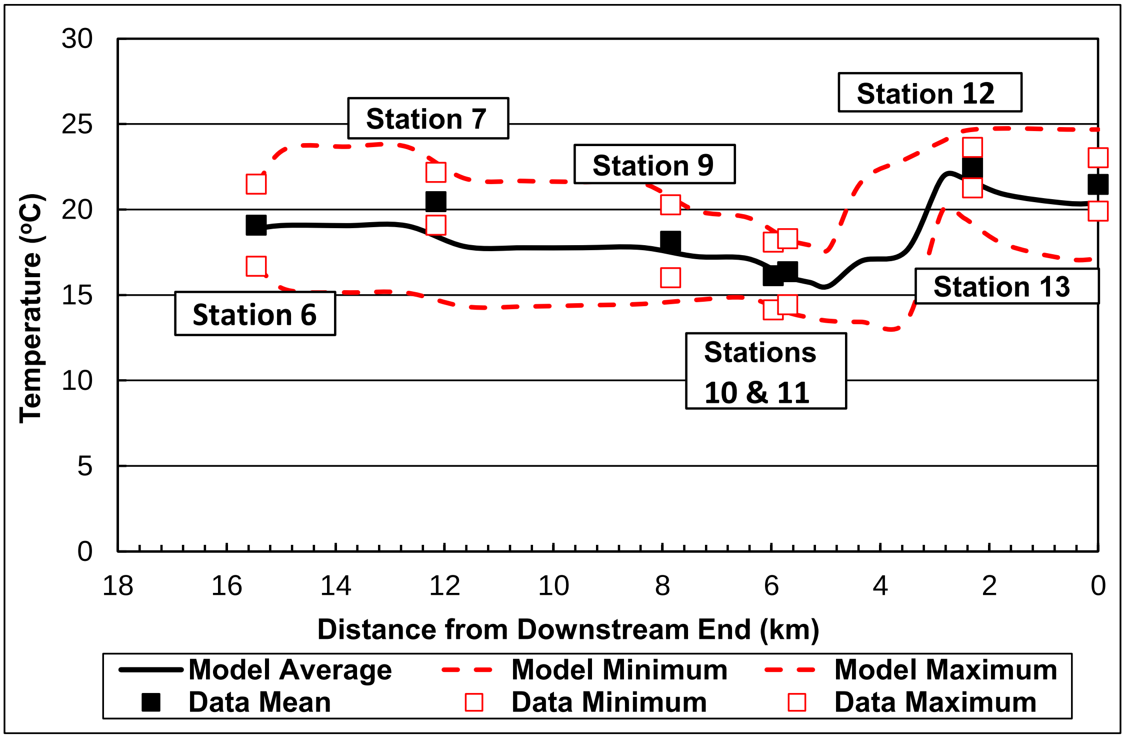

Figure B-4 Temperature model results comparison with measures data for 8/20/2008

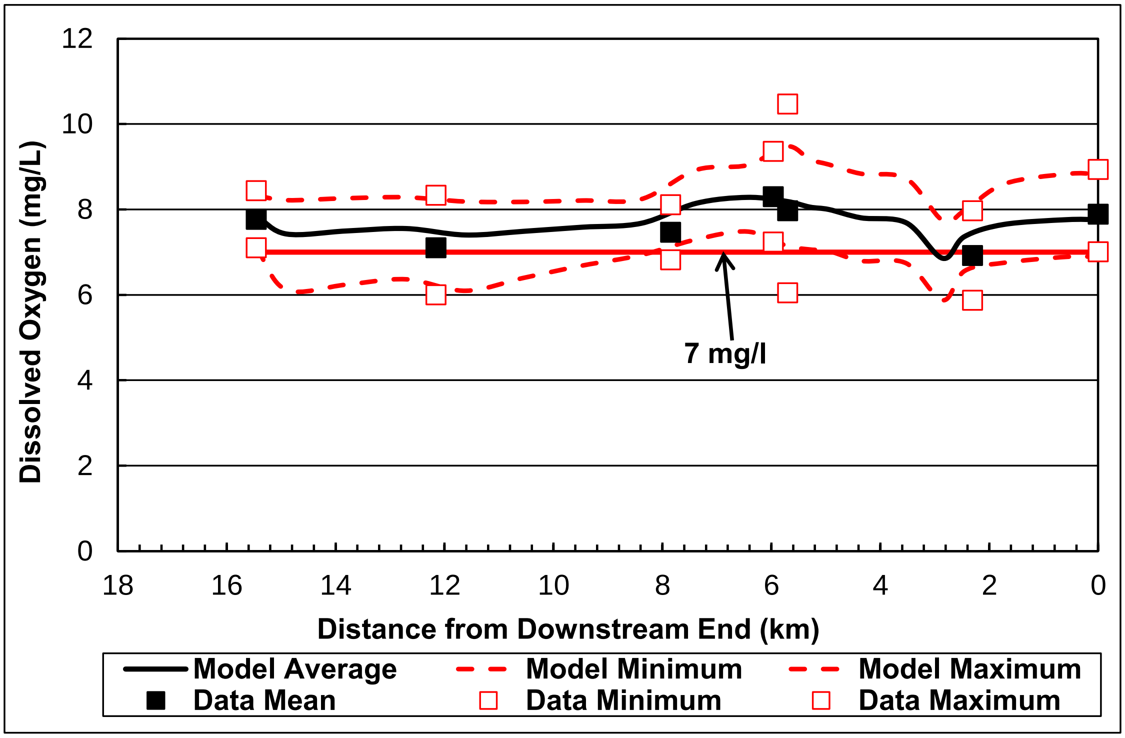

Figure B-5 Dissolved Oxygen model results comparison with measures data for 8/20/2008

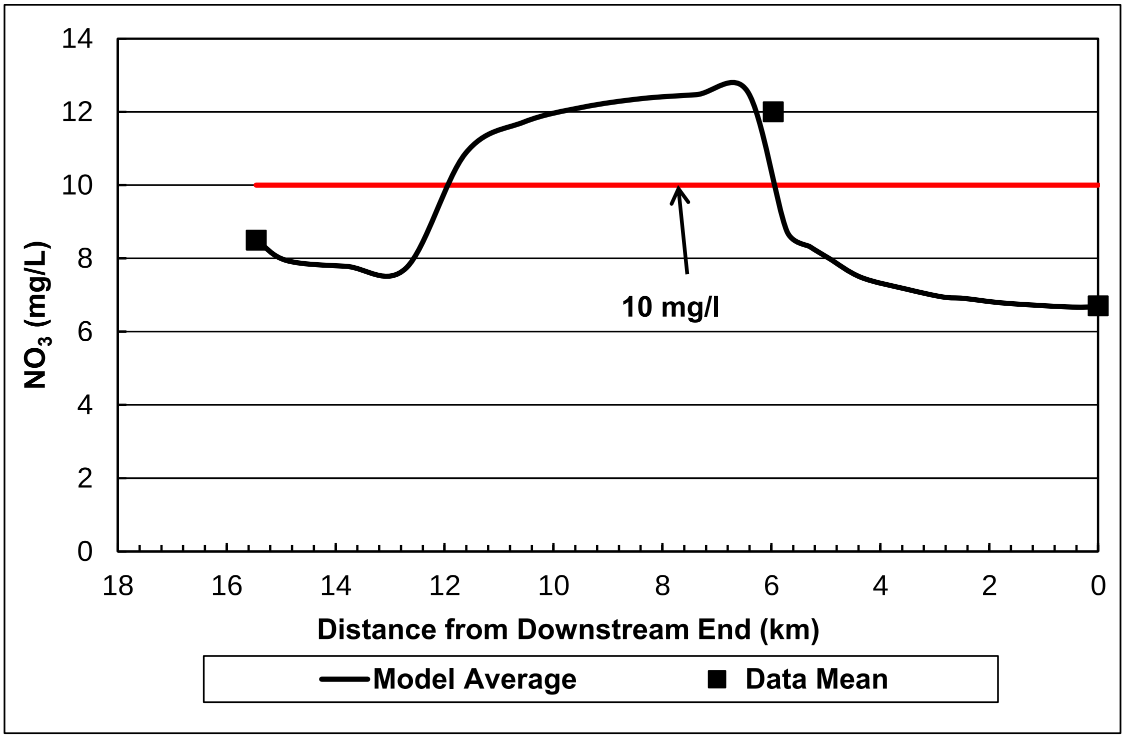

Figure B-6 Nitrate model results comparison with measures data for 8/20/2008.

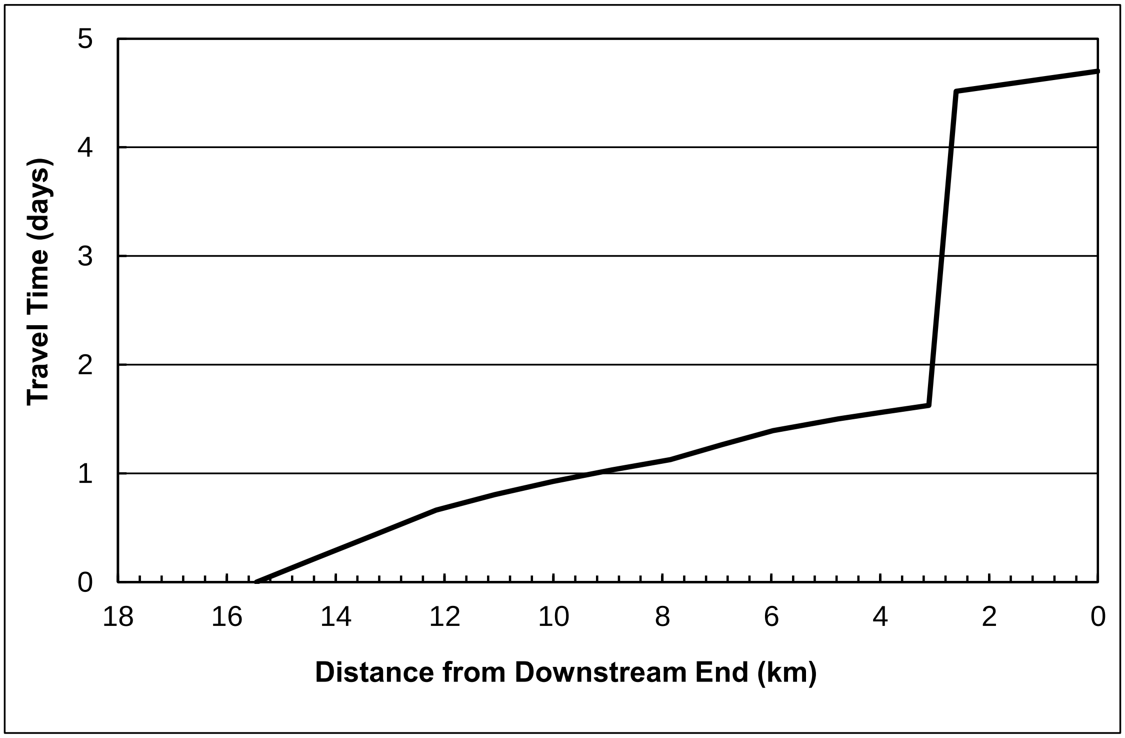

Figure B-7 Water Travel Time starting at Station 6

Diurnal results were also analyzed for dissolved oxygen. Results were compared for Stations 7 (Figure B-8) and 13 (Figure B-9). Station 7 is directly downstream of the headwaters location and Station 13 represents the end of the model. The modeled results are represented by the solid line while the measured values are represented by the square points. The Blue dashed line represented the DO saturation concentration. The model results compare well with the measured values at the two locations. DO concentrations in the creek are the lowest in the early morning and highest in the late afternoon. Time of peak DO concentration varies between the two locations. At Station 7 the peak value was recorded at around 19:00 while at Station 13 the peak value was recorded in the early afternoon at around 14:00.

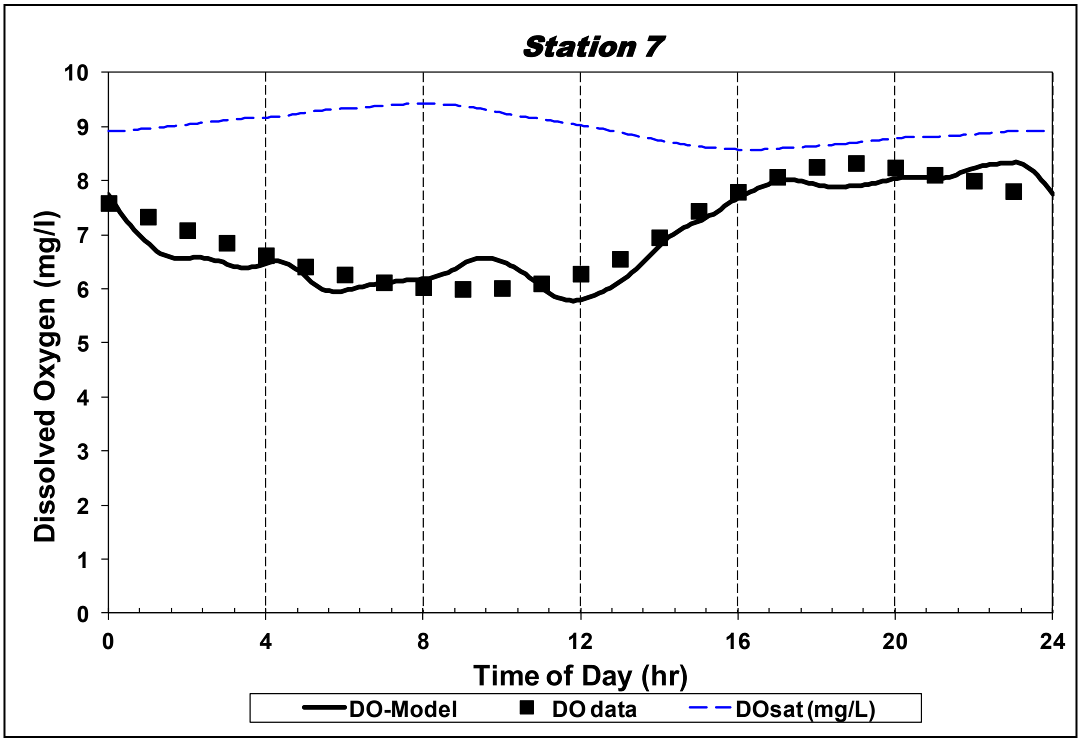

Figure B-8 Diurnal DO concentrations comparison with measures data for 8/20/2008 at Station 7.

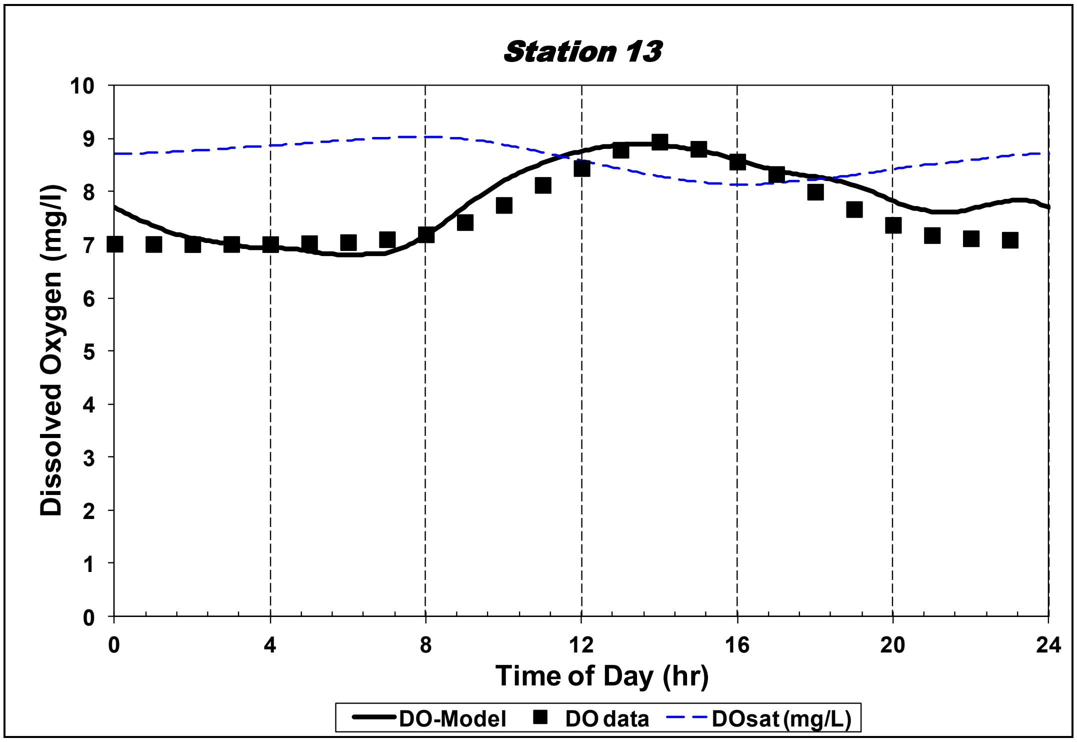

Figure B-9 Diurnal DO concentrations comparison with measures data for 8/20/2008 at Station 13.

Model Sensitivity

The sensitivity of the model was examined for 7 parameters that influence dissolved oxygen concentrations. Table B-5 shows the results of this analysis. Under existing conditions the daily average DO concentrations for August 20th, 2008 was 7.54 mg/l. Results show that the model is most sensitive to SOD rates and coverage with increased DO concentrations associated with decreased SOD. CBOD oxidation and nutrient hydrolysis rates are less sensitive to dissolved oxygen throughout Little Rock Creek. Reductions in all parameters provide increased average daily DO concentrations except for bottom algae coverage. The results of this analysis suggest that SOD plays a significant role in the DO level in Little Rock Creek during this low flow event when compared to water column processes.

Table B-5 Sensitivity results for model parameters

Action	*Average Daily DO Concentration (mg/l)*	*Percent change from existing*
Existing Conditions	7.54	
Reduce prescribed SOD rate in all reaches by 50%	8.09	7.26%
Reduce SOD channel coverage in all reaches to 50%	8.09	7.30%
Remove bottom algae coverage for all reaches	7.51	-0.45%
Reduce $CBOD_{fast}$ loading by 50%	7.63	1.16%
Reduce NO_3 loading by 50%	7.65	1.42%
Reduce detritus load by 50%	7.55	0.06%
Reduce phytoplankton load by 50%	7.56	0.21%

Model Simulations

Various model simulations were conducted to determine how the impoundment and inflow of groundwater into Little Rock Creek influences the dissolved oxygen and temperature levels. Three simulations were run. The first simulation modeled the creek with the impoundment removed. The second simulation modeled the creek with double the groundwater inflow while maintaining the overall load of pollutants to the creek. The final simulation modeled the creek with the removal of the impoundment and doubling of groundwater flow to the creek.

Impoundment Removal

The first scenario looked at how the removal of the impoundment would change downstream temperature and dissolved oxygen levels. This scenario was implemented by reducing the width of reach Station 12 (Impoundment) from 150 m to 10.24 m and removing the weir at the outflow of the impoundment. These changes reduced the overall travel time from the headwater to the outflow from 4.7 days to 2.6 days. The impoundment area has little shade allowing the water to warm up during the daytime hours. By reducing the water residence in areas with little to no shade coverage the average temperatures are reduced. Results from this simulation are displayed in Figures B-10, B-11 and B-12 for temperature, dissolved oxygen and nitrate respectively. The impoundment removal had little effect on dissolved oxygen levels and nitrate levels, but average temperatures dropped between Station 11 and 13. Maximum temperature dropped as well but at a lower rate than average temperatures. No effect was seen upstream of Station11 for all three parameters.

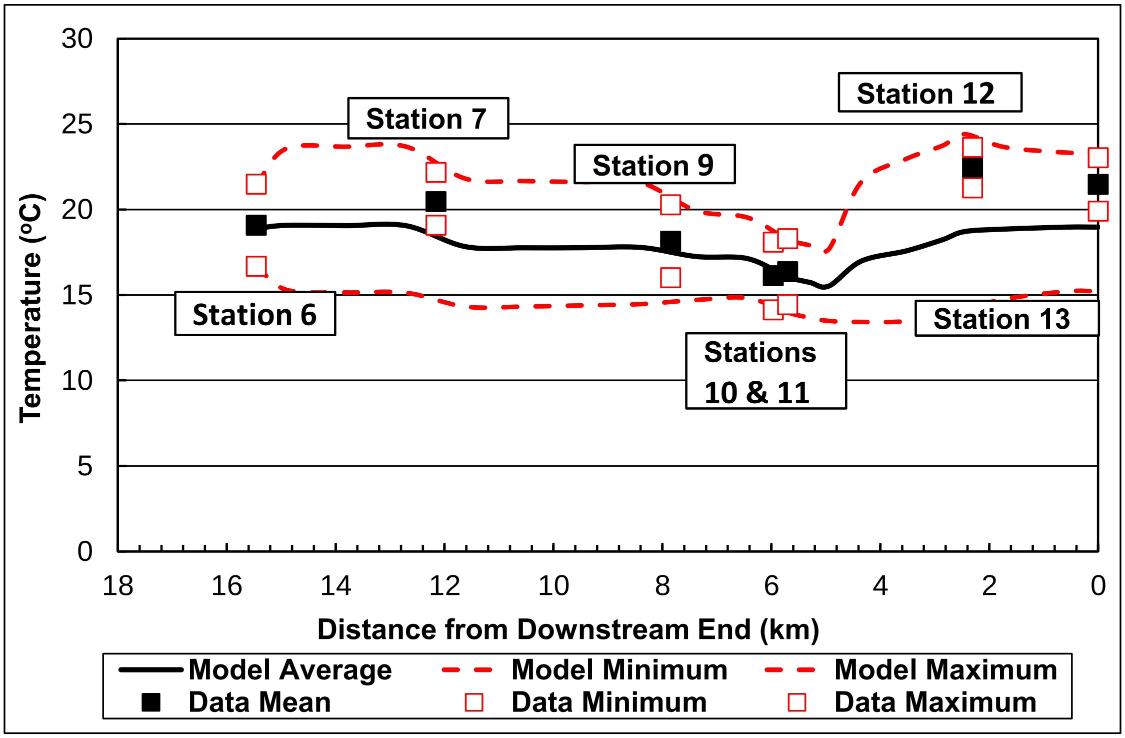

Figure B-10 Temperature profile after impoundment removal.

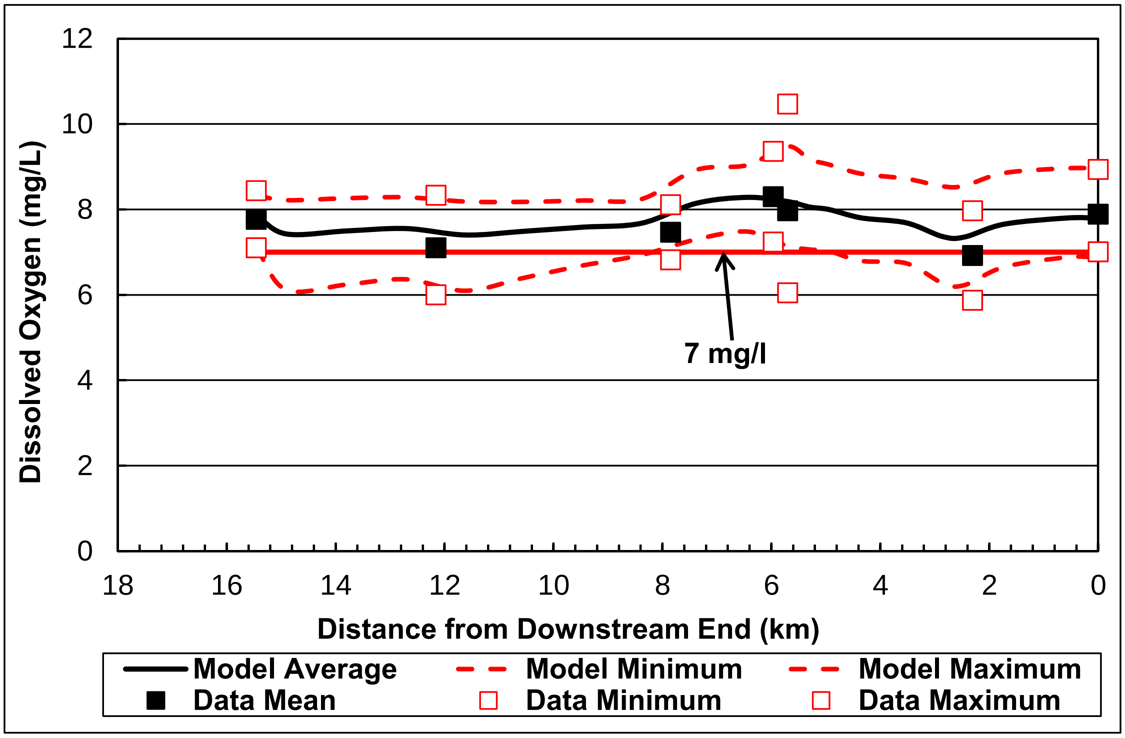

Figure B-11 DO profile after impoundment removal.

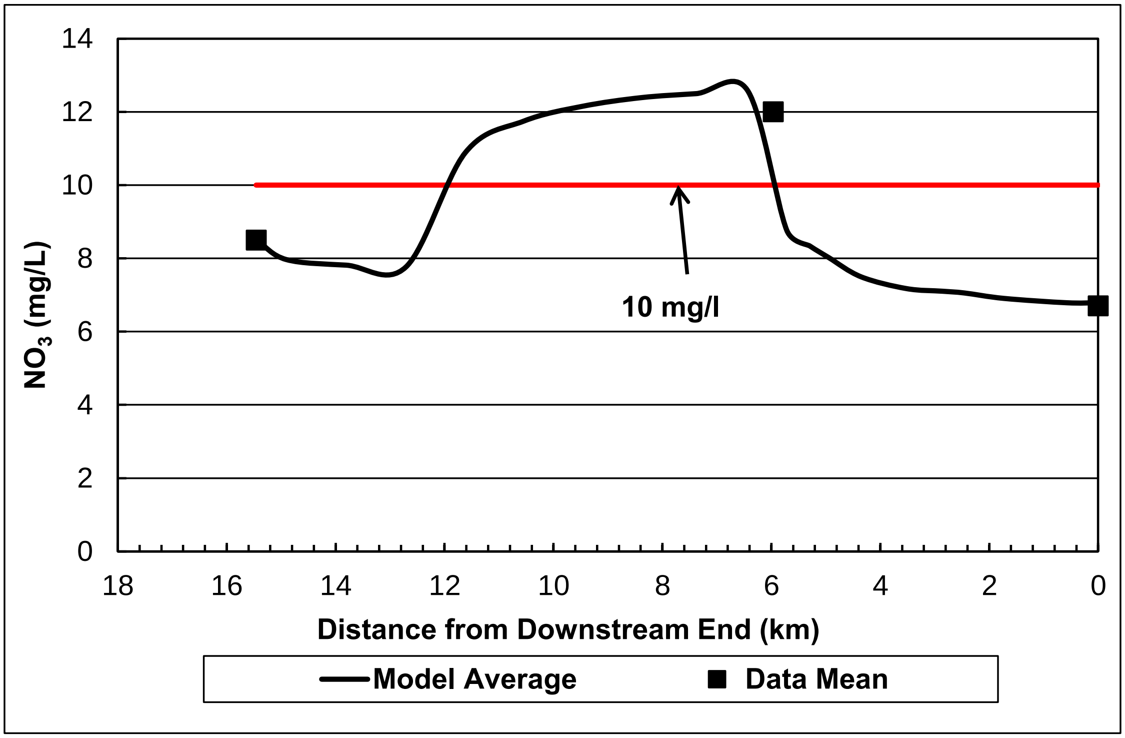

Figure B-12 Nitrate profile after impoundment removal.

Double groundwater inflow

The Little Rock Creek Stressor Identification report (Benton SWCD, 2009) cites lower groundwater levels as a possible contributor to the impairments for dissolved oxygen and temperature. To assess this claim a scenario was simulated with twice the groundwater inflow into the creek, which was conservatively lower than the groundwater modeling results of the low pumping condition scenario (described in the Pumping Scenarios section of Appendix A), since a comparison of the low and high pumping condition modeling results showed that a 40% reduction in annual pumping volumes resulted in 2.34 times more flow during the critical QUAL2K calibration period of August, 2008. Under this scenario the amount of groundwater entering from each of the three sources discussed previously were doubled. The groundwater source between Station 7 and 10 was extended to Station 6, which allowed for the whole system to experience increased groundwater flow. The chemical loads were held constant, resulting in a halving of the chemical constituent concentrations, assuming that the groundwater system has reached chemical equilibrium. These changes resulted in adjustments to temperature (Figure B-13), DO (Figure B-14), and nitrate (Figure B-15). Since the calibrated groundwater temperature was 10^{o}C, temperature reductions occurred throughout the system. Temperature remained high near the impoundment. DO oxygen levels increased throughout the system due to oxygen demand concentration reductions and the higher flow of groundwater. The lower groundwater concentration of nitrate also decreased the nitrate concentration in the creek.

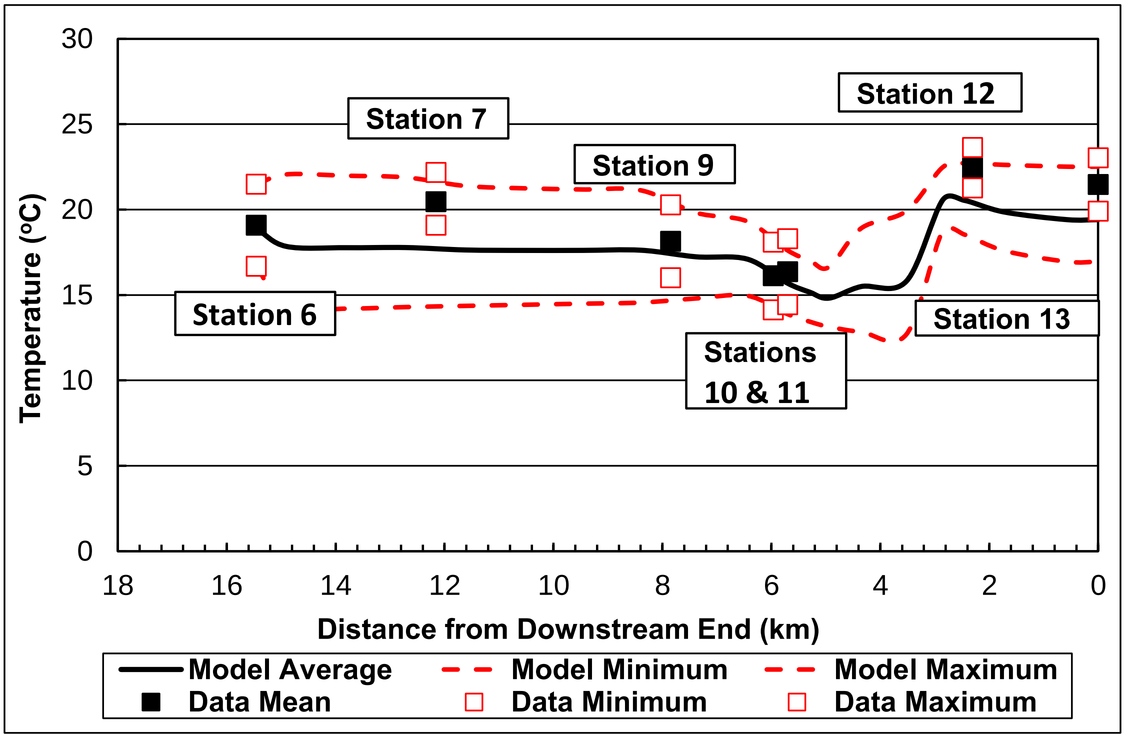

Figure B-13 Temperature profile with doubled groundwater flow

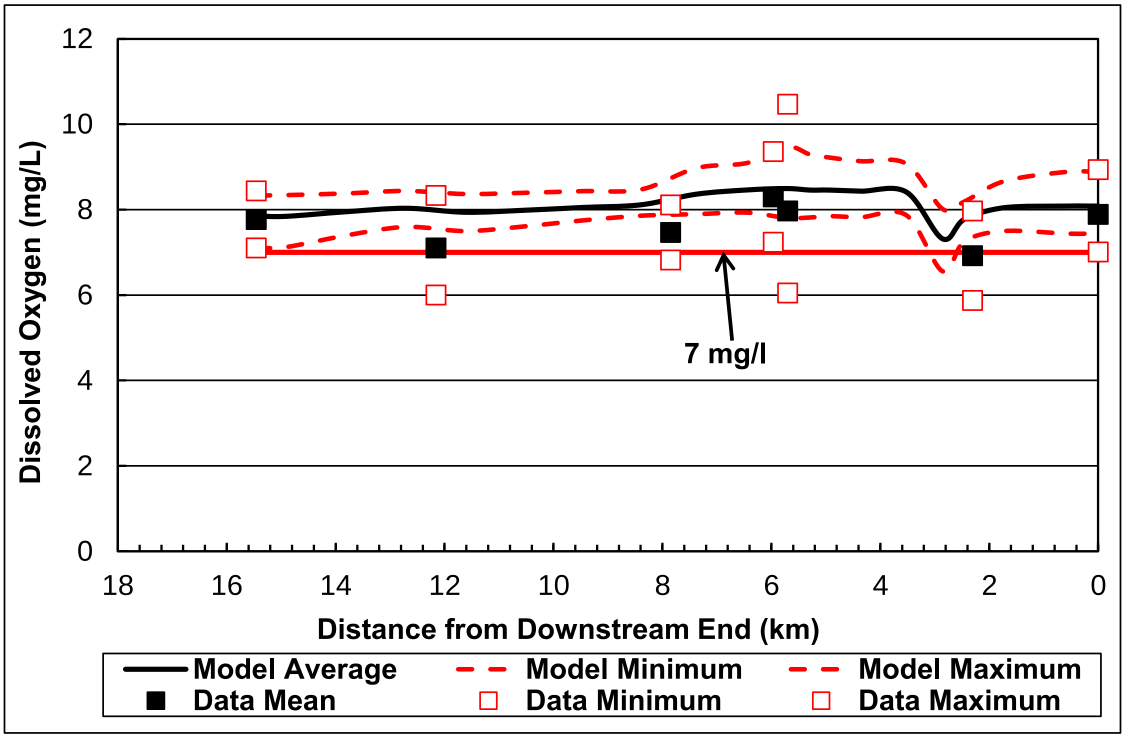

Figure B-14 Dissolved Oxygen profile with doubled groundwater flow

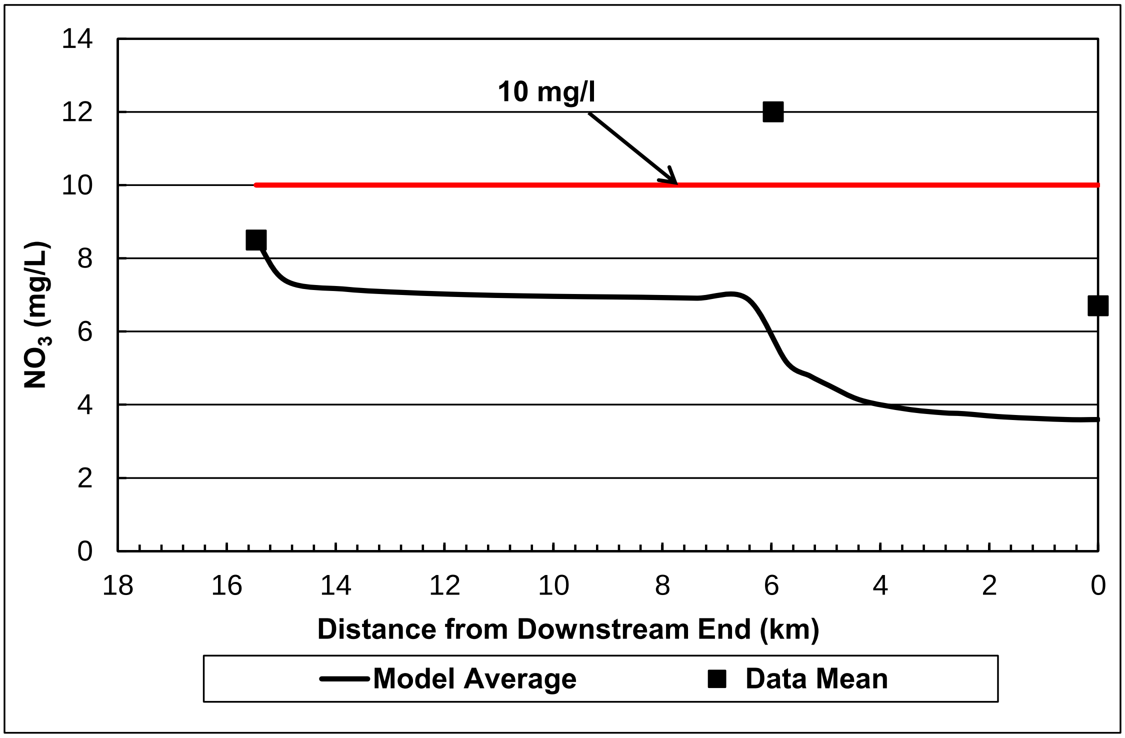

Figure B-15 Nitrate profile with doubled groundwater flow.

Impoundment removal with double groundwater inflow

The final scenario combined both of the previous simulation by removing the impoundment while also doubling the groundwater inflow. This scenario resulted in the improvement of all three parameters. Results are shown in Figures B-16, B-17 and B-18 for temperature, dissolved oxygen and nitrate respectively. This scenario combined the temperature advantages downstream of Station 11 gained by removing the impoundment with the advantages for all three parameters throughout the creek gained by increased groundwater flow into the system.

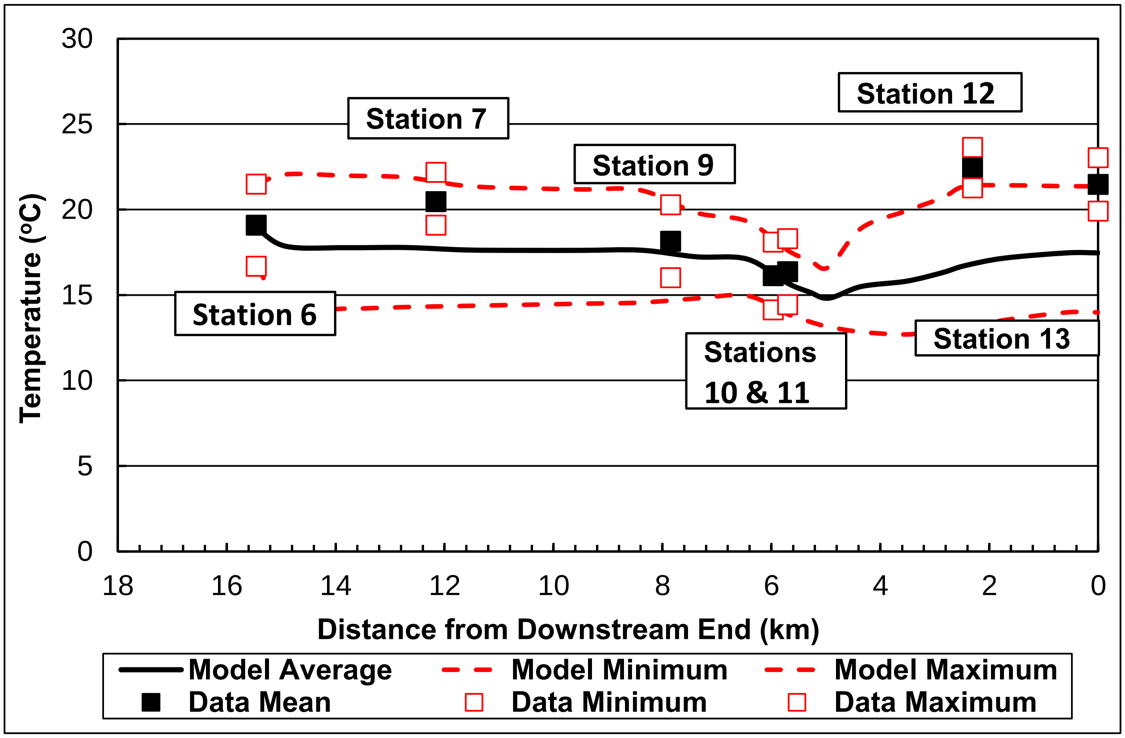

Figure B-16 Temperature profile with double groundwater flow

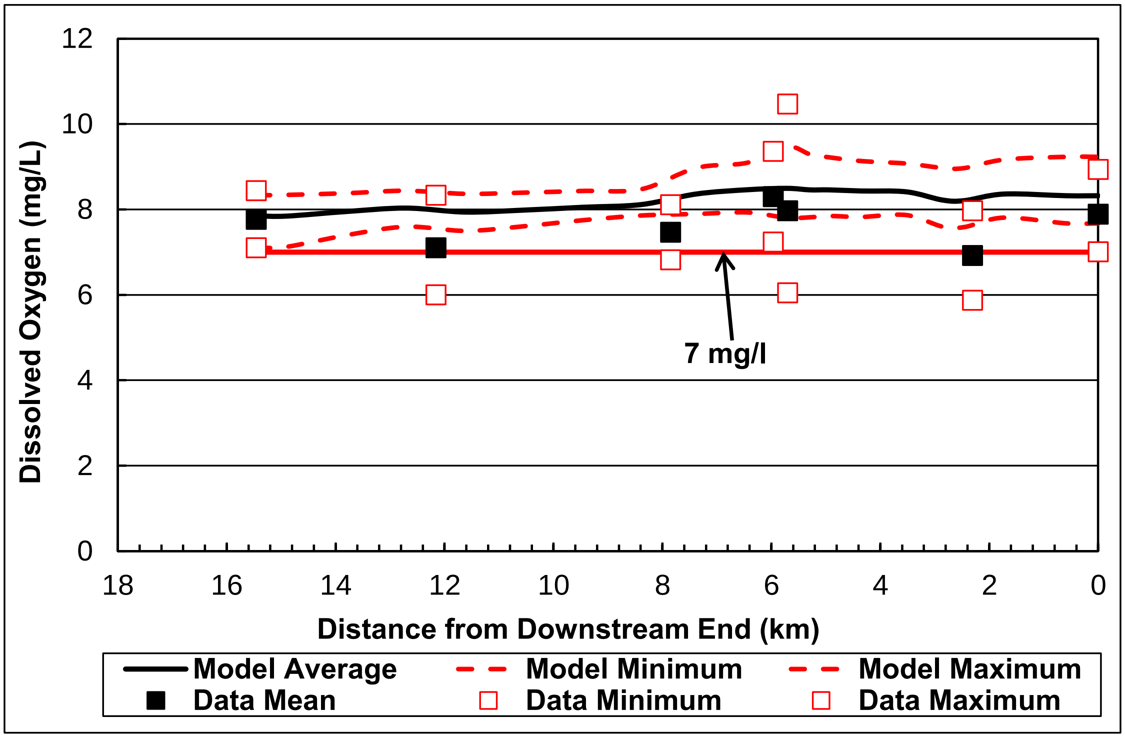

Figure B-17 Dissolved Oxygen profile with double groundwater flow

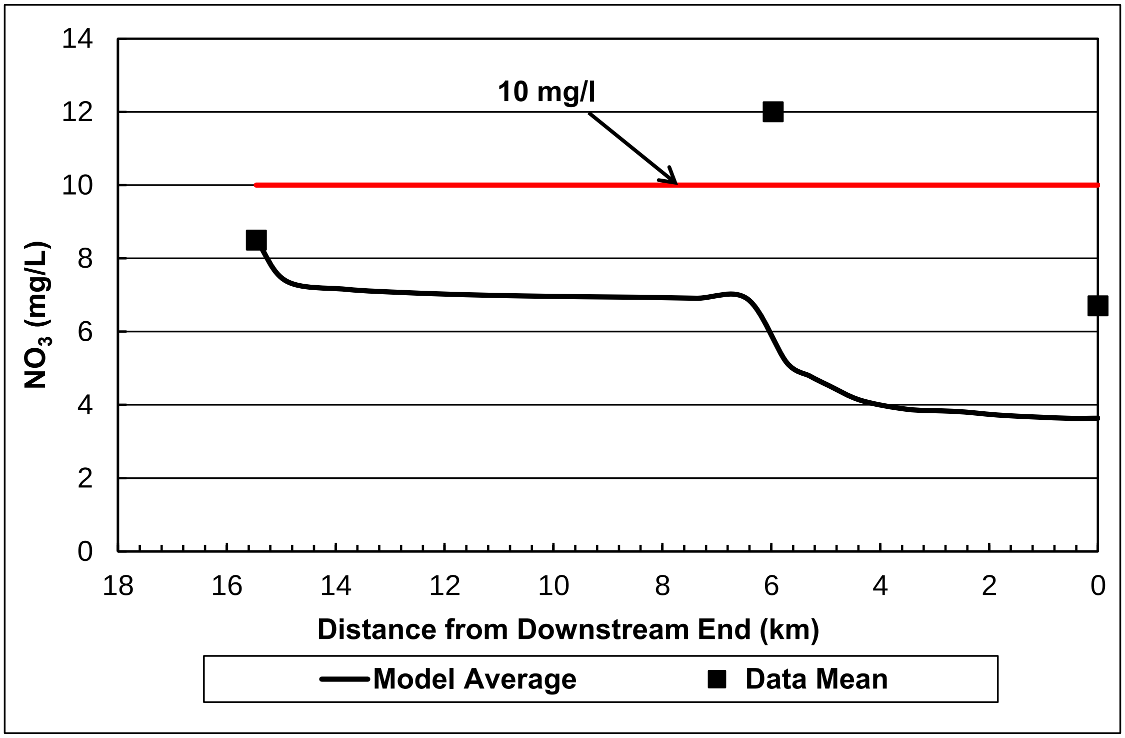

Figure B-18 Nitrate profile with double groundwater flow.

Discussion

A QUAL2K model was created to simulate conditions in Little Rock Creek observed on August 20, 2008. Low flow conditions were present on this date with high water temperatures, low dissolved oxygen concentrations and high nitrate concentrations. Water quality data collected from various agencies (MPCA, Benton SWCD, and the USGS) were used to set up and calibrate the model to existing conditions. The calibrated model was used to simulate three mitigation scenarios. The first scenario involved removing the man-made impoundment located between Stations 11 and 12. The second scenario involved doubling the groundwater flow into the system while maintaining the same chemical loads. The final scenario combined the first two mitigations measured. Results are shown in comparisons to each other in Figures B-19 – B-23.

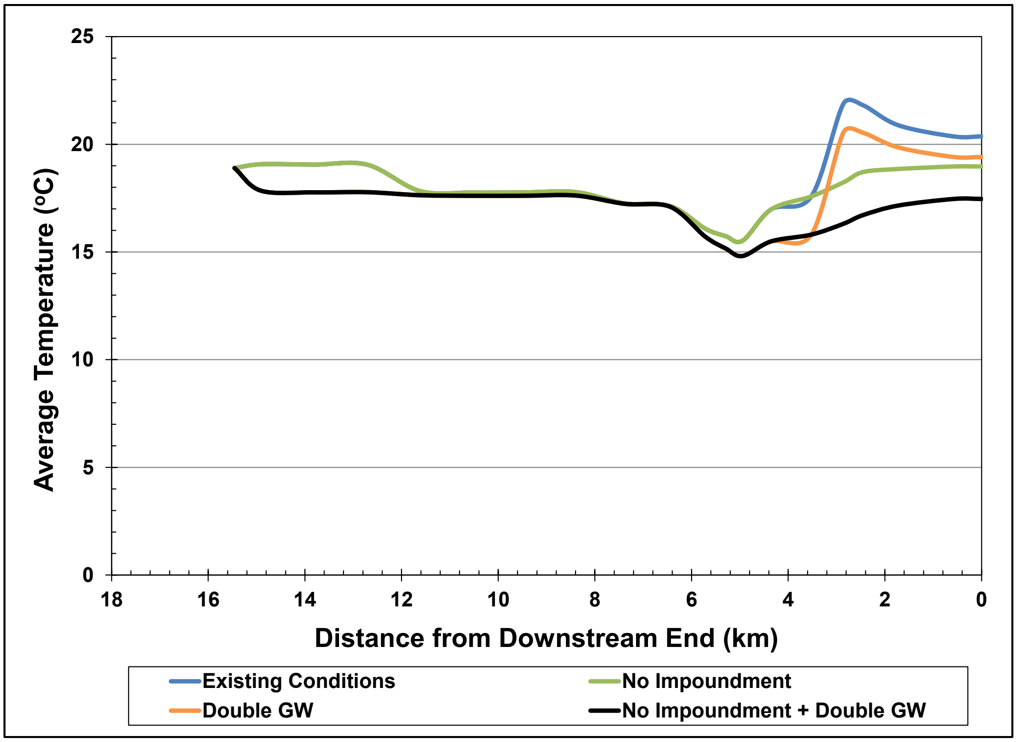

Figure B-19 Average Creek Temperatures for each QUAL2K model run on date 8/20/2008

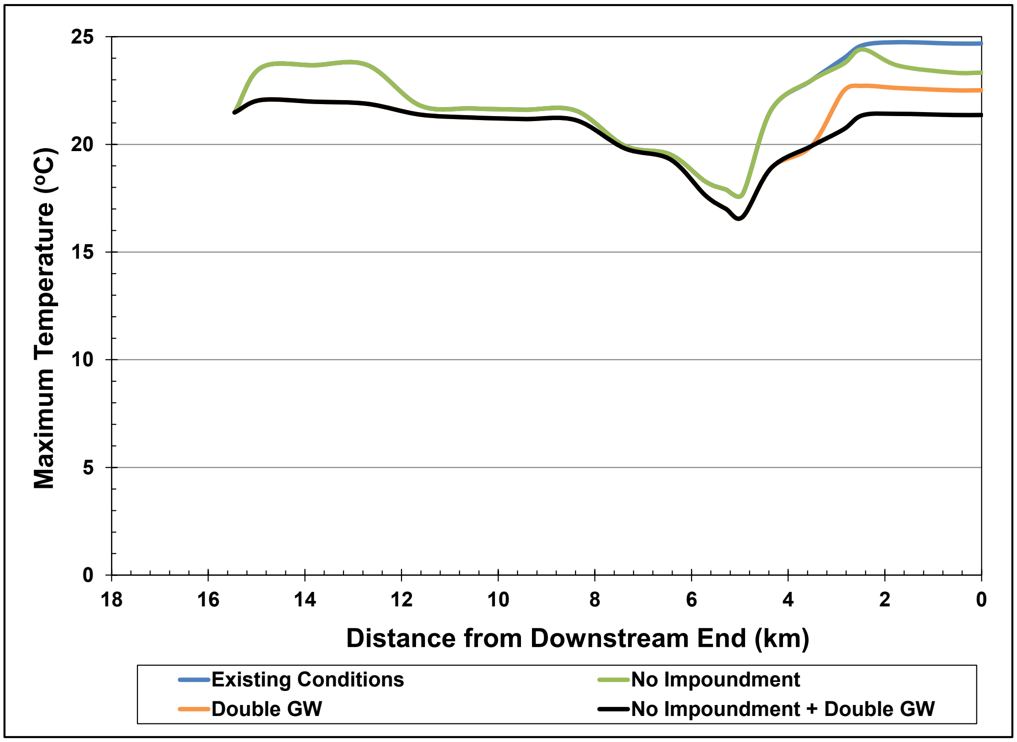

Figure B-20 Maximum Creek Temperatures for each QUAL2K model run on date 8/20/2008

The average and maximum temperatures in Little Rock Creek under existing conditions and for each scenario are shown in Figures B-19 and B-20. By removing the impoundment temperatures downstream of Station 11 are decreased. Average temperatures decrease more significantly than maximum temperatures due to the lack of shade throughout that section of Little Rock Creek. By removing the impoundment, the water residence time in areas with low shade coverage is reduced resulting in lower average temperatures downstream of where the impoundment was located. Doubling the groundwater flows into the creek results in reduced temperatures throughout the creek. The groundwater flow was calibrated at 10 ^{o}C. By increasing the flow of this low temperature water into the system both maximum and average temperatures are reduced. Combining both mitigation measures creates the lowest temperature throughout the entire creek.

The average and minimum dissolved oxygen concentrations in Little Rock Creek under existing conditions and for each scenario are shown in Figures B-21 and B-22. The lowest average dissolved oxygen concentrations were modeled in the impoundment. By removing the impoundment these average concentrations are increased above 7 mg/l. No change is noticed at any other location in the creek due to the removal of the impoundment. Increased dissolved oxygen levels are estimated throughout the creek when the groundwater flow is doubled. Both the minimum and average concentrations are elevated above 7 mg/l except in the impoundment where minimum concentrations still dip to 6.5 mg/l. When the impoundment is removed, as well, all concentrations are elevated above the 7 mg/l level.

Average nitrate levels are shown in Figure B-23 for all four model runs. Removing the impoundment has no effect on nitrate concentrations in Little Rock Creek. Doubling groundwater flow rates results in reduced nitrate concentrations. This reduction is caused by the lower nitrate concentrations in the groundwater.

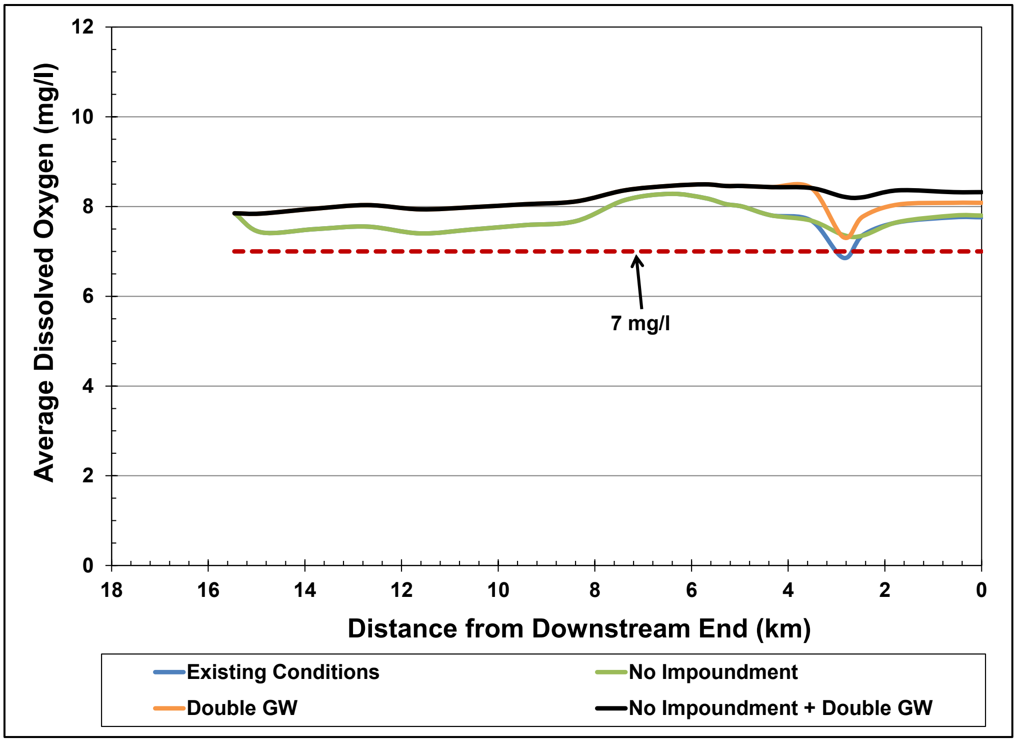

Figure B-21 Average Dissolved Oxygen Concentrations for each QUAL2K model run on 8/20/08

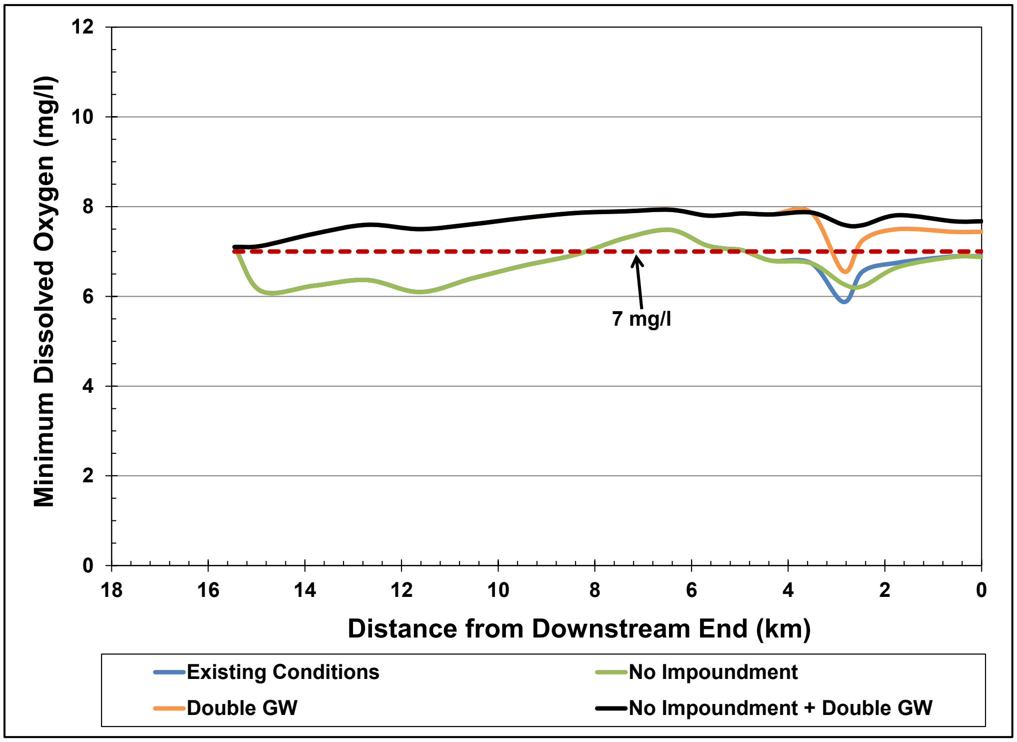

Figure B-22 Minimum Dissolved Oxygen Concentrations for each QUAL2K model run on 8/20/08

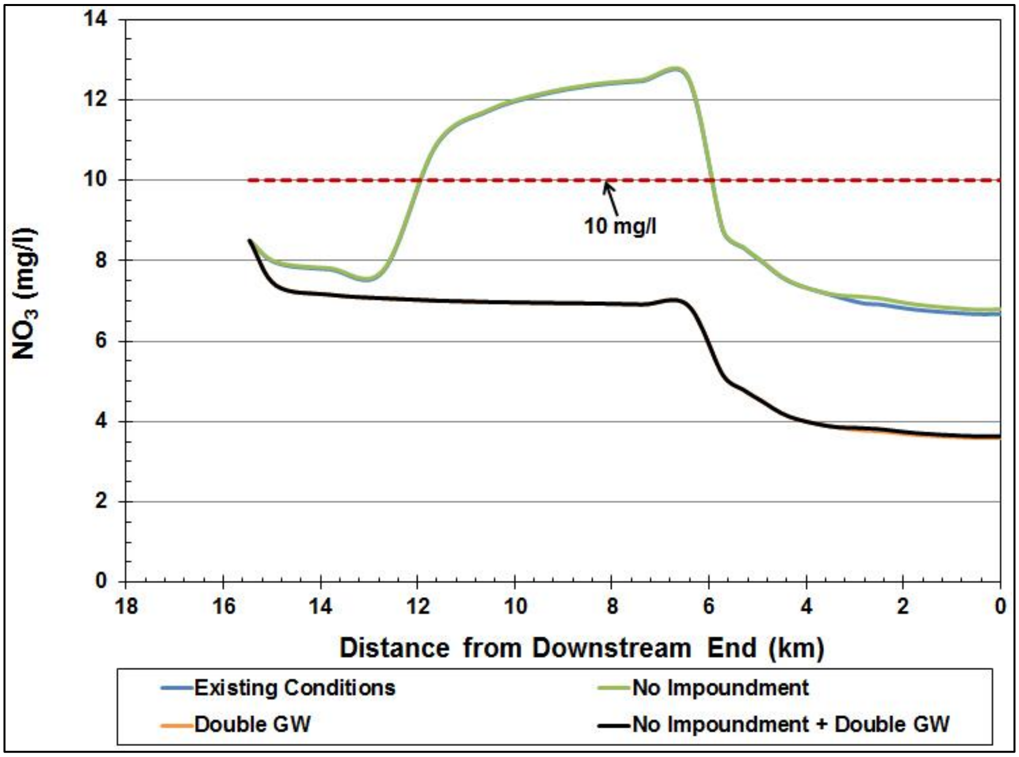

Figure B-23 Average NO_3 Concentrations for each QUAL2K model run on 8/20/08

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