North Fork Crow and Lower Crow Bacteria, Turbidity, and Low Dissolved Oxygen TMDL Assessment Report

Wenck File #2366-02

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TMDL Summary

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Location	Upper Mississippi River Basin; Central Minnesota	Executive Summary p. xii Section 1.2; p1-1
303(d) Listing Information	Total of 7 listings for bacteria, turbidity and low dissolved oxygen (DO) in 6 assessment unit ID's: *See Table 1.3, p1-9*	Table 1.3, p1-9
Applicable Water Quality Standards/ Numeric Targets	*See Section 1.7* Bacteria: *See Section 2.1* Turbidity: *See Section 3.1* Low DO: *See Section 4.1*	Bacteria Section 2.1, p2-1 Turbidity Section 3.1, p3-1 Low DO Section 4.1, p4-1
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EPA/MPCA Required Elements	Summary	TMDL Page Number
Load Allocation	Bacteria: *See Section 2.6.5* Turbidity: *See Section 3.8.5* Low DO: *See Section.4.8.3*	Bacteria Section 2.6.5, p2-10 Turbidity Section 3.8.5, p3-12 Low DO Section 4.8.3, p4-16
Margin of Safety	Bacteria: An explicit 10% MOS was used, in addition to an implicit MOS. The implicit MOS was applied as part of the WLA by assuming the point sources are always discharging at permitted limits. *See Section 2.6.2* Turbidity: An explicit MOS based on the difference between the 50th and 45th percentile in each flow zone was used, in addition to an implicit MOS. The implicit MOS was applied as part of the WLA by assuming the point sources are always discharging at permitted limits. *See Section 3.8.2* Low DO: An explicit 10% MOS was used, in addition to an implicit MOS. The MOS is implicit by incorporating conservative model assumptions. *See Section 4.8.5*	Bacteria Section 2.6.2, p2-6 Turbidity Section 3.8.2, p3-8 Low DO Section 4.8.5, p4-19
Seasonal Variation	Bacteria: Load duration curve methodology accounts for seasonal variations; *See Section 2.6* Turbidity: Load duration curve methodology accounts for seasonal variations; *See Section 3.8* Low DO: TMDL was developed to target the critical conditions, i.e., late summer low flow period after a storm event. *See Sections 4.5 & 4.6*	Bacteria Section 2.6, p2-5 Turbidity Section 3.8, p3 -7 Low DO Section 4.5 p4-8 Section 4.6, p 4-13

EPA/MPCA Required Elements	Summary	TMDL Page Number
Reasonable Assurance	Information is presented regarding BMP's to address impairments of bacteria, turbidity and low DO. Since there are several sources and some common delivery pathways, most of the strategies have multiple water quality benefits in terms of load reductions through implementation. NPDES permits provide assurances for permitted sources to comply with WLAs; *See Section 6.0.*	Section 6.0 p6-1
Monitoring	A general overview of follow-up monitoring is included; *See Section 6.4*	Section 6.4, p6-4
Implementation	This report sets forth an implementation framework, general load reduction strategies, and a rough approximation of the overall implementation cost to achieve the TMDL. A separate more detailed implementation plan will be developed within one year after EPA approval of this TMDL report. *See Section 5.0*	Section 5.0, p5-1
Public Participation	The following meetings were held over the course of the project: Public Meeting Dates: August 2, 2007 November 6, 2008 July 22, 2009 August 13, 2009 September 16, 2009 May 12, 2010 June 3, 2010 September 13 & 14, 2011 September 22, 2011 September 28, 2011 The public notice comment period took place from June 18, 2012 –Sept. 4, 2012	Section 7.0, p7-1

Executive Summary

According to the Minnesota Pollution Control Agency website, "the federal Clean Water Act (CWA) requires states to adopt water-quality standards to protect waters from pollution. These standards define how much of a pollutant can be in the water and still allow it to meet designated uses, such as drinking water, fishing and swimming. The standards are set on a wide range of pollutants, including bacteria, nutrients, turbidity and mercury. A water body is 'impaired' if it fails to meet one or more water quality standards."

Section 303(d) of the Federal Clean Water Act (CWA) requires the Minnesota Pollution Control Agency (MPCA) to identify water bodies that do not meet water quality standards and to develop total maximum daily pollutant loads for those water bodies. A total maximum daily load (TMDL) is the amount of a pollutant a water body can accept while still meeting state water quality standards. TMDL projects allocate pollutant loads to point and non-point sources within the watershed.

The North Fork Crow River Total Maximum Daily Load (TMDL) project addressed seven impairments on six reaches of the North Fork Crow and Lower Crow River. These reaches are on Minnesota's final 2008 and draft 2010 303(d) impaired water list because they are part of a Class 2 water body, designated to support aquatic life and recreational use. High levels of bacteria and turbidity and low levels of dissolved oxygen prevent these river reaches from meeting their designated uses. The goal of this TMDL is to quantify the pollutant reductions needed in each of these reaches to meet State water quality standards as required by the Clean Water Act.

The headwaters for the North Fork Crow River are located in Pope County, at Grove Lake. The North and South Forks of the Crow River converge in Rockford, MN to become the Lower Crow River. The Lower Crow River flows northeast along the borders of Wright and Hennepin Counties until it empties in to the Mississippi River at the common boundary between Otsego and Dayton. The North Fork Crow River and Lower Crow River watershed is approximately 950,000 acres and includes the Cities of St. Michael, Buffalo, Rockford, Howard Lake, Cokato, Litchfield, Paynesville, Spicer, New London, Belgrade, and Brooten. Agriculture accounts for the majority of landuse activities within the North Fork Crow and Lower Crow River watershed and the relative percentage of cultivated landuse is slightly above the typical range for the North Central Hardwood Forest (NCHF) ecoregion. Permitted municipal and industrial dischargers and a small number of unsewered communities also exist in the watershed. The North Fork Crow and Lower Crow watershed is predominately comprised of three agroecoregions, the Alluvium & Outwash, Steep Dryer Moraine and the Rolling Moraine.

Fecal coliform **bacteria** are an indicator organism, meaning that not all the species of bacteria of this category are harmful, but they are usually associated with harmful organisms transmitted by fecal contamination. They are found in the intestines of warm-blooded animals, including humans and livestock. The presence of fecal bacteria in water suggests the presence of fecal matter and associated bacteria (i.e. some strains of *E. coli*), viruses, and protozoa (i.e. Giardia and *Cryptosporidium*) that are pathogenic to humans when ingested (USEPA 2001a). The TMDL~~s~~ reported loads are based on meeting the 2008 state chronic standard for *E. coli* of 126 colony-forming units (cfu) /100 ml. The TMDLs were established using a load duration approach as described by Cleland (2002) which integrates flow and the bacteria standard to provide loading capacities and allocations across the full range of flows. Sources that contribute bacteria to the system were found to vary depending on hydrologic conditions. During dry conditions, over-grazed riparian pasture and failing septic systems (including "straight pipe" septics) were determined to be the largest sources of bacteria. During wet conditions, surface applied manure, over-grazed pastures, and feedlots without runoff controls were the largest contributors.

Turbidity in water is caused by suspended sediment, organic material, dissolved salts, and stains that scatter light in the water column, making the water appear cloudy. Excess turbidity can degrade aesthetic qualities of water bodies, increase the cost of treatment for drinking water or food processing uses, and harm aquatic life. Adverse ecological impacts caused by excessive turbidity include hampering the ability of aquatic organisms to visually locate food, impaired gill function, and smothering of spawning beds and benthic organism habitat. Since turbidity is a measure of light scatter and adsorption, loads need to be developed for a surrogate parameter. Total suspended solids (TSS) is a measurement of the amount of sediment and organic matter suspended in water and is often used as a turbidity surrogate to define allocations and capacities in terms of daily mass loads. The TMDL reported loads are based on meeting the turbidity standard of 25 nephelometric turbidity units (NTU) corresponding to a surrogate TSS concentration of 75 mg/L, a level based on paired data collected in the watershed. The TMDLs were also established using a load duration approach. The primary contributing sources to the North Fork Crow and Lower Crow River turbidity impairments are soil loss from upland areas and streambank erosion during high flows and algal turbidity during low flow conditions.

Dissolved oxygen (DO) is an important water quality parameter for the protection and management of aquatic life. All higher life forms, including fish and aquatic macroinvertebrates, are dependent on minimum levels of oxygen for critical life cycle functions such as growth, maintenance, and reproduction. Problems with low dissolved oxygen in river systems are often the result of excessive loadings of carbonaceous biochemical oxygen demand (CBOD) and nitrogenous biochemical oxygen demand (NBOD), particularly in combination with high temperatures and low flow conditions. The breakdown of organic compounds in the water column and/or sediment consumes water column DO. Organic matter loading to streams can come from both natural (plant, leaf and periphyton debris, in-situ primary production) and anthropogenic (wastewater effluent, agricultural animal feces) sources. The amount of oxygen that a given volume of water can hold is a function of atmospheric pressure, water temperature, and the amount of other substances dissolved in the water. The TMDLs were based on meeting the dissolved oxygen standard of 5.0 mg/L as a daily minimum. Historic DO monitoring indicates that summer base-flow is the critical condition for DO in each impaired stream. Thus, the TMDLs were established using an EPA supported steady state model referred to as the River and Stream Water Quality (QUAL2K) Model. The data used to build and calibrate each model were collected during summer low-flow water quality synoptic surveys in 2008 and 2009. Using the calibrated synoptic survey QUAL2K models, model scenarios were established whereby headwater DO conditions and/or CBOD, NBOD and SOD were adjusted until each impaired stream exhibited a minimum DO greater than 5.0 mg/L. The final (TMDL) model scenario was then used to calculate the wasteload allocation, load allocation and margin of safety for each impaired reach.

A general strategy for the implementation of nonpoint source-related actions to address the bacteria, turbidity and dissolved oxygen impairments in the North Fork of the Crow River watershed is provided in this document. Specific strategies will be included in the implementation plan scheduled to be developed within one year of EPA's approval of this report. Nonpoint contributions are not regulated and, therefore, efforts toward reductions will need to proceed on a voluntary basis. Point sources are regulated through the National Pollutant Discharge Elimination System (NPDES) program.

1.0 Introduction

1.1 PURPOSE

Section 303(d) of the Clean Water Act establishes a directive for developing Total Maximum Daily Loads (TMDLs) to achieve Minnesota water quality standards established for designated uses of State waterbodies. Under this directive, the State of Minnesota has directed that a TMDL be prepared to address bacteria and turbidity exceedances as well as low dissolved oxygen in reaches located in the North Fork Crow and Lower Crow River watershed. The goal of the TMDL study is to quantify the pollutant reductions needed to meet State water quality standards. This report presents the results of the study.

A TMDL is defined as the maximum quantity of a pollutant that a water body can receive and continue to meet water quality standards for designated beneficial uses. Thus, a TMDL is simply the sum of point sources and nonpoint sources in a watershed. A TMDL can be represented in a simple equation as follows:

$$\begin{aligned} \text{TMDL} = &\ \Sigma \text{ Wasteload Allocation (WLA; Point Sources)} \\ &+ \Sigma \text{ Load Allocation (LA; nonpoint sources)} \\ &+ \text{Margin of Safety (MOS)} \end{aligned}$$

The wasteload allocation is the sum of the loads from all point sources and the load allocation is the sum of the load from all nonpoint sources. The Margin of Safety represents an allocation to account for variability in environmental data sets and uncertainty in the assessment of the system. Other factors that must be addressed in a TMDL include seasonal variation, future growth, critical conditions, and stakeholder participation.

This TMDL report provides waste load allocations (WLAs), load allocations (LAs) and Margin of Safety (MOS) needed to achieve the state standard for each parameter in each impaired reach of the North Fork Crow and Lower Crow River systems.

1.2 WATERSHED STUDY AREA

The North Fork Crow River and Lower Crow River watershed is located in eight counties in west-central Minnesota: Wright, Meeker, Kandiyohi, Stearns, Pope, Hennepin, McLeod, and Carver (Figure 1.1). The headwaters for the North Fork Crow River are located in Pope County, at Grove Lake. The North and South Forks of the Crow River converge in Rockford, Minnesota to become the Lower Crow River. The Lower Crow River flows northeast along the borders of Wright and Hennepin Counties until it empties in to the Mississippi River at the common boundary between Otsego and Dayton.

The total watershed area of the North Fork – Lower Crow River watershed is approximately 950,000 acres. Each impaired watershed is comprised of various subwatersheds that discharge to the North Fork Crow and Lower Crow Rivers. The individual impairment sections of this TMDL report include a detailed map of each impaired reach/tributary. All of the project areas are located within the North Central Hardwood Forest (NCHF), where the topography ranges from nearly flat to rolling to steep sloped.

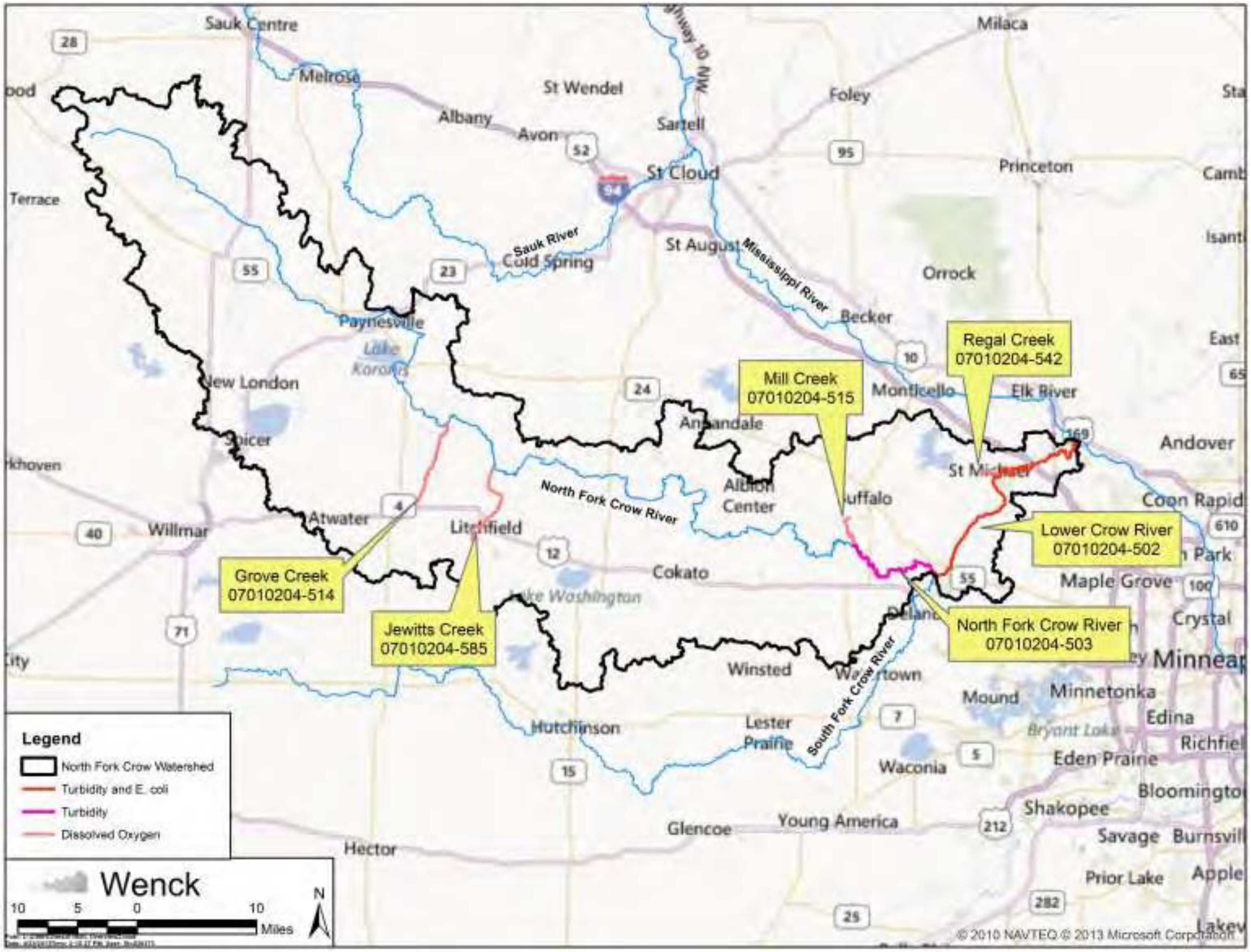

Figure 1.1. North Fork – Lower Crow River watershed impairments addressed in this TMDL study.

1.3 SUMMARY BY ECOREGIONS, AGROECOREGIONS AND LAND COVER

The majority of the watershed lies in the North Central Hardwood Forest (NCHF) ecoregion, characterized by varying landscapes of rolling hills and smaller plains (Figure 1.2). The uplands are forested by hardwoods and conifers, and the plains are livestock pastures, hay fields, and row crops. Six percent is Western Corn Belt Plains (WCP) ecoregion, characterized by fertile soils, and extensive cultivation for row crops.

An ecoregion is a geographical area where the landuse (agriculture, forest, prairie, etc.), underlying geology, potential native plant community, and soils are relatively similar. Ecoregion divisions are relatively coarse with seven ecoregions covering the entire state of Minnesota.

Advancement in land management research suggests

> "…that watershed management in highly agricultural watersheds will be most effective when hydrologic watersheds are used as a framework that is complemented by agroecoregions to identify, and target regions where specific combinations of best management practices for agricultural sediment and phosphorus abatement are most appropriate." (Hatch et. al., 2001)

The concept of agroecoregions arose out of discussions organized and funded by the Minnesota Department of Agriculture beginning in 1995 (Mulla, 2002). According to Mulla,

> "Agroecoregions are zones having unique soil, landscape, and climatic characteristics which confer unique limitations and potentials for crop and animal production. Each agroecoregion contains unique physiographic factors that influence the potential for production of nonpoint source pollution and the potential for adoption of farm management practices."

The North Fork Crow River Watershed is predominately comprised of three agroecoregions, Rolling Moraine, Steep Dryer Moraine, and Alluvium & Outwash (Figure 1.2). Table 1.1 summarizes the percentage acres by agroecoregion within the project area watershed.

Figure 1.2. Ecoregions in the North Fork Crow River Watershed.

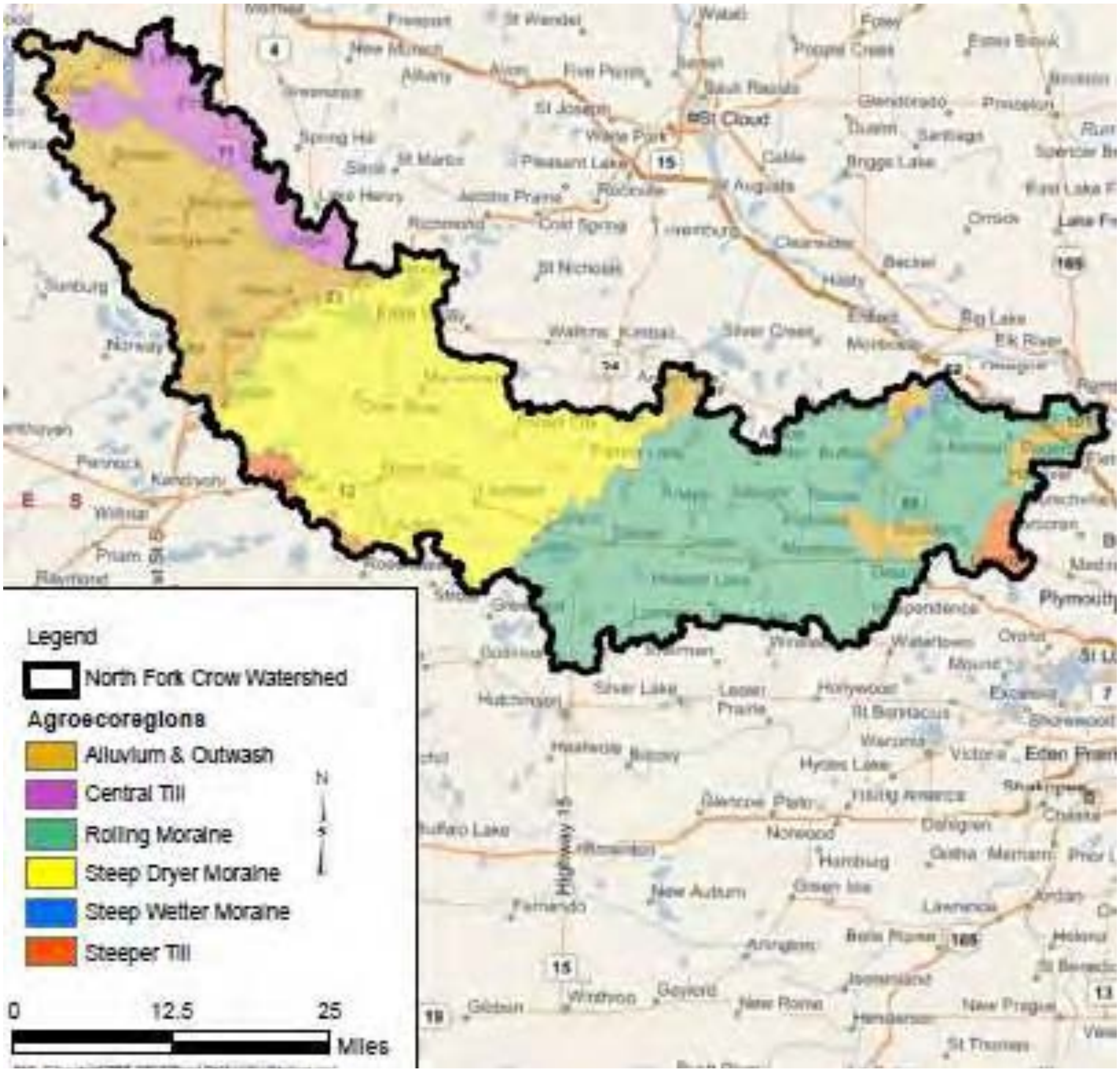

Figure 1.3. Agroecoregions in the North Fork Crow River Watershed.

Table 1.1. North Fork Crow River Watershed Agroecoregions Summary.

Agroecoregion Type	Percentage of Type
Alluvium & Outwash	21.7%
Central Till	7.7%
Rolling Moraine	37.0%
Steep Dryer Moraine	31.1%
Steep Wetter Moraine	0.3%
Steeper Till	2.2%
TOTAL	100.0%

The Alluvium & Outwash agroecoregion is located primarily in the upper reaches of the North Fork Crow River watershed. Soils are either fine-textured alluvium or coarse-textured outwash, located on flat to moderately steep slopes and generally well drained. Water erosion rates can be severe, while wind erosion can be high to severe.

The Steep Dryer Moraine agroecoregion covers the middle portions of the North Fork Crow River watershed. Most of the landscape developed from glacial moraines. Soils are predominantly loamy, on very steep slopes and well drained. Water erosion rates can be severe to extreme, while wind erosion can be moderate to severe.

The Rolling Moraine agroecoregion covers the bottom third of the North Fork Crow River watershed and is characterized by fine textured soils (loamy or sandy). The soils are well-drained located on steep to very steep slopes, having severe to extreme water erosion potential and moderate wind erosion rates.

Based on 50 years of precipitation values available from Minnesota State Climatologist for Buffalo, MN, near the center of the study area, the average annual precipitation is 29.16 inches. The average monthly distribution of precipitation is shown in Figure 1.4.

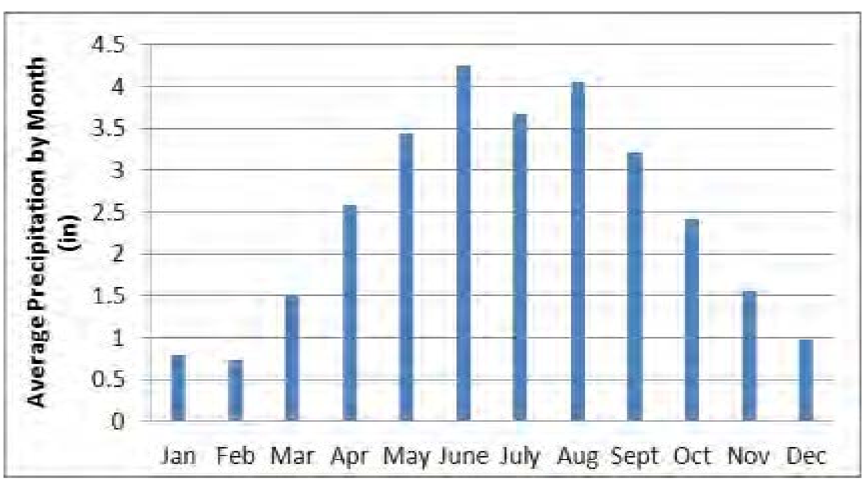

Figure 1.4. Average Monthly Distribution of Precipitation at Buffalo, MN.

1.4 LANDUSE SUMMARY

Land use for the North Fork – Lower Crow and South Fork Crow River watersheds were calculated using the 2009 National Agricultural Statistics Service GIS landcover file. The dominant landuses in both watersheds are hay and pasture and row crops (Table 1.2). The South Fork Crow River has a significantly higher percentage of corn/soybean rotations whereas the North Fork – Lower Crow River watershed has more hay and pasture land. The remaining land area is comprised of forest and shrubland, lakes and wetlands, developed land and non-corn/soybean crops.

Table 1.2. Watershed Landuse in the Crow River Watershed

	Percent of Total	
Landuse	North Fork Crow – Lower Crow Watershed	South Fork Crow Watershed
Corn/Soybeans	35%	60%
Hay and Pasture	32%	18%
Wetlands and Open Water	12%	7%
Forest and Shrubland	11%	5%
Urban/Roads	8%	8%
Grains and other Crops	2%	2%

Source: 2009 NASS landcover

1.5 IMPAIRMENT SUMMARY

This TMDL report addresses eight impairments on seven reaches in the North Fork Crow and Lower Crow River watershed. The MPCA's projected schedule for TMDL completions, as indicated on Minnesota's 303(d) impaired waters list (as noted in Table 1.3), implicitly reflects Minnesota's priority ranking of this TMDL. 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 waterbody; technical capability and willingness locally to assist with the TMDL; and appropriate sequencing of TMDLs within a watershed or basin.

Table 1.3. Impairments in the North Fork Crow and Lower Crow River watershed addressed in this TMDL.

Reach Name on 303(d) List/Description	Yr Listed	Assessment Unit ID	Affected use	Pollutant or stressor	Target start// completion
Crow River: South Fork Crow River to Mississippi River	2004	07010204-502	Aquatic recreation	Fecal coliform/*E. coli*	2006//2012
	2002		Aquatic life	Turbidity	2006//2012
Crow River: North Fork, Mill Creek to South Fork Crow River	2004	07010204-503	Aquatic life	Turbidity	2006//2012
Grove Creek: Unnamed Creek to North Fork Crow River	2004	07010204-514	Aquatic life	Low oxygen	2006//2012
Jewitts Creek (CD 19, 18, 17): Headwaters (Lake Ripley 47-0134-00) to North Fork Crow River	2004	07010204-585	Aquatic life	Low oxygen	2006//2012
Mill Creek: Buffalo Lake to North Fork Crow River	1994	07010204-515	Aquatic life	Low oxygen	2006//2012
Regal Creek: Wetland upstream of CSAH-35 in St. Michael, MN to Crow River	2004	07010204-542	Aquatic life	Low oxygen	2006//2012

[1] Reaches on 2010 303(d) impaired waters list

1.6 BENEFICIAL USE CLASSIFICATIONS

This TMDL report addresses exceedances of the state standards for bacteria, turbidity and dissolved oxygen in the North Fork Crow River watersheds of Minnesota. A discussion of beneficial water use classes in Minnesota and the standards for those classes is provided in order to define the regulatory context and explain the rationale behind the environmental result of the TMDL. All waters of Minnesota are assigned classes based on their suitability for the following beneficial uses (Minn. Rules Ch. 7050.0140 and 7050.0220):

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 resources value

A. Cold water sport fish (trout waters), also protected for drinking water
B. Cool and warm water sport fish, also protected for drinking water
C. Cool and warm water sport fish, indigenous aquatic life, and wetlands, and
D. Limited resource value waters

Classification as a 2B water is intended to protect cool and warm water fisheries, while classification as a 2C water is intended to protect indigenous fish and associated aquatic communities, a 3C classification protects water for industrial use and cooling. All surface waters classified as Class 2 are also protected for industrial, agricultural, aesthetics, navigation, and other uses (Classes 3, 4, 5, and 6, respectively). Minn. Rules Ch. 7050 contains general provisions, definitions of water use classes, specific standards of quality and purity for classified waters of the state, and the general and specific standards for point source dischargers to waters of the state.

The designated beneficial use for Class 2 waters (the most protective use class in the project area) is as follows (Minn. Rules Ch. 7050.0140):

> **Class 2 waters, aquatic life and recreation**. Aquatic life includes all waters of the state which do or may support fish, other aquatic life, bathing, boating, or other recreational purposes, and where quality control is or may be necessary to protect aquatic or terrestrial life or their habitats, or the public health, safety, or welfare.

According to Minn. Rules Ch. 7050.0470, Jewitts Creek is specifically listed as a 2C water. The remaining reaches are not listed in 7050.0470 and therefore classified as 2B, 3C, 4A, 4B, 5, and 6 waters (Minn. Rules Ch. 7050.0430). Table 1.4 summarizes the beneficial use classifications by assessment unit ID (AUID).

Table 1.4. Beneficial Use Classifications.

Reach Name on 303(d) List/Description	Assessment Unit ID	Class
Crow River: South Fork Crow River to Mississippi River	07010204-502	2B, 3C, 4A, 4B, 5, and 6
Crow River: North Fork, Mill Creek to South Fork Crow River	07010204-503	2B, 3C, 4A, 4B, 5, and 6
Grove Creek: Unnamed Creek to North Fork Crow River	07010204-514	2B, 3C, 4A, 4B, 5, and 6
Jewitts Creek (CD 19, 18, 17): Headwaters (Lake Ripley 47-0134-00) to North Fork Crow River	07010204-585	2C
Mill Creek: Buffalo Lake to North Fork Crow River	07010204-515	2B, 3C, 4A, 4B, 5, and 6
Regal Creek: Wetland upstream of CSAH-35 in St. Michael, MN to Crow River	07010204-542	2B, 3C, 4A, 4B, 5, and 6

1.7 CRITERIA USED FOR LISTING

The criteria used for determining stream reach impairments are outlined in the MPCA document Guidance Manual for Assessing the Quality of Minnesota Surface Waters for Determination of Impairment – 305(b) Report and 303(d) List, January 2010. The applicable water body classifications and water quality standards are specified in Minnesota Rules Chapter 7050. Minnesota Rules Chapter 7050.0470 lists water body classifications and Chapter 7050.0222 (subp. 5) lists applicable water quality standards for the impaired Class 2C reaches.

The information provided in the Introduction section (1.0) applies to all of the seven impaired reaches where the beneficial use is impaired by a combination of pollutants or stressors (bacteria, turbidity and/or low dissolved oxygen.) The Bacteria (2.0), Turbidity (3.0) and Dissolved Oxygen (4.0) sections present somewhat repetitive material with slight variations incorporated to specifically address the pollutant or stressor. The Implementation (5.0), Reasonable Assurances (6.0) and Public Participation (7.0) sections apply to all of the impairments.

2.0 Bacteria Impairment

2.1 FECAL COLIFORM BACTERIA AND *E. coli* OVERVIEW

Fecal coliform bacteria are an indicator organism, meaning that not all the species of bacteria of this category are harmful but are usually associated with harmful organisms transmitted by fecal contamination. They are found in the intestines of warm-blooded animals, including humans. The presence of fecal bacteria in water suggests the presence of fecal matter and associated bacteria (i.e. some strains of *E. coli*), viruses, and protozoa (i.e. Giardia and Cryptosporidium) that are pathogenic to humans when ingested (USEPA 2001). The decision to list the reaches identified was originally based on a fecal coliform standard, which was in effect prior to the most recent rule revision in 2008.

The fecal coliform standard contained in Minn. Rules Ch. 7050.0222 subpart 5, fecal coliform water quality standard for Class 2B waters, states that fecal coliform concentrations shall "not exceed 200 organisms per 100 milliliters as a geometric mean of not less than five samples in any calendar month, nor shall more than ten percent of all samples taken during any calendar month individually exceed 2000 organisms per 100 milliliters. The standard applies only between April 1 and October 31." Impairment assessment is based on the procedures contained in the Guidance Manual for Assessing the Quality of Minnesota Surface Waters for Determination of Impairment (MPCA 2005).

With the revisions of Minnesota's water quality rules in 2008, the state changed to an *E. coli* standard because it is a superior potential illness indicator and costs for lab analysis are less (MPCA 2007). The revised standards now state:

"*E. coli* concentrations are not to exceed 126 organisms per 100 milliliters as a geometric mean of not less than five samples representative of conditions within any calendar month, nor shall more than ten percent of all samples taken during any calendar month individually exceed 1,260 organisms per 100 milliliters. The standard applies only between April 1 and October 31"

The *E. coli* concentration standard of 126 cfu/100 ml was considered reasonably equivalent to the fecal coliform standard of 200 cfu/100 ml from a public health protection standpoint. The SONAR (Statement of Need and Reasonableness) section that supports this rationale uses a log plot to show the relationship between these two parameters. The relationship has an r^2 value of 0.69. The following regression equation was deemed reasonable to convert fecal coliform data to *E. coli* equivalents:

$$E\ coli \text{ Concentration (equivalents)} = 1.80 \times (\text{Fecal Coliform Concentration})^{0.81}$$

2.2 OVERVIEW OF *E. coli* IMPAIRED REACH AND WATERSHED

This TMDL applies to the *E. coli* bacteria impairment for the Lower Crow River from its junction with the South Fork Crow River to its outflow to the Mississippi River (Figure 2.1). Data from the Crow River's primary monitoring stations in this reach served as the basis of the impairment determination and were used to support development of the TMDL.

2.3 WATERSHED LANDUSE

Land use for the watershed draining directly to the Lower Crow River *E. coli* impaired reach and the North Fork Crow River upstream of the impaired reach was calculated using the 2009 National Agricultural Statistics Service (NASS) GIS landcover file (Table 2.1). Land use in both watersheds is primarily hay and pasture and corn and soybean rotations. The remaining land area is comprised of forest and shrubland, lakes and wetlands, developed land and non-corn/soybean crops.

Table 2.1. Landuse summary in the North Fork Crow watershed and Lower Crow River impaired reach direct watershed (2009 NASS)

Landuse	Percent of Total	
	[1]Lower Crow River Watershed	[2]North Fork Crow River Watershed
Hay and Pasture	38%	32%
Corn/Soybeans	18%	37%
Forest and shrubland	15%	11%
Wetlands and Open Water	14%	11%
Urban/Roads	13%	7%
Grains and other Crops	2%	2%

[1] Only includes Lower Crow River impaired reach watershed downstream of North Fork Crow and South Fork Crow Rivers
[2] Includes North Fork Crow River watershed upstream of Lower Crow River impaired reach

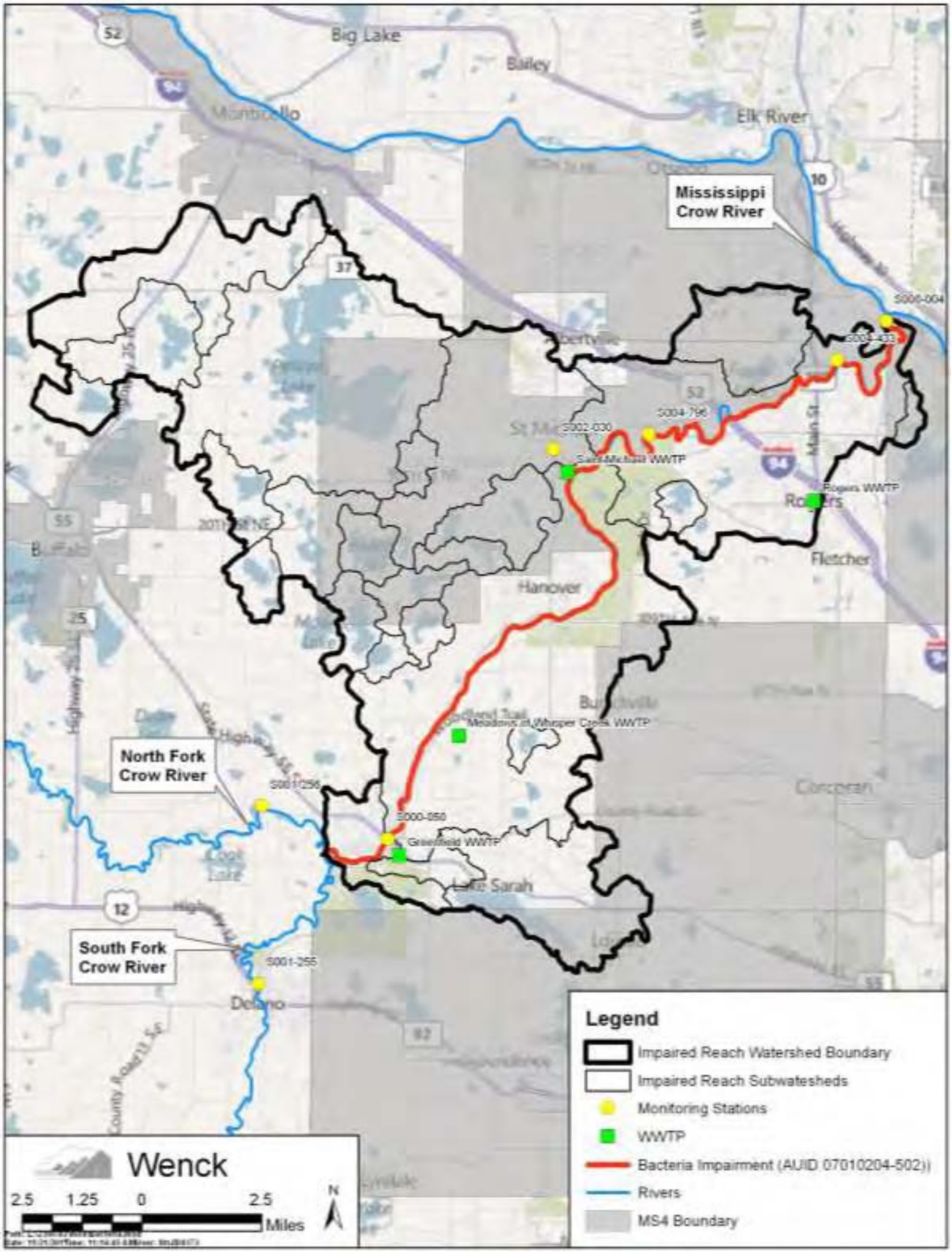

Figure 2.1. Lower Crow River *E. coli* impaired reach watershed, sampling locations and wastewater treatment facilities.

2.4 DATA SOURCES FOR LOWER CROW RIVER

2.4.1 STORET Data

The bacteria data used for the development of this TMDL are grab samples collected by multiple agencies over the past 10 years during the bacteria index period (April 1 through October 31). Although data prior to this period exists, the more recent data better represent current conditions in the watershed. Samples were analyzed for fecal coliform prior to 2004 and more recently *E. coli*. During some sampling events, both parameters were analyzed (Table 2.2). Figure 2.1 shows the location of the monitoring stations at which samples were collected to support this TMDL. All data were obtained through Minnesota Pollution Control Agency's STORET online database.

Table 2.2. Lower Crow River bacteria sampling 2000-2009.

STORET ID	River	Location	Parameter	Number of Samples	Years	Paired
S000-004	Lower Crow Main-Stem	CSAH 36 Crossing	Fecal Coliform	2	2000	10
			E. coli	29	2000 - 2007	
S004-433	Lower Crow Main-Stem	53rd St NE Crossing	Fecal Coliform	0	NA	none
			E. coli	10	2007	
S004-796	Lower Crow Main-Stem	CSAH 116 Crossing	Fecal Coliform	0	NA	none
			E. coli	32	2008 - 2009	
S000-050	Lower Crow Main-Stem	MN Hwy 55 Crossing	Fecal Coliform	14	2001	8
			E. coli	8	2002	
S002-030	Lower Crow Tributary	Regal Creek at CSAH 19	Fecal Coliform	1	2003	none
			E. coli	44	2007 – 2009	
S001-256	N. Fork Crow Main-Stem	Farmington Ave Crossing	Fecal Coliform	12	2001 – 2003	7
			E. coli	60	2002 – 2009	
S001-255	S. Fork Crow Main-Stem	Bridge Ave Crossing	Fecal Coliform	5	2001 - 2003	none
			E. coli	43	2007 - 2009	

Note: Only samples collected during the index period (April through October) were included in this report.

It should be noted that four of the seven monitoring sites in Table 2.2 are located on the bacteria impaired reach of The Crow River. The S002-030 site is located on a tributary to the main-stem near St. Michael, Minnesota. Stations S001-256 and S001-255 (North and South Fork Crow Rivers, respectively) are located upstream of the listed reach but appear to be ~~a~~ major contributors to the lower reach impairment and will be included in the source assessment portion of this report.

2.4.2 Streamflow Data

Stream flow data was crucial to support development of the bacteria allocations for this TMDL. Streamflow data paired with bacteria measurements allow bacteria exceedances to be evaluated by flow regime which, in turn provides insight into potential sources.

There are three stations in/or upstream of the bacteria impaired reach watershed with continuous flow data since 2000 (Table 2.3). There is one USGS flow monitoring station (S000-050) on the

Lower Crow River located at the Highway 55 crossing in Rockford, MN (Figure 2.1). It should be pointed out that this station is located near the upstream boundary of the Lower Crow River impaired reach rather than its outlet to the Mississippi River. In order to simulate flow to the end of the reach, USGS measured flows were multiplied by the watershed ratio (area) of the entire Crow River and the amount draining to the USGS monitoring station. The MPCA has also monitored continuous flow at stations S001-256 and S001-255 near the outlets of the North Fork Crow River and South Fork Crow River, respectively.

Table 2.3. Flow monitoring stations within (and nearby) the Lower Crow River Watershed.

STORET ID	Location	DNR ID	USGS ID	Flow Provider	Years of Operation since 2000	Flow Record Length (Days)	Notes
S000-050	Crow River at MN Hwy 55	18087001	05280000	USGS	00-09	32,023	In listed Reach
S001-256	N. Fork Crow River at Farmington Ave	18088001	05278400	DNR/MPCA	02; 04-06	680	Outside listed reach
S001-255	S. Fork Crow River at Bridge St	19001001	05279400	DNR/MPCA	03, 05, 06, 08	1,083	Outside listed reach

2.5 IMPAIRMENT OVERVIEW BY REACH AND SEASON

Data from the four monitoring sites on the Lower Crow River bacteria impaired reach were analyzed to help determine spatial and seasonal variability of bacteria violations. Since the bacteria standard is now expressed as *E. coli*, all fecal coliform data was converted to *E. coli* "equivalent" values using the equation discussed in section 2.1. These data were combined with *E. coli* data collected since 2004 to develop the database for developing allocations. *E. coli* is presented over *E. coli* equivalent data when both fecal coliform and *E. coli* samples were collected on the same day.

Listing criteria requires *E. coli* concentrations not to exceed 126 cfu/ 100 ml as a geometric mean of not less than five samples representative of conditions within any calendar month. Since 2000, stations S004-796 (June) and S000-004 (September) were the only stations with 5 or more samples exceeding the monthly *E. coli* geomean standard. Station S000-050 June and August monthly geomeans exceeded the *E. coli* standard, however there were less than 5 samples collected in each of these months (4 samples in June and 3 in August). None of the monthly geomeans exceed 126 cfu/ 100 ml when *E. coli* measurements from all sampling stations are combined in to one dataset (Figure 2.2).

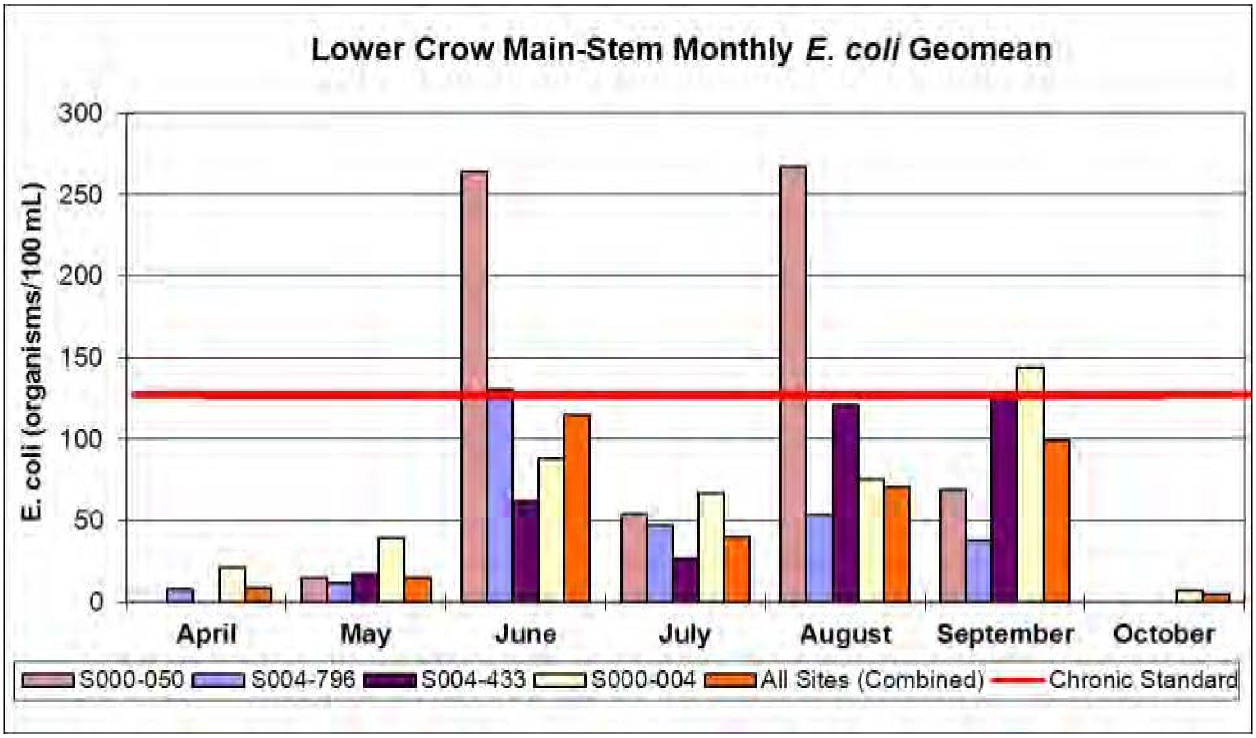

Figure 2.2. Monthly E. coli geomeans for each monitoring station in the Lower Crow River impaired reach.

Listing criteria also requires that no more than 10% of samples for any given month exceed the "acute" standard of 1,260 cfu/ 100 ml. Table 2.4 shows there has been a total of five *E. coli* samples on the Lower Crow River that have exceeded 1,260 cfu/ 100 ml.

Table 2.4. Individual E. coli exceedances 2000-2009.

Site	Samples	Chronic Exceedances (Count)	Acute Exceedances (Count)	Acute Exceedances (Month)
S000-050	14	6	2	June-2002 August-2001
S004-796	32	5	2	June-2008 August-2009
S004-433	10	2	0	NA
S000-004	31	3	1	September-2005
Total	87	16	5	

2.6 ALLOCATION METHODOLOGY

2.6.1 Overview of Load Duration Curve Approach

Assimilative capacities for each reach were developed from load duration curves (Cleland 2002). Load duration curves assimilate flow and *E. coli* data across stream flow regimes and provide assimilative capacities and load reductions necessary to meet water quality standards.

A flow duration curve was developed using the 20-year (1990-2009) average daily flow record from the Rockford USGS station (S000-050). This period was chosen because it balances a reasonably long period of record with hydrologic conditions reflective of current landuse. The curved line relates mean daily flow to the percent of time those values have been met or exceeded (Figure 2.3). For example, at the 50% exceedance value, the river was at 570 cubic feet per second or greater 50% of the time. The 50% exceedance is also the midpoint or median flow value. The curve is then divided into flow zones including very high (0-10%), high (10-40%), mid (40-60%), low (60-90%) and dry (90 to 100%) flow conditions.

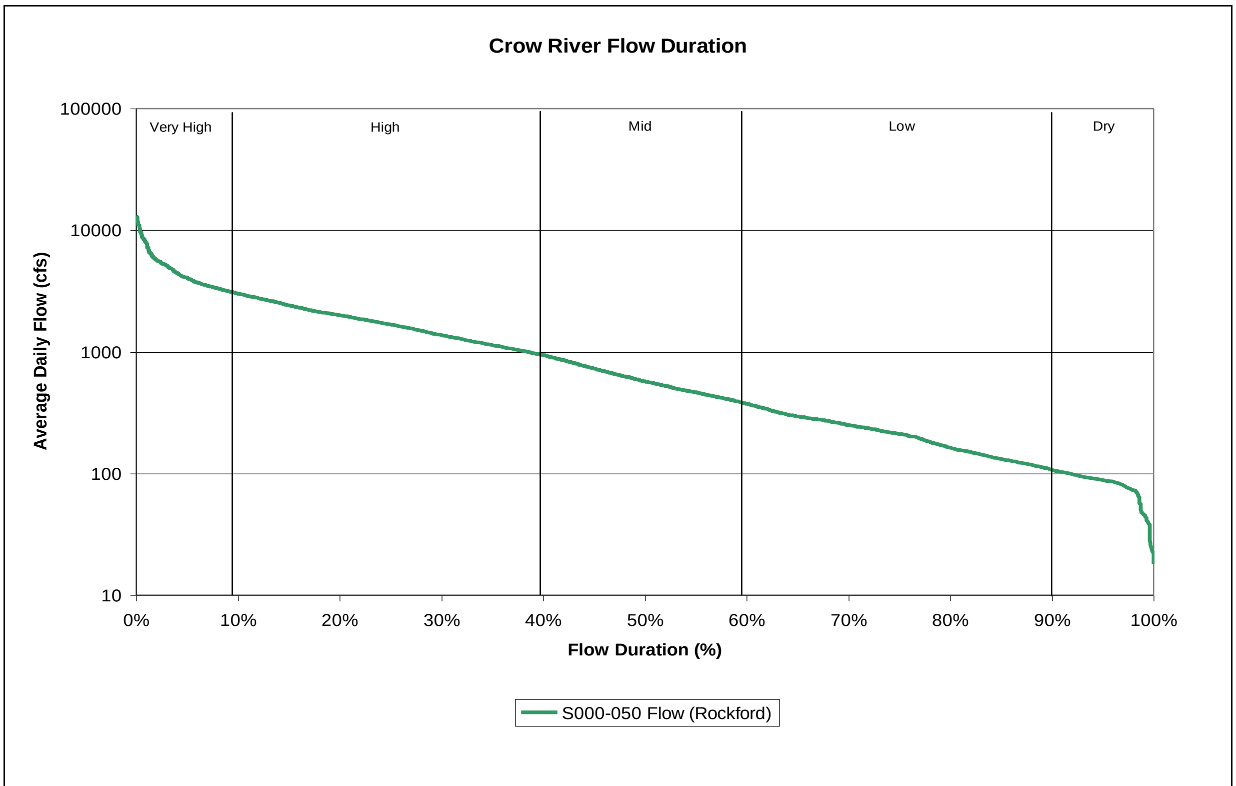

Figure 2.3. Flow duration curve for the Rockford USGS station (S000-050) since 1990.
Note: This curve is based on continuous average daily flow data over the past 20 years (1990-2009).

The *E. coli* listing criteria is based on analyzing monitored grab samples in terms of monthly geomeans from April through October. Thus, it is more appropriate to create load duration curves for this time period using average monthly flow, not average daily flow. To do this, average monthly flows (represented in cfs) for the 20-year flow record were calculated for April through October only and multiplied by the chronic *E. coli* standard (126 cfu/ 100 ml). This value was then converted to a daily load in billions of cfu/100 ml per day (Figure 2.4). Now the line represents the assimilative capacity of the stream for each month represented as average daily flow. To develop the TMDL, the median load of each flow zone is used to represent the total daily loading capacity (TDLC) for that flow zone.

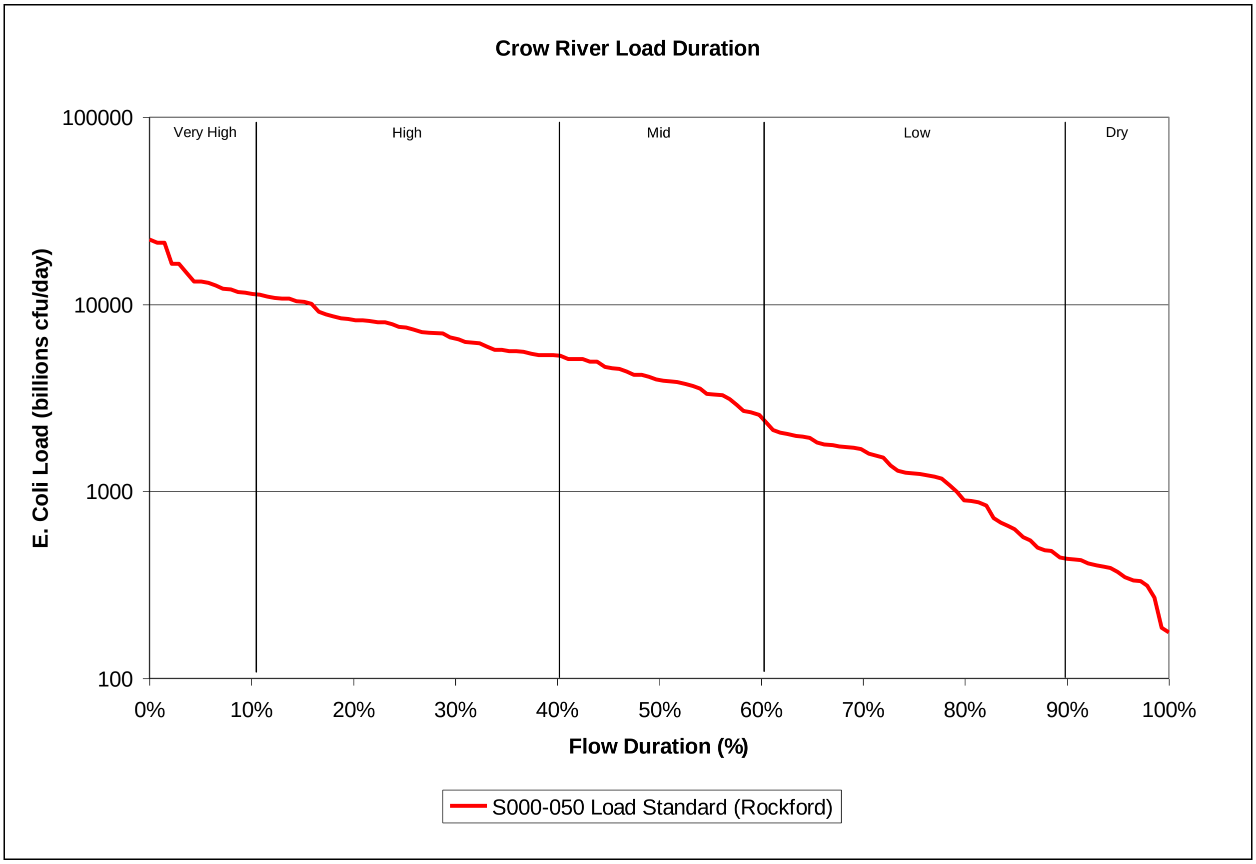

Figure 2.4. Rockford USGS station (S000-050) *E. coli* load duration curve.
Note: The curve represents the maximum allowable daily *E. coli* load (based on the 126 cfu/100 ml *E. coli* standard) and were developed using monthly flows (represented as average daily flow in cfs) from April through October over the past 20 years.

2.6.2 Margin of Safety

The margin of safety (MOS) accounts for uncertainties in both characterizing current conditions and the relationship between the load, wasteload, monitored flows and in-stream water quality. The purpose of the MOS is to account for uncertainty so the TMDL allocations result in attainment of water quality standards. An explicit MOS equal to 10% of the total load was applied where10% of the loading capacity for each flow regime was subtracted before allocations were made among wasteload and non-point sources. A similar MOS approach was applied in the Groundhouse River Bacteria TMDL (MPCA 2009).

2.6.3 South Fork Crow River Boundary Condition

The lower portion of the South Fork Crow River (AUID 07010204-502) from Buffalo Creek to its confluence with the North Fork Crow River is currently impaired for fecal coliform and will be addressed in a future TMDL study. Thus, the entire South Fork Crow River upstream of the Lower Crow River is considered a boundary condition in this TMDL study. This report does not calculate or assign allocations to wasteload and non-point sources in the South Fork Crow River watershed. The South Fork Crow River watershed represents approximately 46% of the entire Crow River watershed (Table 2.5). The load allocation for the South Fork Crow River boundary condition was calculated by multiplying the South Fork's watershed fraction (46%) by the Crow River's total loading capacity after the margin of safety was subtracted (Table 2.8). The load will be refined as a part of the South Fork Crow River Watershed Restoration and Action Plan that is currently in development.

Table 2.5. Crow River watershed descriptions.

Watershed	Description	Size (acres)	Percent of Total
South Fork Crow River	SFC River watershed upstream of Lower Crow River bacteria impaired reach	794,086	46%
North Fork Crow River	NFC River watershed upstream of Lower Crow River bacteria impaired reach	861,225	49%
Lower Crow River	Lower Crow River impaired reach direct watershed downstream of NFC and SFC River confluence	88,689	5%
TOTAL	Entire Crow River Watershed	1,744,000	100%

2.6.4 North Fork and Lower Crow River Wasteload Allocations

Wasteload allocations in the North Fork Crow and Lower Crow River watersheds were divided into two categories: permitted wastewater dischargers and Municipal Separate Storm Sewer Systems (MS4). The following sections describe how each of these load allocations was estimated.

2.6.4.1 NPDES Wastewater Dischargers

There are twenty active NPDES wastewater dischargers in the North Fork Crow - Lower Crow River watershed (Table 2.6). Load allocations for continuous wastewater sources were calculated by multiplying the facility's influent design flow by the *E. coli* standard (126 cfu/100 ml). Stabilization pond facilities only discharge a few times a year, so effluent volumes greatly exceed daily influent flows. Effluent volumes for these facilities were calculated by multiplying the ponds' surface area, volume and average daily drawdown (typically 6 inches per day) during discharge. Current discharge design flows for each permitted wastewater source were provided by the MPCA and presented in Table 2.6.

Table 2.6. Description of NPDES wastewater dischargers and E. coli allocations for the Lower Crow River impaired reach.

Facility Name	NPDES ID#	Location	Facility Type	Effluent Design Flow (MGD)	Allocated Load (billions organisms/day)
Facilities located in the North Fork Crow River Watershed above impaired reach					
Annandale/Maple Lake/Howard Lake WWTP	MN0066966	NFC	continuous	1.18	5.7
Atwater WWTP	MN0022659	NFC	pond	1.38	6.6
Belgrade WWTP	MN0051381	NFC	pond	1.48	7.1
Brooten WWTP	MN0025909	NFC	pond	1.06	5.1
Buffalo WWTP	MN0040649	NFC	continuous	3.60	17.2
Cokato WWTP	MN0049204	NFC	continuous	0.73	3.5
Darwin WWTP	MNG580150	NFC	pond	0.33	1.6
Dassel WWTP	MN0054127	NFC	pond	1.22	5.8
Green Lake SSWD WWTP	MN0052752	NFC	continuous	0.89	4.2
Grove City WWTP	MN0023574	NFC	continuous	0.22	1.1
Litchfield WWTP	MN0023973	NFC	continuous	2.37	11.3
Montrose WWTP	MN0024228	NFC	continuous	0.78	3.7
Paynesville WWTP	MN0020168	NFC	pond	1.47	4.2
Rockford WWTP	MN0024627	NFC	continuous	0.65	3.1
Saint Michael WWTP	MN0020222	NFC	continuous	2.45	11.7
South Haven WWTP	MN0064611	NFC	continuous	0.03	0.1
Facilities located in the Lower Crow River Watershed (AUID 07010204-502)					
Greenfield WWTP	MN0063762	Lower Crow	continuous	0.20	1.0
Meadows of Whisper Creek WWTP	MN0066753	Lower Crow	continuous	0.02	0.1
Otsego East WWTP	MN0064190	Lower Crow	continuous	1.65	7.9
Rogers WWTP	MN0029629	Lower Crow	continuous	1.60	7.6
NPDES Permitted Total				**23.31**	**108.6**

Note: TMDL allocations include all facilities located in the North Fork-Lower Crow River watershed and upstream of the impaired reach.

Discharge monitoring reports (DMRs) were downloaded to assess the typical monthly bacteria geomean concentrations at which each facility discharges. It should be noted that NPDES wastewater permit limits for bacteria are currently expressed in fecal coliform concentrations, not *E. coli*. However, the fecal coliform permit limit for each wastewater treatment facility (200 organisms/100 ml) is equivalent to this TMDL's 126 organism/100 ml *E. coli* criterion. The fecal coliform-*E. coli* relationship is documented extensively in the SONAR for the 2007-2008 revisions of Minnesota Rule Chapter 7050.

2.6.4.2 MS4

There are 12 Municipal Separate Storm Sewer Systems (MS4s) that are completely within or have a portion of their municipal boundary in the North Fork Crow - Lower Crow River watershed (Table 2.5; Figure 2.1). There are two additional municipalities, Rogers and Albertville who, according to MPCA rules, now require NPDES permits since their population exceeded 5,000 in the 2010 census. Stormwater from Rogers, Albertville and the 12 MS4 communities drains to the impaired reaches discussed in this report and are therefore assigned WLAs.

For this TMDL, MS4 allocations were calculated using the following equation for urban runoff (MPCA, 2008):

$Q = C\, iA$

Where:
Q = peak runoff rate (in cfs)
C = runoff coefficient
i = rainfall (inches per hour)
A = urbanized area (acres)

This equation is intended to estimate runoff from small sites but was used here because it is a simple equation with minimal inputs that should account for higher runoff rates in urban areas. 2009 NASS landuse data indicate approximately 24% of the land within the North Fork Crow and Lower Crow MS4/municipality boundaries is currently "developed". The developed land was assigned typical runoff coefficients according to the MPCA's Stormwater Manual (MPCA 2008). An aggregate MS4 runoff coefficient was then determined by calculating an area-weighted mean runoff coefficient of the developed land within the MS4/municipality boundaries. This approach yielded an area weighted runoff coefficient of 0.51 which represents a mixture of multi and single family residential landuse. This coefficient is intended to account for future growth within the 14 cities/MS4s which ultimately provides reserve capacity.

Monthly rainfall totals for the past 20 years from April through October were downloaded from the Minnesota State Climatology Office website for the Rockford Weather station (http://climate.umn.edu) to represent watershed rainfall (i). MS4 areas (A) were calculated in GIS by clipping the MPCA's MS4 municipality shapefiles (www.pca.state.mn.us/) to the North Fork Crow - Lower Crow River watershed boundary. Monthly runoff volumes for each MS4 were calculated for the entire 20-year period in which flow monitoring data was available. The 20-year estimated runoff volume for the MS4 coverage area was then divided by total observed flow at the outlet of the Crow River over the past 20 years to estimate the total MS4 runoff fraction. This value was used to calculate the proportion of the Crow River's total loading capacity allocated to each MS4 (Table 2.7).

Table 2.7. Summary of Permitted MS4s in the Lower Crow River Watershed.

MS4	Permit #	Area (acres)	*E. coli* Allocation (billions organisms/day)				
			Very High	High	Mid	Low	Dry
Hennepin County MS4	MS 400138	52	0.3	0.2	0.1	<0.1	<0.1
Loretto City MS4	MS 400030	95	0.5	0.3	0.2	<0.1	<0.1
Corcoran City MS4	MS 400081	1,211	6.8	3.9	2.0	0.6	0.2
Dayton City MS4	MS 400083	754	4.2	2.4	1.3	0.4	0.1
Independence City MS4	MS 400095	2,182	12.2	7.0	3.6	1.2	0.3
Medina City MS4	MS 400105	425	2.4	1.4	0.7	0.2	<0.1
Buffalo City MS4	MS 400242	5,706	32.0	18.2	9.5	3.0	0.9
Monticello City MS4	MS 400242	76	0.4	0.2	0.1	<0.1	<0.1
Otsego City MS4	MS 400243	2,709	15.2	8.7	4.5	1.4	0.4
St Michael City MS4	MS 400246	22,927	128.6	73.2	38.2	12.1	3.6
MNDOT Metro District MS4	MS 400170	52	0.3	0.2	<0.1	<0.1	<0.1
Litchfield City MS4	MS 400253	3,435	19.3	11.0	5.7	1.8	0.5
Albertville City	None	1,486	8.3	4.8	2.5	0.8	0.2
Rogers City	None	2,071	11.6	6.6	3.5	1.1	0.3
MS4 Totals		**43,181**	**242.1**	**138.1**	**71.9**	**22.8**	**6.8**

2.6.5 North Fork and Lower Crow River Source Load Allocations

The load allocation is the remaining load after the MOS and all upstream boundary conditions and wasteload allocations are subtracted from the total load capacity of each flow zone. The load allocation includes non-MS4 urban runoff, agricultural runoff, and natural background contributions. Although the TMDL does not explicitly assign allocations to each of these sources, a detailed analysis of the role of each of these sources is provided in Section 2.9. The North Fork Crow River watershed (upstream of the listed reach) and the Lower Crow River watershed load allocation were calculated by multiplying the total non-point source load by the watershed percentages presented in Table 2.5.

2.7 TOTAL MAXIMUM DAILY LOADS

Table 2.8 presents the total loading capacity, margin of safety, wasteload allocations and the remaining load allocations for the North Fork Crow and Lower Crow River watersheds. The table also presents all load allocations in terms of the percent of total loading capacity in each flow category.

Table 2.8. Lower Crow E. coli impaired reach TMDL load allocations for each flow zone.

Crow River 07010204-502		Flow Zones				
		Very High	High	Mid-Range	Low	Dry
		E. Coli Load (billions of organisms/day)				
Total Daily Loading Capacity		13,671	7,784	4,061	1,290	383
Margin of Safety (MOS)		1,367	778	406	129	38
Upstream Boundary Condition (S Fork Crow River)		5,602	3,190	1,664	528	157
Wasteload Allocations	NPDES Wastewater Dischargers	109	109	109	109	109
	MS4 Communities	242	138	72	23	7
Load Allocation	N Fork Crow River	5,758	3,236	1,641	454	65
	Lower Crow River	593	333	169	47	7
Value expressed as percentage of total daily loading capacity						
Total Daily Loading Capacity		100%	100%	100%	100%	100%
Margin of Safety (MOS)		10%	10%	10%	10%	10%
Upstream Boundary Condition (S Fork Crow River)		41%	41%	41%	41%	41%
Wasteload Allocation	NPDES Wastewater Dischargers	<1%	1%	3%	8%	28%
	Lower Crow MS4 Communities	2%	2%	2%	2%	2%
Load Allocation	N Fork Crow River	42%	42%	40%	35%	17%
	Lower Crow River	4%	4%	4%	4%	2%

2.8 IMPACT OF GROWTH ON ALLOCATIONS

2.8.1 Point Sources

As discussed in Section 2.6.1, this TMDL study uses the load duration curve method to determine the loads required to attain water quality standards. This method uses river flows to determine the allowable loads of *E. coli* during different flow conditions. One concern that arose in the development of the TMDLs is if and how new or expanded dischargers could increase discharges, and under what conditions.

For *E. coli*, the in-stream water quality criteria and required effluent limits contained in MPCA NPDES permits are identical. A study by Tetratech (Cleland, 2011), illustrates the impact of new or expanding dischargers of total suspended solids (TSS) in an impaired waterbody. Although the study focuses on TSS in the Zumbro River, the process is similar for *E. coli* in the North Fork Crow River. The study demonstrates that TSS discharges from the facilities, which have concentrations below the in-stream targets, actually provide assimilative capacity and contribute to lower in-stream TSS concentrations. For *E. coli* in the North Fork Crow River, the facilities are discharging at the water quality criteria, and actually discharging well-below the effluent limit.

The WLAs presented in this TMDL are based upon current discharges (Table 2.6). However, facilities will certainly expand in the future, and it is likely that new NPDES-permitted facilities will be located in the watershed, and therefore changes will occur in the allocations. For the non-stormwater facilities, the NPDES permits limit the discharge effluent to at/below the in-stream *E. coli* criteria. When a facility expands, it will increase both load and flow. This will raise (increase) the load duration curve based upon the amount of "new" flow and load. This effect will be most pronounced in lower flows, when conventional point sources have the greatest impact. The increased flow will effectively increase the overall assimilative capacity of the river, as the flow increase will likely be larger proportionally than the load increase.

The analysis summarized above demonstrates that current discharges can be expanded and new NPDES discharges can be added and will not degrade *E. coli* concentrations but will likely help reduce in-stream *E. coli* concentrations, provided the permitted NPDES discharges remain at/below the in-stream targets. Based on this circumstance, a streamlined process is envisioned for updating the TMDL wasteload allocations when there are new or increased discharges of discharges where the permits ensure the *E. coli* concentrations are at/below the in-stream targets. The process envisioned for updating TMDL WLAs is summarized blow. This process will apply to the non-stormwater facilities identified in Table 2.6 of this TMDL study.

1. A new or expanding discharger would file with the MPCA permit program a permit modification request or an application for a permit reissuance. The permit application information would include documentation of the current and proposed future flow quantities, from which, taking into account the permitted discharge concentrations, the future *E. coli* loads.
2. The MPCA permit program will notify the MPCA TMDL program upon receipt of the request/application, and provide the appropriate information, including the proposed discharge flow.
3. Assuming the NPDES program finds the permit issuance or modification is approvable, the MPCA permit program will prepare a draft permit and a fact sheet. [Need to decide how to handle minors, for which a fact sheet might normally not be prepared.] The fact sheet will include information on future discharge volumes and a discussion summarizing the future growth analysis presented above. A short discussion will be included noting

that for *E. coli*, the effluent limit is at/below the instream *E. coli* target and the increased discharge will protect water quality with respect to pathogens. The Fact Sheet would include a table showing the new loading capacity of the river and the new WLA. The Fact Sheet would state that the TMDL will be updated in conjunction with the permit action. This provides a public notice of the update to the WLA, along with the permit. Stakeholders will, per usual, have the opportunity to comment on the proposed permit and the update to the WLA.

4. The MPCA permit program will notify the EPA TMDL program of the proposed action at the very beginning of the public comment period, and send a copy of the permit fact sheet. The permit program will also ensure the MPCA TMDL program receives a copy of the fact sheet.
5. EPA (both the permit program and TMDL program) will review the Fact Sheet and provide any comments to MPCA as soon as possible.
6. MPCA will consider any comments provided by EPA and by stakeholders/interested parties on the proposed permit action and the update to the WLA. If EPA offered no adverse comments and no adverse comments on the WLA update were received from stakeholders/ interested parties, MPCA will proceed with the permit action. If there are adverse comments on the WLA update, MPCA will consult with U.S. EPA. Comments on the TMDL would need to be addressed by MPCA before proceeding further.
7. EPA will notify MPCA that the update to the TMDL is approved after confirming that either no TMDL comments were received or all TMDL comments have been appropriately addressed. This notification will occur as soon as possible after the confirmation is completed.
8. EPA will document the revision in the administrative record for the TMDL. Through this process EPA will maintain an up-to-date record of the applicable WLA for permitted facilities in the watershed.

EPA will document the revision in the administrative record for the TMDL. Through this process EPA will maintain an up-to-date record of the applicable WLA for permitted facilities in the watershed.

2.8.2 Municipal Storm Sewer Systems

There are currently 12 MS4s and 2 additional cities in the North Fork Crow and Lower Crow River watersheds that require or will require NPDES permits. There are no current plans to expand or develop MS4 communities in the watershed for the foreseeable future. However, future transfer of loads in this TMDL may be necessary if any of the following scenarios occur within the North Fork Crow and Lower Crow River 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. Ultimately, increases in urban stormwater also increase the loading capacity of the receiving water thereby supplying their own increases in receiving water assimilative capacity. Consequently, as long as stormwater discharges are held to the current 126 cfu/100 ml *E. coli* standard, increases in stormwater will not impact attainment of the water quality standards.

2.8.3 Agriculture Practices

The amount of land in agricultural land use in the North Fork Crow-Lower Crow River watershed is likely to remain fairly constant over the next several decades. The watershed is comprised mainly of row crops (corn and soybeans) with some land used for pasture and hay. While the majority of the landscape is likely to remain in an agricultural land use, it is possible a modest shift between pasture/hay and row crops may occur. Any such shift would likely not affect the loading capacity of the stream, since that capacity is based on long-term flow records over which time land use changes have likely occurred. Thus, slight shifts in land use should not appreciably change the magnitude of the land use runoff variability that the period of record already reflects.

2.9 POLLUTANT SOURCE ASSESSMENT

This section is intended to present information that is helpful in identifying the potential sources of elevated bacteria concentrations in the Lower Crow River impaired reach watershed. The first section addresses seasonal influences and looks at the relationships between elevated bacteria concentrations and flow. The second section addresses the potential influence of tributary and the major upstream river inflows to this reach. The final section contains estimates of the potential sources of bacteria available for transport by source category for the Lower Crow River watershed.

2.9.1 Exceedances by Season and Flow Regime

Individual *E. coli* samples show exceedances during summer and fall but rarely in the spring (Figure 2.5). April and May are usually the months with the lowest bacteria concentrations, despite the fact that there is little crop canopy cover, surface runoff is typically high and there is often significant manure application during this time. This suggests seasonality of bacteria concentrations are also influenced by stream water temperature. Fecal bacteria are most productive at temperatures similar to their origination environment in animal digestive tracts.

Thus, these organisms are expected to be at their highest concentrations during the warmer summer months when water temperatures are highest. High *E. coli* concentrations continue in to the fall which may be attributed to additional applications of manure. It is important to note that although manure is not typically applied to cropland from June 1 through October 1, manure may be applied to pastures either through spreading or direct application from the animals. Consequently, summer allocations during runoff events are likely related to pasture management rather than cropland.

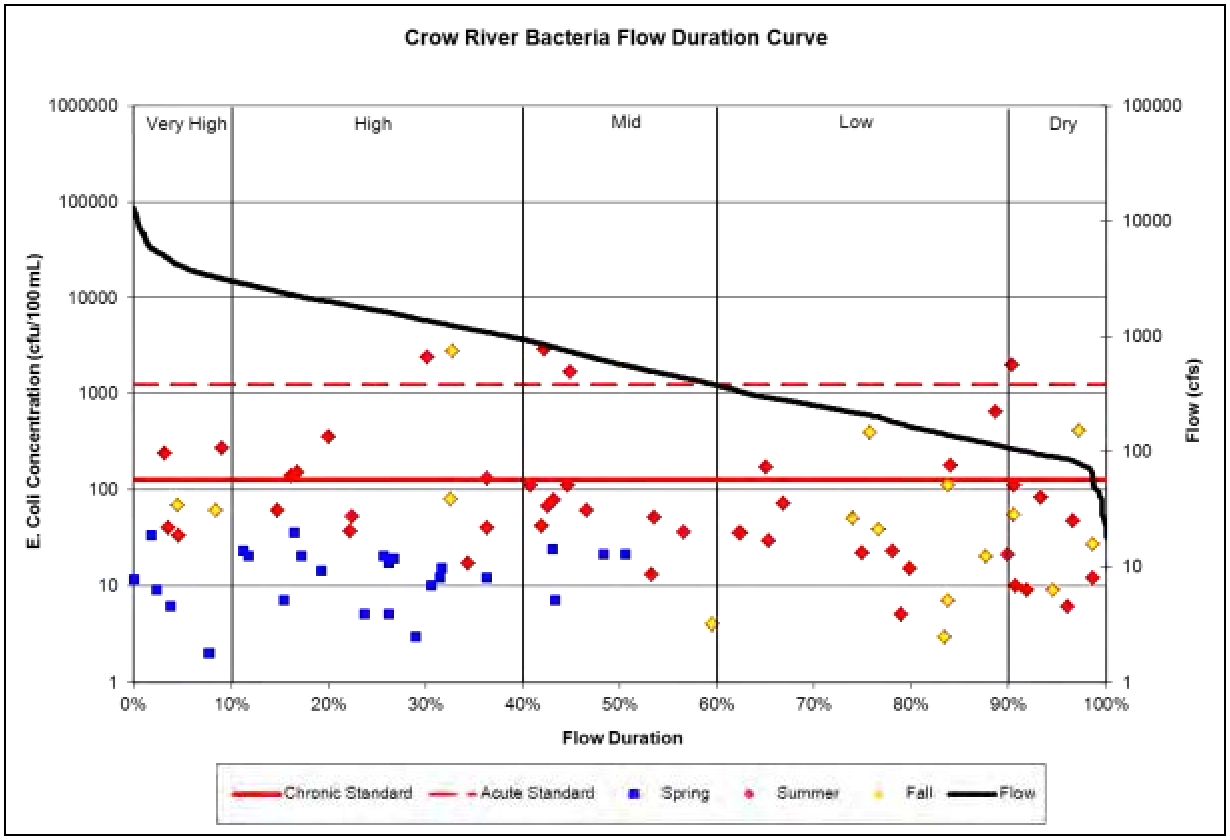

Figure 2.5. Individual E. coli measurements in the Lower Crow River impaired reach plotted by season and flow regime.
Note: Flow frequencies were developed using average daily flows over the past 20 years from the USGS monitoring station in Rockford, MN. Fecal coliform and *E. coli* data (2000-2009) from five monitoring stations within the listed reach were combined and plotted as one dataset. All fecal coliform measurements were converted to *E. coli* equivalents using the regression equation discussed in section 2.1.

The relationship between flow and bacteria concentrations aid in identifying potential sources of elevated bacteria concentrations. Table 2.9 shows the conceptual relationship between flow and loading sources under various flow conditions. Under low flows, runoff processes are minimal as bacteria concentrations are primarily driven by wastewater treatment plants, failing SSTS, SSTS systems with “straight pipe” connections to tile or storm drains and animals in or near the receiving water. Conversely, at high flows, runoff from land with bacteria concentrations such as feedlots, urban areas and cropland often dominate. Violations appear to occur across all flow regimes in the bacteria-listed reach of the Lower Crow River. This suggests that, at times, all of the aforementioned flow-driven sources may contribute to high bacteria concentrations observed throughout this reach.

Table 2.9. Conceptual Relationship between Flow Regime and Potential Pollutant Sources.

Point Source Contributing Source Area	Flow Regime				
	Very High	High	Mid	Low	Dry
NPDES Permitted Treatment Facilities				M	H
Septic System w/ "Straight Pipe" connection				M	H
Livestock in receiving water				M	H
Sub-surface treatment systems			H	M	
Stormwater Runoff – Impervious Areas		H	H	H	
Combined Sewer Overflows	H	H	H		
Stormwater Runoff – Pervious Areas	H	H	M		
Bank Erosion	H	H	M		

Note: Potential relative importance of source areas to contribute loads under given hydrologic condition (H: High; M: Medium), based on USEPA Doc. 841-B-07-006.

These analyses suggest the following:

- Bacteria data collected at all four stations covers a reasonably good range of flow conditions, with most of the stations showing a good distribution of samples across high, mid-, and low flow regimes.
- Violations during low flow conditions suggest concentrations are driven by sources such as SSTSs (especially those with straight-pipe connections to drainage systems) and pastures which provide livestock with direct access to streams.
- Numerous exceedances occur during summer and fall medium-high flow conditions which reflect the probable role of warm-weather precipitation events generating runoff episodes that deliver bacteria to the Lower Crow River and its tributaries.

2.9.2 Bacteria Levels of Tributary and Upstream Reaches

The junction of the North and South Fork Crow Rivers in Rockford, MN mark the upstream boundary of the Lower Crow bacteria-listed reach. Bacteria data from two stations upstream of this confluence suggest both may be substantial contributors to bacteria exceedances in the Lower Crow River over the last ten years (Figure 2.6).

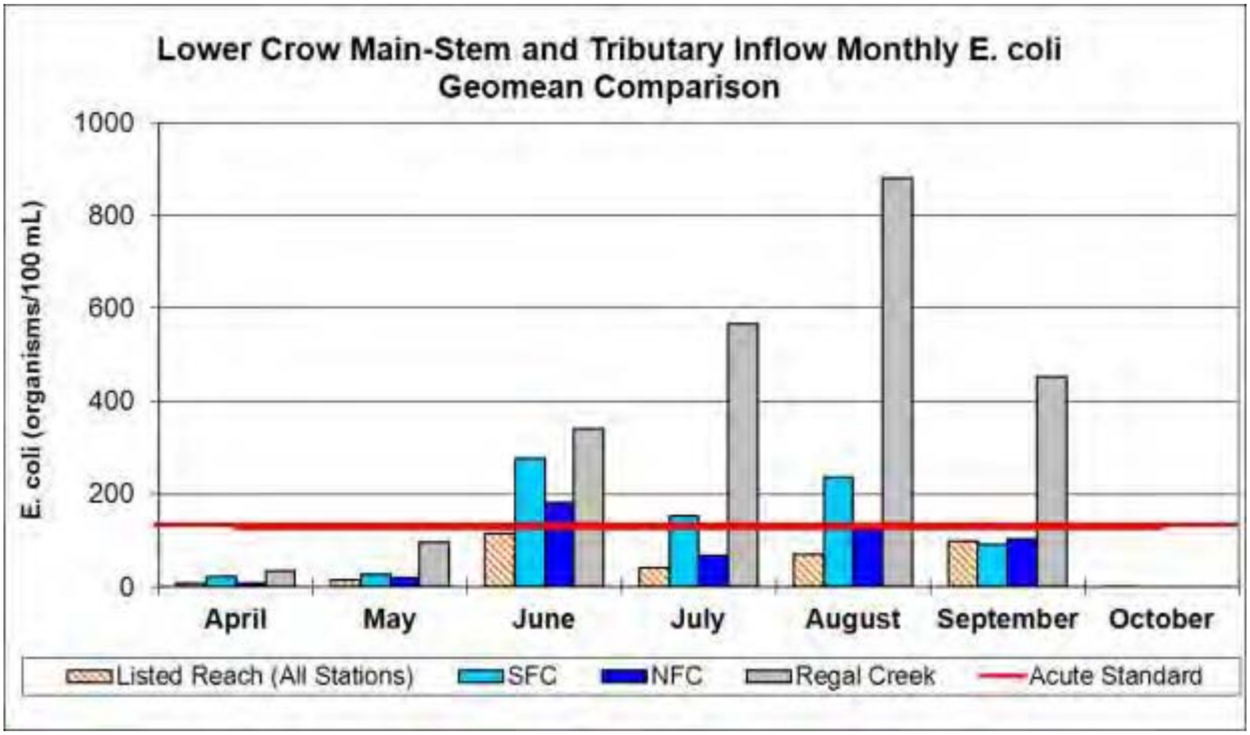

Figure 2.6. Monthly *E. coli* geomeans for the Lower Crow impaired reach. Data set includes converted fecal coliform as well as *E. coli* data.
Note: Regal Creek (tributary to Lower Crow River) and upstream monitoring stations near the outlet of the North Fork Crow and South Fork Crow River.

Based on the above, it appears that:

- Elevated bacteria concentrations in the South Fork Crow River and the North Fork Crow River upstream of the listed reach are contributors to the exceedances of the bacteria standard in June and August at the Rockford monitoring station near the upper end of the impaired reach.
- The persistent and sustained high *E. coli* concentrations from June through September in Regal Creek are significantly higher than the bacteria concentrations in the listed reach of the Crow River. However, Regal Creek's flow contribution represents a very small portion of the total flow in the Crow River watershed. Thus, Regal Creek's *E. coli* load alone would not significantly impact *E. coli* concentrations in the main-stem Lower Crow River impaired reach.
- Virtually all bacteria samples for Regal Creek that were taken at mid, dry, and low-flow regimes are high. This suggests sources that generate and transport bacteria regardless of runoff conditions such as septic systems, livestock in the stream, wildlife, etc. may be important contributors.

2.9.3 Potential Bacteria Source Inventory

The purpose of the bacteria source assessment is to develop a comparison of the number of bacteria generated by the major known sources in the project area as an aid in focusing source identification activities. Only subwatersheds that drain directly to the Lower Crow River between South Fork Crow River and the Mississippi River (reach 07010205-501) were included in the source inventory since this is the only reach listed as impaired (Figure 2.1). The source assessment is not directly linked to the total maximum loading capacities and allocations, which are a function of the water quality standards, stream flow (i.e, dilution capacity), and NPDES permit limits for point sources. Further, the inventory itself uses fecal coliform concentrations as the metric, not *E coli*. This is because the inventory assessment is intended to evaluate the relative magnitude of bacteria loads being generated within the major source categories. The relative source comparisons are expected to be the same, regardless of whether fecal coliform or *E coli* units are used.

2.9.3.1 Livestock

There are a number of pathways by which fecal coliform produced by livestock can reach surface waters such as runoff from feedlots, overgrazed pastures, surface application of manure and incorporated manure. Following is a description of these sources.

2.9.3.1.1 Feedlots and Overgrazed Pastures near Streams

A feedlot is a lot or building intended for confined feeding, breeding, raising or holding of animals specifically designed as a confinement area in which the concentration of animals is such that a vegetative cover cannot be maintained. These facilities are specifically designed as a confinement area in which manure may accumulate or where the concentration of animals is such that vegetative cover cannot be maintained within the enclosure. Concentrated Animal Feeding Operations (CAFOs) are generally feedlots containing over 1,000 animal units (there are also thresholds based on large animal numbers which alter this threshold somewhat) and must be permitted under both state and federal law. CAFOs are regulated under the NPDES program and are subject to a zero surface discharge requirement from the site. However, the manure generated by these feedlots is often spread on the land and still represents a potential bacterial load that is important to track. Registered feedlots are generally those feedlots that don’t qualify as CAFOs but are still capable of holding 50 or more animal units. These operations are not regulated under the NPDES permit program and do not have a discharge requirement. However, they must abide by state rules prohibiting pollution of state waters and may be subject to additional local requirements.

Animal units are the standardized measurement of animals for various agricultural purposes. A livestock animal that consumes, on average, 26 pounds of dry matter forage per day is the standard metric for one animal unit. This number is based on the feeding requirements for a 1,000 pound beef cow. According to the 2010 MPCA database, there are 75 registered feedlots in the Lower Crow River impaired reach watershed. These feedlots house approximately 4,734 total animal units. The majority of the animal units are dairy (2,695 units) followed by beef (1,780 units) and swine (23 units) other (236). A map showing the approximate location (as points) and size (total animal units) of each feedlot is shown in Figure 2.7. GIS data showing the exact location and feedlot boundary are not available.

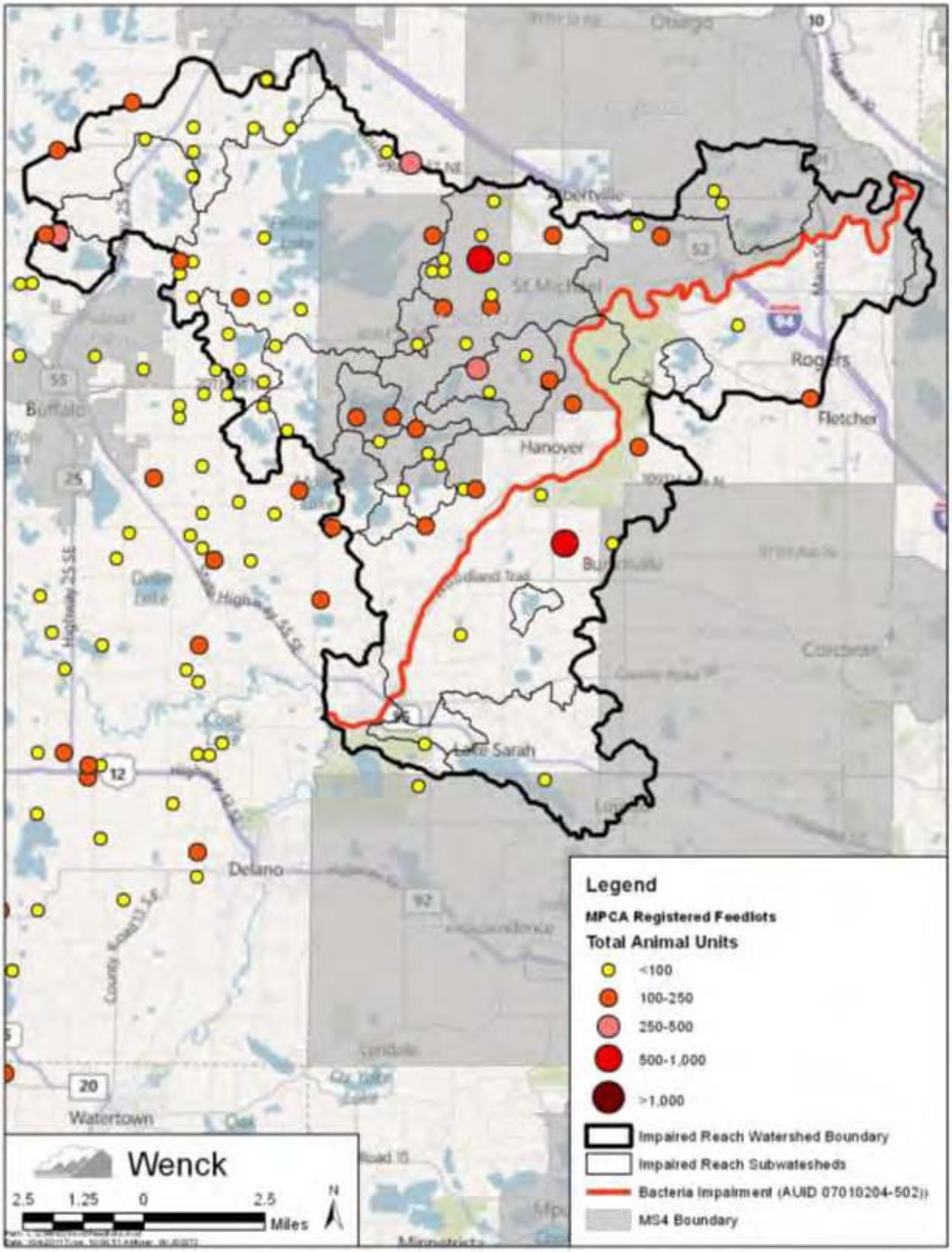

Figure 2.7. 2010 MPCA registered feedlots in the Lower Crow River Watershed.

Feedlots and open lot cattle and dairy facilities within 500 feet of a stream have a higher likelihood of animal access to the stream and therefore higher likelihood of delivering bacterial loads to the receiving water. The Lower Crow River impaired reach has one potential feedlot (32 animal units) within 500 feet of the river. To address overgrazed pastures, this report adopts the assumptions made in the Southeast Regional Fecal Coliform TMDL that 1% of dairy and beef cattle are in overgrazed pastures (MPCA 2002).

2.9.3.1.2 Manure Application

A significant proportion of the cropland in the Lower Crow River watershed receives some sort of manure application. Most hog manure is applied as a liquid and is often injected directly into the soil or incorporated after surface spreading with agriculture tillage equipment. Application of incorporated manure typically occurs in the fall when pits are full and crops have been removed. However, some pits are emptied earlier in the year if needed. When this happens, it is often done prior to spring planting although many farmers do not rely on application during this time if the top-soil is over-saturated.

Most beef and poultry manure is applied as a solid. Dairy manure is applied as both liquid and solid manure. In most cases, the larger dairy operations have liquid manure pits, while the smaller dairies haul manure as a solid. Most liquid manure is injected into the soil or incorporated within 24 hours. Solid manure is spread on the soil surface where it should be incorporated into the ground within 24 hours. Again, a large portion of manure applications occur in the fall when animal waste pits are emptied out. However, some farmers (especially small dairy farmers) will spread this manure year round.

2.9.3.2 Human

2.9.3.2.1 Septic Systems (SSTS)

Failing or nonconforming subsurface sewage treatment systems (SSTSs) can be an important source of bacteria to surface waters. Currently, knowledge of the exact number and status of SSTSs in the Crow River watershed is unclear. MPCA's 2004 "10 Year Plan to upgrade and Maintain Minnesota's On-site Treatment Systems" report to the Minnesota Legislature is the most recent published document that includes information regarding the performance of SSTSs in the Crow River watershed (MPCA, 2004). This study provides county annual reports from 2002 that include estimated failure rates for each county in the state of Minnesota. The report differentiates between systems that are generally failing and those that are an imminent threat to public health and safety (ITPHS). Generally failing systems are those that do not provide adequate treatment and may contaminate ground or surface water. For example a generally failing system may have a functioning, intact tank and soil absorption system, but fails to protect ground water by providing a less than sufficient amount of unsaturated soil between where the sewage is discharged and the ground water or bedrock. Systems considered ITPHS are severely failing or were never designed to provide adequate raw sewage treatment. Examples include

SSTSs that discharge to the ground surface or directly to surface water bodies such as ditches, streams or lakes.

To date, there has been no specific watershed-wide SSTS survey for the Lower Crow River *E. coli* impaired reach. County failure estimates are presented in Table 2.10. For the Southeast Minnesota Regional TMDL study (MPCA 2002), the MPCA estimated a 44% SSTS failure rate. It was estimated that approximately 65% of Wright County SSTSs are not currently in compliance (Sean Riley-Wright County Planning and Zoning, personal communication). Since failing septic rates appear to vary considerably by county and location in the watershed, a conservative SSTS failure rate of 55% was assumed for this TMDL. This rate assumes all failing systems are ITPHS and all of the bacteria waste from these systems is delivered to surface waters. ITPHS systems are illegal in Minnesota and must be fixed immediately fixed and upgraded when found. Based on 2000 census data, rural population in the Lower Crow River watershed is 4,497, which is approximately 20% of the total population. Assuming there are approximately 2.8 people per household, there are just over 1,600 rural households that dispose of wastewater through on-site SSTSs. Using the 55% discussed previously, one could expect around 883 failing SSTS throughout the watershed.

Table 2.10 SSTS failure rates by county in Crow River watershed

County	Generally Failing ISTSs	ITPHS ISTSs
Carver	50%	15%
Hennepin	25%	5%
Kandiyohi	50%	15%
McLeod	20%	30%
Meeker	10%	5%
Pope	20%	10%
Stearns	30%	2%
Wright	35%	5%

2.9.3.2.2 NPDES-permitted wastewater dischargers

There are 20 NPDES-permitted wastewater dischargers in the North Fork Crow and Lower Crow River watersheds with fecal coliform permit limits. Discharge Monitoring Reports (DMRs) were downloaded from the MPCA STORET database to assess effluent bacteria concentrations for each point source. By rule, these facilities are not to discharge treated wastewater with fecal coliform concentrations that exceed 200 organisms/100ml (126 cfu/100 ml *E. coli* concentration). Results show that there are fifteen facilities in the North Fork-Lower Crow River watershed that have measured effluent fecal coliform at least one time since 1998 (Appendix A). The data shows all 15 facilities rarely exceed the fecal coliform permitted concentration limit and typically discharge well below their limit.

2.9.3.3 Wildlife

Wildlife in the Lower Crow River watershed encompasses a broad group of animals. For this assessment, deer and geese were assumed to be the main contributors while other wildlife was grouped into one separate category.

The Minnesota Department of Natural Resources (MnDNR) modeled deer population densities for several nearby areas. MnDNR staff provided estimates of about 5 deer per square mile for most of the watershed, with up to 15 deer per square mile closer to the river valleys (Jeff Miller- MnDNR Wildlife Division in Willmar, personal communication). This report assumes an average deer density of 6 deer per square mile for the entire watershed.

Goose densities were estimated using the Southeast Minnesota Regional TMDL where they assumed a goose population of 20,000 individuals which equates to a density of approximately 2.8 geese per square mile.

2.9.3.4 Urban Stormwater Runoff

Untreated urban stormwater has demonstrated bacteria concentrations as high as or higher than grazed pasture runoff, cropland runoff, and feedlot runoff (USEPA 2001, Bannerman et al. 1993, 1996). There is a moderate amount of urban area land cover in the Lower Crow River. Consistent with the methodology outlined in the Southeast Minnesota Regional Bacteria TMDL (MPCA 2002), urban bacteria contributions were assumed to come exclusively from improperly managed waste from dogs and cats. Using the approach in that study, it was assumed that there were 0.58 dogs/household and 0.73 cats/household in the urban areas. Deer and geese densities in urban centers were assumed to be the same as those discussed in the previous section.

EPA guidance states that MS4 stormwater allocations in a TMDL must now be included in the TMDL as a Wasteload Allocation. MS4 permittees must review the adequacy of their Stormwater Pollution Prevention Program (SWPPP) to meet approved WLAs and, if necessary, modify the SWPPP.

2.9.4 Lower Crow Watershed Bacteria Production by Source

Table 2.11 summarizes the major sources of bacteria in the Lower Crow River impaired reach watershed. Estimates of the rural population with inadequate wastewater treatment are based on the assumed SSTS failure rate (55%). Additionally, pet numbers are derived from a national survey and may not directly reflect conditions in the counties comprising the two subwatersheds. Deer populations are from model estimates and geese population estimates are based on densities used in the Southeast Regional TMDL. This summary does, however, provide a reasonable estimate of fecal coliform producers throughout the watershed as well as the comparative densities in each category.

There are 75 registered livestock facilities that house over 4,734 animal units, particularly dairy and beef cows. Approximately two-thirds of the human population in the Lower Crow River watershed discharges to a municipal wastewater treatment facility.

Table 2.11. Inventory of Fecal Coliform Bacteria Producers in the Lower Crow River Watershed.

Category	Sub-Category		Animal Units or Individuals
Livestock	The Basin contains an estimated 72 registered livestock facilities ranging in size from a few animal units to several hundred	Dairy	2,695 animal units
		Beef	1,780 animal units
		Swine	23 animal units
		Poultry	<1 animal units
		Other	236 animal units
Human[1]	Rural Population with Inadequate Wastewater Treatment[2]		2,473 people
	Rural Population with Adequate Wastewater Treatment		2,023 people
	Municipal Wastewater Treatment Facilities		26,100 people
Wildlife	Deer (average 6 per square mile)		825 deer
	Geese[3]		385 geese
	Other		Other wildlife was assumed to be the equivalent of deer and geese combined in the watershed.
Pets	Dogs and Cats in Urban Areas[4]		28,841 dogs and cats

[1]Based on 2000 census data
[2]Assumes 55% failure rate for septic systems
[3]Rough estimate, likely representing maximum numbers; geese densities based on Southeastern Minnesota Regional Bacteria TMDL (MPCA 2002) densities (2.8 per square mile)
[4] People divided by 2.8 people/household multiplied by 0.58 dogs/household, 0.73 cats/household as used in the Southeast Minnesota Regional TMDL (MPCA 2002).

2.9.5 Lower Crow River Bacteria Available for Transport

Each bacteria source was assigned a percentage that attempts to predict the likelihood of that animal's bacteria reaching the Lower Crow River and its tributaries (Table 2.12). It is important to note that this process assumes that all bacteria produced in the watershed remain in the watershed. For example, all dairy cow manure is potentially available for runoff. However, only 1% of the bacteria load associated with dairy manure and potentially available for runoff is assumed to be from overgrazed pastures near streams and waterways while 64% is assumed to be from surface applied manure in the watershed. Similarly, it was assumed that 10% of the bacteria load associated with cat and dog waste in urban areas was improperly managed and potentially available for transport. These assumptions are gross approximations that were first developed as part of the Southeast Regional TMDL (MPCA, 2002), then altered to reflect typical conditions within the watershed.

Table 2.12. Assumptions Used to Estimate the Amount of Daily Fecal Coliform Production Available for Potential Runoff or Discharge into the Streams and Rivers of the North Fork Crow River Watershed Project Area.

Category	Source	Assumption
Livestock	Overgrazed Pasture near Streams or Waterways	1% of Dairy Manure 1% of Beef Manure
	Feedlots or Stockpiles without Runoff Controls	1% of Dairy 5% of Beef Manure 1% Poultry Manure
	Surface Applied Manure	64% of Dairy Manure 94% of Beef Manure 99% of Poultry Manure 10% Swine Manure; 20% of this manure applied in Spring 20% of this manure applied in Summer 60% of this manure applied in Fall
	Incorporated Manure	34% of Dairy Manure 90% of Swine Manure; 20% of this manure applied in the Spring 80% of this manure applied in Fall
Human	Failing Septic Systems and Unsewered Communities	All waste from failing septic systems and unsewered communities
	Municipal Wastewater Treatment Facilities (excluding bypasses)	Calculated directly from WWTF discharge (April through October) and the geometric mean fecal coliform concentration (2004 data)
Wildlife	Deer	All fecal matter produced by deer in basin
	Geese	All fecal matter produced by geese in basin
	Other Wildlife	The equivalent of all fecal matter produced by deer and geese in basin
Urban Stormwater Runoff	Improperly Managed Waste from Dogs and Cats	10% of waste produced by estimated number of dogs and cats in basin

Next, potential fecal coliform runoff loads were estimated for the Lower Crow River watershed (Table 2.13). Daily fecal coliform production estimates for each animal unit or individual were also derived from the Southeast Regional TMDL and are based on literature values (MPCA 2002). Some small differences may occur when fecal coliform production is estimated based on animal unit definitions. However, these differences would fall within the standard deviation of production numbers and would not increase the accuracy of the data justifying their use for individuals in Wright and Hennepin counties.

Table 2.13. Summary of estimated daily fecal coliform available for potential delivery to the Lower Crow River from impaired reach watershed.

Category	Source	Animal Type	Total Fecal Coliform Available(10^9)	Total Fecal Coliform Available by Source(10^9) (% of total bacteria potentially available)
Livestock	Overgrazed Pasture near Streams or Waterways	Dairy Animal Units	1,568	3,154 (0.9%)
		Beef Animal Units	1,586	
	Feedlots or Stockpiles without Runoff Controls	Dairy Animal Units	1,568	9,499 (2.7%)
		Beef Animal Units	7,930	
		Poultry Animal Units	<1	
	Surface Applied Manure	Dairy Animal Units	100,383	249,560 (70.7%)
		Beef Animal Units	149,082	
		Swine Units	75	
		Poultry Animal Units	20	
	Incorporated Manure	Dairy Animal Units	53,329	54,006 (15.3%)
		Beef Animal Units	0	
		Swine Units	677	
		Poultry Animal Units	0	
Human	Failing Septic Systems and Unsewered Communities	People	4,946	22,559 (6.4%)
	Municipal Wastewater Treatment Facilities	People	17,613	
Wildlife	Deer	Deer	413	1,134 (0.3%)
	Geese	Geese	154	
	Other Wildlife	Equivalent of deer plus geese	567	
Urban Stormwater Runoff	Improperly Managed Waste from Dogs and Cats	Dogs and Cats	12.978	12,978 (3.7%)
Total			6,433	352,890

Based on the outcome of the bacteria pollutant source inventory, the results suggest that:

- Livestock are the biggest generator of bacteria in the impaired reach watershed.
- The largest potential sources are those activities associated with application of manure to the land. Generally speaking, mobilization of bacteria from manure spreading activities is likely to be a problem when runoff processes carry recently applied manure to receiving waters.
- Over-grazed pastures near streams and waterways and failing septic systems/unsewered communities appear to be relatively small sources based on the small load of bacteria

generated compared to livestock. However, these sources can be some of the most significant contributors to bacteria impairments during low flow conditions when dilution is minimal since bacteria from these sources are often delivered efficiently to the receiving water (as in the case of straight-pipe connections with septic systems and livestock defecating directly into a stream).

3.0 Turbidity Impairments

3.1 TURBIDITY STANDARD

Turbidity is a measure of the cloudiness or haziness of water caused by suspended and dissolved substances in the water column. Turbidity can be caused by increased suspended soil or sediment particles, phytoplankton growth, and dissolved substances in the water column. Excess turbidity can degrade aesthetic qualities of water bodies, increase the cost of treatment for drinking water or food processing uses, and harm aquatic life. Adverse ecological impacts caused by excessive turbidity include hampering the ability of aquatic organisms to visually locate food, negative effects on gill function, and smothering of spawning beds and benthic organism habitat.

The turbidity standard found in Minn. R. 7050.0222 subpart 4 for 2B waters is 25 nephelometric turbidity units (NTUs). Impairment assessment procedures for turbidity are provided by MPCA (2005). The water body is added to the impaired waters list when greater than ten percent of the data points collected within the previous 10 year period exceed the 25 NTU standard (or equivalent values for total suspended solids or transparency tube data). This TMDL is written for Class 2B waters, as this is the most protective class in these stream reaches.

Since turbidity is a measure of light scatter and adsorption, turbidity cannot be expressed as a mass load which is required for TMDLs. Consistent with TMDL protocol, TSS was evaluated for use as a surrogate for turbidity. Section 3.6 provides additional detail on the development of the site specific TSS surrogate standard.

3.2 OVERVIEW OF TURBIDITY IMPAIRED REACHES AND WATERSHEDS

This section includes TMDLs for two impaired reaches in the North Fork – Lower Crow River watershed (Table 1.3). Figure 3.1 shows the locations of each impaired reach, the subwatersheds that drain directly to each impaired reach and the locations of the key monitoring stations for which flow and TSS data were collected to support these TMDLs. The lower portion of the South Fork Crow River (AUID 07010204-502) from Buffalo Creek to its confluence with the North Fork Crow River is currently impaired for turbidity and will be addressed in the South Fork Crow River Watershed Restoration and Protection Plan which, at the time of this report, is in development. Thus, the South Fork Crow River was treated as upstream boundary conditions in this TMDL study. This TMDL's turbidity source assessment section specifically focuses on the subwatersheds that drain directly to each impaired reach (AUID 07010204-502 and 07010204-503) since the upstream reaches are not impaired for turbidity.

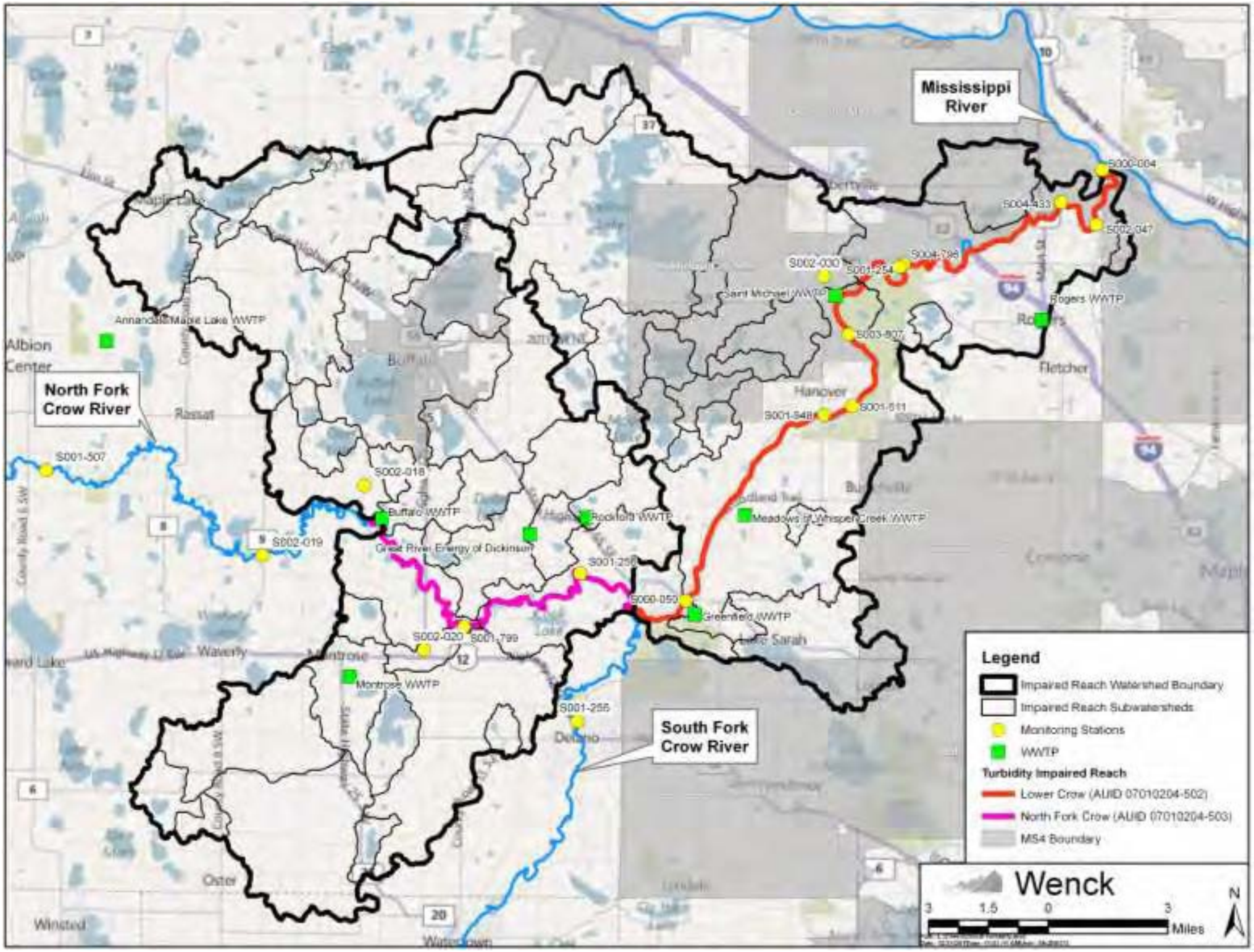

Figure 3.1. North Fork Crow and Lower Crow turbidity impaired reaches and watersheds.

3.3 WATERSHED LANDUSE

Land use for the watersheds that discharge directly to the Lower Crow River and North Fork Crow River turbidity impaired reaches and the North Fork Crow River upstream of the impaired reaches was calculated using the 2009 National Agricultural Statistics Service (NASS) GIS landcover file (Table 3.1). Landuse in each watershed is primarily hay and pasture and corn and soybean rotations. The remaining land area is comprised of forest and shrubland, lakes and wetlands, developed land and non-corn/soybean crops.

Table 3.1. Landuse summary in the North Fork Crow watershed and Lower Crow River impaired reach direct watershed (2009 NASS).

Landuse	Percent of Total		
	[1]Lower Crow River Impaired Watershed	[2]North Fork Crow River Impaired Watershed	[3]North Fork Crow River Watershed
Hay and Pasture	38%	38%	31%
Corn/Soybeans	18%	25%	38%
Forest and shrubland	15%	13%	11%
Wetlands and Open Water	14%	13%	11%
Urban/Roads	13%	10%	7%
Grains and other Crops	2%	1%	2%

[1] Only includes Lower Crow River impaired reach watershed downstream of North Fork Crow and South Fork Crow Rivers
[2] Only includes North Fork Crow River impaired reach watershed upstream of South Fork Crow River
[3] Includes North Fork Crow River watershed upstream of Lower Crow River and North Fork Crow impaired reaches

3.4 TURBIDITY RELATED WATER QUALITY DATA

Three types of data are collected to assess turbidity in surface waters. The first is a direct measure of turbidity using a turbidimeter in either a lab or in the field. The second is a measure of transparency of the water using a field transparency tube (T-tube). The third is a measure of the mass of solids in the water column typically measured as total suspended solids (TSS). The CROW and MPCA have collected turbidity, T-tube and TSS data at nine monitoring stations on the main-stem Lower Crow River impaired reach and three stations on the North Fork Crow River impaired reach (Table 3.2). A more detailed summary of monitoring data is provided in Appendix B.

Table 3.2. Available turbidity-related water quality measurements for main-stem Lower Crow River reach 502 and reach 503 of the North Fork Crow River.

STORET ID	Impaired Reach	Location	Years Monitored	Type of data	Measurements
S000-004	Lower Crow	Crow River at CSAH-36	99-07	Turbidity Transparency TSS	30 34 53
S002-047		Crow River West of CSAH-13	02-09	Transparency	102
S004-433		Crow River East of CSAH-36	07	Transparency TSS	20 10
S004-796		Crow River at CSAH-116	07-09	Transparency TSS	85 22
S001-254		Crow River at CSAH-22	06-07	Transparency TSS	53 14
S003-807		Crow River at 22nd Circle (St. Michael)	05	Transparency	23
S001-511		Crow River near Riverview Rd (Hanover)	00-09	Transparency	120
S001-948		Crow River at CR-145 (Hanover)	02	Transparency	17
S000-050		Crow River at Hwy-55 (Rockford)	99-06	Turbidity Transparency TSS	60 35 117
S001-256	North Fork Crow	N Fork Crow River at Farmington Ave	01-09	Turbidity Transparency TSS	54 51 135
S001-978		N Fork Crow River 3 miles W of Rockford	01	Transparency	56
S001-799		N Fork Crow River 2 miles NW of Delano	02-09	Transparency	14

3.5 STREAMFLOW DATA

Flow data for each reach is crucial to calculate daily load allocations for each reach. Flow data were used to develop flow regimes so that turbidity violations could be characterized based on whether they occurred most often during high, medium, or low flow events. This information helps provide insight on potential sources during low/base-flow as well as storm/run-off related events. There is one historic flow monitoring station located in each turbidity impaired reach. Both monitoring stations coincide with one of the primary turbidity grab sample sites (Table 3.3 and Figure 3.1).

Table 3.3. Flow monitoring stations within the North Fork and Lower Crow impaired reaches.

Reach	STORET ID	Location	DNR ID	USGS ID	Flow Provider	Years of Operation since 2000	Flow Record Length (Days)
502	S000-050	Crow River at MN Hwy 55	18087001	05280000	USGS	00-09	3,653
503	S001-256	N. Fork Crow River at Farmington Ave	18088001	05278400	DNR/MPCA	02; 04-06	680

While turbidity, transparency and TSS samples were collected in the North Fork Crow River impaired reach over multiple years, only four seasons of continuous flow data were available for this reach. The Rockford USGS station (S000-050), located on the Lower Crow River, has the longest and most complete flow record in the Crow River watershed (Figure 3.1). Flow regression relationships between this station and the Farmington Avenue station (S001-256) were used to fill data gaps and create a continuous 10-year flow record for the North Fork listed reach (Appendix C).

3.6 DEVELOPMENT OF A TSS SURROGATE

To determine the TSS equivalent to the 25 NTU turbidity standard, over 100 paired lab turbidity and TSS samples collected between 1999-2009 were analyzed from 3 sites located within the main-stem of the North Fork and Lower Crow River impaired reaches. Over half of the paired data are based on measurements taken with a meter that reads turbidity in Nephelometric Turbidity Ratio Units (NTRUs), while other data used meters that express turbidity in standard Nephelometric Turbidity Units (NTUs). These two are not equivalent, but can be related using the following equation (MPCA 2007):

$$NTU = 10^{(-0.0734+0.926*Log(NTRU))}/1.003635$$

Since the turbidity standard is expressed in NTUs, all NTRU data were converted to "NTU equivalents" using the aforementioned equation prior to analyzing paired data relationships.

MPCA protocol recommends using only paired measurements with a turbidity value of 40 NTU or less and TSS values greater than 10 mg/L (MPCA 2008). A total of 124 paired turbidity/TSS samples met these criteria and were used to develop the relationship. A simple regression of the natural logarithm of TSS and turbidity was completed using the paired data available for all sites within the impaired reaches (Figure 3.2). Initially, regression relationships were setup individually for each reach, however differences between the two were not statistically significant and both were combined into one dataset and regression. The analysis indicates that the turbidity standard of 25 NTU corresponds to a surrogate TSS concentration of 72 mg/L for this data set. However, informal guidance provided by MPCA suggests applying a Duan's smearing correction to the surrogate to account for the bias introduced when re-transforming the non-linear regression. After applying this bias correction method to the data set, the corrected TSS surrogate value for the 25 NTU standard is 75 mg/L.

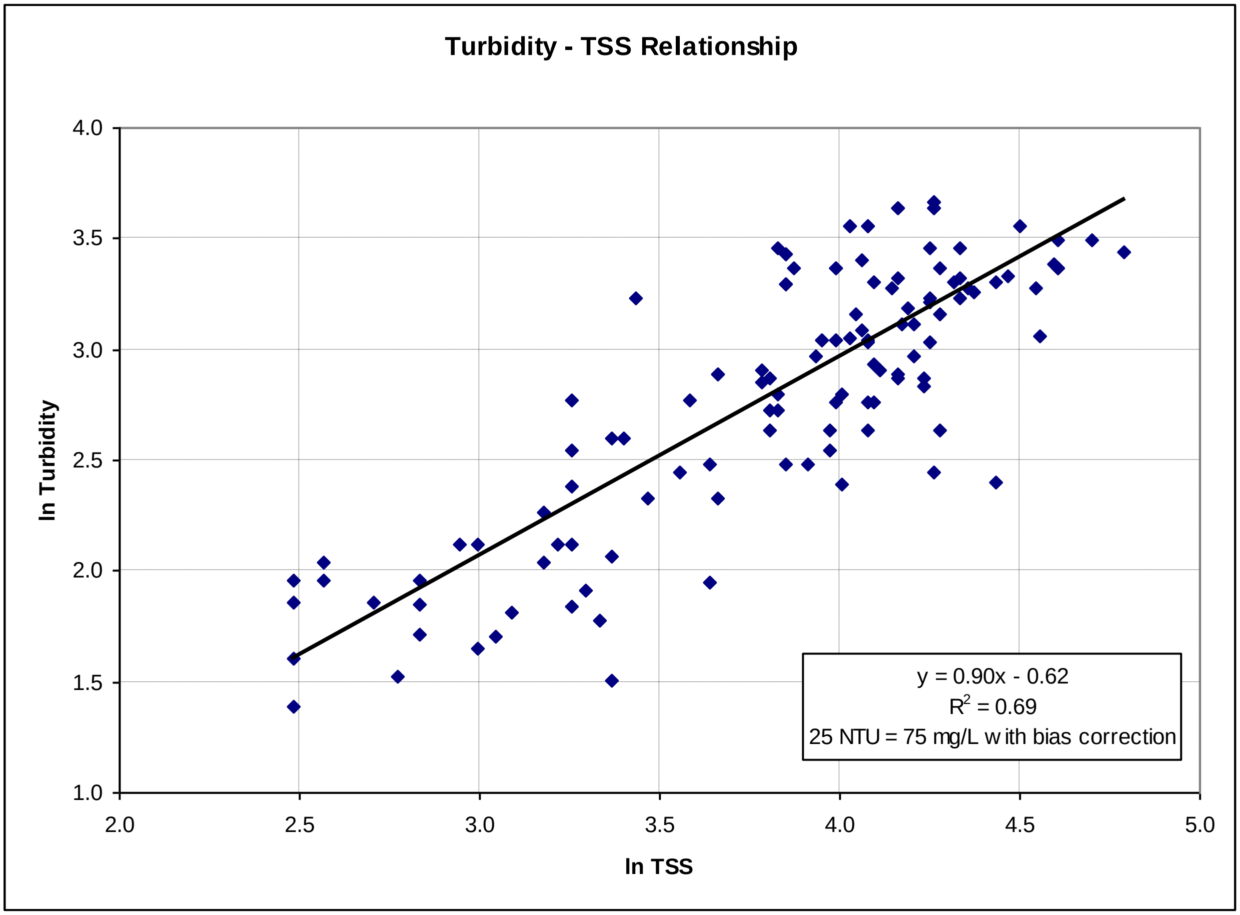

Figure 3.2. Turbidity/Total Suspended Solids Relationship for three sites within the North Fork Crow and Lower Crow River Watershed.

3.7 DEGREE OF IMPAIRMENT

The MPCA recognizes transparency and TSS as reliable surrogates of turbidity which can be used to assess impairments at sites where there are an inadequate number of turbidity observations (MPCA, 2010). For transparency, a transparency tube measurement of less than 20 centimeters indicates a violation of the 25 NTU turbidity standard. For TSS, a measurement of more than 100 mg/L indicates a violation of the turbidity standard in the North Central Hardwood forest ecoregion. If sufficient turbidity measurements exist, only turbidity measurements are used to determine impairment. Both impaired reaches of the North Fork Crow and Lower Crow River have the 20 independent turbidity observations required to assess an impairment. However, all three parameters were evaluated for each reach in this TMDL report to investigate trends and take full advantage of the North Fork – Lower Crow River dataset. The only change from the MPCA's assessment guidelines is the 100 mg/L NCHF TSS surrogate threshold was replaced with the 75 mg/L surrogate discussed in the previous section. Also, in a few cases there were measurements recorded from multiple stations within the same impaired reach on the same day. To avoid double counting, data from all sites within each reach were grouped together and consolidated (averaged) by date to provide one dataset for each reach.

Table 3.4 summarizes the turbidity, transparency and TSS data collected in each reach from 1999 through 2009. These data suggest more than 10% of the turbidity, transparency and TSS samples in each reach were in violation of their standard or assessment threshold. It is interesting to note that turbidity and transparency had significantly higher incidence of exceedance compared to TSS. This suggests impairments may have occurred at TSS concentrations below the surrogate standard. This will be discussed in further detail in the source assessment section.

Table 3.4. Turbidity related water quality exceedances in the Lower Crow and North Fork Crow turbidity impaired reaches.

Impaired Reach	Parameter	Years Monitored	Measurements	Exceedances	Percent Exceedances
Lower Crow	Turbidity	99-06	76	23	30%
	Transparency	99-09	489	193	39%
	TSS	99-09	216	35	16%
North Fork Crow	Turbidity	01-09	53	14	26%
	Transparency	01-09	114	52	46%
	TSS	01-09	135	15	11%

Note: Exceedances are based on the 25 NTU turbidity standard, the 20 cm transparency surrogate assessment threshold, and the 75 mg/L surrogate established in the TMDL study.

3.8 ALLOCATION METHODOLOGY

3.8.1 Overview of Load Duration Curve Approach

Assimilative capacities for the streams were developed from load duration curves (Cleland 2002). Load duration curves assimilate flow and TSS data across stream flow regimes and provide assimilative capacities from which reductions can be derived by comparing to measured loads.

Flow duration curves were developed using the flow data discussed in Section 3.5 (Figure 3.3). The curved line relates mean daily flow to the percent of time those values have been met or exceeded. For example, at the 50% exceedance value for the Lower Crow, the river discharged at 360 cubic feet per second or greater 50% of the time. The 50% exceedance is also the midpoint or median flow value. The curve is then divided into flow zones including very high (0-10%), high (10-40%), mid (40-60%), low (60-90%) and dry (90 to 100%) flow conditions.

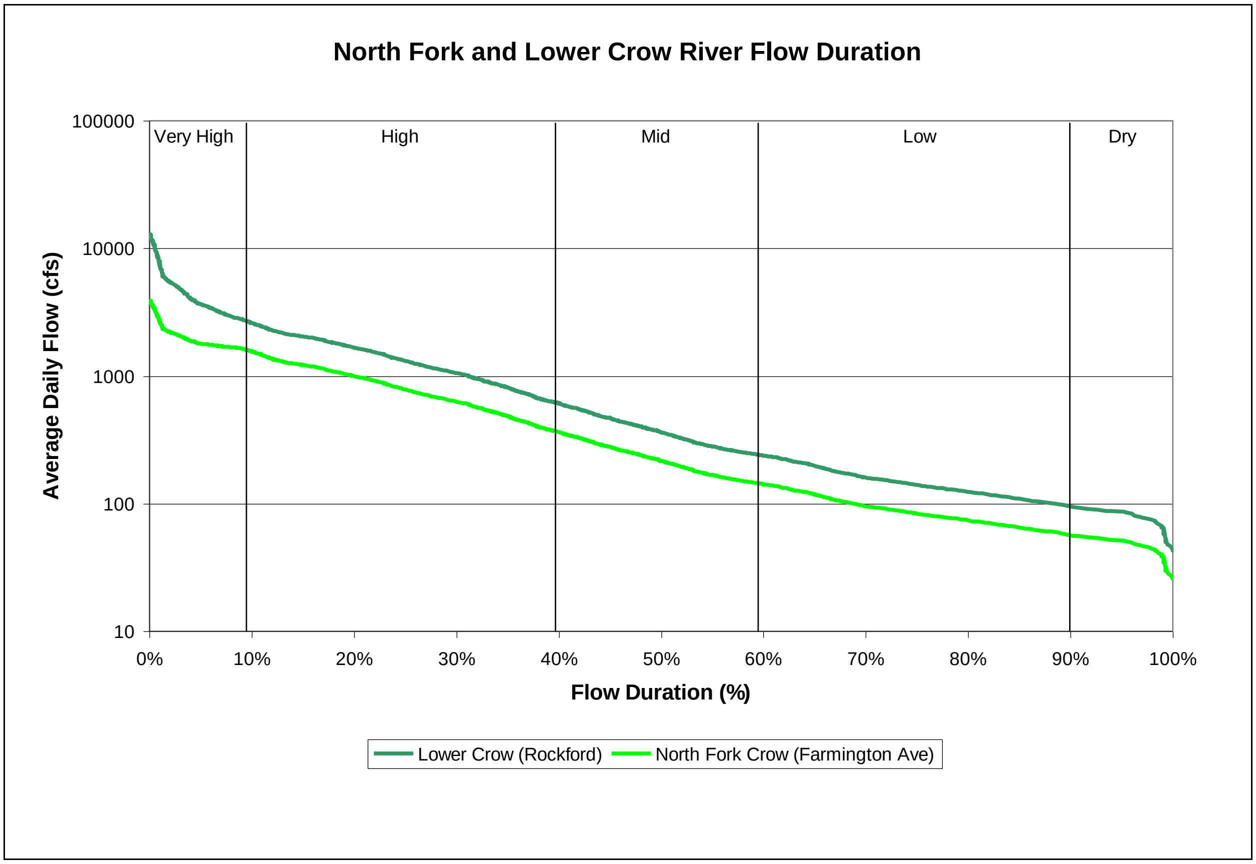

Figure 3.3. Flow duration for North Fork and Lower Crow River monitoring stations.

To develop a load duration curve, all average daily flow values were multiplied by the TSS-surrogate (75 mg/L) and converted to a daily load to create "continuous" load duration curves. Now the line represents the assimilative capacity of the stream for each daily flow. To develop the TMDL, the median load of each flow zone is used to represent the total daily loading capacity (TDLC) for that flow zone. The TDLC can also be compared to current conditions by plotting the measured load by exceedance for each water quality sampling event. Each value that is above the TDLC line represents an exceedance of the water quality standard while those below the line are below the water quality standard. These figures are presented in Section 3.10.

3.8.2 Margin of Safety

The purpose of the margin of safety (MOS) is to account for uncertainty that the allocations will result in attainment of water quality standards. The MOS was determined as the difference between the median flow of each flow regime and the 45th percentile flow in each zone. The resulting value was converted to a daily load by multiplying by the TSS standard and set as the MOS for each flow category. This methodology accounts for variability in the data set without over protecting the high end of the flow zone and under-protecting the low end of the flow zone. The data in each flow zone are treated as a distribution and assumes any reduction efforts will affect the entire distribution.

3.8.3 South Fork Crow River Boundary Condition

The lower portion of the South Fork Crow River (AUID 07010204-502) from Buffalo Creek to its confluence with the North Fork Crow River is currently impaired for turbidity and will be addressed in the South Fork Crow River Watershed Restoration and Protection Plan. Thus, the entire South Fork Crow River upstream of the Lower Crow River is considered a boundary condition in the Lower Crow River portion of this TMDL study. As a result, this report does not calculate or assign allocations to wasteload and non-point sources in the South Fork Crow River watershed. The South Fork Crow River watershed represents approximately 46% of the entire Crow River watershed (Table 3.5). The allocation for the South Fork Crow River boundary condition was calculated by multiplying the South Fork's watershed area fraction by the Crow River's total loading capacity after the margin of safety was subtracted (Table 3.10).

Table 3.5. Crow River watershed descriptions.

Watershed	Description	Size (acres)	Percent of Total
South Fork Crow River	SFC River watershed upstream of Lower Crow River bacteria impaired reach	794,086	46%
North Fork Crow River	NFC River watershed upstream of North Fork River turbidity impaired reach	764,432	44%
North Fork Crow River Impaired Reach	NFC River impaired reach direct watershed upstream of the Lower Crow River impaired reach	96,793	5%
Lower Crow River Impaired Reach	Lower Crow River impaired reach direct watershed downstream of NFC and SFC River confluence	88,689	5%

3.8.4 Wasteload Allocations

The wasteload allocations were divided into four primary categories including NPDES permitted wastewater dischargers, MS4 permits, and NPDES-permitted construction and industrial stormwater. Following is a description of how each load allocation was assigned.

3.8.4.1 NPDES Wastewater Dischargers

There are twenty two active NPDES wastewater dischargers in the North Fork Crow and Lower Crow River watershed that have been assigned TSS effluent limits. Each facility's maximum daily effluent TSS load was established by the MPCA and is a function of the facility's design flow and permitted TSS concentration limit (Table 3.6).

Table 3.6. Permitted WWTP TSS allocations for the North Fork Crow and Lower Crow River turbidity impaired reaches.

Facility Name	NPDES ID#	Facility Type	Effluent Design Flow (MGD)	Permitted TSS Concentration Limit (mg/L)	Permitted Load (tons/day)
Facilities located in the North Fork Crow River watershed upstream of impaired reaches					
Annandale/Maple Lake/Howard Lake WWTP	MN0066966	Continuous	1.184	30	0.148
Atwater WWTP	MN0022659	Pond	1.385	45	0.260
Belgrade WWTP	MN0051381	Pond	1.483	45	0.278
Brooten WWTP	MN0025909	Pond	1.061	45	0.199
Bushmills Ethanol	MN0067211	Continuous	0.144	30	0.018
Cokato WWTP	MN0049204	Continuous	0.726	45	0.136
Darwin WWTP	MNG580150	Pond	0.326	45	0.061
Dassel WWTP	MN0054127	Pond	1.222	45	0.229
Faribault Foods - Cokato	MN0030635	Continuous	0.550	30	0.089
Green Lake SSWD WWTP	MN0052752	Continuous	0.889	30	0.111
Grove City WWTP	MN0023574	Continuous	0.224	30	0.028
Litchfield WWTP	MN0023973	Continuous	2.370	30	0.237
Paynesville WWTP	MN0020168	Pond	1.466	45	0.274
Facilities located in the North Fork Crow River impaired reach direct watershed (AUID 07010204-503)					
Montrose WWTP	MN0024228	Continuous	0.781	45	0.147
Buffalo WWTP	MN0040649	Continuous	3.600	30	0.451
Great River Energy of Dickinson	MN0049077	Continuous	0.030	30	0.004
Rockford WWTP	MN0024627	Continuous	0.651	30	0.081
Facilities located in the Lower Crow River impaired reach direct watershed (AUID 07010204-502)					
Greenfield WWTP	MN0063762	Continuous	0.200	30	0.012
Meadows of Whisper Creek WWTP	MN0066753	Continuous	0.020	30	0.003
Otsego East WWTP	MN0064190	Continuous	1.650	30	0.138
Rogers WWTP	MN0029629	Continuous	1.602	30	0.200
Saint Michael WWTP	MN0020222	Continuous	2.445	30	0.306
North Fork Crow River (AUID 07010204-503) facility totals			**18.092**		**2.751**
Lower Crow River (AUID 07010204-502) facility totals			**23.739**		**3.410**

3.8.4.2 MS4s

There are 12 Municipal Separate Storm Sewer Systems (MS4s) that are completely within or have a portion of their municipal boundary in the North Fork Crow and Lower Crow River watersheds (Tables 3.7 and 3.8). There are two additional municipalities, Rogers and Albertville who will now require NPDES permits since their population exceeded 5,000 in the 2010 census. Stormwater from Rogers, Albertville and the 12 MS4 communities contributes to the water quality impairments discussed in this report and are therefore given WLAs.

The proportion of each reach's total loading capacity allocated to Rogers, Albertville and the 12 MS4 (Tables 3.7 and 3.8) communities was calculated using the same methodology described in Section 2.6.4.2.

Table 3.7. Wasteload allocations for all MS4 communities that contribute directly to or are upstream of the North Fork Crow River turbidity impaired reach (07010204-503).

MS4	Area (acres)	TSS Allocation (tons/day)				
		Very High	High	Mid	Low	Dry
Buffalo City MS4	5,675	9.5	3.9	1.1	0.4	0.3
St Michael City MS4	122	0.2	<0.1	<0.1	<0.1	<0.1
Litchfield City MS4	3,435	5.7	2.3	0.7	0.3	0.2
MS4 Totals	**9,232**	**15.4**	**6.3**	**1.8**	**0.7**	**0.5**

Table 3.8. Wasteload allocations for all MS4 communities that contribute directly to or are upstream of the Lower Crow River turbidity impaired reach (07010204-502).

MS4	Permit #	Area (acres)	TSS Allocation (tons/day)				
			Very High	High	Mid	Low	Dry
Hennepin County MS4	MS 400138	52	<0.1	<0.1	<0.1	<0.1	<0.1
Loretto City MS4	MS 400030	95	0.1	<0.1	<0.1	<0.1	<0.1
Corcoran City MS4	MS 400081	1,211	1.5	0.5	0.1	<0.1	<0.1
Dayton City MS4	MS 400083	754	0.9	0.3	<0.1	<0.1	<0.1
Independence City MS4	MS 400095	2,182	2.7	0.9	0.3	0.1	<0.1
Medina City MS4	MS 400105	425	0.5	0.2	<0.1	<0.1	<0.1
Buffalo City MS4	MS 400242	5,706	7.1	2.4	0.7	0.3	0.2
Monticello City MS4	MS 400242	76	<0.1	<0.1	<0.1	<0.1	<0.1
Otsego City MS4	MS 400243	2,709	3.4	1.1	0.3	0.1	<0.1
St Michael City MS4	MS 400246	22,927	28.4	9.7	2.8	1.1	0.7
MNDOT Metro District MS4	MS 400170	52	<0.1	<0.1	<0.1	<0.1	<0.1
Litchfield City MS4	MS 400253	3,435	4.3	1.5	0.4	0.2	0.1
Albertville City	None	1,486	1.8	0.6	0.2	<0.1	<0.1
Rogers City	None	2,071	2.6	0.9	0.3	<0.1	<0.1
MS4 Totals		**43,181**	53.5	18.3	5.2	2.0	1.4

3.8.4.3 Construction and Industrial Stormwater

Construction and industrial stormwater wasteload allocations were established based on estimate percentage of land in the watershed that is currently under construction or permitted for industrial use. A recent permit review across the entire North Fork Crow - Lower Crow River watershed showed minimal construction (<1% of watershed area) and industrial activities (<0.5% of the watershed area). To account for future growth (reserve capacity), allocations in the TMDL were rounded up to 1% for construction stormwater and 0.5% for industrial stormwater.

3.8.5 Load Allocations

The load allocation is the remaining load after the MOS and all upstream boundary conditions and wasteload allocations are subtracted from the total load capacity of each flow zone. Load allocations for the North Fork Crow River watersheds upstream of each listed reach and the North Fork Crow and Lower Crow River watersheds that drain directly to each impaired reach were calculated by multiplying the total non-point source load by the watershed fractions presented in Table 3.5.

3.9 ALLOCATIONS BY REACH

Tables 3.9 and 3.10 present the total loading capacity, margin of safety, wasteload allocations and the remaining load allocations for impaired reaches 07010204-503 and 07010204-502. The tables also present load allocations in terms of the percent of total loading capacity in each flow category.

Table 3.9. North Fork Crow River impaired reach TSS total daily loading capacities and allocations.

North Fork Crow River 07010204-503		Flow Zones				
		Very High	High	Mid-Range	Low	Dry
		TSS Load (tons/day)				
Total Daily Loading Capacity		362.3	158.3	43.8	17.0	10.5
Margin of Safety (MOS)		3.8	12.1	2.0	0.7	0.2
Wasteload Allocations	NPDES Wastewater Dischargers	2.8	2.8	2.8	2.8	2.8
	MS4 Communities	15.4	6.3	1.8	0.7	0.5
	Construction Stormwater	3.6	1.5	0.4	0.2	0.1
	Industrial Stormwater	1.8	0.7	0.2	0.1	0.1
Load allocation	NFC Watershed Upstream of Impaired Reach	297.3	119.7	32.5	11.1	6.0
	NFC Impaired Reach Watershed	37.6	15.2	4.1	1.4	0.8
Value expressed as percentage of total daily loading capacity						
Total Daily Loading Capacity		100%	100%	100%	100%	100%
Margin of Safety (MOS)		1%	8%	5%	4%	2%
Wasteload Allocation	NPDES Wastewater Dischargers	1%	2%	6%	16%	27%
	MS4 Communities	5%	4%	4%	4%	4%
	Construction Stormwater	1%	1%	1%	1%	1%
	Industrial Stormwater	<1%	<1%	<1%	<1%	<1%
Load allocation	NFC Watershed Upstream of Impaired Reach	82%	76%	74%	66%	58%
	NFC Impaired Reach Watershed	10%	9%	9%	8%	7%

Table 3.10. Lower Crow River impaired reach TSS total daily loading capacities and allocations.

Crow River 07010204-502		Flow Zones				
		Very High	High	Mid-Range	Low	Dry
		TSS Load (tons/day)				
Total Daily Loading Capacity		763.1	273.5	75.6	29.3	19.3
Margin of Safety (MOS)		22.9	20.9	3.4	1.3	0.4
Boundary Condition (S Fork Crow River)		337.1	115.0	32.9	12.7	8.6
Wasteload Allocations	NPDES Wastewater Dischargers	3.4	3.4	3.4	3.4	3.4
	MS4 Communities	53.5	18.3	5.2	2.0	1.4
	Construction Stormwater	4.0	1.4	0.4	0.2	0.1
	Industrial Stormwater	2.0	0.7	0.2	0.1	0.1
Load allocation	NFC Watershed Upstream of Impaired Reach	308.4	103.2	27.3	8.7	4.8
	Lower Crow Impaired Reach Watershed	31.8	10.6	2.8	0.9	0.5
Value expressed as percentage of total daily loading capacity						
Total Daily Loading Capacity		100%	100.00%	100.00%	100%	100.00%
Margin of Safety (MOS)		3%	7%	4%	4%	2%
Boundary Condition (S Fork Crow River)		44%	42%	43%	43%	44%
Wasteload Allocation	NPDES Wastewater Dischargers	<1%	1%	5%	12%	18%
	MS4 Communities	7%	7%	7%	7%	7%
	Construction Stormwater	1%	1%	1%	1%	1%
	Industrial Stormwater	<1%	<1%	<1%	<1%	<1%
Load allocation	NFC Watershed Upstream of Impaired Reach	40%	38%	36%	30%	25%
	Lower Crow Impaired Reach Watershed	4%	4%	4%	3%	3%

3.10 NECESSARY REDUCTIONS TO MEET TMDL

Individual TSS measurements for each impaired reach were plotted on load duration curves (Figures 3.4 and 3.5). Values that lie above the standard load duration curve (red line) represent samples that exceed the 75 mg/L TSS-surrogate. The data shows TSS exceedances were recorded across all flow regimes. Also plotted are the maximum TSS monitored loads for each flow regime and the TMDL target (median minus MOS) loading capacity for each flow zone. The difference between these two provides a general percent reduction in TSS that will be needed to remove each reach from the impaired waters list.

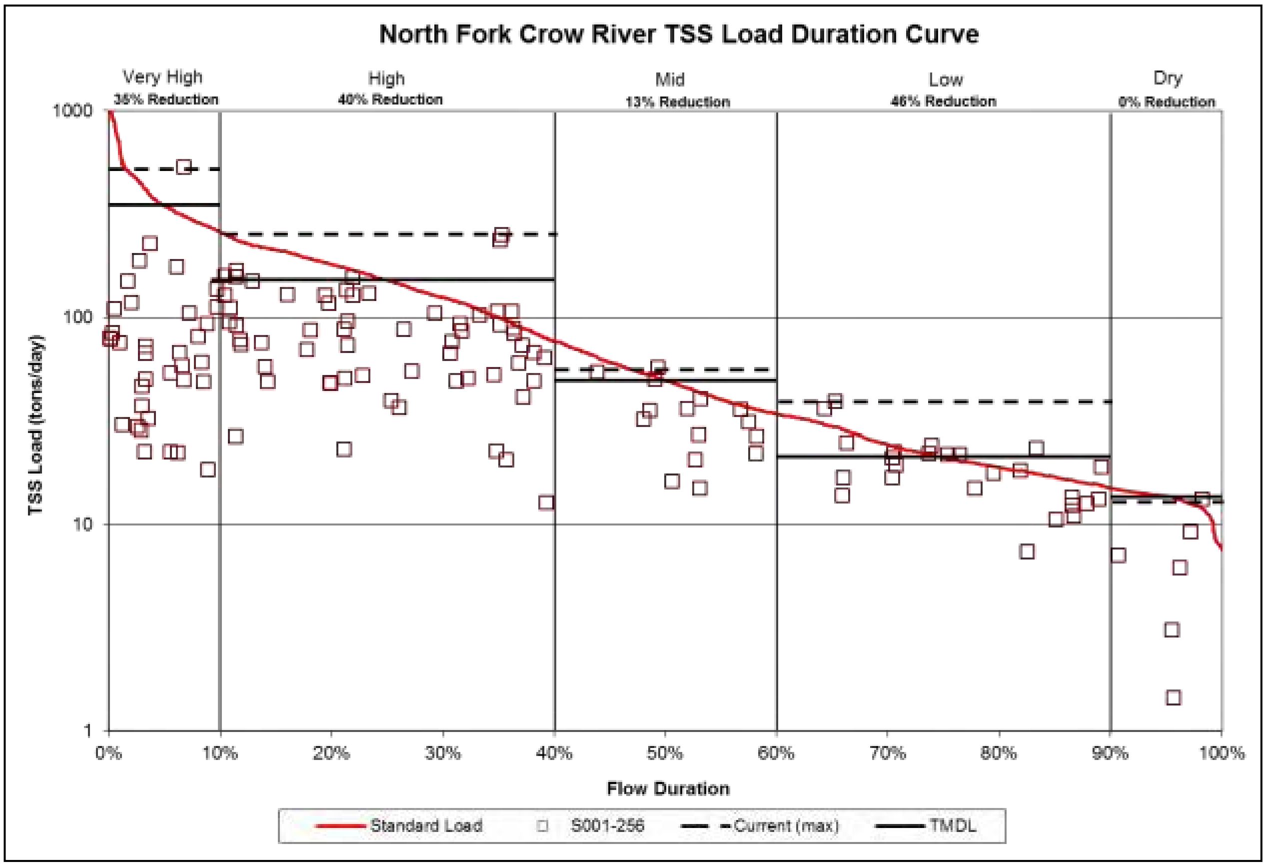

Figure 3.4. North Fork Crow River Impaired Reach (07010204-503) TSS Load Duration Curve and necessary TSS reductions to meet TMDL.

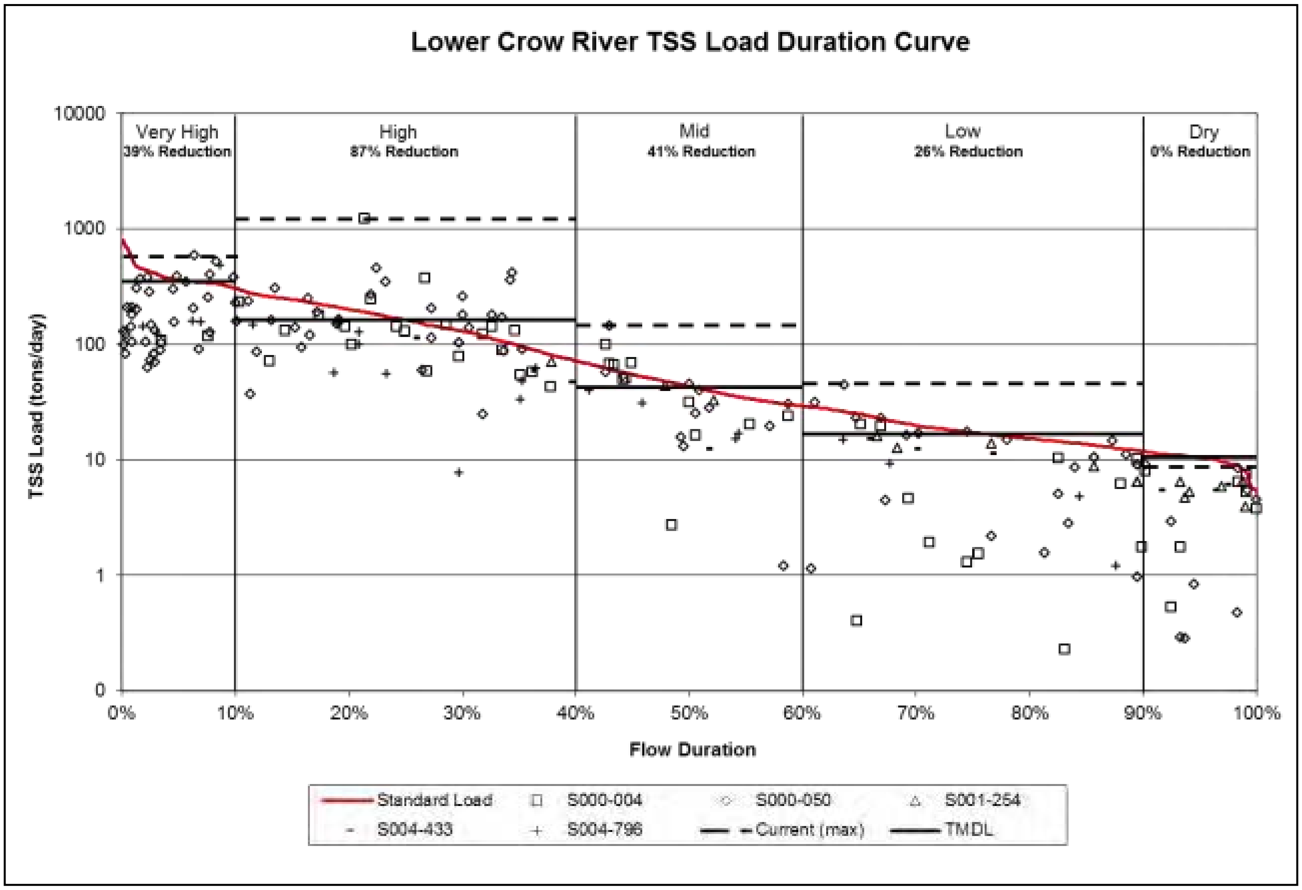

Figure 3.5. Lower Crow River Impaired Reach (07010204-502) TSS Load Duration Curve and necessary TSS reductions to meet TMDL.

3.11 IMPACT OF GROWTH ON ALLOCATIONS

3.11.1 NPDES Wastewater Dischargers

As discussed in Section 3.8.1, this TMDL study uses the Load Duration Curve method to determine the loads required to attain water quality standards. This method uses river flows to determine the allowable loads of TSS under different flow conditions. One concern that arose in the development of the TMDLs is if and how new or expanded dischargers could increase discharges, and under what conditions.

A comparison between the in-stream TSS targets (Appendix F) and technology-driven TSS effluent limits contained in MPCA NPDES permits shows that the effluent limits are below the in-stream targets. As shown in a study by Tetratech (Cleland, 2011), discharges from the facilities, which have TSS concentrations below the in-stream targets, actually provide assimilative capacity and contribute to lower in-stream TSS concentrations. Although facilities are discharging below the in-stream targets, they are still discharging the pollutant of concern

(TSS), and therefore individual WLAs are required. The WLAs as calculated in Tables 3.9 and 3.10 are based upon the current wet-weather design flow multiplied by the permitted effluent limit calculated as a daily load in tons per day.
These WLAs are based upon current discharges. However, facilities will certainly expand in the future, and it is likely that new NPDES-permitted facilities will be located in the watershed, and therefore changes will occur in the allocations. For the non-stormwater facilities, the NPDES permits limit the discharge effluent to below the in-stream TSS concentration target. When a facility expands, it will increase both load and flow. This will raise (increase) the load duration curve based upon the amount of "new" flow and load. This effect will be most pronounced in lower flows, when conventional point sources have the greatest impact. The increased flow will effectively increase the overall assimilative capacity of the river, as the flow increase will be larger proportionally than the load increase.

The analysis summarized above demonstrates that current discharges can be expanded and new NPDES discharges can be added, will not degrade TSS concentrations but rather will help reduce in-stream TSS concentration, provided the permitted NPDES discharges remain below the in-stream targets. Based on this somewhat unique circumstance, a streamlined process is envisioned for updating the TMDL wasteload allocations when there are new or increased discharges of discharges where the permits ensure the TSS concentrations are below the in-stream targets. The process envisioned for updating TMDL WLAs is summarized blow. This process will apply to the non-stormwater facilities identified in Appendix F of this TMDL study.

1. A new or expanding discharger would file with the MPCA permit program a permit modification request or an application for a permit reissuance. The permit application information would include documentation of the current and proposed future flow quantities, from which, taking into account the permitted discharge concentrations, the future TSS loads.
2. The MPCA permit program will notify the MPCA TMDL program upon receipt of the request/application, and provide the appropriate information, including the proposed discharge flow.
3. Assuming the NPDES program finds the permit issuance or modification is approvable, the MPCA permit program will prepare a draft permit and a fact sheet. [Need to decide how to handle minors, for which a fact sheet might normally not be prepared.] The fact sheet will include information on future discharge volumes and a discussion summarizing the future growth analysis presented above. A short discussion will be included noting that for TSS, the effluent limit is below the instream TSS target and the increased discharge will protect water quality with respect to turbidity. The Fact Sheet would include a table showing the new loading capacity of the river and the new WLA. The Fact Sheet would state that the TMDL will be updated in conjunction with the permit action. This provides a public notice of the update to the WLA, along with the permit. Stakeholders will, per usual, have the opportunity to comment on the proposed permit and the update to the WLA.
4. The MPCA permit program will notify the EPA TMDL program of the proposed action at the very beginning of the public comment period, and send a copy of the permit fact

sheet. The permit program will also ensure the MPCA TMDL program receives a copy of the fact sheet.

5. EPA (both the permit program and TMDL program) will review the Fact Sheet and provide any comments to MPCA as soon as possible.
6. MPCA will consider any comments provided by EPA and by stakeholders/interested parties on the proposed permit action and the update to the WLA. If EPA offered no adverse comments and no adverse comments on the WLA update were received from stakeholders/ interested parties, MPCA will proceed with the permit action. If there are adverse comments on the WLA update, MPCA will consult with U.S. EPA. Comments on the TMDL would need to be addressed by MPCA before proceeding further.
7. EPA will notify MPCA that the update to the TMDL is approved after confirming that either no TMDL comments were received or all TMDL comments have been appropriately addressed. This notification will occur as soon as possible after the confirmation is completed.
8. EPA will document the revision in the administrative record for the TMDL. Through this process EPA will maintain an up-to-date record of the applicable WLA for permitted facilities in the watershed.

3.11.2 Municipal Separate Storm Sewer Systems

There are currently 12 MS4s and 2 additional cities in the North Fork Crow and Lower Crow River watersheds that require or will require NPDES permits. There are no current plans to expand or develop MS4 communities in the watershed for the foreseeable future. However, future transfer of loads in this TMDL may be necessary if any of the following scenarios occur within the North Fork Crow and Lower Crow River 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. Ultimately, increases in urban stormwater also increase the loading capacity of the receiving water thereby supplying their own increases in receiving water assimilative capacity. Consequently, as long as stormwater discharges are below the in-stream target for these TMDLs, increases in stormwater will not impact attainment of the water quality standard.

3.11.3 Agriculture Practices

The amount of land in agricultural land use in the watershed is likely to remain fairly constant over the next several decades. The watersheds are comprised mainly of row crops (corn and soybeans) and pasture and hay land. While the majority of the landscape is likely to remain in an agricultural land use, it is possible a modest shift from pasture/hay to row crops could occur. Any such shift would likely not affect the loading capacity of the streams, since that capacity is based on long-term flow values that incorporate land use variability, and slight shifts in land use should not appreciably change the magnitude of the land use-driven flow variability that the period of record already reflects.

3.12 ASSESSMENT OF TURBIDITY SOURCES

When assessing turbidity in streams, the first step is to determine the relative proportions of external and internal sources. External sources include sediment loading from outside the stream channel such as field and gully erosion, point source dischargers, livestock grazing and stormwater from construction sites and impervious surfaces. Internal sources of sediment and turbidity include sediment resuspension, bank erosion and failure, and in-channel algal production. Identifying turbidity sources in large river systems is often difficult due to complex flow patterns and interactions throughout the watershed. However, a general sense of the timing, magnitude and sources of turbidity and sediment can be developed using available data to provide a weight of evidence for potential sources. Following is a description of the methods and data used to develop a better understanding of the primary sources. It is important to note that these estimates do not affect the established TMDL allocations which are calculated using the load duration curves for each listed reach.

3.12.1 Flow and Seasonal Variability

Sampling results for all three turbidity related parameters were grouped by season and flow regime (Figures 3.6 and 3.7; Appendix B). Violations in the North Fork Crow impaired reach are most common during summer (June through August) and fall (September through November) and during mid, low and dry flow conditions. Exceedance occurrence was also high during these conditions in the Lower Crow River impaired reach. Unlike the North Fork Crow reach, however, violations occurred in greater than 10% of the spring (March through May) and very high and high flow samples. This analysis suggests efforts in the North Fork Crow River watershed may need to focus on low-flow related turbidity sources whereas the Lower Crow River will need to address sources common during all seasons and flow regimes.

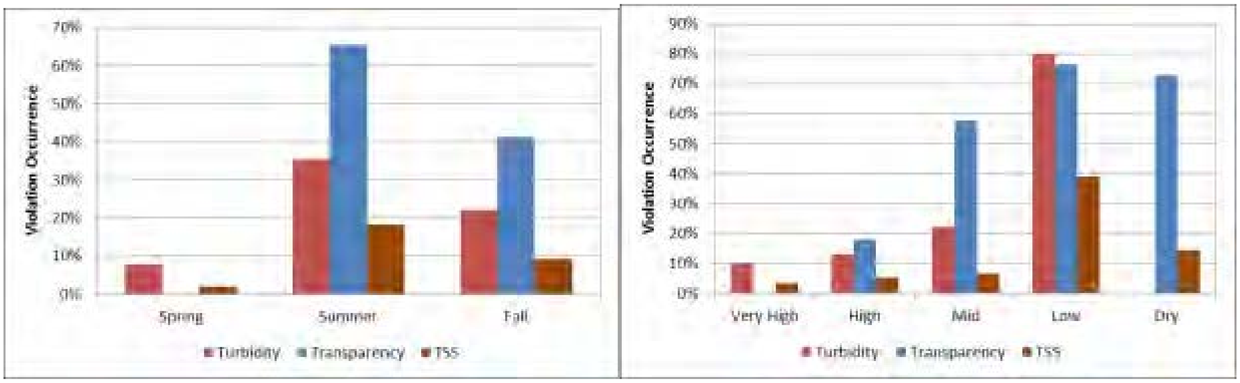

Figure 3.6. North Fork Crow impaired reach turbidity related water quality violations by season and flow regime.

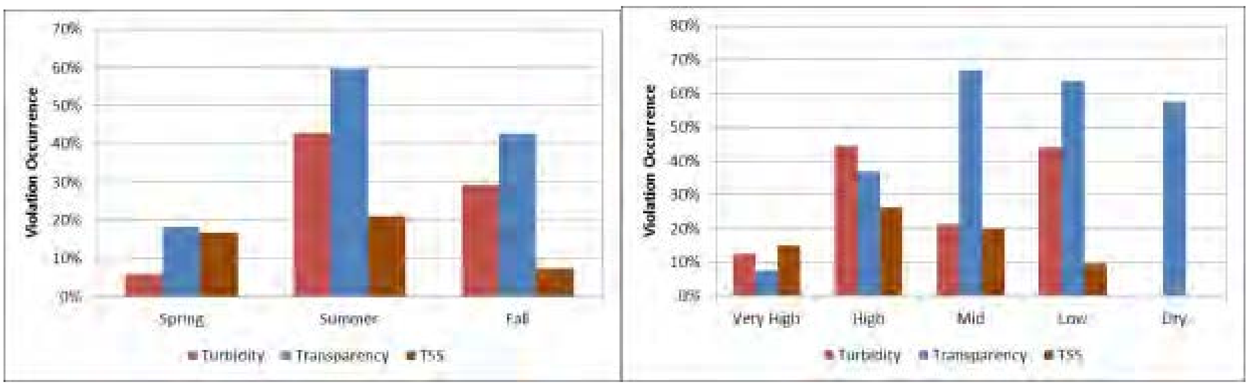

Figure 3.7. Lower Crow River impaired reach turbidity related water quality violations by season and flow regime.

3.12.2 Field Erosion

Average upland sediment loss in the impaired reach watersheds was modeled using the Universal Soil Loss Equation (USLE). This model provides an assessment of existing soil loss from upland sources and the potential to assess sediment loading through the application of Best Management Practices (BMPs). USLE predicts the long term average annual rate of erosion on a field slope based on rainfall pattern, soil type, topography, land use and management practices. The general form of the USLE has been widely used in predicting field erosion and is calculated according to the following equation:

$$A = R \times K \times LS \times C \times P$$

Where A represents the potential long term average soil loss (tons/acre) and is a function of the rainfall erosivity index (R), soil erodibility factor (K), slope-length gradient factor (LS), crop/vegetation management factor (C) and the conservation/support practice factor (P). USLE only predicts soil loss from sheet or rill erosion on a single slope as it does not account for potential losses from gully, wind, tillage or streambank erosion.

Raster layers of each USLE factor were constructed in ArcGIS for the North Fork Crow and Lower Crow River impaired reach watershed study areas. Potential soil loss was calculated for each grid cell and then added together to estimate gross annual average potential soil loss for five subwatersheds. A sediment delivery ratio was then applied to the gross average soil loss to estimate sediment loading from the five subwatersheds to the main-stem North Fork Crow and Lower Crow River impaired reaches. Sediment delivery ratios are intended to compensate for areas of sediment deposition that become increasingly important with increasing catchment area (Vanoni, 1975). The model represents the maximum amount of soil loss that could be expected under existing conditions for all areas of the watershed. It assumes all agricultural practices are subject to maximum soil loss fall plow tillage methods and no support practices (P-factor = 1.00). Model results for each subwatershed are presented in Table 3.11 and illustrated in Figure 3.8.

Model results suggest the small tributaries near the main-stem may deliver a large amount of sediment to the North Fork Crow and Lower Crow River impaired reaches. This is likely due to the lower percentage of wetlands and higher slopes near the river valley in these subwatersheds.

Table 3.11. Average annual soil loss by subwatershed for the North Fork Crow - Lower Crow River impaired reach watersheds.

Subwatershed	Gross Soil Loss (tons/year)	Sediment Delivery Ratio	Sediment Yield to main-stem (tons/year)	Average Sediment Yield (tons/acre/year)
Mill Creek	76,611	0.10	7,652	0.20
CD31	31,690	0.12	3,865	0.19
Lower NFC	53,035	0.14 - 0.19	8,402	0.22
NFC Reach Watershed Totals	**161,336**		**19,919**	**0.21**
Lower Crow	72,467	0.11 - 0.21	9,343	0.18
Regal Creek	43,415	0.10	4,414	0.12
Lower Crow Reach Watershed Totals	**115,882**		**13,757**	**0.16**

Note: Subwatershed locations and boundaries are shown in Figure 3.8.

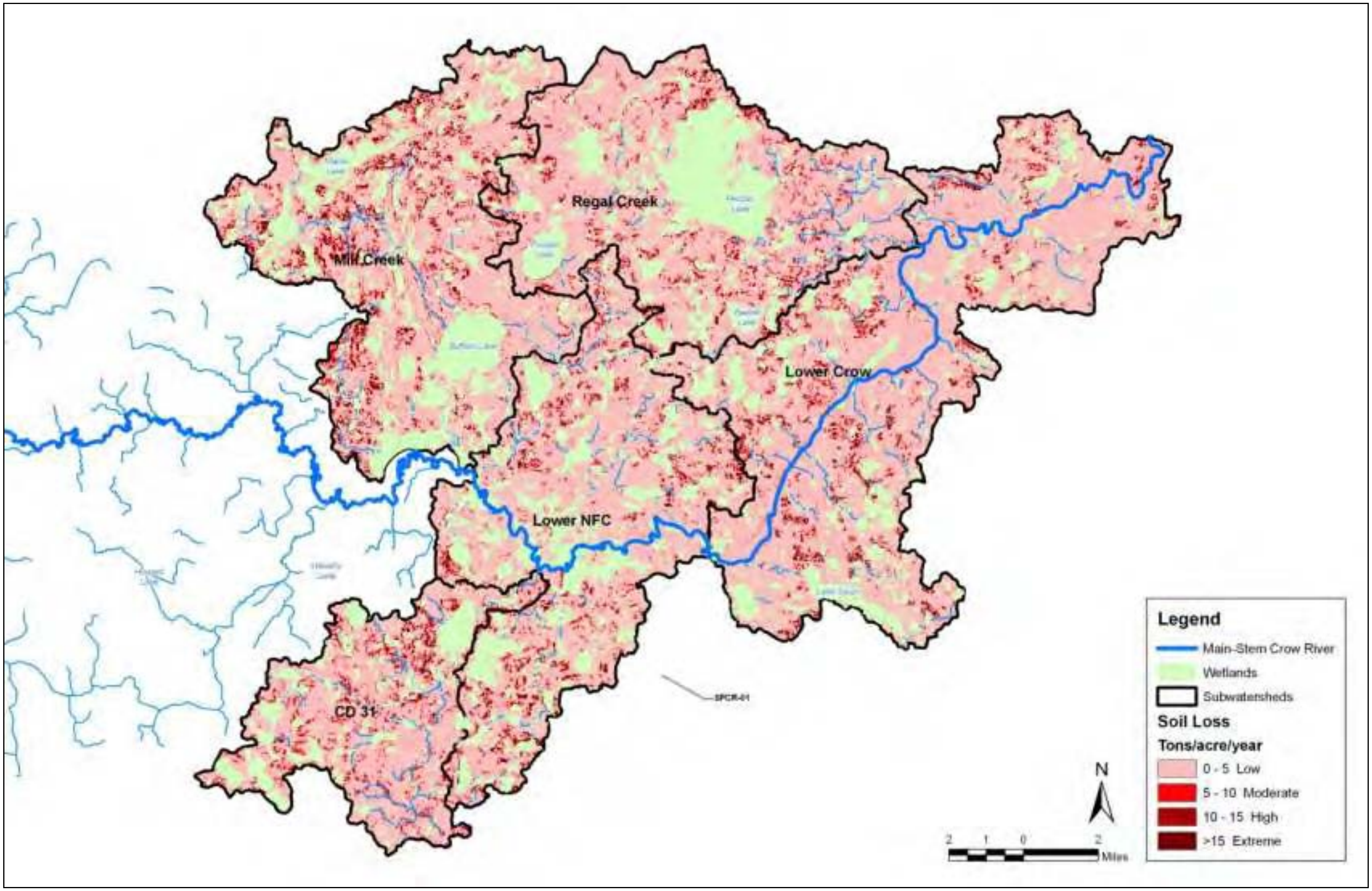

Figure 3.8. Average annual soil loss per acre for the North Fork Crow and Lower Crow River impaired reach study areas calculated using the USLE.

3.12.3 Bank Erosion

Beside upland field erosion, another primary source of TSS in streams is soil particles detached from the streambank. Streambank erosion is a natural process that can be accelerated significantly as a result of change in the watershed or to the stream itself. Bank conditions along the Lower Crow River impaired reach (AUID 07010204-502) were evaluated to determine whether soil loss from streambank erosion may be a significant contributor of sediment to the main-stem. The banks were surveyed for stability and amount of observed soil loss by severity. Only major erosion features were noted and measured during the survey as it was assumed that these problem areas account for a majority of the bank erosion within the listed reach. Bank erosion in the non-measured portions of the reach was assumed to be relatively low and set to the average of the three lowest surveyed erosion features.

Annual soil loss was estimated using the field data and a method developed by the Natural Resources Conservation Service referred to as the "NRCS Direct Volume Method," or the "Wisconsin Method," (Wisconsin NRCS 2003). Soil loss is calculated by:

1. measuring the amount of exposed streambank in a known length of stream;
2. multiplying that by a rate of loss per year;
3. multiplying that volume by soil density to obtain the annual mass for that stream length; and then
4. converting that mass into a mass per stream mile.

The Direct Volume Method is summarized in the following equation:

$$\frac{\text{(eroding area) (lateral recession rate) (density)}}{\text{2000 lbs/ton}} = \text{erosion in tons/year}$$

Appendix D provides a more detailed summary of the survey and bank loss calculation methods and assumptions. Total annual bank loss (erosion) for the main-stem Lower Crow River impaired reach was estimated to be approximately 8,269 tons/year (Table 3.12).

Table 3.12. Surveyed bank loss measurements for the Lower Crow River turbidity impaired reach.

Measurement	Result/Estimate
Erosion Features noted	31
Maximum measured soil (bank) loss	6,600 tons/yr/mi
Minimum measured soil (bank) loss	34 tons/yr/mi
Non-surveyed soil (bank) loss - assumed	62 tons/yr/mi
Total length of surveyed erosion features	4.35 miles
Total Reach Length	24.98 miles
Total surveyed soil (bank) loss	6,988 tons/yr
Total non-surveyed soil (bank) loss	1,281 tons/yr
Total Lower Crow River soil (bank) loss	**8,269 tons/yr**

The Lower Crow River impaired reach streambanks most susceptible to erosion are those that are high compared to bankfull elevation, and rooting depths shallow compared to bank height, or where banks are nearly vertical. These are characteristics typical of overly-incised streams. Erosion features in this stream assessment where measured erosion features suggest a higher rate of annual soil loss tended to have higher, more vertical banks and shallower rooting depths. Channel incision often associated with changes in hydrologic regime such as adding flow from stormwater or agricultural tiling, or stream straightening. The resulting increase in stream power and shear stress accelerates streambank erosion. Significant changes in land use and land cover in the watershed can alter the historic bankfull elevation, increasing its frequency and subjecting additional streambank to erosive flows. Based on the stream assessment findings it is likely that watershed and hydrologic regime modifications in the watershed have resulted in increased rates and volumes of streambank soil loss.

3.12.4 Algal Turbidity

Chlorophyll-a measurements were collected periodically from 2001-2009 at the two main monitoring stations within each impaired reach (S001-256 and S000-050) as well as the South Fork Crow River monitoring station in Delano (S001-255). There were a total of 35 sampling events at these stations in which chlorophyll-a, TSS and transparency was measured. Data from each station were combined into one dataset to assess the role algae plays in turbidity and transparency violations in and upstream of the impaired reaches. The data suggests transparency is lowest when TSS and chlorophyll-a concentrations are highest during low flow conditions (Figure 3.9).

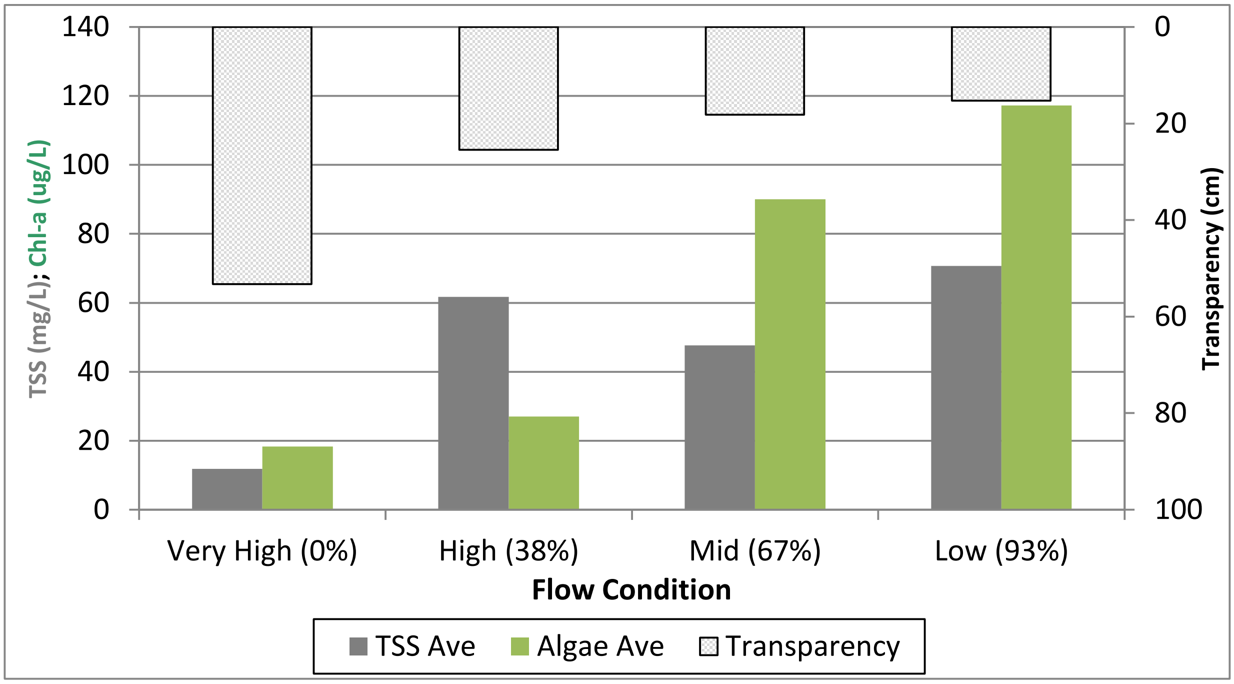

Figure 3.9. TSS, chlorophyll-a and transparency paired measurements in the North Fork Crow, South Fork Crow and Lower Crow Rivers.
Note: Data was grouped and averaged by the flow categories used to establish the TMDL allocations for the Lower Crow impaired reach (07010204-502).
Note: Transparency violation (<20 cm) occurrence is listed next to each flow zone.

To determine algae's contribution to low transparency levels in the North Fork, South Fork and Lower Crow Rivers, the light extinction coefficient (K_e) for each of the 35 sampling events was calculated based on the following equation:

(1) K_e (m) = 1.7/transparency (m)

Despite some scatter, there is a positive correlation between the increase in light extinction and increases in chlorophyll-a (Appendix E). The regression relationship suggests that for each 1 µg/L increase in chlorophyll-a the light extinction coefficient (K_e) increases by approximately 0.0424/m. This value was used to estimate the component of light extinction due to absorption of light by chlorophyll-a using the equation:

(2) K_e (chl-a) = 0.042 x chl-a (µg/L)

Assuming light extinction throughout the Crow River is due to light reduction by both algae and streambank/upland TSS sources, a non-algal TSS light extinction coefficient may be calculated by subtracting the chlorophyll-a light extinction coefficient from the total light extinction coefficient:

(3) K_e (TSS) = K_e (m) – K_e (chl-a)

Finally, the non-algal TSS light extinction coefficient may be divided by the TSS concentration to calculate the increase in light extinction per unit of TSS (Appendix E). The average value of all 35 measurements was 0.154 which was used in the following equation to calculate light extinction as a function of chlorophyll-a and TSS:

(4) Ke (m) = 0.042 x chl-a (μg/L) + 0.154 x TSS (mg/L)

This equation was applied to the 35 samples to estimate the percent light extinction attributed to algae and non-algal TSS under different flow conditions (Figure 3.10). During the very high and high flow zones, there were fewer transparency violations as light extinction was driven by non-algal turbidity sources. During mid and low flow conditions, however, transparency violations increase as algae plays a much larger role (40%-45%) in reducing water clarity. Consequently, reductions in algal production will be critical in attaining the water quality standards for turbidity.

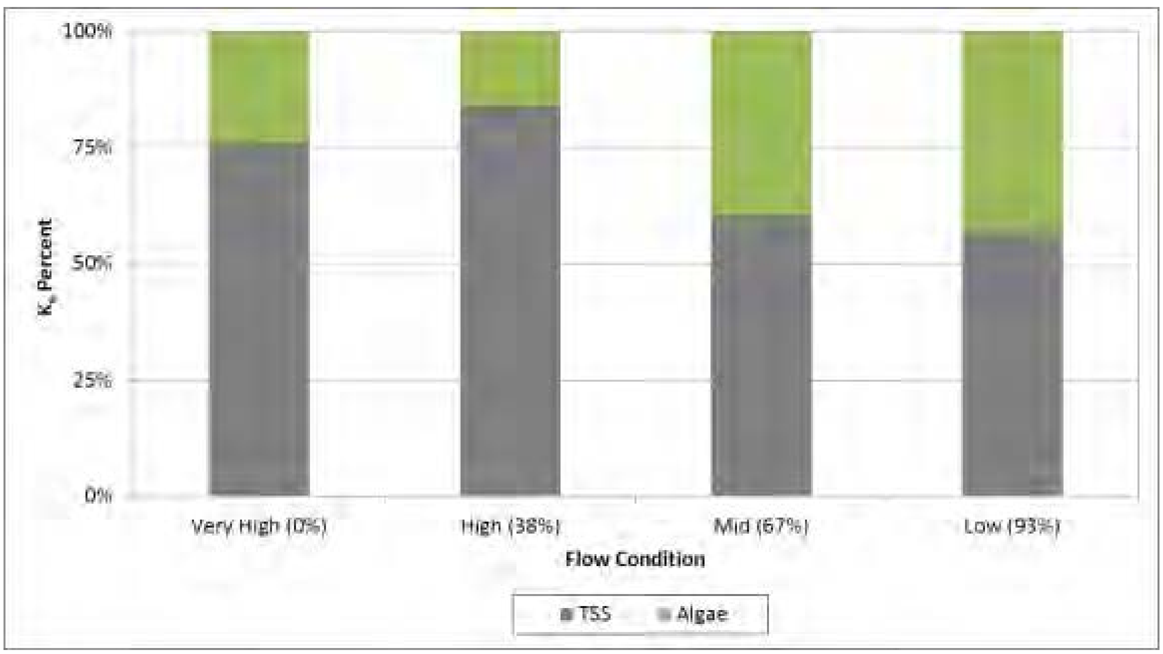

Figure 3.10. Percent light extinction from algae and non-algal sources in the North Fork Crow, South Fork Crow and Lower Crow Rivers.
Note: Data was grouped and averaged by the flow categories used to establish the TMDL allocations for the Lower Crow impaired reach (07010204-502).
Note: Transparency violation (<20 cm) occurrence is listed next to each flow zone.

3.12.5 Upstream and Tributary Sources

Both the North Fork Crow River (767,687 acres) and the South Fork Crow River (799,146 acres) watersheds upstream of the impaired reaches are extremely large and account for a majority of the flow in each reach. While the turbidity source assessment modeling to this point has focused on the subwatersheds that drain directly to each impaired reach, upstream contributions from North Fork Crow and South Fork Crow Rivers cannot be ignored.

Stations S002-019 and S001-507 are the closest monitoring sites on the North Fork Crow River upstream of the North Fork Crow impaired reach (AUID 07010204-503) with turbidity-related water quality data (Figure 3.1). Water quality data for both stations show very few TSS and transparency violations since 2001 (Table 3.13). Violations are significantly higher at the monitoring stations within the impaired reach suggesting sources of turbidity are generated in-stream between the upstream stations and the listed reach and/or within the impaired reach watershed itself.

South Fork Crow station S001-255 in Delano is located in the turbidity impaired reach of the South Fork Crow River (AUID 07010205-508) and has relatively good turbidity related water quality data. Turbidity and TSS measurements from this station are occasionally high as exceedances are very close to the 10% needed to be considered impaired. Transparency measurements are consistently low and similar to transparency measured downstream in the Lower Crow River impaired reach. These data suggests the South Fork Crow River is likely a significant source of turbidity to the Lower Crow River impaired reach.

Table 3.13. Main-stem monitoring stations located upstream of the North Fork Crow and Lower Crow River impaired reaches.

Station	Impaired Reach	Parameter	Years Monitored	Measurements	Exceedances	Percent Exceedance
NFC S001-507	North Fork Crow	Turbidity	--	--	--	--
		Transparency	01-09	260	7	3%
		TSS	--	--	--	--
NFC S002-019		Turbidity	01	5	0	0%
		Transparency	09	7	0	0%
		TSS	01-09	44	1	2%
SFC S001-255	Lower Crow	Turbidity	01-09	35	4	11%
		Transparency	04-09	59	31	53%
		TSS	01-09	112	10	9%

There are 3 major tributaries in the North Fork Crow and Lower Crow impaired reach watershed with turbidity related monitoring data (Figure 3.1 and Table 3.14). Data from the County Ditch 31 (S002-020) and Regal Creek (S002-030) monitoring stations indicate these tributaries contribute very little to the turbidity impairment in the main-stem impaired reaches. Mill Creek (S002-018) TSS and turbidity measurements are low, however there have been a number of transparency violations in recent years. A closer look at these violations reveals most have occurred between July and early September during relatively low-flow conditions. While no chlorophyll-a data were collected during these measurements, it is very likely the violations may be driven by algal turbidity from Deer Lake which outlets to Mill Creek.

Table 3.14. Monitoring stations located on tributaries to the North Fork Crow and Lower Crow River impaired reaches.

Station	Impaired Reach	Parameter	Years Monitored	Measurements	Exceedances	Percent Exceedance
Mill Cr S002-018	North Fork Crow	Turbidity	01-03	15	0	0%
		Transparency	07-09	17	7	41%
		TSS	01-09	84	1	1%
CD31 S002-020		Turbidity	01-03	14	0	0%
		Transparency	07-09	17	0	0%
		TSS	01-09	79	1	1%
Regal Cr S002-030	Lower Crow	Turbidity	01-03	14	0	0%
		Transparency	01-09	119	3	3%
		TSS	01-09	102	1	1%

3.12.6 Permitted WWTP Contributions

There are 22 NPDES wastewater dischargers in the North Fork Crow and Lower Crow River watersheds with TSS permit limits. Discharge monitoring reports (DMRs) were downloaded from the MPCA's Environmental Data Access (EDA) website to assess TSS concentrations for each point source. By rule, effluent TSS concentrations are not to exceed 30 mg/L for facilities with a continuous effluent discharge and 45 mg/L for stabilization pond facilities that discharge periodically. Monitoring reports show 17 of the facilities have monitored effluent TSS concentrations at least once since 1999 (Appendix F). Results indicate all facilities rarely exceed their TSS permitted concentration limit and typically discharge well below their limit.

3.12.7 Turbidity Source Summary

Turbidity assessments in large river systems are often complex due to the variety of pollutants, inputs and variables that contribute to impairment. The turbidity source assessment for this TMDL focused on three primary sources: upland field erosion, stream bank erosion and algal turbidity. These three sources were calculated independently using available GIS data, survey results, literature values and monitoring data (Table 3.15). Results suggest a majority of the annual sediment load likely comes from field erosion during runoff events (high flows). However, a radio-isotope study of riverine depositional sites in the South Fork Crow River suggested field sources are only 39% of in-stream sediment sources while bank erosion is 61% (Schottler, et. al., 2010). Furthermore, USLE was used to identify the potential for field erosion and does not explicitly account for the numerous lakes and wetlands that can act as sediment sinks. Consequently, field erosion is likely less important than bank erosion for this impaired reach although it may impact local wetlands and lakes. Monitoring data suggests turbidity violations are very common during mid, low and dry flow conditions when field inputs are not contributing. Low-flow source assessment indicates in-stream algae production is a major source of reduced transparency during these flow conditions. Thus, implementation should focus on the following: stabilization of failing and sensitive streambanks and reducing in-stream algae growth. Secondarily, BMPs for upland areas with high erosion potential will benefit the stream reaches.

Table 3.15. Estimated sources of turbidity for the North Fork-Lower Crow River.

Reach	Field vs Bank Soil Loss		Algae vs Non-Algae Sources	
	Sediment Yield to main-stem (tons/year)	Total Estimate Bank Soil Loss (tons/year)	High Flow**	Mid-Low Flow**
North Fork Crow River Impaired Reach	19,919	4,522*	20% algae 80% non-algae	41% algae 59% non-algae
Lower Crow River Impaired Reach	13,757	8,269		
Total	33,676	12,791		
Percent Total	**72%**	**28%**		

*North Fork Crow turbidity impaired reach bank loss was estimated using the average bank loss rate (tons/year/mi) calculated for the Lower Crow River impaired reach. North Fork Crow River stream bank conditions were not surveyed for this TMDL study.
**Estimated based on percent light extinction using chlorophyll-a/TSS/transparency paired data for each flow condition.

4.0 Low Dissolved Oxygen Impairment

4.1 DISSOLVED OXYGEN WATER QUALITY STANDARDS

Minnesota's standard for dissolved oxygen in Class 2B waters is a daily minimum of 5.0 mg/L, as set forth in Minn. R. 7050.0222 (4). This dissolved oxygen standard requires compliance with the standard 50 percent of the days at which the flow of the receiving water is equal to the $7Q_{10}$.The criteria used for determining stream reach impairments are outlined in the MPCA document Guidance Manual for Assessing the Quality of Minnesota Surface Waters for Determination of Impairment – 305(b) Report and 303(d) List, January 2010. The applicable water body classifications and water quality standards are specified in Minnesota Rules Chapter 7050. Minnesota Rules Chapter 7050.0407 lists water body classifications and Chapter 7050.2222 (5) lists applicable water quality standards for the impaired reaches.

All five North Fork Crow and Lower Crow River tributary reaches were designated as impaired under the listing standards in place prior to the 2010 assessment cycle, in which a water body was considered impaired for dissolved oxygen if it met the following criteria:

- There are at least 10 observations in the most recent 10 years, of which at least 5 observations are in the most recent 5 years, or
- At least 10 observations in the most recent 5 years, and evidence of action in the watershed sufficient to change impairment status, and
- In either case, more than 10% of observations are below the minimum dissolved oxygen water quality standard.

4.2 OVERVIEW OF IMPAIRED REACH

Four tributary streams in the Lower Crow and North Fork Crow River watersheds were placed on the State of Minnesota's 303(d) list of impaired waters from 1994-2004 for low levels of dissolved oxygen impairing aquatic life (Figures 4.1 and 4.2).

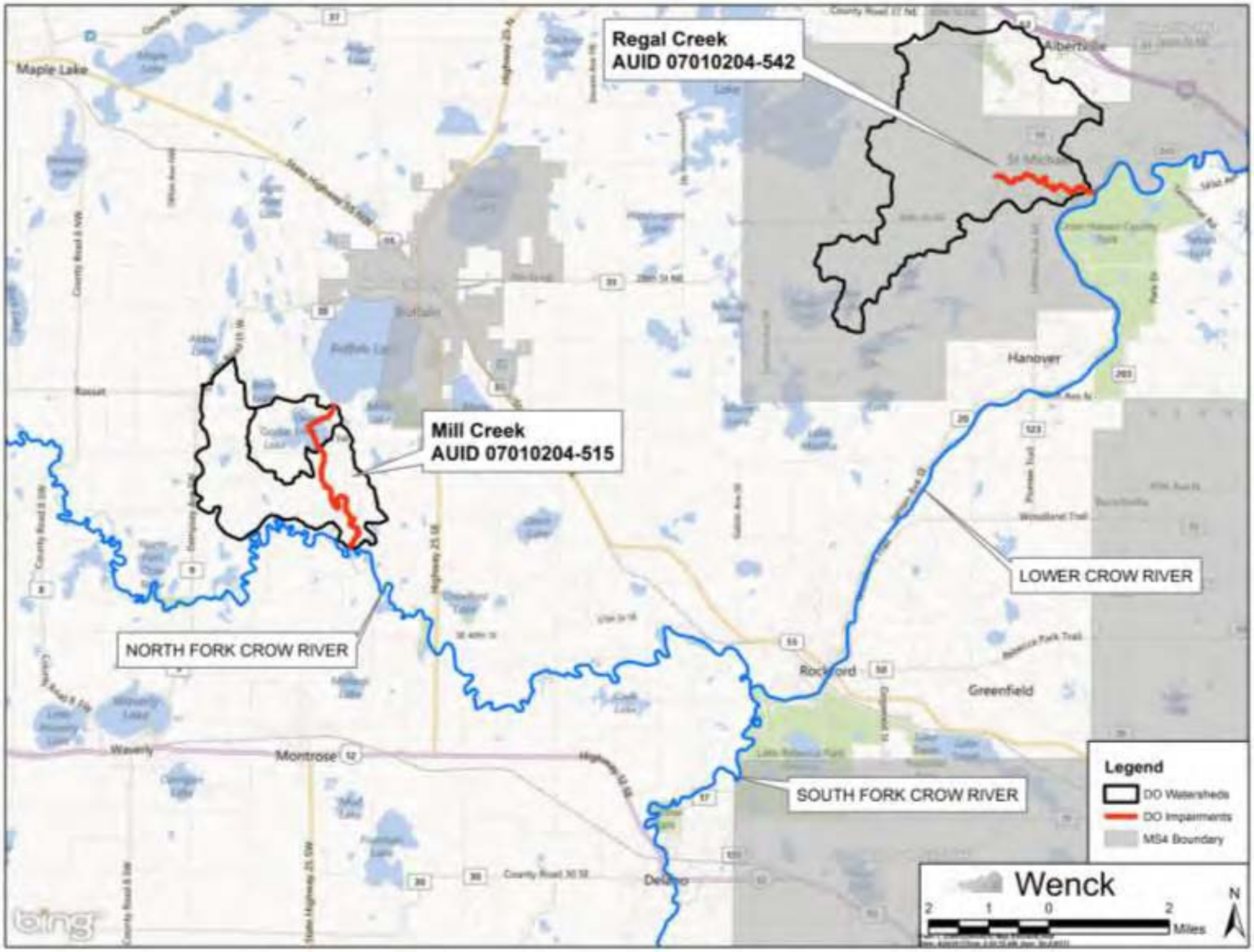

Figure 4.1. Mill Creek and Regal Creek dissolved oxygen impairments.

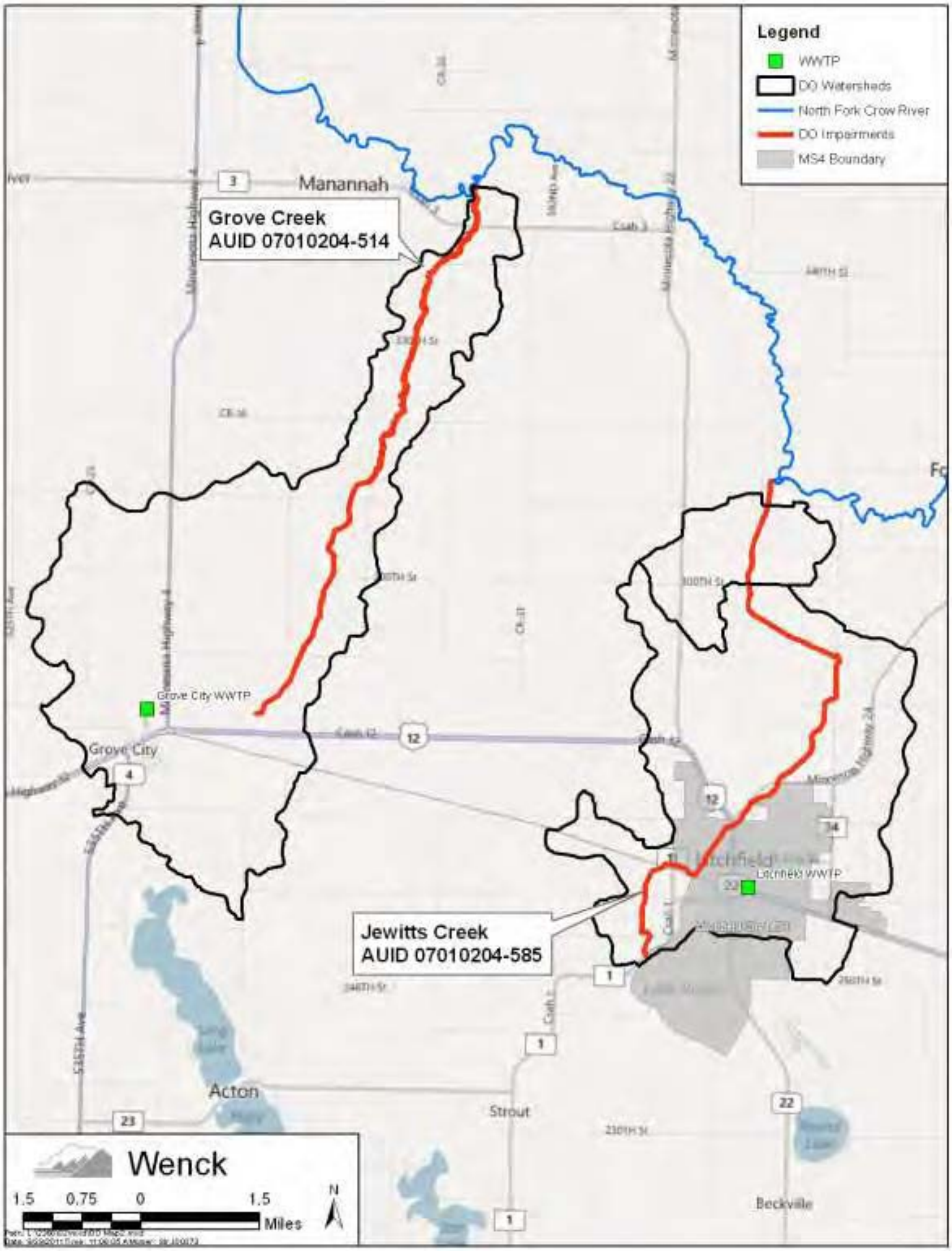

Figure 4.2. Grove and Jewitts Creek dissolved oxygen impairments.

Table 4.1 shows the 2010 revised dissolved oxygen (DO) impairment assessment criteria and the relevant data for the 5 tributary impaired reaches. Based on these data, all streams exceed the revised DO impairment listing criteria.

Table 4.1. Summary of dissolved oxygen measurements in each impaired stream

Criterion	Requirement	Tributary/Reach	Supporting Data
Number of independent observations	20 observations (over at least 2 years)	Jewitts Creek	132 total observations (01-09)
		Grove Creek	103 total observations (01-09)
		Mill Creek	110 total observations (01-09)
		Regal Creek	126 total observations (01-09)
May-September observations	Must be taken prior to 9:00 a.m. over at least two years	Jewitts Creek	7 May-Sep pre-9:00 am observations (08-09)
		Grove Creek	4 May-Sep pre-9:00 am observations (08-09)
		Mill Creek	14 May-Sep pre-9:00 am observations (01-02)
		Regal Creek	40 May-Sep pre 9:00 am observations (01-03, 08)
DO standard must be met prior to 9:00 a.m. during May-September AND	90% of the time (no more than 10% below standard)	Jewitts Creek	7 observations, 2 (29%) <5.0 mg/L
		Grove Creek	4 observations, 1 (25%) <5.0 mg/L
		Mill Creek	14 observations, 5 (36%) <5.0 mg/L
		Regal Creek	40 observations, 11 (28%) <5.0mg/L
DO standard must be met during October-April	90% of the time (no more than 10% below standard)	Jewitts Creek	27 observations, 2 (7%) <5.0 mg/L
		Grove Creek	23 observations, 1 (4%) <5.0 mg/L
		Mill Creek	24 observations, 0 (0%) <5.0 mg/L
		Regal Creek	28 observations, 0 (0%) <5.0 mg/L
Total violations	Must be at least 3	Jewitts Creek	33 (25%) total observations <5.0 mg/L
		Grove Creek	15 (15%) total observations <5.0 mg/L
		Mill Creek	21 (19%) total observations <5.0 mg/L
		Regal Creek	17 (13%) total observations <5.0 mg/L

4.3 DATA USED IN THE TMDLS

The five dissolved oxygen TMDLs incorporate historic monitoring data as well as specific monitoring conducted for this TMDL report. The data includes:

- 2000-2009 historic water quality data for all sites within each impaired stream/reach. Data was downloaded from the MPCA's STORET online database (http://www.pca.state.mn.us/index.php/environmental-data/index.html)
- TMDL travel-time dye and synoptic surveys conducted on Jewitts and Grove Creek in September, 2008; Regal Creek in late August, 2009; and on Mill Creek in September, 2009
- Continuous DO data collected throughout the summer months by the MPCA using in-situ YSI data sondes deployed in Jewitts and Grove Creeks in 2008 and 2009, and Mill and Regal Creeks in 2009
- Longitudinal DO survey data collected by the CROW and MPCA staff to assess DO as a stressor to aquatic life. This sampling was part of the North Fork Crow River Watershed Project.

4.4 WATERSHED AND STREAM CHARACTERIZATION

4.4.1 Jewitts Creek

Jewitts Creek flows 8.6 miles through Meeker County, from the outlet of Ripley Lake through Litchfield, MN to the North Fork Crow River (River Mile 107.5). The creek's watershed is comprised of two main subbasins: the Ripley Lake subwatershed to the south (5,912 acres) and the larger downstream subwatershed to the north (20,252 acres). The headwater outflow from Ripley Lake is dam controlled. The creek is narrow, shallow, straight, and moderately sloped. The average slope for the whole length of Jewitts Creek is 5.7 feet per mile. Between Highway 34 and 300th Street, the creek becomes channelized through a large wetland (Shultz Wetland Complex) where it also merges with outflow from Shultz Lake under higher-flow conditions.

Agriculture dominates the landscape: 45% of land within the watershed is used for row crops and other agricultural uses (Table 4.2). The remaining watershed area is comprised of grasslands, forest, open water, wetlands and urban and developed rural land. The watershed includes one municipality, Litchfield, with a wastewater treatment facility considered in the TMDL study.

Table 4.2. Landuse summary table for the entire Jewitts Creek Watershed.

Landuse Type	Acres	Percentage
Cultivated Land	11,884	45%
Grassland/Pasture	4,577	17%
Developed	3,780	14%
Wetlands	2,183	8%
Forest	1,970	8%
Open Water	1,770	7%
Total	26,164	100%

Jewitts Creek has six water quality stations with DO measurements available through the MPCA's STORET database (Table 4.3). Station JC-06 (S001-502) is the long-term monitoring station for the MPCA and the CROW's intensive watershed monitoring program. Thirty-three of the 132 STORET DO field measurements collected on Jewitts Creek were below the 5.0 mg/L DO standard. All but one of the thirty-three violations was recorded at station JC-06 downstream of the Shultz Wetland System. Appendix G contains a more detailed discussion of Jewitts Creek historic DO data.

Table 4.3. Jewitts Creek DO observations from 2001-2009.

Site	STORET ID	Observations	Violations	Percent Violations
JC-02	S002-525	4	0	0%
JC-04	S000-923	25	0	0%
JC-05	S000-921	15	1	7%
JC-06	S001-502	87	32	37%
JC-07	S000-294	1	0	0%
Total		132	33	25%

4.4.2 Grove Creek

Grove Creek flows 10.4 miles through Meeker County, from the outlet of Long Lake to the North Fork Crow River (River Mile 117.8). The creek's watershed is comprised of two main subbasins: the Long Lake subwatershed to the south (8,403 acres) and the larger downstream subwatershed to the north (22,680 acres). The creek is narrow, shallow, straight, and moderately sloped. The average slope for the whole length of Grove Creek is 4.4 feet per mile. Agriculture dominates the landscape: 62% of land within the watershed is used for row and other agricultural uses while 12% of the watershed is grassland, some of which may be used as pasture (Table 4.4). The remaining watershed area is comprised of forest, open water, wetlands and urban and developed rural land. The watershed includes one municipality, Grove City, with a wastewater treatment facility considered in the TMDL study.

Table 4.4. Landuse summary table for the Grove Creek Watershed.

Landuse Type	Acres	Percentage
Cultivated Land	19,224	62%
Grassland/Pasture	3,813	12%
Forest	2,640	8%
Developed	2,537	8%
Open Water	1,484	5%
Wetlands	1,385	4%
Total	31,083	100%

Grove Creek has six water quality stations with DO measurements available through the MPCA's STORET database (Table 4.5). Station GC-07 (S000-847) is the long-term monitoring station for the MPCA and the CROW's intensive watershed monitoring program. Fifteen of the 113 STORET DO field measurements collected on Grove Creek were below the 5.0 mg/L DO standard (Figure 4.5). Appendix G contains a more detailed discussion of Grove Creek historic DO data.

Table 4.5. Grove Creek DO observations from 2001-2009.

Site	STORET ID	Observations	Violations	Percent Violations
GC-02	S000-854	1	1	100%
GC-03	S000-851	1	0	0%
GC-04	S000-850	1	1	100%
GC-05	S000-848	1	0	0%
GC-06	S000-897	13	3	23%
GC-07	S000-847	86	10	12%
Total		103	15	15%

4.4.3 Mill Creek

Mill Creek flows approximately 2.63 miles from the outlet of Deer Lake which is southwest of Buffalo, MN. This stretch of Mill Creek (AUID 07010204-515) was listed as impaired for dissolved oxygen in 2006. The system is wide near the Deer Lake headwaters and narrows and straightens moving downstream near its junction with the North Fork Crow River. For the TMDL study, the Mill Creek watershed was considered to be the 2,804 - acre watershed downstream of Deer Lake that also includes a subwatershed that drains from a wetland west of Mill Creek via an unnamed tributary that joins the main stem near river mile 1.93. Agriculture dominates the landscape: 43% is used for grassland and pasture while 15% is cultivated for row crops (Table 4.6). The wetland in the western portion of the Mill Creek watershed covers approximately 20% of the landscape while forest, lakes and developed land comprise the remainder of the watershed.

Table 4.6. Landuse summary table for the Mill Creek Watershed.

Landuse Type	Acres	Percentage
Grassland/Pasture	1,211	43%
Wetlands	551	20%
Cultivated Land	427	15%
Forest	332	12%
Developed	219	8%
Lakes	64	2%
TOTAL	2,804	100%

Mill Creek has two STORET water quality stations with DO measurements available through the MPCA's STORET database (Table 4.7). Station MillCr-03 (S002-018) is the long-term monitoring station for the MPCA and the CROW intensive watershed monitoring program. MillCr-02 is a station established by Wenck Associates, Inc. at the outlet of Deer Lake to sample dissolved oxygen and other water quality parameters as part of a two-day synoptic survey study that took place on September 1st and 2nd, 2009. Twenty one of the 110 STORET DO field measurements collected on Mill Creek were below the 5.0 mg/L DO standard. Appendix G contains a more detailed discussion of Mill Creek historic DO data.

Table 4.7. Mill Creek DO observations from 2001-2009.

Site	STORET ID	Observations	Violations	Percent Violations
MillCr-02	S005-838	2	0	0%
MillCr-03	S002-018	108	21	19%
Total		110	21	19%

4.4.4 Regal Creek

Regal Creek flows approximately 3.5 miles through Wright County, from its headwater wetland through St. Michael, MN to the North Fork Crow River. This stretch of Regal Creek (AUID 07010205-542) was listed as impaired for dissolved oxygen in 2005. The creek has a rock-sand bottom and is narrow, shallow, and moderately sloped. For the TMDL study, the Regal Creek watershed was considered to be the 7,000 - acre watershed that drains to the headwater wetland and the creek itself. Agriculture dominates the landscape: 36% of land within the watershed is used for grassland and pasture while 31% is cultivated for row crops and other agricultural uses (Table 4.10). The city of St. Michael also comprises a large portion of the watershed (22%) while forest, wetlands and lakes each account for less than 10%.

Table 4.8. Landuse summary for Regal Creek Watershed.

Landuse Type	Acres	Percentage
Grassland/Pasture	2,491	36%
Cultivated	2,168	31%
Developed	1,521	22%
Forest	565	8%
Wetlands	193	3%
Lakes	72	1%
Total	7,009	100%

Regal Creek has three water quality stations with dissolved oxygen measurements available through the MPCA's STORET database (Table 4.11). Station RC-02 (S002-030) was established in 2001 as the long-term monitoring station for the MPCA and the Crow River Organization of Water's intensive watershed monitoring program. Stations RC-01 (S005-834) and RC-02 (S005-835) are additional stations set-up by Wenck Associates, Inc. to sample dissolved oxygen and other water quality parameters as part of a two-day synoptic survey study that took place on August 26th and 27th, 2009. Seventeen of the 124 STORET DO field measurements (13%) collected on Regal Creek were below the 5.0 mg/L DO standard (Table 4.11). Appendix G contains a more detailed discussion of Regal Creek historic DO data.

Table 4.9. Regal Creek DO observations from 2001-2009.

Site	STORET ID	Observations	Violations	Percent Violations
RC-01	S005-834	2	2	100%
RC-02	S002-030	122	15	12%
RC-03	S005-835	2	0	0%
Total		126	17	13%

4.5 FACTORS INFLUENCING DISSOLVED OXYGEN IN STREAMS

Dissolved oxygen is required by most aquatic organisms for survival. If DO drops below acceptable levels, fish and other aquatic organisms may die or be harmed. DO concentrations go through a diurnal cycle in most rivers and streams with concentrations reaching their daily maximum levels in late afternoon when photosynthesis by aquatic plants is highest. Minimum DO concentrations typically occur early in the morning around sunrise when respiration rates exceed photosynthesis and oxygen is being consumed by aquatic organisms faster than it is replaced. Stream DO is also affected by water column and/or sediment oxygen consumption that occurs through the breakdown of organic compounds. Loading of organic matter to streams can come from both natural (plant and leaf debris, in-situ primary production) and anthropogenic (wastewater effluent, animal feces) sources. Critical conditions for stream DO usually occur during late summer when flows are low and water temperatures and stream metabolism is high.

4.5.1 Breakdown of Organic Matter

Oxygen depletion in streams commonly occurs from loading and subsequent breakdown of organic matter within the system. Loading of biochemical oxygen demanding (BOD) substances can be traced to both natural and anthropogenic sources. The most common human-related inputs are associated with effluent from wastewater treatment plants. Litchfield WWTF and Grove City are the only wastewater treatment facilities that discharge directly to one of the six listed reaches. There are also several nonpoint source factors within the listed reach watersheds that may cause oxygen depletion and the low DO levels observed throughout the system.

Total BOD is comprised of two components: nitrogenous biochemical oxygen demand (NBOD) and carbonaceous biochemical oxygen demand (CBOD). CBOD is the reduction of organic carbon to carbon dioxide through the metabolic action of microorganisms. NBOD is the term for the oxygen required for nitrification, which is the biologic oxidation of ammonia to nitrate. NBOD is typically calculated by subtracting CBOD from total BOD. Carbonaceous demand is usually exerted first, normally as a result of a lag in the growth of the nitrifying bacteria necessary for oxidation of the nitrogen forms. High ammonia levels are typically associated with elevated NBOD as it indicates organic matter is decomposing rapidly within the system or there are significant inputs of human/animal waste.

Ammonia concentrations in the four impaired reaches are typically low as median levels in each reach are at or near detection limit (Figure 4.3). Five-day BOD ($CBOD_5$) monitoring indicates concentrations are occasionally high in Mill Creek, and Regal Creek, BOD_5 concentrations are also within the range for typical streams in the North Central Hardwood Forest (NCHF) ecoregion (Figure 4.4).

Figure 4.3. Box plots of historic ammonia sampling for each listed reach since 2000.
Note: The upper and lower edge of each box represent the 75th and 25th percentile of the data range for each site. Error bars above and below each box represent the 95th and 5th percentile of the dataset. The purple dash is the median ammonia concentration of all data collected.

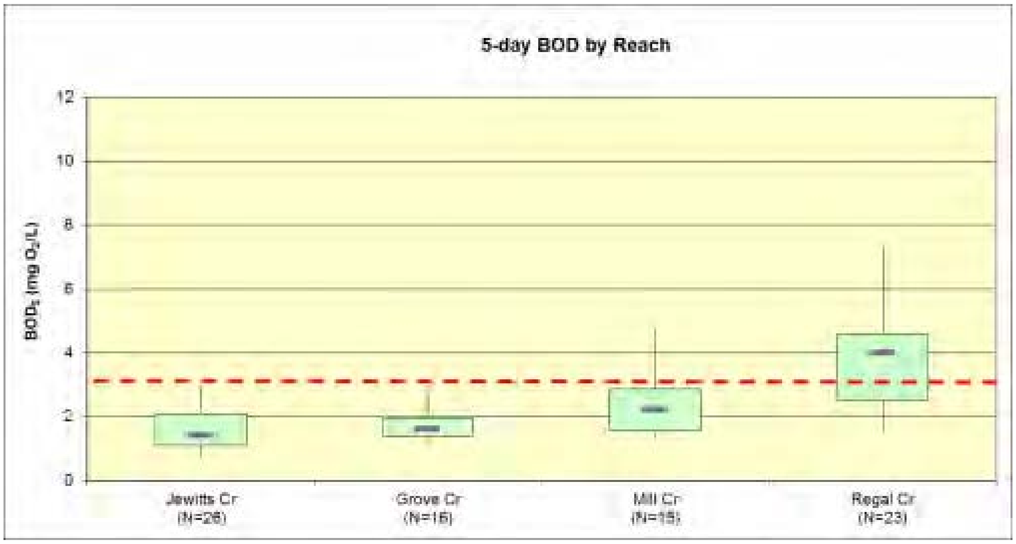

Figure 4.4. Box plots of historic BOD_5 sampling for each listed reach since 2000.
Note: The upper and lower edge of each box represent the 75th and 25th percentile of the data range for each site. Error bars above and below each box represent the 95th and 5th percentile of the dataset. The purple dash is the median BOD_5 concentration of all data collected. The dashed red line shows the upper end BOD_5 concentration (3.2 mg O_2/L) for non-impacted streams in the North Central Hardwood Forest Ecoregion.

4.5.2 Sediment Oxygen Demand

Another factor that influences dissolved oxygen concentrations in streams is sediment oxygen demand (SOD). SOD is the aerobic decay of organic materials that settle to the bottom of the stream. In natural, free-flowing streams, SOD is usually considered negligible because frequent scouring during storm events prevents long-term accumulation of organic materials. However, all of the DO impaired streams in this TMDL have been ditched, straightened and over-widened in certain reaches, and/or flow through major wetland complexes. These stream modifications have lowered average velocity throughout these reaches resulting in accumulation of organic matter and fine sediment particles. Field observations confirm these streams contain very soft, organic-rich and sometimes peaty sediments that are subject to very little bottom scouring.

SOD is difficult and expensive to measure and typically expresses a high level of variability in natural systems. Because of these difficulties, SOD is often estimated using modeling tools. For this TMDL, SOD was calculated for each reach using a QUAL2K model. In some cases, additional SOD was prescribed to certain reaches in order to calibrate model predicted DO to observed conditions. These prescribed conditions represent the accumulation of organic matter in the channel from overwidened conditions and additional organic substrates from connected wetland areas and watershed runoff.

4.5.3 Nutrients and Eutrophication

High in-stream nutrient concentrations can accelerate primary production allowing for increases in biological activities. When plants and algae die, bacteria decomposing the plant tissue consume DO while at the same time releasing nutrients into the water column. Median historic total phosphorus concentrations for each impaired stream exceed the proposed state phosphorus standard of 100 µg/L for streams in the North Central Hardwood Forest Ecoregion (Figure 4.5). Phosphorus concentrations for Jewitts Creek are especially high and occasionally exceed 1,000 µg/L.

Despite high TP concentrations, chlorophyll-a typically remain below 20 µg/L in Jewitts, Grove, Regal Creeks (Figure 4.6). Mill Creek chlorophyll-a concentrations are higher, typically between 20-50 µg/L. These data suggest that water column primary production likely plays a role in dissolved oxygen dynamics in each system, however there is no water quality evidence indicating the systems are experiencing severe algae blooms or eutrophication.

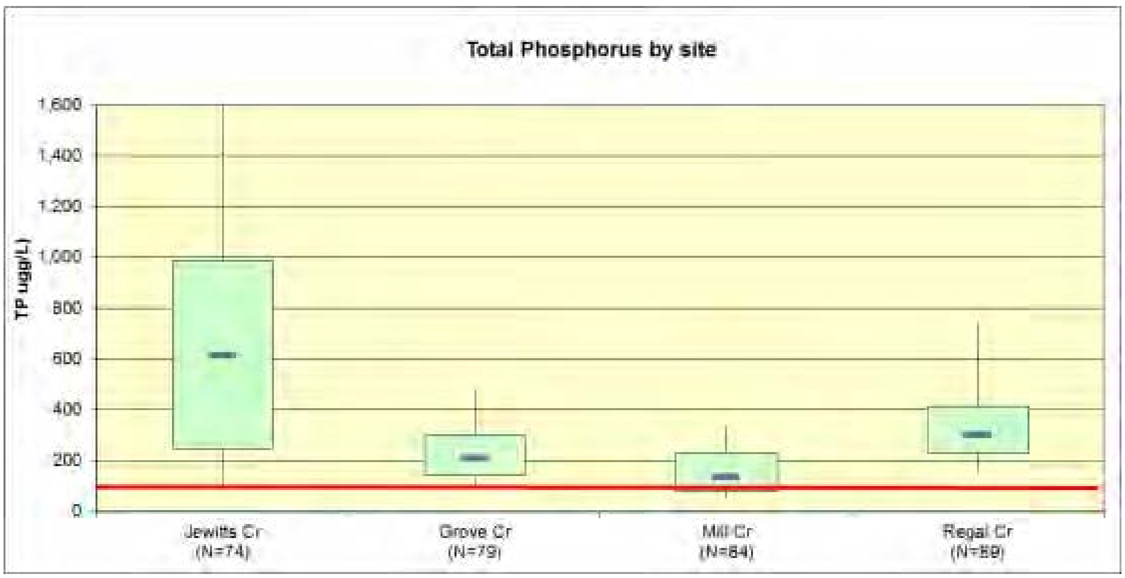

Figure 4.5. Box plots showing total phosphorus sampling for all six impaired reaches since 2000.
Note: The upper and lower edge of each box represent the 75th and 25th percentile of the data range for each site. Error bars above and below each box represent the 95th and 5th percentile of the dataset. The purple dash is the median total phosphorus concentration of all data collected. The solid red line shows the proposed total phosphorus standard (100 µg/L) for rivers/streams in the North Central Hardwood Forest Ecoregion.

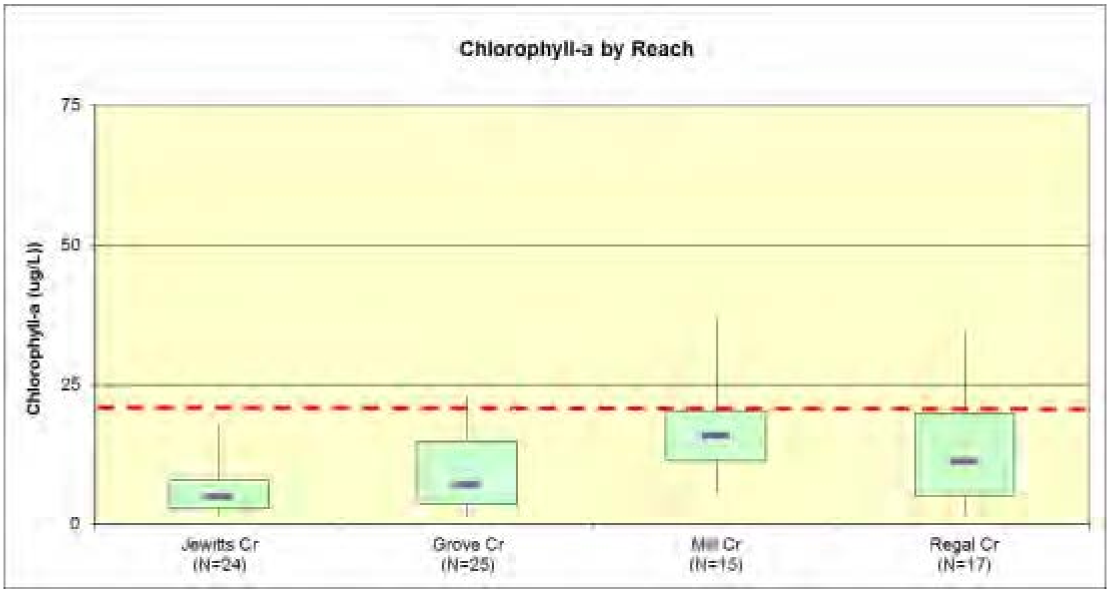

Figure 4.6. Box plots showing chlorophyll-a sampling for all six impaired reaches since 2000.
Note: The upper and lower edge of each box represent the 75th and 25th percentile of the data range for each site. Error bars above and below each box represent the 95th and 5th percentile of the dataset. The purple dash is the median chlorophyll-a concentration of all data collected. The dashed red line shows the chlorophyll-a standard (20 µg/L) for shallow lakes in the North Central Hardwood Forest Ecoregion.

4.5.4 Canopy Coverage and Water Temperature

Canopy coverage may also have a significant effect on stream dissolved oxygen concentrations. Decreased shading leads to more light penetration which has the potential to increase primary production and raise mean water temperatures, which in turn decreases the solubility of oxygen in water. DO solubility in water is temperature-dependent in that cold water holds more dissolved oxygen than warmer water. Canopy coverage for the impaired streams is quite variable. All four systems flow through predominately agricultural or urban landscapes where much of the native trees and other vegetation has been altered or removed.

Water temperatures for all DO impaired streams are close to the upper end of typical North Central Hardwood Forest streams (2-21°C; Figure 4.7). Maximum daily temperatures fall slightly outside this range (typically in the 20-25°C range, with some days at 25-30°C). So despite some very high mid-summer water temperatures, these systems fall within the typical range for smaller, warm water streams in their ecoregion. Water temperatures and canopy coverage likely play a role in the oxygen concentrations and biogeochemical cycling in these impaired reaches and all aquatic systems.

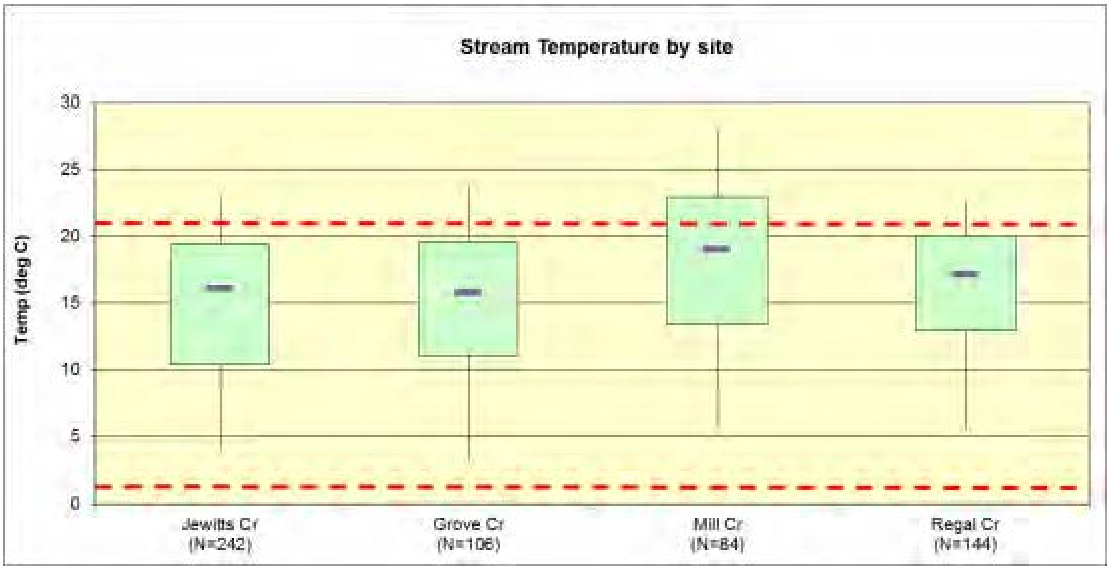

Figure 4.7. Box plots showing historic temperatures for all six impaired reaches since 2000.
Note: The upper and lower edge of each box represent the 75th and 25th percentile of the data range for each site. Error bars above and below each box represent the 95th and 5th percentile of the dataset. The purple dash is the median temperature of all data collected. The dashed red lines shows typical temperature range for non-impacted streams in the North Central Hardwood Forest Ecoregion.

4.6 CRITICAL CONDITIONS

Dissolved oxygen TMDL protocol states the DO standard should be met under the 7-day, 10 year low-flow condition (7Q10). With the exception of Regal Creek, continuous flow was measured for all DO impaired reaches from 2008-2010. While it is not possible to establish a reliable 7Q10 with only 3 seasons of flow data, 3-year flow durations (flow rankings) were established for each stream to ensure synoptic surveys were performed under critical low-flow conditions (Table 4.10; Figure 4.8). Jewitts and Grove Creek surveys were conducted under flow conditions (92% exceedance interval) that were likely very close to a 7Q10. The Mill Creek synoptic survey was performed at the 74% exceedance interval and there were no DO violations recorded during the 2 day survey event. In this case, the model was built and calibrated for the September 1-2 synoptic survey and then used to simulate a 97% flow event on August 3, 2009 when multiple DO violations were recorded using a continuous DO data Sonde.

Table 4.10. Synoptic survey flows compared to long-term flow records.

Stream	Date	[1]Measured Flow (cfs)	[2]Ave Daily Flow (cfs)	Crow River 7-day Ave Flow (cfs)	[3]Crow River 7Q10 (cfs)
Grove Creek	9/3/08	2.31	2.29	135	67
Jewitts Creek	9/3/08	2.76	2.92	135	
Mill Creek (synoptic)	9/1/09	17.14		791	
Mill Creek (simulated)	8/3/09	17.14	23.62	107	
Regal Creek	8/26/09	6.03	--	1,004	

[1] Gaged flow measured during synoptic survey
[2] Average daily flow calculated by MPCA using continuous flow monitoring equipment
[3] Crow River 7 day, 10 year low flow condition for the Crow River USGS station at Rockford station calculated using April-October flows from 1980 through 2009.

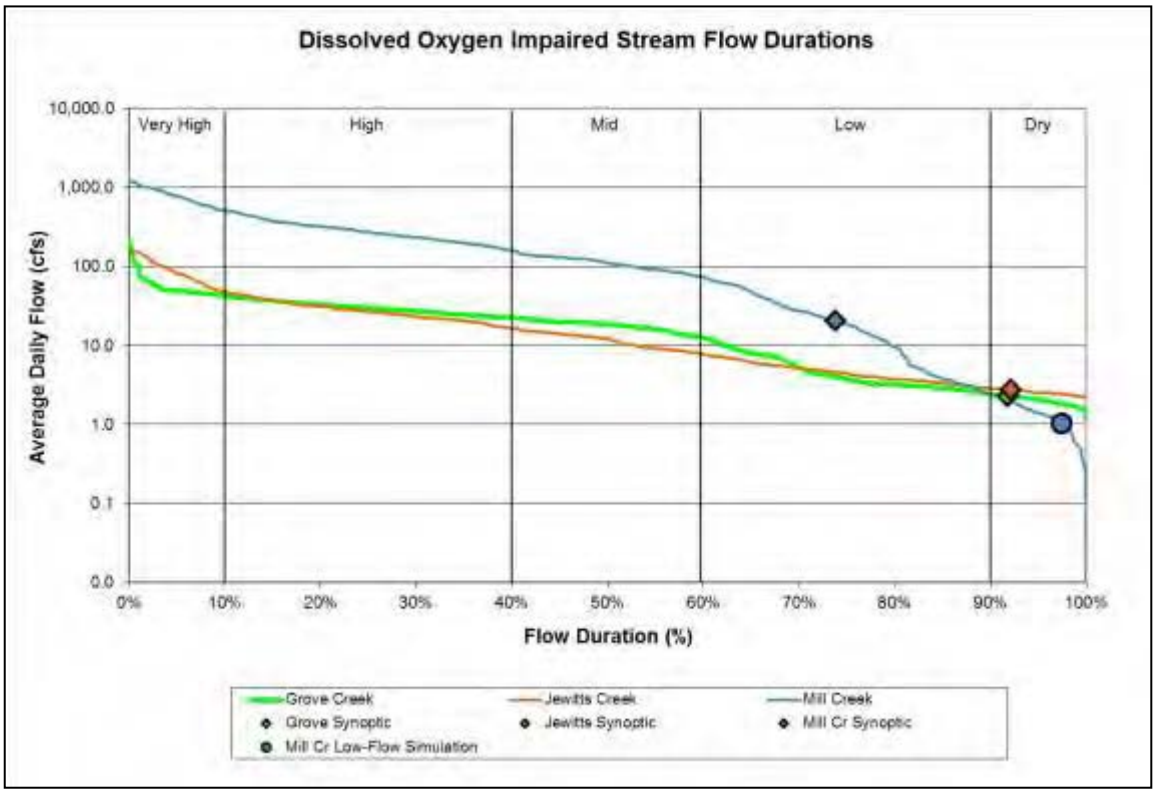

Figure 4.8. Dissolved oxygen impaired reach 3-year flow duration curves (2008-2010).

4.7 MODELING APPROACH

The computational framework, or model, chosen for determining the DO TMDL for each impaired stream was the River and Stream Water Quality Model (QUAL2K). QUAL2K (USEPA 2009) is a public domain model that is widely used and supported by the EPA for TMDL development. This model represents the stream as a well-mixed channel and is intended to be applied to steady-state flow conditions. Historic DO monitoring indicates that summer base-flow is the critical condition for DO in each stream making this an appropriate model for analyzing DO violations. As a result, data from the summer low-flow synoptic survey was used to build and calibrate one event specific QUAL2K model for each impaired stream.

For each model, stream reaches and physical features were built into the model first before proceeding to hydraulic calibration. With the diffuse flow inputs incorporated, the conservative water quality parameters (such as water temperature and conductivity) were adjusted to match monitored observations. Then, chlorophyll-a (phytoplankton production), nutrients (phosphorus and nitrogen components), and carbonaceous biochemical oxygen demand (CBOD) were calibrated by adjusting tributary/groundwater contributions and/or kinetic coefficients within the range of published values. In some cases, reach specific kinetic rates and in-stream nutrient fluxes were assigned to model geochemical processes believed to be unique to certain reaches. Finally, sediment oxygen demand (SOD) was turned on and adjusted for each reach to match observed dissolved oxygen data.

4.8 TMDL ALLOCATION METHODOLOGY

There was at least one DO violation measured during each of the low-flow synoptic survey sampling events. As discussed in Appendix H, the QUAL2K model runs were able to capture these violations after certain calibration adjustments were made. Headwaters, diffuse sources (tributary and groundwater), effluent from wastewater treatment facilities and in-stream sources (sediment fluxes and algae production) were identified as the major contributors of flow and oxygen demanding pollutant loads to each of the impaired streams. The numerical TMDL is the sum of the wasteload allocation (WLA), load allocation (LA), and the margin of safety (MOS). The TMDL for each impaired stream was written using the low-flow synoptic survey calibrated model to solve the TMDL equation for a numeric dissolved oxygen target of 5.0 mg/L (daily minimum). Section 4.9 describes the stream conditions and necessary load reduction scenarios required for each stream to meet DO water quality standards.

4.8.1 Oxygen Deficit Terms

Dissolved oxygen is consumed both in the water column and at the sediment interface. For water quality samples, oxygen demand is typically expressed as a concentration in terms of the mass of oxygen consumed per liter of water (mg-O_2/L). For this TMDL, oxygen demand will be expressed throughout the entire impaired reach/stream as mass of oxygen-demanding substances available per day.

Carbonaceous biochemical oxygen demand (CBOD) represents the oxygen equivalent (amount of oxygen that microorganisms require to breakdown and convert organic carbon to CO_2) of the carbonaceous organic matter in a sample.

A second source is nitrogenous biochemical oxygen demand (NBOD). A wide variety of micro-organisms rapidly transform organic nitrogen (ON) to ammonia nitrogen (NH_3-N). Bacteria then transform NH_3-N to nitrate through an oxygen consuming process called nitrification. For this TMDL, NBOD was calculated by multiplying the sum of organic nitrogen and ammonia nitrogen by 4.33. The factor 4.33 is the stoichiometric ratio (mass basis) of oxygen demand to nitrogen that is used in the QUAL-2K modeling and TMDL calculations.

Finally, sediment oxygen demand (SOD) is the aerobic decay of organic materials in stream bed sediments and in peat soils in wetlands. SOD rates are defined in units of oxygen used per surface area per day (g-O_2/m^2/day). QUAL2K predicts SOD by calculating the delivery and breakdown of particulate organic matter from the water column. There are two sources of SOD – model-predicted and additional SOD prescribed by the modeler. As noted above and in Appendix H, prescribed SOD was necessary in some model reaches to adequately calibrate the model to observed data. Prescribed SOD represents a load that is unidentified, deposited during non-steady state conditions or which QUAL2K has difficulty modeling, for example, the additional SOD generated by stagnant pools when flushing rates are low. SOD rates are defined in units of oxygen used per surface area per day (g-O_2/m^2/day).

4.8.2 Load Capacity

For dissolved oxygen TMDLs, the loading capacity is the maximum allowable oxygen demand (CBOD+NBOD+SOD) the stream can withstand and still meet water quality standards. To determine this number, SOD rates and pollutant loading from headwaters, wastewater treatment facilities and/or tributary/diffuse sources were adjusted until it was clear model-predicted minimum daily DO in each reach never dropped below the 5.0 mg/L standard.

4.8.3 Load Allocations

The Load Allocation is oxygen demand from non-point sources such as headwater, tributary and groundwater sources and from the sediments. Water quality and flow data from the low-flow synoptic surveys were used to calculate or project the CBOD and NBOD loads for headwater, groundwater and tributary inputs. The load from the sediments includes both internal SOD and ammonia release from the sediments to the overlying water column. The current loads were calculated within the QUAL2K model by integrating model-predicted and prescribed oxygen consumption and ammonia release rates across the wetted area of each reach. SOD TMDL loads were calculated the same way using the SOD and/or ammonia reductions necessary to meet the TMDL. For a complete discussion of the methods and assumptions used to build, calibrate and validate these models and the associated release rates refer to Appendix H.

4.8.4 Wasteload Allocations

4.8.4.1 NPDES Wastewater Dischargers

Both Grove and Jewitts Creek have municipal wastewater treatment plants that discharge to the impaired reach or a tributary to the impaired reach (Figure 4.2). The Litchfield WWTF discharges to Jewitt's Creek and was originally designed to treat an average wet weather flow of 1.9 million gallons per day (MGD) with a $CBOD_5$ mass load limit of 72 kg/day (Table 4.11). In 2004, the city of Litchfield expanded its facility which included improvements to the existing influent pumping, screenings and grit removal systems; new primary clarifier mechanisms; four new aeration basins designed for biological phosphorus and nitrogen removal; two new final clarifiers; back-up chemical addition for phosphorus removal; anaerobic sludge digestion and sludge thickening improvements; electrical improvements, and a new plant control system. These improvements increased the Litchfield WWTF average wet weather design flow to 2.37 MGD. Since the facility discharges to an impaired water, Litchfield WWTF's $CBOD_5$ effluent limit remained 'frozen' at the pre-expansion mass load limit of 72 kg/day. The $CBOD_5$ effluent concentration limit, however, was reduced from 10.0 mg/L to 5.0 mg/L in the post-expansion permit. Thus, the load generated by the new wet weather design flow (2.37 MGD) and the $CBOD_5$ concentration limit (5.0 mg/L), 44.9 kg/day, is less than the 'frozen' $CBOD_5$ mass load limit. Prior to the facility improvements, Litchfield WWTF had been granted a variance from the applicable ammonia standard. This variance was discontinued in the post-expansion permit which effectively prevented an increase in ammonia load to Jewitts Creek.

Grove City WWTF's current permit contains a $CBOD_5$ load and concentration limit but no ammonia effluent limits or monitoring requirements (Table 4.11). For the purposes of this TMDL, Litchfield WWTF's current ammonia concentration limit was used to represent the Grove City WWTF current permitted conditions. Neither the Litchfield nor Grove City WWTFs are permitted for TKN and/or organic nitrogen. Permitted loads for Grove City WWTF were calculated by multiplying the facility's June-September wet weather design flow by its $CBOD_5$ and ammonia concentration limits.

Table 4.11. June-September permitted flow, concentration and load limits for the WWTFs that discharge to DO impaired reaches in the North Fork Crow River watershed.

Facility	Receiving Water	Allocated Flow (MGD)	Current$CBOD_5$ Limits		Current Ammonia Limits	
			Concentration (mg/L)	Load (kg/day)	Concentration (mg/L)	Load (kg/day)
Litchfield WWTF	Jewitts Creek	2.37	10.0 (pre-expansion) 5.0 (post-expansion)	72.0*	2.1	18.8
Grove City WWTF	Unnamed tributary to Grove Creek	0.224	15.0	12.7	2.1**	1.8

* Frozen CBOD daily loading limit based on pre-2004 expansion with a wet weather design flow of 1.9 MGD
** Grove City currently not permitted for ammonia. The Litchfield WWTF concentration limit was used to calculate ammonia limit

The Grove City and Litchfield WWTFs were represented in the QUAL2K model by setting flow, CBOD, ammonia and other water quality parameters equal to the average values reported in each facility's discharge monitoring report (DMR) for the month of September, 2008. Appendix H provides a more detailed summary of the DMR data used to calibrate each QUAL2K model. During the surveys, both facilities were discharging at flows, CBOD and ammonia concentrations below their permitted limits. TMDL guidelines require point sources be allocated at their permit limits. To account for this, a new model run was established whereby Litchfield and Grove City WWTF flow and water quality concentrations were increased to their permit limits (Table 4.11). This run, referred to in this report as "current" conditions, was the model run used as the starting point to set and adjust stream conditions and water quality parameters to meet DO standards and set TMDL allocations. It should be noted that the permitted effluent concentration and load used to represent the WLA for each wastewater treatment facility are only applicable from June - September which are considered the "critical" low-flow conditions for these TMDLs.

4.8.4.2 Municipal Stormwater

Stormwater discharges are regulated under the National Pollution Discharge Elimination System (NPDES) State of Minnesota General Stormwater Permit. Litchfield (MS400253) and St. Michael (MS400246) are the only permitted Municipal Separate Storm Sewer Systems (MS4) located in the DO impaired reach watersheds. Litchfield's MS4 boundary accounts for approximately 19% of the Jewitts Creek DO impaired reach watershed downstream of Lake Ripley (Figure 4.2). During the low-flow synoptic survey, there was an estimated 2.4 cfs non-WWTF flow increase between West 4th Street in Litchfield to the stream's confluence with the North Fork Crow River. Since it was impossible to determine the exact location and source of these inflows (i.e. groundwater, tributary, lake/wetland/pond outflow etc.), 19% of this flow was assigned to the Litchfield MS4 wasteload allocation. The St. Michael MS4 occupies a majority of the Regal Creek DO impaired reach watershed (Figure 4.1). During the August 26, 2009 synoptic survey, there was no measured flow increase between Regal Creek headwaters (RC-01) and the downstream most monitoring station (RC-03). Thus, no MS4 allocation was given to St. Michael in this TMDL for low-flow conditions. Instead, all of the allocation was assigned to the Regal Creek headwaters.

Future transfer of loads in this TMDL may be necessary if any of the following scenarios occur within the North Fork Crow and Lower Crow River 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. Ultimately, increases in urban stormwater also increase the loading capacity of the receiving water thereby supplying their own increases in receiving water assimilative capacity.

4.8.4.3 Construction and Industrial Stormwater

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 WLA 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 WLA in this TMDL. It should be noted that all local stormwater management requirements must also be met.

Construction and industrial stormwater wasteload allocations were not established because the allocations for DO demanding substances is based on a low flow conditions where no watershed runoff is expected to occur. For Jewitts Creek, a flow increase was measured between the headwaters and the confluence with the North Fork Crow River, 19% of which was assigned to the City of Litchfield MS4. Although this increase is assigned to the MS4, it is likely the result of additional groundwater inputs or drainage from watershed storage areas, neither of which is the result of runoff from industrial or construction areas. Therefore, the allocation under this flow scenario is by default zero. If in the future it is deemed necessary to assign an allocation to these sources based on better data, the TMDL contains transfer of load language to accommodate these changes.

4.8.5 Margin of Safety

The purpose of the margin of safety (MOS) is to account for uncertainty that the load reductions will result in the desired improvement to water quality. The MOS may be implicit, that is, incorporated into the TMDL through conservative assumptions in the analysis. The MOS may also be explicit and expressed in the TMDL as a set aside load. An explicit MOS of 10% of the sediment oxygen demand load allocation was used for the TMDL equation. These TMDLs require significant reductions to SOD as the MOS should be applied to the oxygen deficit terms that require a measurable reduction to achieve the standard. SOD for this TMDL study were not measured directly as they were calculated using model predicted rates and variables. Thus, a 10% MOS accounts for the uncertainty in model predicted SOD loads and the uncertainty in how the stream may respond to changes in SOD loading.

It is also important to note that the model scenarios were set to predict the stream meeting the DO standard 100% of the time at the low flow condition whereas the standard only requires meeting the DO standard 50% of the time at the low flow condition. Consequently, the current modeling provides an implicit Margin of Safety.

4.9 TMDL ALLOCATIONS

4.9.1 Grove Creek

The current permitted conditions model run for Grove Creek predicts daily minimum DO below 5.0 mg/L in reaches 1, 3, 4 and 5 (Figure 4.9). Monitoring station GC-02 (River km 16.67) represents the headwaters for this model as this was the furthest upstream road crossing (Highway 12) that exhibited flow during the September 3 synoptic survey. Early morning dissolved oxygen at this station was below the 5.0 mg/L DO standard. During model calibration, prescribed SOD was applied to reaches 4 and 5 in order to adjust the longitudinal DO profile to meet observed conditions. Thus, the first model run scenario was setup to increase headwater DO to 5.0 mg/L and remove prescribed SOD from reaches 4 and 5. This scenario greatly improved minimum DO levels throughout Grove Creek, however DO violations were still predicted for reaches 1, 3, and 4.

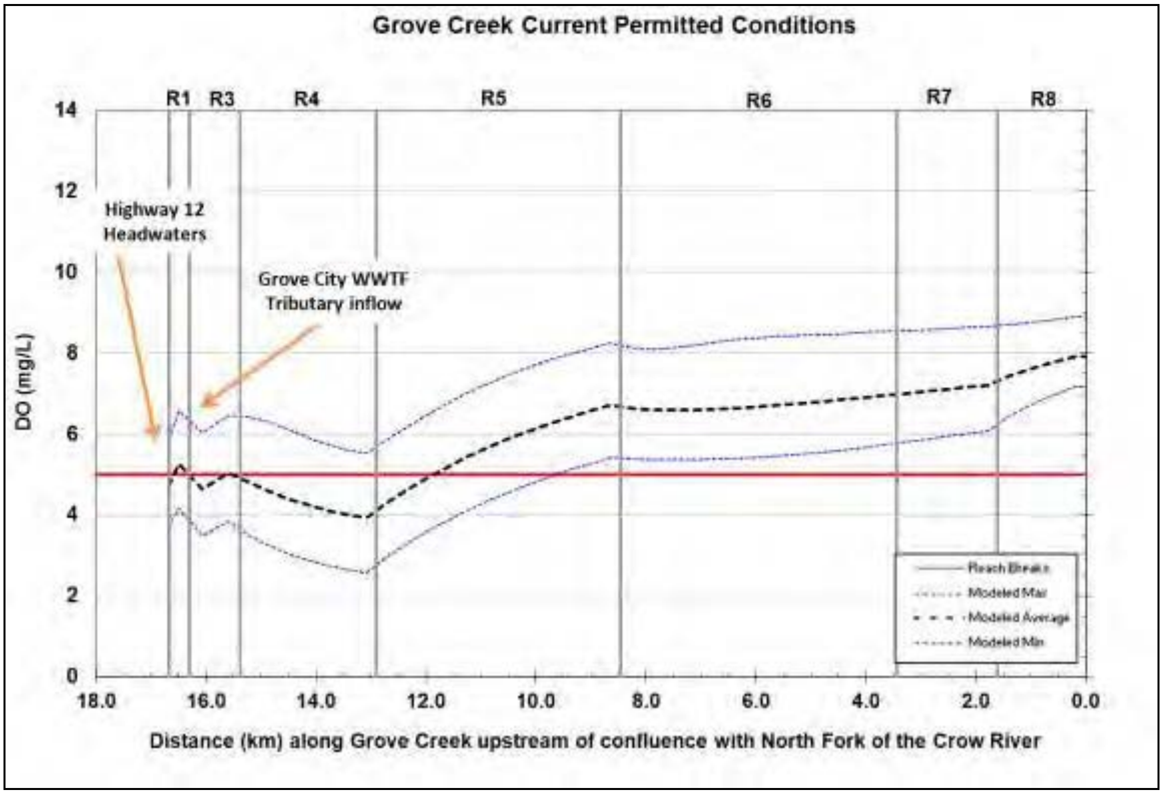

Figure 4.9. Grove Creek current permitted conditions QUAL2K model run.

Reach 2 models the 2.7 mile tributary to Grove Creek whose headwaters was setup as the continuous effluent from the Grove City WWTF. Under permitted conditions, flow from this tributary enters Grove Creek with DO below 5.0 mg/L and measureable levels of CBOD and ammonia. Subsequent model scenarios suggest Grove City would need to reduce effluent CBOD to 5.0 mg/L in order for Grove Creek reaches 1, 3 and 4 to meet the DO standard. Alternatively, the standard would also be achieved if CBOD effluent concentrations were 10.0 mg/L and the Grove City WWTF were to adopt an ammonia effluent concentration limit of 1.0 mg/L (Figure 4.10).

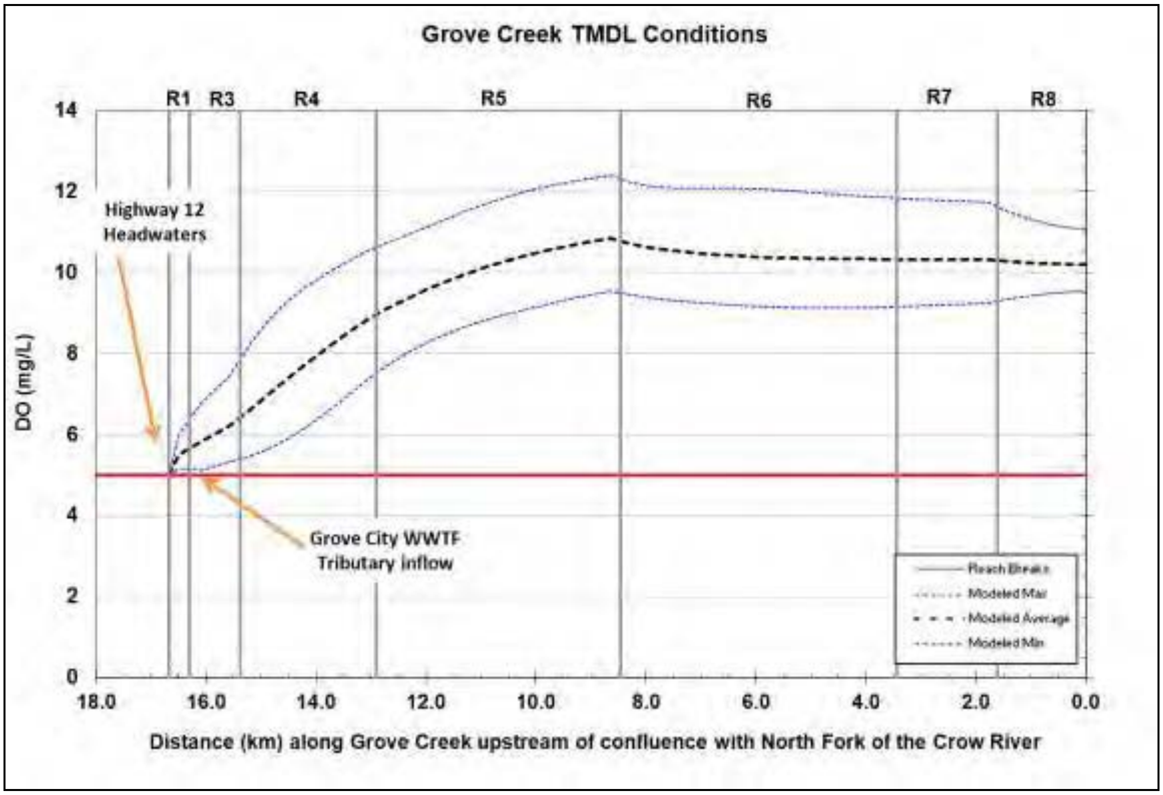

Figure 4.10. Grove Creek TMDL scenario QUAL2K model run.

TMDL allocations were set for both Grove City WWTF CBOD/ammonia effluent concentration scenarios (Tables 4.12 and 4.13). Both Scenarios call for a total maximum daily oxygen demand of approximately 644 kg/day which is a 64% reduction from current conditions. These TMDLs will require changes to Grove City's June-September CBOD and/or ammonia effluent permit concentrations and loads. However, a majority of the reduction will need to come from sediment processes in reaches 4 and 5.

Table 4.12. Grove Creek total maximum daily oxygen demand to meet DO standards (Option 1).

	Oxygen Demand (kg/day) from:						Total Oxygen Demand (kg/day)	
	CBOD		NBOD		SOD			
Source	Current	TMDL	Current	TMDL	Current	TMDL	Current	TMDL
Grove City WWTP	12.7	4.2	7.7	7.7	--	--	20.4	11.9
Headwaters	2.4	2.4	18.7	18.7	--	--	21.1	21.1
Sediment Fluxes	0.0	0.0	195.9	130.0	1,548.9	420.4	1,744.8	550.4
Tribs/Groundwater	0.0	0.0	14.2	14.2	--	--	14.2	14.2
Margin of Safety	--	--	--	--	--	46.7	--	46.7
Total	15.1	6.6	236.5	170.6	1,548.9	467.1	1,800.5	644.3

[1] Grove City WWTF was allocated using a design flow of 0.224 MGD. Under this scenario, effluent concentrations may not exceed 5.0 mg/L CBOD and 2.1 mg/L ammonia-N.

Table 4.13. Grove Creek total maximum daily oxygen demand to meet DO standards (Option 2).

Source	Oxygen Demand (kg/day) from: CBOD Current	CBOD TMDL	NBOD Current	NBOD TMDL	SOD Current	SOD TMDL	Total Oxygen Demand (kg/day) Current	Total Oxygen Demand (kg/day) TMDL
Grove City WWTP	12.7	8.5	7.7	3.7	--	--	20.4	12.2
Headwaters	2.4	2.4	18.7	18.7	--	--	21.1	21.1
Sediment Fluxes	0.0	0.0	195.9	130.0	1,548.9	420.4	1,744.8	550.4
Tribs/Groundwater	0.0	0.0	14.2	14.2	--	--	14.2	14.2
Margin of Safety	--	--	--	--	--	46.7	--	46.7
Total	15.1	10.9	236.5	166.6	1,548.9	467.1	1,800.5	644.6

[1] Grove City WWTF was allocated using a design flow of 0.224 MGD. Under this scenario, effluent concentrations may not exceed 10.0 mg/L CBOD and 1.0 mg/L ammonia-N.

4.9.2 Jewitts Creek

The current permitted conditions model run for Jewitts Creek predicts DO violations in each modeled reach (Figure 4.11). Monitoring station JC-02 (River km 16.67) was the furthest upstream road crossing that exhibited flow during the September 3rd synoptic survey and was selected to represent the headwaters for the Jewitts Creek model. Early morning dissolved oxygen at this station was below the 5.0 mg/L DO standard. Another DO problem area occurs in reach 3 where Jewitts Creek flows through the Schultz Wetland System (Figure 4.11). A significant amount of prescribed SOD was required in this reach to calibrate the model to monitored DO concentrations. For these reasons, the first model run scenario was setup to increase headwater DO to 5.0 mg/L and remove prescribed SOD throughout the entire system. This scenario greatly improved minimum DO levels throughout Jewitts Creek, however DO violations were still predicted in reaches 2 and 3.

A second set of model scenarios were setup whereby Litchfield WWTF ammonia and $CBOD_5$ loads were decreased from their current limits until the DO standard was achieved (Figure 4.13).

The scenario assumes a $CBOD_5$ effluent concentration limit of 5.0 mg/L is enforced over the current 'frozen' $CBOD_5$ mass load limit of 72 kg/day. This requires Litchfield WWTF's 'frozen' limit to be dropped and replaced by a daily mass load limit of 44.9 kg/day.

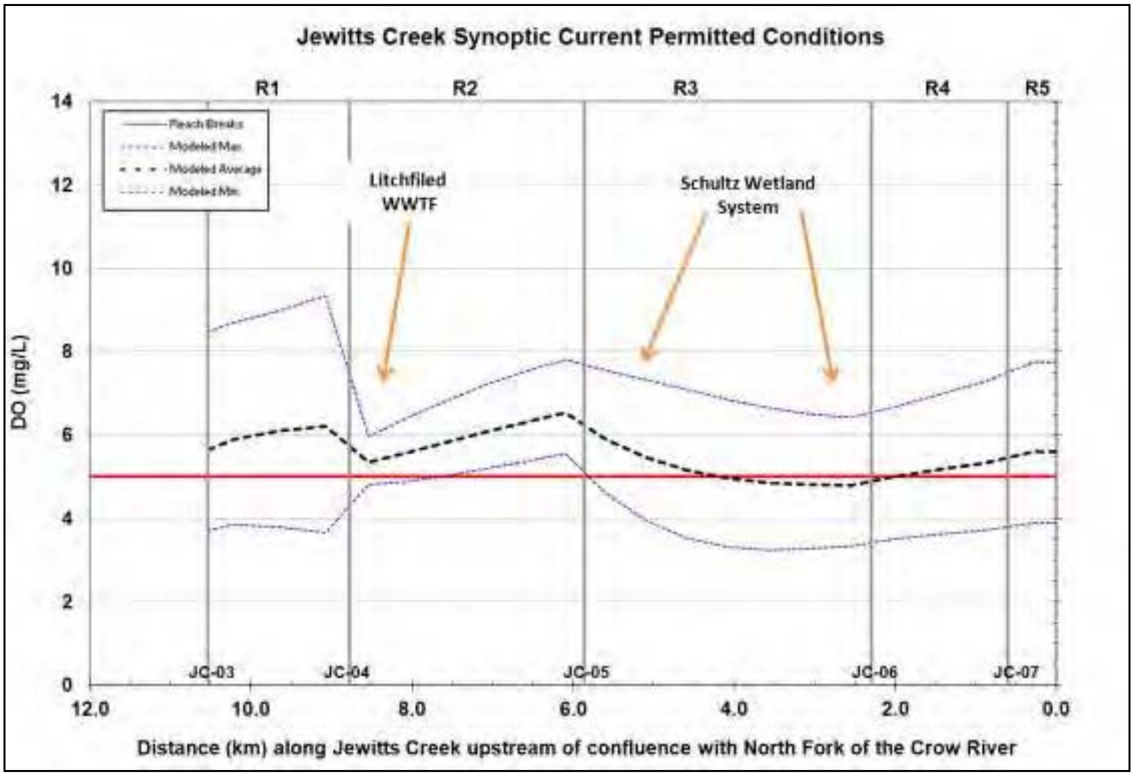

Figure 4.11. Jewitts Creek current permitted conditions QUAL2K model run.

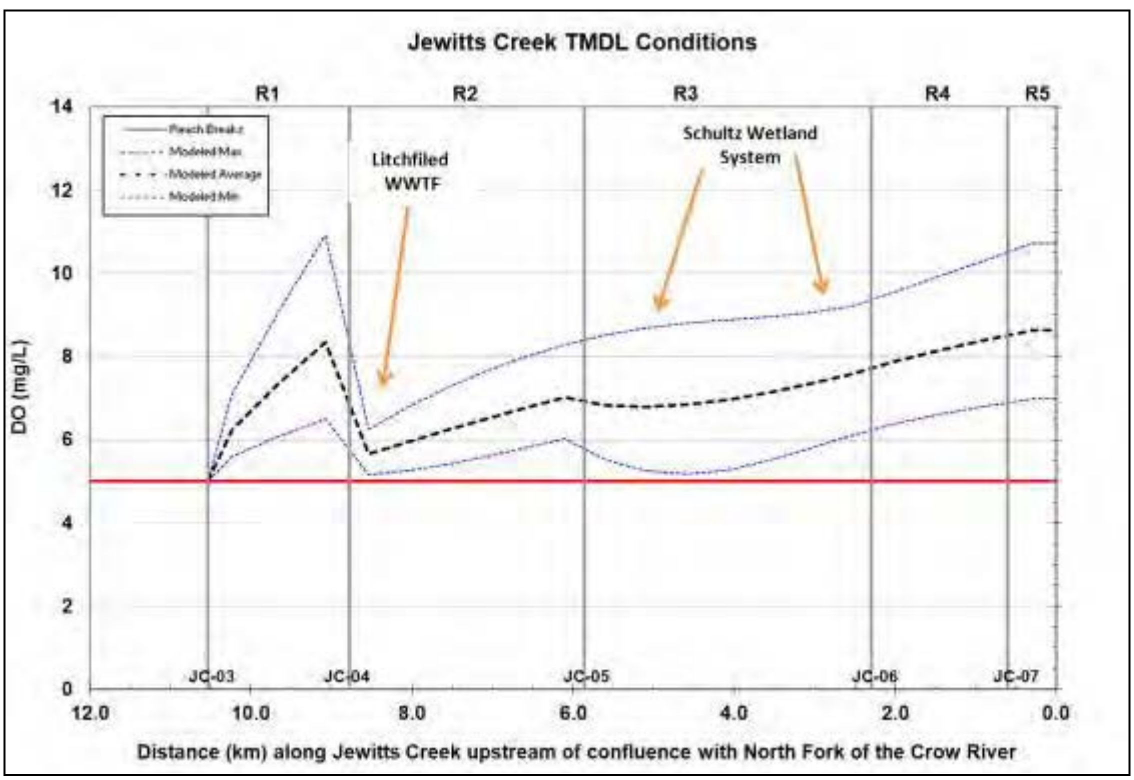

Figure 4.12. Jewitts Creek TMDL scenario QUAL2K model run.

TMDL allocations were set for Litchfield WWTF ammonia and $CBOD_5$ effluent concentration scenarios (Table 4.14). The scenario calls for total maximum daily oxygen demands of 219.4 kg/day which equals 39% reductions from current conditions The TMDL requires changes to Litchfield WWTF's June-September $CBOD_5$ and/or ammonia effluent load limits. However, the model demonstrates the facility will meet TMDL conditions under any effluent design flow as long as it meets its current concentration limits of 5.0 mg/L for CBOD and 2.1 mg/L for ammonia. That said, a majority of the reduction will need to come from non-point source sediment processes, most notably SOD in the Schultz Wetland System.

Table 4.14. Jewitts Creek total maximum daily oxygen demand to meet DO standards.

	Oxygen Demand (kg/day) from:						Total Oxygen Demand (kg/day)	
	CBOD		NBOD		SOD			
Source	Current	TMDL	Current	TMDL	Current	TMDL	Current	TMDL
[1]Litchfield WWTP	72.0	44.9	81.6	81.6	--	--	153.6	126.5
Litchfield MS4	0.0	0.0	10.4	10.4	--	--	10.4	10.4
Headwaters	0.0	0.0	16.3	16.3	--	--	16.3	16.3
Sediment Fluxes	0.0	0.0	5.9	4.5	131.7	16.0	137.6	20.5
Tribs/Groundwater	0.0	0.0	43.9	43.9	--	--	43.9	43.9
Margin of Safety	--	--	--	--	--	1.8	--	1.8
Total	72.0	44.9	158.1	156.7	131.7	17.8	361.8	219.4

[1] Litchfield WWTF was allocated using a flow of 2.37 MGD and effluent concentrations of 5.0 mg/L $CBOD_5$ and 2.1 mg/L ammonia-N.

4.9.3 Mill Creek

Monitoring station MilC-02, located at the outlet of Deer Lake, has demonstrated high chlorophyll-a concentrations and large diurnal DO swings during previous sampling events. Continuous DO monitoring on 8/3/2009 downstream of Deer Lake at MilC-03 during low-flow conditions shows large diurnal DO variability and numerous DO violations (Figure 4.13). The 9/1/09 synoptic survey event data and subsequent continuous DO monitoring suggest the Unnamed Tributary entering Mill Creek from the west near river kilometer 3.0 does not contribute low dissolved oxygen or significant loading of oxygen demanding pollutants (ammonia, algae or CBOD). Summer (June through September) water quality sampling from 2003-2006 indicates Deer Lake does not currently meet the shallow lake chlorophyll-a or TP water quality standards for lakes in the North Central Hardwood Forests Ecoregion (Table 4.15). This suggests reductions to meet DO water quality standards will need to come from the stream's headwaters at Deer Lake.

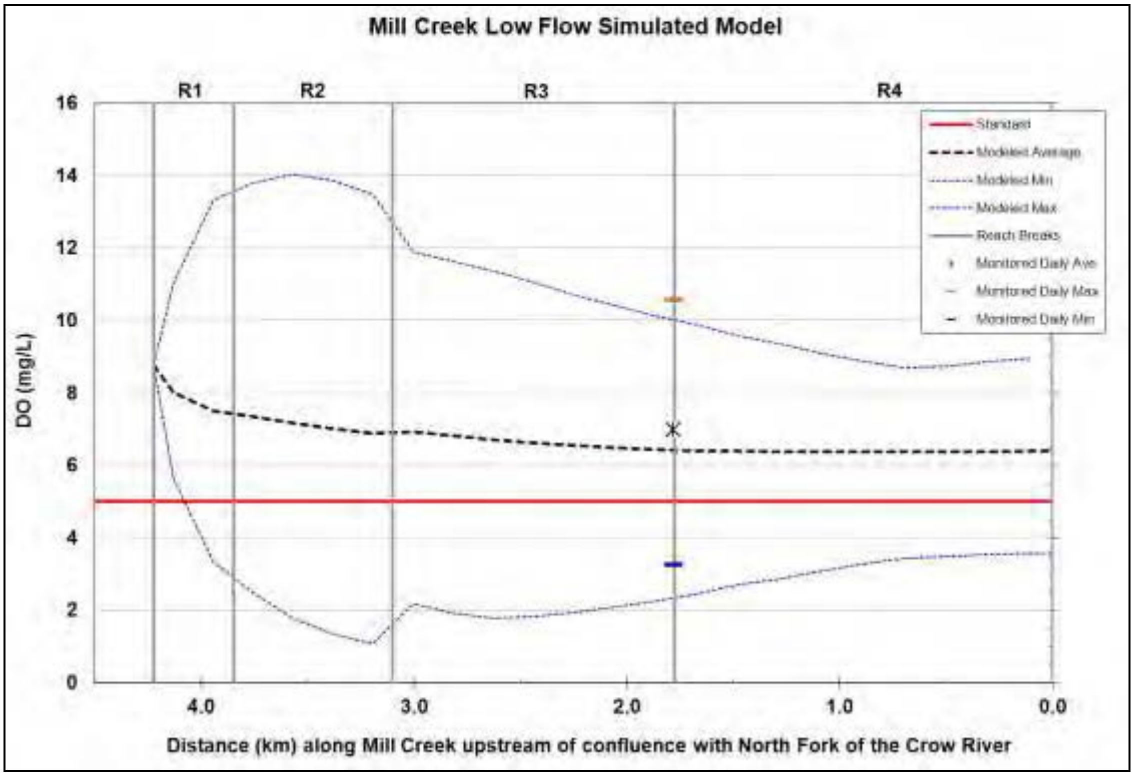

Figure 4.13. Mill Creek current conditions model run.

Table 4.15. Deer Lake water quality monitoring.

Year	Chlorophyll-a		Total Phosphorus	
	Samples	Average (µg/L)	Samples	Average (µg/L)
2003	4	54	4	83
2004	3	63	3	94
2005	4	52	4	83
2006	2	45	2	59
[1]**Standard**	**20**		**60**	

[1] Indicates standard for shallow lakes in the North Central Hardwood Forest Ecoregion

The first Mill Creek model scenario was setup to evaluate the stream's DO response if Deer Lake were to meet the 20 µg/L chlorophyll-a and 60 µg/L TP standards. This scenario greatly improved minimum DO throughout Mill Creek, however not enough to meet the minimum DO standard in all four reaches. A second model scenario suggests a CBOD limit of 8.0 mg/L for Mill Creek's headwaters (Deer Lake) will also be needed in order to meet DO standards for each modeled reach (Figure 4.14). This scenario establishes a total maximum daily oxygen demand of 38.7 kg/day for Mill Creek to meet DO standards (Table 4.16). This TMDL limit will require a 24% reduction from current conditions which, as discussed previously, will be accomplished by reducing TP, CBOD and chlorophyll-a.

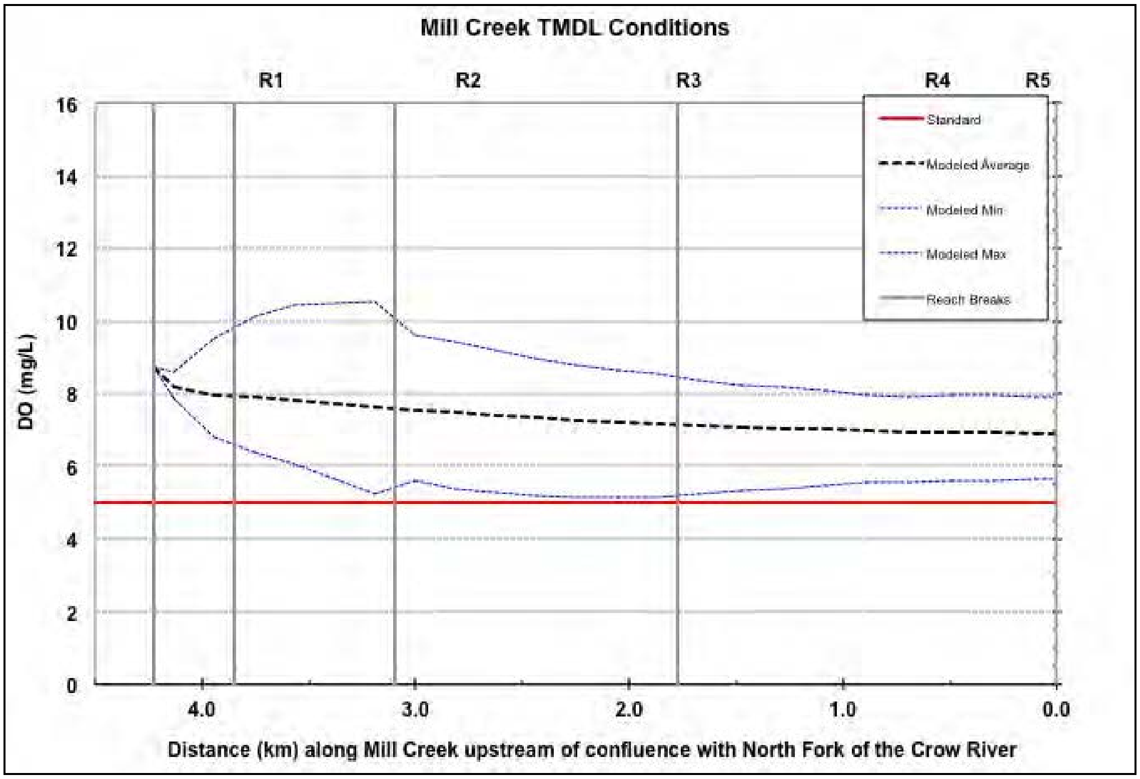

Figure 4.14. Mill Creek TMDL scenario QUAL2K model run.

Table 4.16. Mill Creek total maximum daily oxygen demand to meet DO standards.

Source	Oxygen Demand (kg/day) from:						Total Oxygen Demand (kg/day)	
	CBOD		NBOD		SOD			
	Current	TMDL	Current	TMDL	Current	TMDL	Current	TMDL
Deer Lake Headwaters	21.4	15.6	13.3	13.3	--	--	34.7	28.9
Tribs/Groundwater	2.9	2.9	2.5	2.5	--	--	5.4	5.4
Sediment Fluxes	0.0	0.0	0.1	0.0	10.6	3.9	10.7	4.0
Margin of Safety	--	--	--	--	--	0.4	--	0.4
Total	24.3	18.5	15.9	15.8	10.6	4.3	50.8	38.7

4.9.4 Regal Creek

Monitoring station RC-01 is located at the County Highway 35 crossing near the downstream end of a wetland west of St. Michael. Extremely low DO levels (<2.0 mg/L) were recorded at this station during the August 26-27 synoptic survey. The longitudinal profile suggests DO increases downstream between RC-01 and RC-03 as no DO violations were recorded at RC-02 or RC-03 during this survey (Figure 4.15). Adjusting headwater conditions so that RC-01 maintains a minimum DO of 5.0 mg/L DO was the first model scenario run for Regal Creek. This scenario effectively increases DO throughout Regal Creek so that model predicted DO never falls below 5.0 mg/L (Figure 4.16). This scenario suggests no oxygen demand load reductions are required for Regal Creek to meet DO standards. A conditional TMDL will be written for Regal Creek whereby the only requirement is that upstream boundary conditions (wetland headwaters) are to maintain minimum DO levels greater than 5.0 mg/L (Table 4.17).

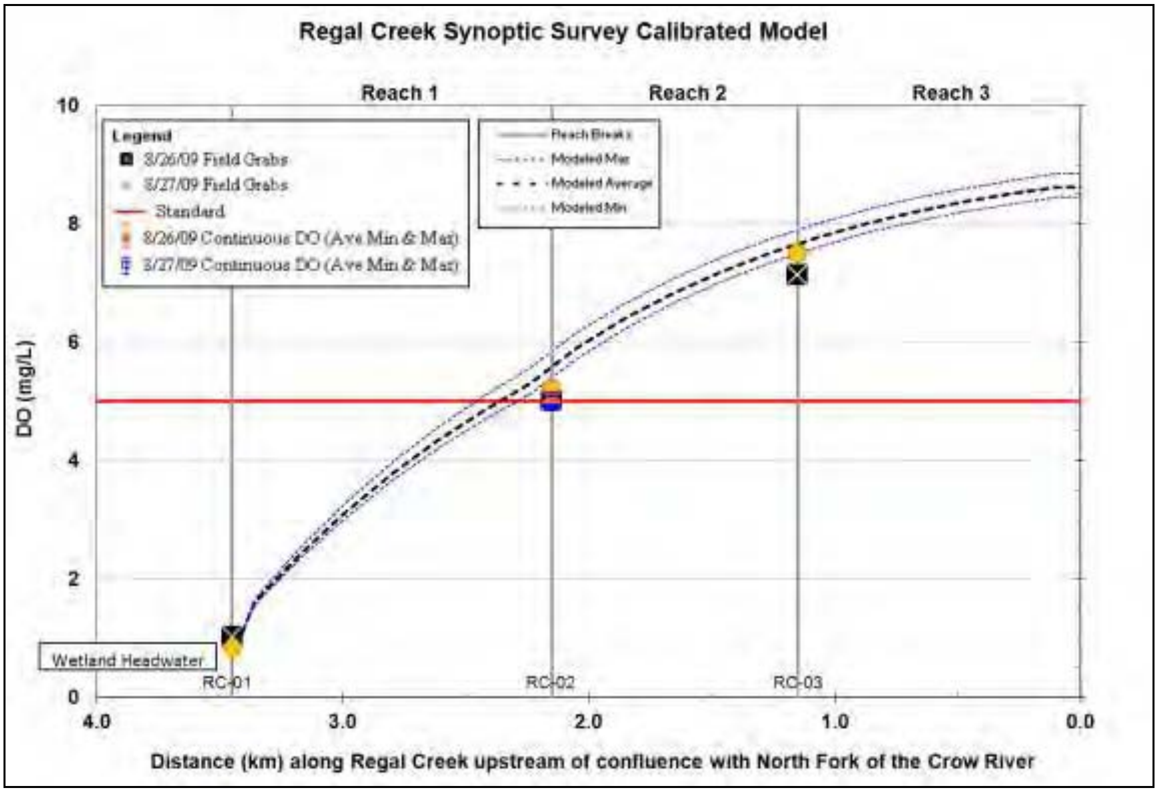

Figure 4.15. Regal Creek current conditions QUAL2k model run.

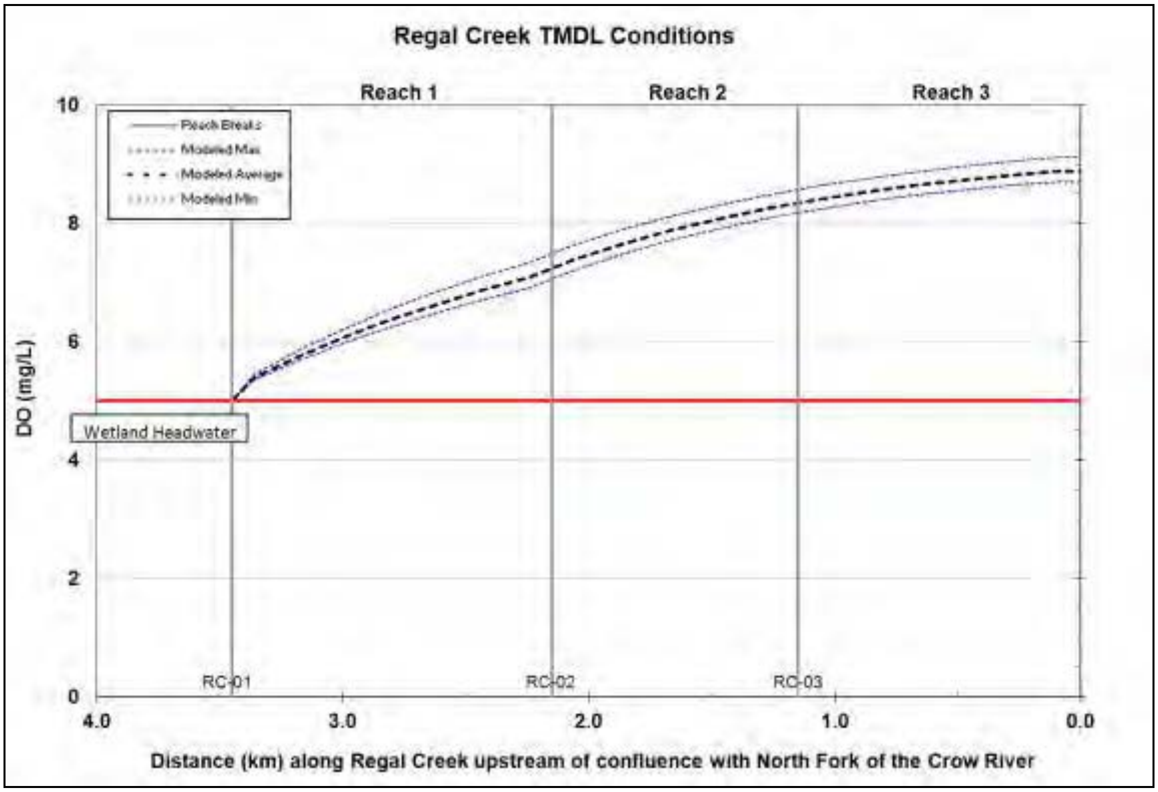

Figure 4.16. Regal Creek TMDL scenario QUAL2K model run.

Table 4.17. Regal Creek total maximum daily oxygen demand to meet DO standards.

Source	Oxygen Demand (kg/day) from:						Total Oxygen Demand (kg/day)	
	CBOD		NBOD		SOD			
	Current	TMDL	Current	TMDL	Current	TMDL	Current	TMDL
Point Sources	--	--	--	--	--	--	--	--
Headwaters	315.7	315.7	128.1	128.1	--	--	443.8	443.8
Sediment Fluxes	--	--	--	--	--	--	--	--
Diffuse Sources	--	--	--	--	--	--	0.0	0.0
Margin of Safety	--	--	--	--	--	--	--	0.0
Total	315.7	315.7	128.1	128.1	0.0	0.0	443.8	443.8

[1] Note: This TMDL requires no oxygen demand load reductions. In order to achieve DO standards, Regal Creek headwaters must maintain a minimum DO of 5.0 mg/L.

5.0 Implementation

5.1 BACTERIA, TURBIDITY AND LOW DISSOLVED OXYGEN STRATEGIES

Since the impairments of bacteria, turbidity and low DO have several sources and some common delivery pathways, most of the strategies have multiple water quality benefits in terms of load reductions through implementation. As the CROW coordinates with its stakeholders on the details of the TMDL implementation plan, some of the following BMPs may be selected to achieve the bacteria, turbidity, and low DO TMDLs. These actions will be further developed in the TMDL implementation plan to be developed within one year of EPA's approval of this TMDL report. The estimated total cost of implementing these and other potential BMPs ranges from $8 million to $10 million. The following provides an overview of implementation options to be considered.

5.1.1 BMP Guidance Based on Agroecoregion

The North Fork Crow River Watershed is predominately comprised of three agroecoregions, Rolling Moraine, Steep Dryer Moraine, and Alluvium & Outwash. A matrix has been developed by Dr. David Mulla of the University of Minnesota to provide general planning-level guidance on the application of BMPs within each agroecoregion. The BMPs were developed through a focus group process that included experts from the University of Minnesota, Minnesota Pollution Control Agency, Minnesota Department of Agriculture, and the Minnesota Board of Water and Soil Resources. Four broad categories of management practices discussed include nutrient management, vegetative practices, tillage practices, and structural practices. Selection of appropriate management practices for the pollutant(s) of concern depends on site-specific conditions, stakeholder attitudes and knowledge, and on economic factors. This information is intended to be used as a starting point in the development of a custom set of BMPs to reduce sources of pollution generation and transport through improved management of uplands and riparian land within the TMDL project area. Reducing sediment generation and transport will also lead to decreases in turbidity, bacteria concentrations, and improve DO in downstream reaches.

Vegetative Practices

- Contour farming
- Strip cropping
- Grassed waterways
- Grass filter strip for feedlot runoff
- Forest management practices
- Alternative crop in rotation
- Field windbreak

- Pasture management, intensive rotation grazing (IRG)
- Conservation Reserve Program (CRP) or Conservation Reserve Enhancement Program (CREP)

Primary Tillage Practices

- Chisel Plow
- One pass tillage
- Ridge till
- Sustain surface roughness

Structural Practices

- Wetland restoration
- Livestock exclusion
- Liquid manure waste facilities

A brief summary of each type of practice as it applies to the TMDL watershed follows.

5.1.1.1 Vegetative Management Practices

Vegetative practices include those focusing on the establishment and protection of crop and non-crop vegetation to minimize sediment mobilization from agricultural lands and decrease sediment transport to receiving waters. The recommended cropping practices are designed in part to slow the speed of runoff over bare soil to minimize its ability to entrain sediment. Grassed waterways and grass filter strips provide settling of entrained sediment which gets incorporated into both the soil and vegetation. Other practices, such as alternative crop rotations, forest management, and field windbreaks are designed to minimize exposure of bare soils to wind and water which can transport soil off-site. Pasture management often emphasizes rotational grazing techniques, where pastures are divided into paddocks, and the livestock moved from one paddock to another before forage is over-grazed. As livestock are moved frequently, forage is able to survive. Maintaining the vegetation, as opposed to bare soil, allows for greater water infiltration, reducing runoff and associated sediment transport.

There are a number of programs available to compensate land owners for moving environmentally sensitive cropland out of production for varying periods of time. These include the Conservation Reserve Program (CRP), Re-Invest in Minnesota (RIM) Reserve Program, and the Conservation Reserve Enhancement Program-Minnesota II (CREP-II). Anticipated benefits in reducing soil erosion and improving water quality are key considerations in deciding what lands can be enrolled in each program

5.1.1.2 Primary Tillage Practices

Certain kinds of tillage practices can significantly reduce the generation and transport of soil from fields. Conservation tillage techniques emphasize the practice of leaving at least some vegetation cover or crop residue on fields as a means of reducing the exposure of the underlying soil to wind and water which leads to erosion. If it is managed properly, conservation tillage can reduce soil erosion on active fields by up to two-thirds (Randall et. al. 2008).

5.1.1.3 Structural Practices

Structural practices emphasize elements that generally require a higher level of site-specific planning and engineering design. Most structural practices focus on watershed improvements to decrease sediment loading to the receiving water. For example, restoration of wetlands can create a natural method of slowing overland runoff and storing runoff water, which can both reduce channel instability and flooding downstream. In addition, the quiescent conditions of a wetland mean that they can be effective at settling out sediment particles in the runoff that reaches them, although accumulation of too much sediment too rapidly can compromise other important functions of the wetland. Livestock exclusion involves fencing or creating other structural barriers to limit or eliminate access to streams by livestock, and may involve directing livestock to an area that is better designed to provide limited access with minimal impact.

5.1.2 Feedlot Runoff Reduction

This strategy is presently under implementation through the MPCA's Open Lot Agreement (OLA) established in October 2000. The OLA has a Full Compliance goal to meet effluent limits in Minn. R. 7053.0305 by October 1, 2010. This program encourages producers to seek information and assistance for practical solutions to treat feedlot runoff that discharges into waters of the state from feedlots that do <u>not</u> require NPDES permits. There are a variety of options for improving open lot runoff problems that reduce nonpoint source loading of bacteria and turbidity, including:

- Move Fences/Change Lot Area
- Eliminate Open Tile Intakes and/or Feedlot Runoff to the Intake
- Install Clean Water Diversions and Rain Gutters
- Install Grass Buffers
- Maintain Buffer Areas
- Construct a Solids Settling Area(s)
- Prevent Manure Accumulations
- Manage Feed Storage
- Manage Watering Devices
- Total Runoff Control and Storage
- Roofs
- Runoff Containment with Irrigation onto Cropland/Grassland
- Vegetated Infiltration Area
- Tile-Drained Vegetated Infiltration Area with Secondary Vegetated Filter Strip
- Sunny Day Release on to Vegetated Infiltration Area or Filter Strip

- Vegetated Filter Strip

5.1.3 Manure Management Planning

Continued cooperation between the Counties and the MPCA through the County Feedlot Program ensures that feedlot owners get assistance to remain compliant with their permits. The Natural Resources Conservation Service offices or Soil and Water Conservation Districts facilitate Environmental Quality Incentives Program (EQIP) or other cost-share programs to put Best Management Practices into place. The development and update of manure management plans continue to reduce bacteria in runoff.

5.1.4 Waste Water Treatment Facilities

Counties, Regional Development Commissions and MPCA staff will work with Waste Water Treatment Facilities to ensure continued compliance.

5.1.5 Subsurface Sewage Treatment Systems (SSTS)

Low interest loan dollars are available to aid landowners in upgrading SSTS.

5.1.6 North Fork Crow River Watershed Restoration and Protection Plan

The Crow River Organization of Water (CROW), the North Fork Crow Watershed District, and the Middle Fork Crow Watershed District have partnered with the MPCA to develop the North Fork Crow River Watershed Restoration and Protection Plan (NFC-MWRPP). The purpose of this plan is to address all impairments in the North Fork Crow River watershed not included in this TMDL study. The NFC-WRPP will include nutrient TMDLs for 34 lakes in the North Fork Crow River watershed. It is assumed the nutrient reduction goals and implementation plans presented in these TMDLs will help reduce TP, chlorophyll-a (algal turbidity) and $CBOD_5$ in the turbidity impaired reaches and many of the dissolved oxygen impaired reaches addressed in this TMDL study.

5.2 SEDIMENT OXYGEN DEMAND LOAD REDUCTION STRATEGIES

The following is a description of potential actions for controlling SOD in the dissolved oxygen listed reaches. These actions will be further developed in the TMDL Implementation Plan.

5.2.1 Wetland Outlet Reaeration

Specific to the low DO impairment, the water discharged from the headwaters often contains less than the 5.0 mg/L DO standard. The reaches downstream are not able to provide reaeration to lift the DO content above 5.0 mg/L. Additional study is necessary to fully understand the specific mechanism or mechanisms accounting for these upstream boundary conditions not meeting the DO standard, and determine the most feasible mitigation approach. Some options might include synoptic surveys to better understand the sources.

Most of the streams with dissolved oxygen issues had headwaters that were low in dissolved oxygen including several wetlands especially Regal Creek and Grove Creek. As the stream flows through these wetlands, dissolved oxygen is depleted, and the water discharged from the wetland often contains less than the 5.0 mg/L DO standard. The reaches downstream are not able to provide reaeration soon enough to lift the DO content above 5.0 mg/L.

Additional study is necessary to fully understand the specific mechanism or mechanisms accounting for this DO sag, and to determine the most feasible mitigation approach. Some options might include adding wetland outlet structures; wetland restoration; mechanical reaeration at wetland outlets; and dechannelization. Because wetlands are naturally low in dissolved oxygen, restoration or dechannelization may not result in the needed downstream improvement, and thus some type or reaeration at the wetland outlets may be the most practical approach. It is not possible to accurately estimate the cost of implementing any of these or other strategies without more study, but the cost is likely in the range of $100,000 to $500,000.

5.2.2 Channel Morphology Alteration

The scenario analysis indicated that creating a low-flow channel that is approximately one-third the channel width and double the channel depth would reduce sediment oxygen demand. Restoring the stream channel using this design standard would require excavation and channel alteration. The estimated cost of stream morphology alteration and stream restoration is $1,000,000 per mile, depending on whether the restoration is retrofitting an in-place channel or is making significant channel modifications

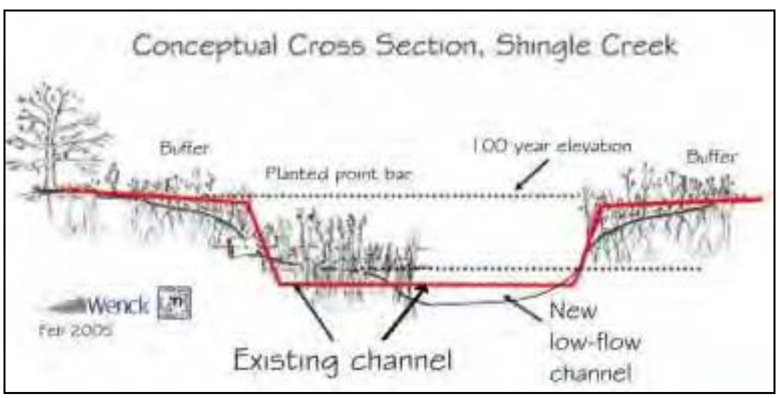

Figure 5.1. Desirable stream cross section with enhanced habitat and a low-flow channel.
SOURCE: SCWMC 2006.

5.3 ADAPTIVE MANAGEMENT

This list of implementation elements and the more detailed implementation plan that will be prepared following this TMDL assessment focuses on adaptive management (Figure 5.2. As the sediment dynamics within the watershed are better understood, management activities will be changed or refined to efficiently meet the TMDL and lay the groundwork for de-listing the impaired reaches.

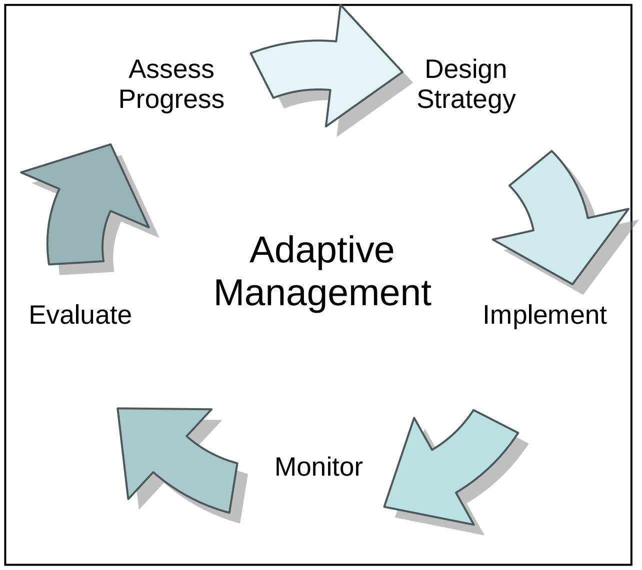

Figure 5.2. Adaptive Management.

6.0 Reasonable Assurance

6.1 INTRODUCTION

When establishing a TMDL, reasonable assurances must be provided demonstrating the ability to reach and maintain water quality endpoints. Several factors control reasonable assurance, including a thorough knowledge of the ability to implement BMPs as well as the overall effectiveness of the BMPs. This TMDL establishes aggressive goals for the reduction of turbidity and *E. coli* loads and the increase in dissolved oxygen levels to improve fish and invertebrate habitat in the North Fork Crow River Watershed.

Many of the goals outlined in this TMDL study are consistent with objectives outlined in the Meeker and Wright County Water management plans. These plans have the same objective of developing and implementing strategies to bring impaired waters into compliance with appropriate water quality standards and thereby establish the basis for removing those impaired waters from the 303(d) Impaired Waters List. These plans provide the watershed management framework for addressing water quality issues. In addition, the stakeholder processes associated with this TMDL effort as well as the broader planning efforts mentioned previously have generated commitment and support from the local government units affected by this TMDL and will help ensure that this TMDL project is carried successfully through implementation.

Various sources of technical assistance and funding will be used to execute measures detailed in the implementation plan scheduled to be developed within one year of approval of this TMDL. Funding resources include a mixture of state and federal programs, including (but not limited to) the following:

- Federal Section 319 Grants for watershed improvements
- Funds ear-marked to support TMDL implementation from the Clean Water, Land, and Legacy constitutional amendment, approved by the state’s citizens in November 2008.
- Local government cost-share funds
- Soil and Water Conservation Districts cost-share funds
- NRCS cost-share funds

Finally, it is a reasonable expectation that existing regulatory programs such as those under NDPES will continue to be administered to control discharges from industrial, municipal, and construction sources as well as large animal feedlots that meet the thresholds identified in those regulations.

6.2 REGULATORY APPROACHES

NPDES Phase II MS4 stormwater permits are in place for the cities of Litchfield, Buffalo, St. Michael, Dayton draining to the North Fork of the Crow River, and the main stem of the Crow River. Under the stormwater program, permit holders are required to develop and implement a Stormwater Pollution Prevention Plan (SWPPP; MPCA, 2004). The SWPPP must cover six minimum control measures:

- Public education and outreach;
- Public participation/involvement;
- Illicit discharge, detection and elimination;
- Construction site runoff control, including post-construction;
- Pollution prevention/good housekeeping

The permit holder must identify BMPs and measurable goals associated with each minimum control measure.

According to federal regulations, NPDES permit requirements must be consistent with the assumptions and requirements of an approved TMDL and associated Wasteload Allocations. See 122.44(d)(1)(vii)(B). To meet this regulation, Minnesota's MS4 general permit requires the following:

"If a USEPA-approved **TMDL(s)** has been developed, you must review the adequacy of your Storm Water Pollution Prevention Program to meet the **TMDL's Waste Load Allocation** set for storm water sources. If the **Storm Water Pollution Prevention Plan** is not meeting the applicable requirements, schedules and objectives of the **TMDL**, you must modify your **Storm Water Pollution Prevention Plan** as appropriate, within 18 months after the TMDL is approved."

The TMDL implementation plan will identify specific BMP opportunities that may help achieve the required load reductions. Permittees can incorporate information from the implementation plan into their SWPPPs.

Construction stormwater activities are considered in compliance with provisions of these TMDLs if they obtain a Construction General Permit under the NPDES program and properly select, install, and maintain all BMPs required under the permit, including any applicable additional BMPs required in Appendix A of the Construction General Permit for discharges to impaired waters, or to meet local construction stormwater requirements if they are more restrictive than requirements of the State General Permit. Industrial stormwater activities are considered in compliance with provisions of the TMDL if they obtain an Industrial Stormwater General Permit or General Permit for Construction Sand and Gravel, Aggregate and Hot Mix Asphalt facilities (MNG49) under the NPDES program and properly select, install and maintain all BMPs required under the permit, or meet local industrial stormwater requirements if they are more restrictive than requirements of the permit.

If an MS4 allocation is needed in the future, load allocation will be moved to the waste load allocation proportional to the amount of land affected.

6.3 LOCAL MANAGEMENT

6.3.1 Crow River Organization of Water

Portions of ten counties in Central Minnesota make up the Crow River Watershed which includes both the North Fork and South Fork Crow Rivers. From the perspective of the Upper Mississippi River Basin, the Crow River is one of its major tributaries to the Mississippi River. The effects of rapid urban growth, new and expanding wastewater facilities and erosion from agricultural lands have been common concerns of many citizens, local, state and regional governments in Central Minnesota. As a result, many groups began meeting in 1998 to discuss management of the Crow River basin consisting of the North Fork and South Fork. The Crow River Organization of Water (CROW) was formed in 1999 as a result of heightened interest in the Crow River. A Joint Powers Agreement has been signed between all ten of the Counties with land in the Crow River Watershed. The CROW Joint Powers Board is made up of one representative from each of the County Boards who signed the agreement. The Counties involved in the CROW Joint Powers include Carver, Hennepin, Kandiyohi, McLeod, Meeker, Pope, Renville, Sibley, Stearns and Wright. The CROW currently focuses on identifying and promoting the following:

- Protecting water quality and quantity
- Protecting and enhancing fish and wildlife habitat and water recreation facilities
- Public education & awareness
- BMP implementation

In summer of 2010, the CROW began working with the Minnesota Pollution Control Agency's new Major Watershed Restoration & Protection Project (MWRPP) approach in the North Fork Crow River Watershed. The idea behind the watershed approach is to provide a more complete assessment of water quality and facilitate data collection for the development of a Total Maximum Daily Loads (TMDLs) and protection strategies. In the watershed approach, the streams and lakes within a major watershed are intensively monitored to determine the overall health of the water resources, identify impaired waters, and identify those waters in need of additional protection efforts to prevent impairments. This process is different from the past approach because previously, monitoring efforts were concentrated in a defined area (a lake or stream reach) to address one impairment. Under the MWRPP approach, all impairments are addressed at the same time. This process provides a communication tool that can inform stakeholders, engage volunteers, and help coordinate local/state/federal monitoring efforts so the data necessary for effective water resources planning is available, citizens and stakeholders are engaged in the process, and citizens and governments across Minnesota can evaluate the progress.

6.3.2 Local Comprehensive Water Management Plans

The North Fork TMDL project area is comprised of areas of Meeker, Wright and Hennepin Counties. Meeker and Wright Counties have each adopted a county water plan that articulates goals and objectives for water and land-related resource management initiatives. Meeker

County's Water Plan was created in 2003 and will expire in 2012. The Wright County Water Plan runs from 2006 through 2015. The area of Hennepin County that impacts the project area for this TMDL project is covered by the Pioneer Sarah Water Management Commission. The Pioneer Sarah WMC has adopted a watershed management plan for the Pioneer-Sarah Creek Watershed, and is currently undergoing an amendment process for the plan.
Addressing impaired waters and assisting in TMDL projects are top priorities in all of these plans. In addition, the implementation section of the plans focus on a number of areas important in restoring impaired waters to a non-impaired status. The following are examples of some of the implementation goals found in the water and watershed management plans.

1.) Provide education and incentives to lake, river riparian and wetland owners to retain or restore native vegetation
2.) Utilize local, state and federal cost share programs for high priority erosion sites
3.) Promote BMP's and provide incentives for buffers
4.) Adopt ordinances to limit erosion and sedimentation from construction, and limit the rate and volume of storm water runoff
5.) Promote rain garden programs
6.) Promote setbacks, fencing and other means of excluding livestock from area surface waters
7.) Conduct annual manure management forum
8.) Continue SSTS low interest loan and inspection programs

6.3.3 County Soil and Water Conservation Districts

The purpose of the County Soil and Water Conservation Districts (SWCDs) is to plan and execute policies, programs, and projects which conserve the soil and water resources within its jurisdictions. They are particularly concerned with erosion of soil due to wind and water. The SWCDs are heavily involved in the implementation of practices that effectively reduce or prevent erosion, sedimentation, siltation, and agricultural-related pollution in order to preserve water and soil as resources. The Districts frequently act as local sponsors for many types of projects, including grassed waterways, on-farm terracing, erosion control structures, and flow control structures. The CROW has established close working relationships with the SWCDs on a variety of projects. One example is the conservation buffer strip cash incentives program that provides cash incentives to create permanent grass buffer strips adjacent to water bodies and water courses on land in agricultural use.

6.4 MONITORING

Two types of monitoring are necessary to track progress toward achieving the load reduction required in the TMDL and the attainment of water quality standards. The first type of monitoring is tracking implementation of Best Management Practices (BMPs) on the ground. The CROW and the SWCDs will track the implementation of these projects annually. The second type of monitoring is physical and chemical monitoring of the resource. The CROW plans to monitor the affected resources on a ten year cycle in conjunction with the North Fork Crow River MWRPP process.

This type of effectiveness monitoring is critical in the adaptive management approach (refer to Figure 5-2). Results of the monitoring identify progress toward benchmarks as well as shape the next course of action for implementation. Adaptive management combined with obtainable benchmark goals and monitoring is the best approach for implementing TMDLs.

7.0 Public Participation

7.1 PUBLIC PARTICIPATION PROCESS

Public participation opportunities were provided during the project in the form of public meetings, electronic newsletters and CROW's website. A display board was developed to be taken to county fairs, MN DNR "Our Waters Our Choice" presentations in counties in the watershed. CROW staff attended local partner meetings to review the TMDL process and receive input on the project. The CROW's Technical Committee is comprised of ten counties within the Crow River Watershed and the following local agencies: SWCD, NRCS, Water Planners, BWSR, MN DNR, USFWS, Metropolitan Council and Cities. The Technical Committee and citizens reviewed project activities and provided comments. The CROW has presented information regarding the TMDL project during its regular scheduled Joint Powers Board and Technical Committee meetings.

<u>Meetings</u>

August 2, 2007 – Public Stakeholder Meeting in Buffalo, MN. Meeting provided an overview of the TMDL process, discussed the North Fork TMDL project, reviewed Phase I data results and discussed Phase II and Phase III in the TMDL process.

November 6, 2008 – Public Stakeholder Meeting in Litchfield, MN. Meeting provided an overview of the TMDL project and generated discussion that provided information to be used in the models.

July 22, 2009 – Public Stakeholder Meeting in Glencoe, MN. Meeting provided information on the bacteria impairment for the North Fork Crow River.

August 13, 2009 – Meeting with Wenck, MPCA and City of St. Michael to review and discuss concerns from the City on the DO impairment on Regal Creek.

September 16, 2009 – Public Stakeholder Meeting in Buffalo, MN. Meeting provided information on the turbidity impairment for the North Fork Crow River.

May 12, 2010 – Meeting with CROW and City of St. Michael attended the MPCA Professional Judgment meeting to discuss concerns the City has with the DO impairment on Regal Creek and provide input to proposed new listings for impairments.

June 3, 2010 – Public Stakeholder meeting in Buffalo, MN. The Meeting provided information on the DO impairment for the North Fork of the Crow River.

September 13 and 14, 2011 – Two public stakeholder meetings to review the findings of the TMDL study as well as the draft TMDL allocations in Buffalo, MN.

September 22, 2011 – Meeting with area WWTF operators to discuss draft TMDL allocations in Buffalo, MN.

September 28, 2011 – Two public stakeholder sessions to receive input on the implementation plan for the NF TMDL project in Buffalo, MN.

Public Notice Period

The public notice period occurred from June 18, 2012 to September 4, 2012. Six (6) comment letters were received during the public notice period. One comment letter was received outside the comment period and therefore was not timely. As a result of the comment letters, minor clarifications were made to the study as appropriate.

8.0 Literature Cited

9.0 Literature Cited

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10.0 Acronyms

AUID	Assessment Unit ID
BOD5	5-Day Biochemical Oxygen Demand
CBOD	Carbonaceous BOD
$CBOD_5$	5-Day Carbonaceous BOD
$CBOD_{20}$	20-Day Carbonaceous BOD
$CBOD_u$	Ultimate Carbonaceous BOD
CE	Computational Element (QUAL-2K)
cfs	cubic feet per second
cfu	colony-forming unit
CRP	Conservation Reserve Program
CREP	Conservation Reserve Enhancement Program
CREP-II	Conservation Reserve Enhancement Program-Minnesota II
CWA	Clean Water Act
CWP	Clean Water Partnership
CROW	Crow River Organization of Water
DEM	Digital Elevation Model
DMR	Discharge Monitoring Reports
ΔDO	Difference between daily maximum and daily minimum dissolved oxygen concentration
DO	Dissolved oxygen
DOQ	Digital Ortho Quadrangle
DRG	Digital Raster Graphic
EPA	Environmental Protection Agency
GIS	Geographical Information System
g O_2/sec	grams of oxygen per second

g O_2/m^2 – day	grams of oxygen per square meter per day
HUC	Hydrologic Unit Code: 8-digit HUC fourth-level (cataloguing unit)
IRG	intensive rotation grazing
LA	Load Allocation
lbs/day	pounds per day
LCC	Land Cover Category
MDNR	Minnesota Department of Natural Resources
MGD	million gallons per day
mg/L	milligrams per liter
mg/ft^3	milligrams per cubic foot
mg/sq ft - day	milligrams per square foot per day
mg O_2/ mg Chl a / day	milligrams of Oxygen per milligram chlorophyll-*a* per day
mg N/ mg Chl a / day	milligrams of Nitrogen per milligram chlorophyll-*a* per day
mg P/ mg Chl a / day	milligrams of Phosphorus per milligram chlorophyll-*a* per day
mi^2	square miles
MOS	Margin of Safety
MPCA	Minnesota Pollution Control Agency
MS4	Municipal Separate Storm Sewer Systems
NASS	National Agricultural Statistics Service
NRCS	Natural Resource Conservation Service
NOAA	National Oceanic and Atmospheric Administration
NPDES	National Pollutant Discharge Elimination System
NTU	Nephelometric Turbidity Units
NBOD	Nitrogenous Biochemical Oxygen Demand
NH_3-N	Total Ammonia-Nitrogen
NO_2/ NO_3-N	Nitrate/ Nitrite- Nitrogen
NPS	Nonpoint Source
NCHF	North Central Hardwood Forest
NFCWD	North Fork Crow River Watershed District

ON	Organic Nitrogen
QA	Quality Assurance
QC	Quality Control
QUAL2E	Enhanced Stream Water Quality Model
QUAL-2K	Modernized Enhanced Stream Water Quality Model
RM	River Mile
RIM	Reinvest in Minnesota
7Q10	Seven day low flow average based on a minimum of ten years of data
SCS	Soil Conservation Service
SOD	Sediment Oxygen Demand
SONAR	Statement of Need and Reasonableness
STATSGO	State Soil Geographic
SSURGO	Soil Survey Geographic
TKN	Total Kjeldahl Nitrogen
TMDL	Total Maximum Daily Load
TN	Total Nitrogen
TP	Total phosphorus
TSS	Total Suspended Solids
USGS	United States Geological Survey
USLE	Universal Soil Loss Equation
Wenck	Wenck Associates, Inc.
WCP	Western Corn Belt Plains
WPA	Wetland Preservation Areas
WMA	Wildlife Management Areas
WLA	Wasteload Allocation
WQBELs	Water Quality Based Effluent Limits
WWTF	Waste Water Treatment Facility
USDA	United States Department of Agriculture

Appendix A

NPDES Permitted Point Source Fecal Coliform DMR Summary

Facility	Location	Months Sampled	Individual Exceedances	Fecal Coliform Average of Monitored Geomeans since 1998 (organisms/100 mL)											
				Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Belgrade WWTP	NFC	1	1				1148								
Rooten WWTP	NFC	5	0				17	1					9		
Buffalo WWTP	NFC	85	0			1	22	29	38	28	33	56	54		
Cokato WWTP	NFC	78	1				15	63	9	3	3	3	3		
Dassel WWTP	NFC	1	0				89								
Green Lake WWTP	NFC	74	1				6	6	26	44	16	9	21		
Greenfield WWTP	Lower Crow	50	3					19	19	46	18	98	88		
Grove City WWTP	NFC	72	5					61	29	78	66	52	115		
Litchfield WWTP	NFC	79	5				86	59	67	64	72	90	84		
Montrose WWTP	NFC	68	1				8	6	31	44	7	11	115		
Otsego WWTP	Lower Crow	124	1	21	14	135	22	21	4	4	4	10	14	8	26
Paynesville WWTP	NFC	52	2			10	13	35	178	37	70	219	44		
Rockford WWTP	NFC	77	10				112	183	78	208	35	123	144		
Rogers WWTP	Lower Crow	70	2					44	26	53	21	35	34		
St Michael WWTP	NFC	86	1			42	23	30	32	18	18	14	40		

Appendix B

Turbidity Related Water Quality Monitoring Summary

Lower Crow River Impaired Reach

STORET Station ID	Measurement Method(s)	Years	Total Measurements	NTU	NTRU
S000-004	Turbidity	99-02	30	0	30
	Transparency	99-07	34	NA	NA
	TSS	99-07	53	NA	NA
S002-047	Turbidity	--	0	NA	NA
	Transparency	02-09	102	NA	NA
	TSS	--	0	NA	NA
S004-433	Turbidity	--	0	NA	NA
	Transparency	07	20	NA	NA
	TSS	07	10	NA	NA
S004-796	Turbidity	--	0	NA	NA
	Transparency	07-09	85	NA	NA
	TSS	08-09	22	NA	NA
S001-254	Turbidity	--	0	NA	NA
	Transparency	06-07	53	NA	NA
	TSS	07	14	NA	NA
S003-807	Turbidity	--	0	NA	NA
	Transparency	05	23	NA	NA
	TSS	--	0	NA	NA
S001-511	Turbidity	--	0	NA	NA
	Transparency	00-09	120	NA	NA
	TSS	--	0	NA	NA
S001-948	Turbidity	--	0	NA	NA
	Transparency	02	17	NA	NA
	TSS	--	0	NA	NA
S000-050	Turbidity	99-06	60	32	28
	Transparency	01-06	35	NA	NA
	TSS	99-06	117	NA	NA

North Fork Crow River Impaired Reach

STORET Station ID	Measurement Method(s)	Years	Measurements	NTU	NTRU
S001-256	Turbidity	2001-2009	54	25	29
	Transparency	2001-2009	51	NA	NA
	TSS	2001-2009	135	NA	NA
S001-978	Turbidity	--	0	NA	NA
	Transparency	2002-2009	56	NA	NA
	TSS	--	0	NA	NA
S001-799	Turbidity	--	0	NA	NA
	Transparency	2001	14	NA	NA
	TSS	--	0	NA	NA

Lower Crow Impaired Reach

STORET Station ID	Measurement Method(s)	Years	Measurements	Exceedances	% Exceedance
S000-004	Turbidity	99-02	30	10	33%
	Transparency	99-07	34	4	12%
	TSS	99-07	53	10	19%
S002-047	Turbidity	--	0	--	--
	Transparency	02-09	102	31	30%
	TSS	--	0	--	--
S004-433	Turbidity	--	0	--	--
	Transparency	07	20	8	40%
	TSS	07	10	0	0%
S004-796	Turbidity	--	0	--	--
	Transparency	07-09	85	24	28%
	TSS	08-09	22	1	5%
S001-254	Turbidity	--	0	--	--
	Transparency	06-07	53	30	57%
	TSS	07	14	0	0%
S003-807	Turbidity	--	0	--	--
	Transparency	05	23	17	74%
	TSS	--	0	--	--
S001-511	Turbidity	--	0	--	--
	Transparency	00-09	120	64	53%
	TSS	--	0	--	--
S001-948	Turbidity	--	0	--	--
	Transparency	02	17	1	6%
	TSS	--	0	--	--
S000-050	Turbidity	99-06	60	24	40%
	Transparency	01-06	35	14	40%
	TSS	99-06	117	24	21%
Total All Data	**Turbidity**	**99-06**	**90**	**34**	**38%**
	Transparency	**99-09**	**489**	**193**	**39%**
	TSS	**99-09**	**216**	**35**	**16%**
Total Consolidated by Date	**Turbidity**	**99-06**	**76**	**23**	**30%**
	Transparency	**99-09**	**413**	**194**	**47%**
	TSS	**99-09**	**190**	**31**	**17%**

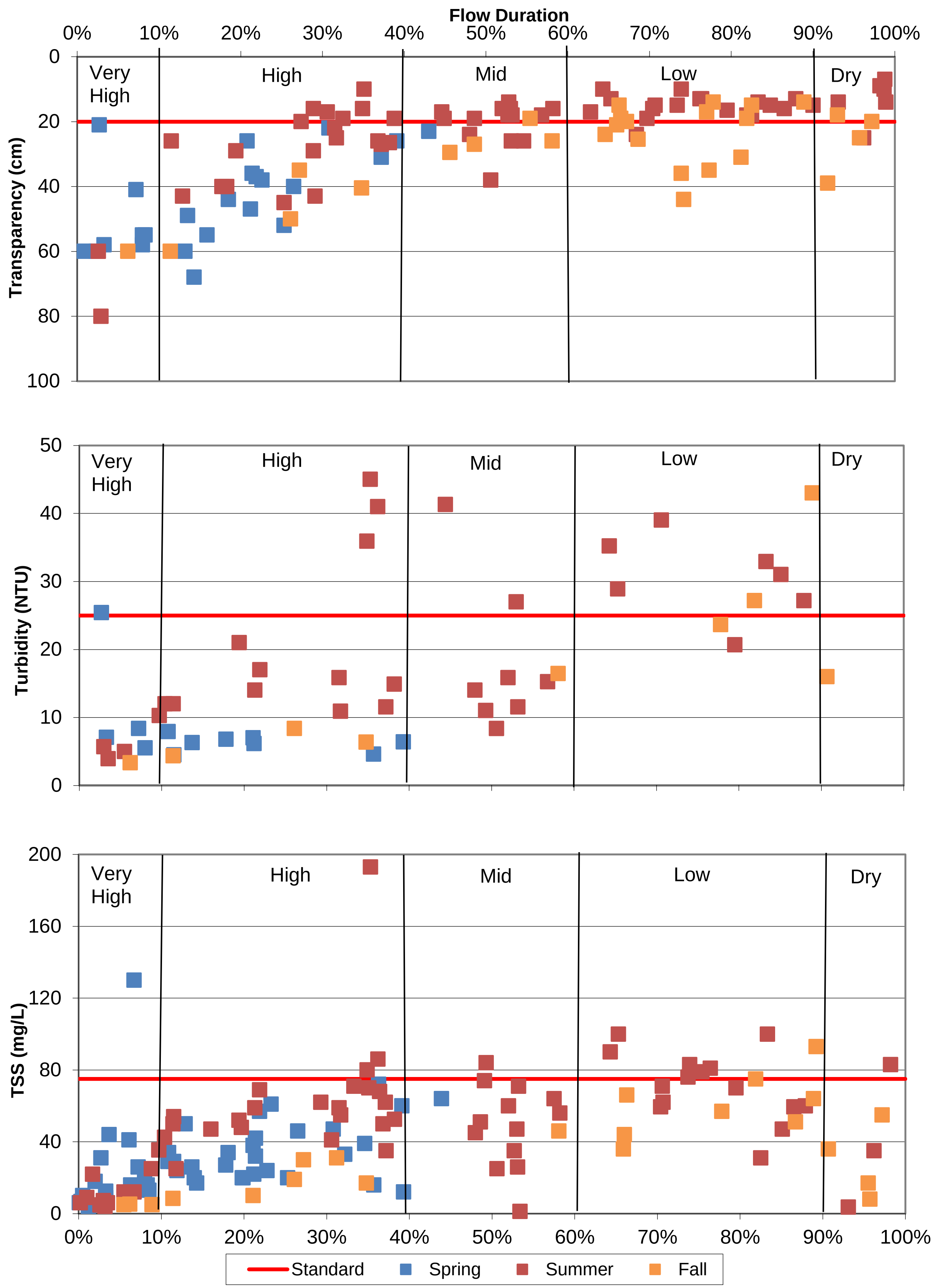
North Fork Crow Impaired Reach

STORET Station ID	Measurement Method(s)	Years	Measurements	Exceedances	% Exceedance
S001-256	Turbidity	2001-2009	54	14	26%
	Transparency	2001-2009	51	23	45%
	TSS	2001-2009	135	13	10%
S001-978	Turbidity	--	0	--	--
	Transparency	2002-2009	56	26	46%
	TSS	--	0	--	--
S001-799	Turbidity	--	0	--	--
	Transparency	2001	14	4	29%
	TSS	--	0	--	--
Total All Data	**Turbidity**		**54**	**14**	**26%**
	Transparency		**121**	**53**	**44%**
	TSS		**135**	**13**	**10%**
Total Consolidated by Date	**Turbidity**		**53**	**14**	**26%**
	Transparency		**114**	**52**	**46%**
	TSS		**135**	**15**	**11%**

North Fork Crow River Sampling by Season and Flow Regime

Parameter		Spring	Summer	Fall
Turbidity	Measurements	13	31	9
	Ave (NTU)	8	20	17
	% Violations	8%	35%	22%
Transparency	Measurements	24	61	29
	Ave (cm)	44	22	28
	% Violations	0%	66%	41%
TSS	Measurements	47	66	22
	Ave (mg/L)	31	52	35
	% Violations	2%	18%	9%

Parameter		Very High	High	Mid	Low	Dry
Turbidity	Measurements	10	23	9	10	1
	Ave (NTU)	8	14	18	31	16
	% Violations	10%	13%	22%	80%	0%
Transparency	Measurements	11	39	19	34	11
	Ave (cm)	55	35	22	19	18
	% Violations	0%	18%	58%	76%	73%
TSS	Measurements	32	58	15	23	7
	Ave (mg/L)	18	44	50	68	34
	% Violations	3%	5%	7%	39%	14%

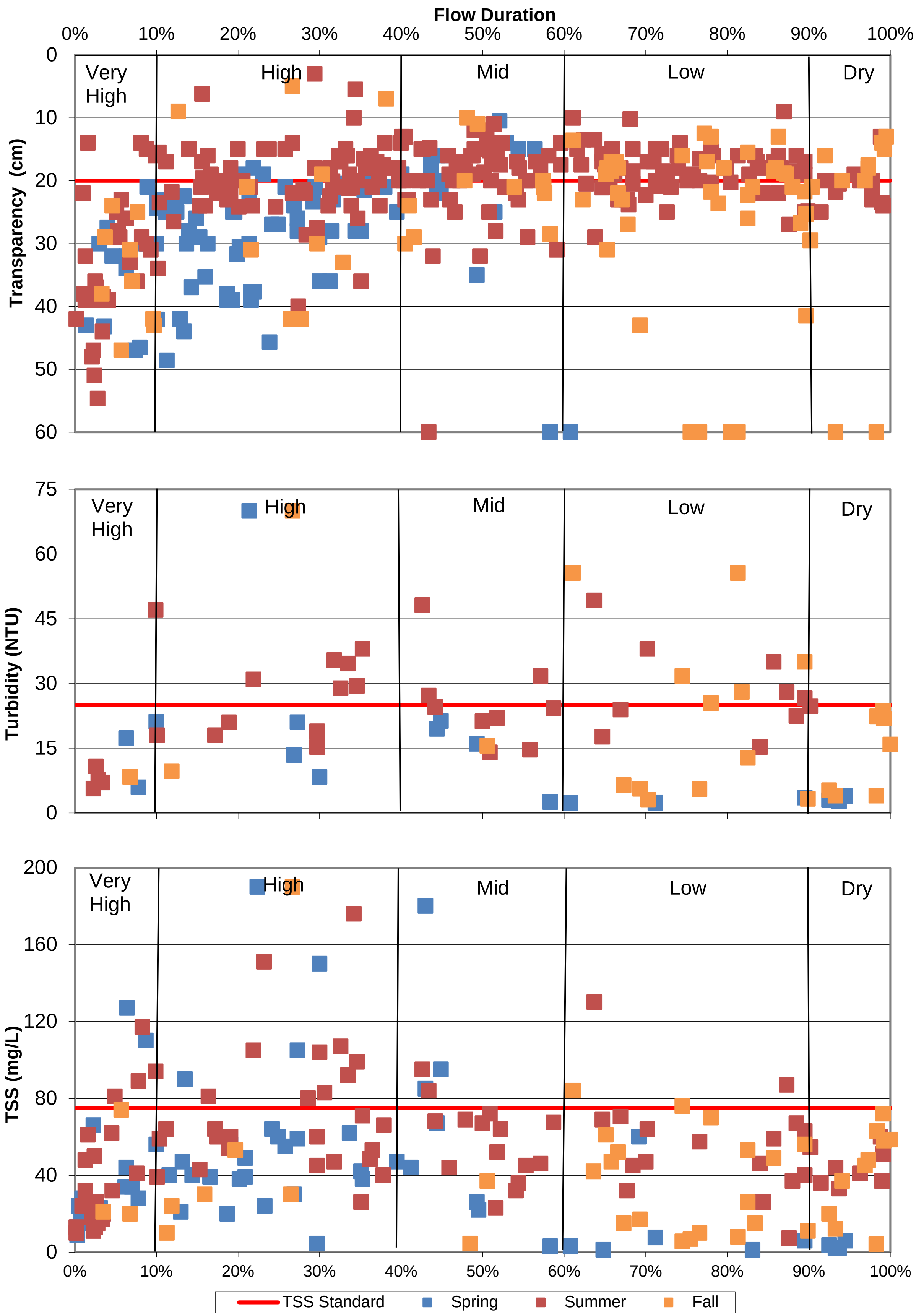


Flow Duration
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%
Transparency (cm)
Very High
High
Mid
Low
Dry
Turbidity (NTU)
TSS (mg/L)
Standard
Spring
Summer
Fall

Lower Crow River Sampling by Season and Flow Regime

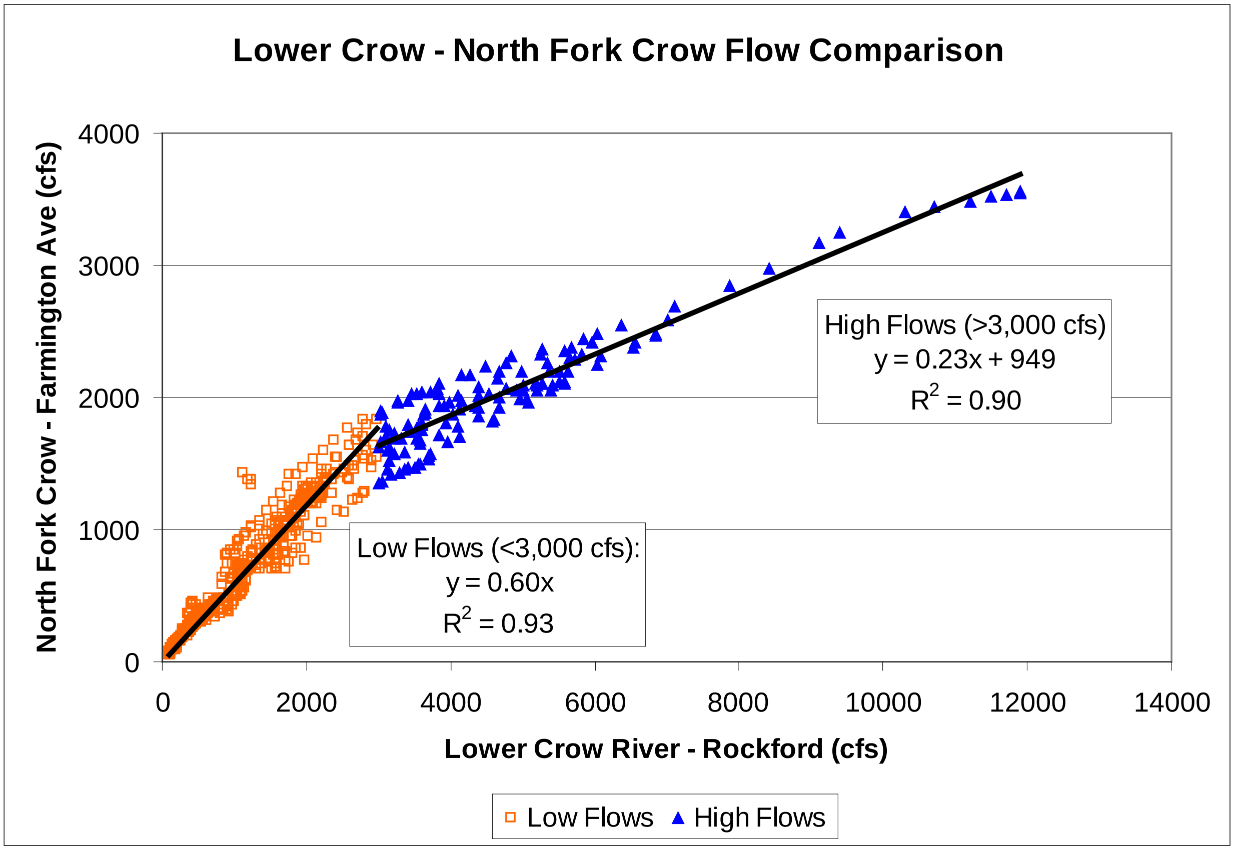
Parameter		Spring	Summer	Fall
Turbidity	Measurements	17	35	24
	Ave (NTU)	14	25	20
	% Violations	6%	43%	29%
Transparency	Measurements	88	243	82
	Ave (cm)	29	21	26
	% Violations	18%	60%	43%
TSS	Measurements	60	90	40
	Ave (mg/L)	53	59	40
	% Violations	17%	21%	8%

Parameter		Very High	High	Mid	Low	Dry
Turbidity	Measurements	8	18	14	25	11
	Ave (NTU)	14	28	22	12	12
	% Violations	13%	44%	21%	44%	0%
Transparency	Measurements	53	144	85	105	26
	Ave (cm)	34	24	21	21	23
	% Violations	8%	37%	67%	64%	58%
TSS	Measurements	40	61	25	42	22
	Ave (mg/L)	40	75	57	41	36
	% Violations	15%	26%	20%	10%	0%


Flow Duration
0% 10% 20% 30% 40% 50% 60% 70% 80% 90% 100%
Transparency (cm)
0 10 20 30 40 50 60
Very High
High
Mid
Low
Dry
Turbidity (NTU)
0 15 30 45 60 75
TSS (mg/L)
0 40 80 120 160 200
TSS Standard
Spring
Summer
Fall

Appendix C

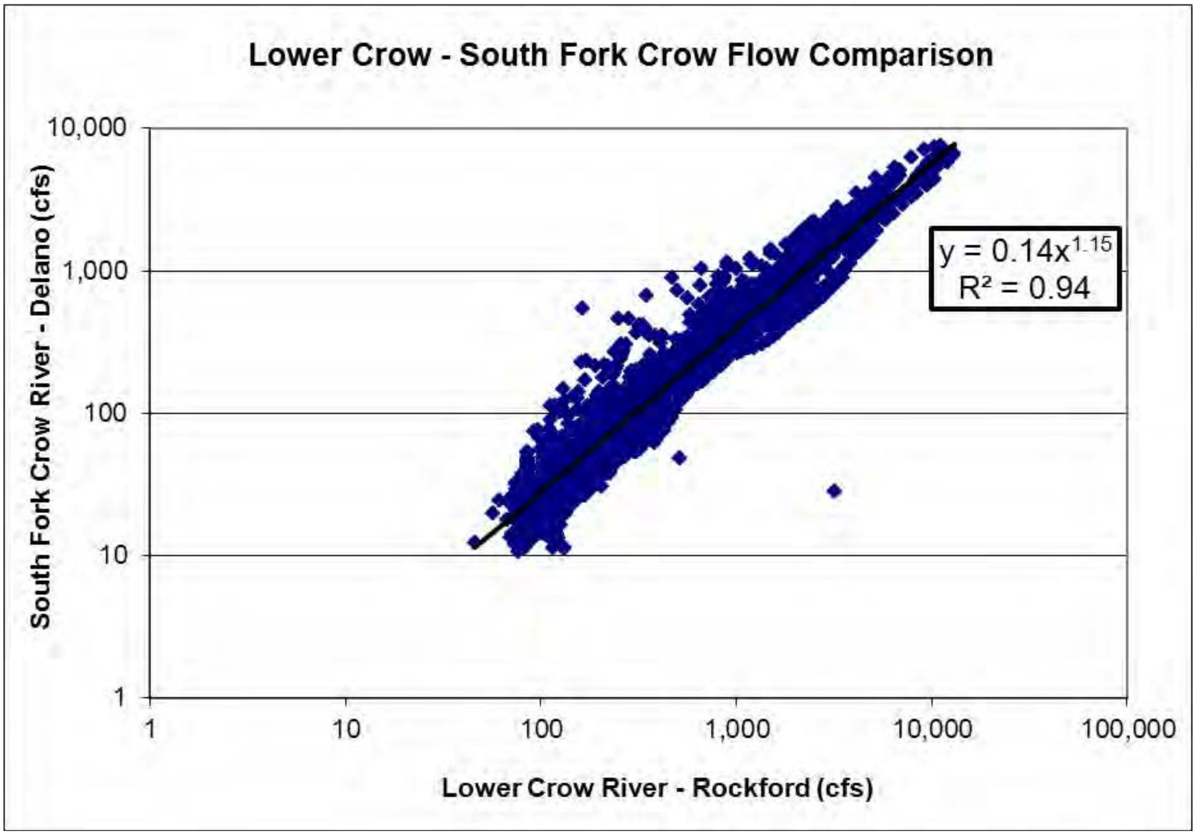
Continuous Flow Monitoring Regressions



Flow regression between the Farmington Ave (North Fork Crow River) and Highway 55 (Lower Crow River in Rockford) monitoring stations.

Notes:

The regression plot suggests the relationship between these two stations is different during high (flows greater than 3,000 cfs) and low (flows less than 3,000 cfs) flows. Thus, two separate regression equations were used to predict flow at the Farmington Avenue station under these conditions. Both equations show good correlation ($R^2 = 0.93$ and 0.90) and were used to fill data gaps and establish a reliable 10-year record for the North Fork impaired reach at Farmington Avenue.



Flow regression between the Bridge Street (South Fork Crow River in Delano) and Highway 55 (Lower Crow River in Rockford) monitoring stations.

Notes:

The regression equation shows good correlation ($R^2 = 0.94$) and was used to fill data gaps and establish a reliable 10-year record for the South Fork Crow River at Bridghe Street in Delano.

Appendix D

Stream Bank Erosion Methods and Results

Bank conditions along the Lower Crow River (impaired reach 502) were evaluated to determine whether soil loss from streambank erosion may be a significant contributor of sediment to the main-stem. The banks were surveyed for stability and amount of observed soil loss by severity. Only major erosion features were noted and measured during the survey as it was assumed that these problem areas account for a majority of the bank erosion within the listed reach. Bank erosion in the non-measured portions of the reach were assumed to be relatively low and set to the average of the three lowest surveyed erosion features.

Annual soil loss was estimated using the field data and a method developed by the Natural Resources Conservation Service referred to as the "NRCS Direct Volume Method," or the "Wisconsin method," (Wisconsin NRCS 2003). Soil loss is calculated by:

1. measuring the amount of exposed streambank in a known length of stream;
2. multiplying that by a rate of loss per year;
3. multiplying that volume by soil density to obtain the annual mass for that stream length; and then
4. converting that mass into a mass per stream mile.

The Direct Volume Method is summarized in the following equation:

$$\frac{\text{(eroding area) (lateral recession rate) (density)}}{\text{2000 lbs/ton}} = \text{erosion in tons/year}$$

The eroding area is in square feet, the lateral recession rate is in feet/year, and density is in pounds/cubic feet (pcf).

Streambank Conditions

The entire length of the Lower Crow River (reach 502) from Rockford to the Mississippi River was canoed by CROW staff and riverbanks were evaluated for bank condition and potential risk for and severity of erosion. A total of 31 were noted and measured during the survey. The following sections describe how each of the parameters in the Direct Volume equation was estimated for these features.

Eroding Area

The eroding area is defined as that part of the streambank that is bare, rilled, or gullied, and showing signs of active erosion such as sloughed soil at the base. The length and width of the eroding face of the streambank is multiplied to get eroding area.

As CROW staff canoed each reach, areas of significant erosion on either side of the streambank was measured and recorded on a field sheet. Most of the reaches that were evaluated contained long stretches of continuous bare streambank. Elsewhere, professional judgment was used to determine which areas were significant.

Lateral Recession Rate

The lateral recession rate is the thickness of soil eroded from a streambank face in a given year. Soil loss may occur at an even rate every year, but more often occurs unevenly as a result of large storm events, or significant land cover change in the upstream watershed. Historic aerial or other photographs, maps, construction records, or other information sources may be available to estimate the total recession over a known period of time, which can be converted into an average rate per year. However, these records are often not available, so the recession rate is estimated based on streambank characteristics that evaluate risk potential. Table 4-2 presents the categories of bank condition that are evaluated and the varying levels of condition and associated risk severity score.

Table 3-1 Bank Condition Severity Rating.

Category	Observed Condition	Score
Bank Stability	Do not appear to be eroding	0
	Erosion evident	1
	Erosion and cracking present	2
	Slumps and clumps sloughing off	3
Bank Condition	Some bare bank, few rills, no vegetative overhang	0
	Predominantly bare, some rills, moderate vegetative overhang	1
	Bare, rills, severe vegetative overhang, exposed roots	2
	Bare, rills and gullies, severe vegetative overhang, falling trees	3
Vegetation / Cover on Banks	Predominantly perennials or rock	0
	Annuals / perennials mixed or about 40% bare	1
	Annuals or about 70% bare	2
	Predominantly bare	3
Bank / Channel Slope	V – shaped channel, sloped banks	0
	Steep V - shaped channel, near vertical banks	1
	Vertical Banks, U – shaped channel	2
	U – shaped channel, undercut banks, meandering channel	3
Channel Bottom	Channel in bedrock / non eroding	0
	Soil bottom, gravels or cobbles, minor erosion	1
	Silt bottom, evidence of active down cutting	2
Deposition	No evidence of recent deposition	1
	Evidence of recent deposits, silt bars	0

A Cumulative Rating score of 0-4 indicates a streambank at slight risk of erosion. A score of 5-8 indicates a moderate risk, and nine or greater a severe risk. The Wisconsin NRCS used its field data from streams in Wisconsin to assign a lateral recession rate for each category (Table 4-3). Professional judgment is necessary to select a reasonable rate within the category.

Table 3-2 Estimated Annual Lateral Recession Rates Per Severity Risk Category.

Lateral Recession Rate (ft/yr)	Category	Description
0.01 - 0.05 feet per year	Slight	Some bare bank but active erosion not readily apparent. Some rills but no vegetative overhang. No exposed tree roots.
0.06 - 0.15 feet per year	Moderate	Bank is predominantly bare with some rills and vegetative overhang. Some exposed tree roots but no slumps or slips.
0.16 - 0.3 feet per year	Severe	Bank is bare with rills and severe vegetative overhang. Many exposed tree roots and some fallen trees and slumps or slips. Some changes in cultural features such as fence corners missing and realignment of roads or trails. Channel cross section becomes U-shaped as opposed to V-shaped.
0.5+ feet per year	Very Severe	Bank is bare with gullies and severe vegetative overhang. Many fallen trees, drains and culverts eroding out and changes in cultural features as above. Massive slips or washouts common. Channel cross section is U-shaped and stream course may be meandering.

At each of the measured erosion areas in the randomly selected quarter sections, CROW staff performed the above severity assessment and recorded on the field sheet the score for each of the condition categories above. The surveyors also evaluated Rosgen's Bank Erosion Hazard Index (BEHI), a measure of bank erosion potential.

Density

At each of the evaluated locations, soil texture was field evaluated and noted on the field sheet.

Annual Streambank Soil Loss

Data were compiled into a spreadsheet database that summarized the following data for each erosion feature: feature stream length, total eroding area, Bank Condition Severity Rating, and soil texture. The selected recession rates in Table 4-4 were applied.

Table 3-3 Assumed Recession Rate Based on Bank Condition.

Bank Condition Severity Rating	Assumed Recession Rate (ft/yr)
≤7	0.15
8-10	0.25
≥11	0.5

The assumed recession rate was multiplied by the total eroding area to obtain the estimated total annual volume of soil loss (Table 4-5). To convert this soil loss to mass, soil texture or actual measured bulk dry density was used to establish a volume weight for the soil. The following volume weights by texture were assumed:

Table 3-4 Assumed Volume Weight for Various Soil Textures.

Soil Texture	Wisconsin NRCS Average Range (lbs/cu-ft) (pcf)	Assumed Volume Weight (lbs/cu-ft) (pcf)
Clay	60-70	65
Silt	75-90	N/A
Silty Clay		75
Silty Clay Loam		80
Sand	90-110	N/A
Sandy Clay		85
Sandy Clay Loam		90
Loam	80-100	N/A
Sandy Loam	90-110	100

N/A = No field-identified soil textures of this type.

The total estimated volume of soil loss for each erosion feature was multiplied by the assumed volume weight and converted into annual tons. As a final step, the mass of each feature was divided by the evaluated stream length in miles to obtain an estimated annual soil loss in tons per mile. Approximately 4.35 total miles of Lower Crow River eroded streambank were noted and measured during the survey. Soil loss from these sites ranged from 34 tons/mi/yr to 6,600 tons/mi/yr with total bank loss approaching 7,000 tons per year (1,600 tons/mi/yr average). There was about 20.63 miles of streambank in the Lower Crow River that was not measured or identified as heavily eroded during the survey. Bank erosion for the non-measured portions was assumed to be relatively low and set to the average of the five lowest surveyed erosion features (62 tons/mi/yr). Applying this average brings the bank erosion grand total to 8,269 tons/year for the main-stem Lower Crow River (Table X.X).

Measurement	Result/Estimate
Erosion Features noted	31
Maximum measured soil (bank) loss	6,600 tons/yr/mi
Minimum measured soil (bank) loss	34 tons/yr/mi
Non-surveyed soil (bank) loss - assumed	62 tons/yr/mi
Total length of surveyed erosion features	4.35 miles
Total Reach Length	24.98 miles
Total surveyed soil (bank) loss	6,988 tons/yr
Total non-surveyed soil (bank) loss	1,281 tons/yr
Total Lower Crow River soil (bank) loss	**8,269 tons/yr**

Streambanks most susceptible to erosion are those that are high compared to bankfull elevation, and rooting depths shallow compared to bank height, or where banks are nearly vertical. These are characteristics typical of overly-incised streams. Erosion features in this stream assessment where measured erosion features suggest a higher rate of annual soil loss tended to have higher, more vertical banks and shallower rooting depths. Channel incision often associated with changes in hydrologic regime such as adding flow from stormwater or agricultural tiling, or stream straightening. The resulting increase in stream power and shear stress accelerates streambank erosion. Significant changes in land use and land cover in the watershed can alter the historic bankfull elevation, increasing its frequency and subjecting additional streambank to erosive flows. Based on the stream assessment findings it is likely that watershed and hydrologic regime modifications in the watershed have resulted in increased rates of and volumes of streambank soil loss.

Appendix E

Algal Turbidity Data Processing

Site	Date	Month	Flow (cfs)	Flow Duration	Trans (cm)	TSS (mg/L)	Chlorophyll a (ug/L)	K_e (1/m)	K_e (Algae)	Ke (TSS)	Ke (TSS)/TSS	Algae %	TSS %
S001-256	8/26/2002	8	2050	3%	60	4.8	5	2.83	0.23	2.61	0.54	8%	92%
S000-050	8/26/2002	8	5000	3%	36	13	9	4.72	0.39	4.33	0.33	8%	92%
S001-256	8/13/2002	8	2260	3%	80	4.8	19	2.13	0.82	1.31	0.27	39%	61%
S000-050	8/13/2002	8	4760	3%	61	15	30	2.79	1.28	1.51	0.10	46%	54%
S000-050	7/16/2002	7	4140	4%	45	20	30	3.78	1.27	2.51	0.13	34%	66%
S001-256	9/12/2002	9	1970	7%	60	5.2	7	2.83	0.31	2.52	0.49	11%	89%
S000-050	9/12/2002	9	3260	7%	31	20	27	5.48	1.15	4.33	0.22	21%	79%
S001-256	7/25/2002	7	1460	11%	26	54	15	6.54	0.64	5.89	0.11	10%	90%
S000-050	7/25/2002	7	2300	11%	17	64	30	10.00	1.28	8.72	0.14	13%	87%
S001-255	4/30/2008	4	1397	12%	31	35	27	5.47	1.15	4.32	0.12	21%	79%
S001-255	6/12/2008	6	836	25%	15	45	40	11.33	1.68	9.65	0.21	15%	85%
S001-256	9/26/2002	9	1010	27%	35	30	14	4.86	0.60	4.26	0.14	12%	88%
S000-050	9/26/2002	9	1240	27%	42	30	20	4.05	0.86	3.18	0.11	21%	79%
S000-050	6/4/2002	6	1080	30%	28	60	40	6.18	1.71	4.47	0.07	28%	72%
S000-050	6/20/2002	6	848	34%	10	176	29	17.00	1.22	15.78	0.09	7%	93%
S001-256	7/10/2006	7	211	51%	16	60	77	10.63	3.24	7.38	0.12	31%	69%
S000-050	7/10/2006	7	344	51%	16	72	165	10.63	7.00	3.63	0.05	66%	34%
S001-256	7/30/2001	7	201	52%	16	47	48	10.63	2.04	8.59	0.18	19%	81%
S000-050	7/30/2001	7	327	52%	15	52	80	11.33	3.38	7.96	0.15	30%	70%
S001-256	6/8/2009	6	181	54%	26	26	45	6.54	1.90	4.63	0.18	29%	71%
S001-255	6/8/2009	6	181	54%	20	29	126	8.50	5.34	3.16	0.11	63%	37%
S001-256	8/3/2006	8	132	64%	10	90	106	17.00	4.49	12.51	0.14	26%	74%
S000-050	8/3/2006	8	215	64%	11	130	123	15.45	5.22	10.24	0.08	34%	66%
S001-256	7/25/2006	7	128	65%	13	100	156	13.08	6.61	6.46	0.06	51%	49%
S000-050	7/25/2006	7	209	65%	18	70	212	9.44	8.97	0.48	0.01	95%	5%
S001-256	7/9/2009	7	111	68%	15	62	45	11.33	1.92	9.41	0.15	17%	83%
S001-255	7/9/2009	7	111	68%	18	38	74	9.44	3.14	6.31	0.17	33%	67%
S001-256	9/18/2006	9	100	78%	14	57	145	12.14	6.15	5.99	0.11	51%	49%
S000-050	9/18/2006	9	132	78%	13	69	198	13.08	8.40	4.68	0.07	64%	36%
S001-256	9/24/2001	9	74	83%	19	75	61	8.95	2.57	6.38	0.09	29%	71%
S000-050	9/24/2001	9	120	83%	18	26	44	9.44	1.87	7.57	0.29	20%	80%
S001-256	8/14/2006	8	71	84%	14	100	147	12.14	6.23	5.91	0.06	51%	49%
S000-050	8/14/2006	8	115	84%	22	46	92	7.73	3.91	3.81	0.08	51%	49%
S001-256	8/30/2006	8	61	89%	13	60	139	13.08	5.89	7.18	0.12	45%	55%
S000-050	8/30/2006	8	102	89%	16	67	100	10.63	4.24	6.39	0.10	40%	60%

Site Notes:

S001-256	NFC River Listed reach
S000-050	Lower Crow Listed reach
S000-020	NFC River - upstream of listed reach
S001-250	SFC River

Equations:

K_e = 1.7/secchi

K_e (algae) = 0.013 x Chl-a (ug/L)

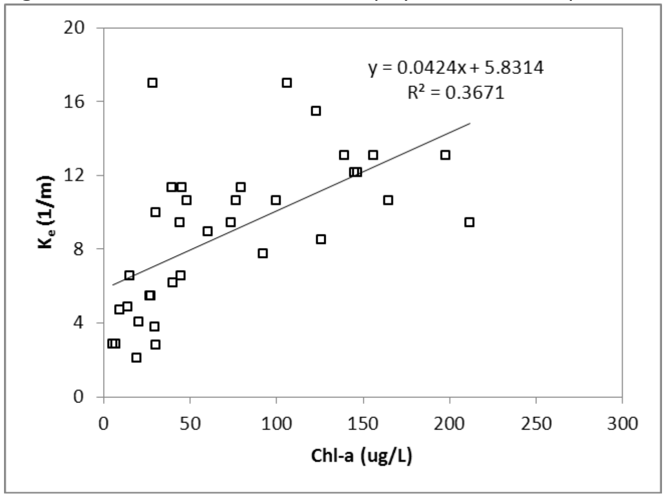
K_e (TSS) = K_e (secchi) - K_e (algae)

Violations:

Transparency violation

TSS violation

Light Extinction coefficient/Chlorophyll-a relationship:



Appendix F

NPDES Permitted Point Source Total Suspended Solids DMR Summary

Facility	Years Sampled	TSS Concentration Monitoring				TSS Load Monitoring			
		Limit (mg/L)	Monitoring Measurments	Violations	Ave (mg/L)	Limit (kg/day)	Monitoring Measurments	Violations	Ave (kg/day)
Belgrade WWTP	2011	45	1	0	37	252	1	0	184
Brooten WWTP	08-11	45	8	0	12	181	8	0	39
Buffalo WWTP	02-11	30	144	0	8	409	144	0	44
Cokato WWTP	00-11	45	133	3	19	124	133	0	23
Dassel WWTP	02, 11	45	2	0	25	208	3	0	45
Faribault Foods	00-11	30	132	0	7	81	131	0	5
Great River Energy	99-11	30	136	9	13		0	--	--
Green Lake WWTP	00-11	30	129	0	4	101	129	0	5
Greenfield WWTP	02-11	30	104	0	6	23	104	0	<1
Grove City WWTP	99-11	30	144	0	6	25	144	0	2
Litchfield WWTP	99-11	30	139	0	6	215	139	0	36
Montrose WWTP	98-11	45	111	1	20	155	111	0	32
Otsego WWTP	00-11	30	124	2	5	125	124	0	3
Paynesville WWTP	00-11	45	76	0	5	249	76	0	51
Rockford WWTP	99-11	30	136	11	18	74	136	0	21
Rogers WWTP	99-11	30	141	0	8	181	141	0	23
St Michael WWTP	98-11	30	150	0	7	277	150	0	23

Appendix G

Dissolved Oxygen Synoptic Survey Tech Memos

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1800 Pioneer Creek Ctr.
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Maple Plain, MN 55359-0249

(763) 479-4200
Fax (763) 479-4242
E-mail: wenckmp@wenck.com

TECHNICAL MEMORANDUM

TO: Diane Sander, Crow River Organization of Water Watershed Coordinator

CC: Maggie Leach, MPCA Regional Impaired Waters Coordinator

FROM: Joe Bischoff, Project Manager
Pamela Massaro, P.E.
Jeff Strom

DATE: May 5, 2010

SUBJECT: County Ditch 31 Dissolved Oxygen TMDL
Historic Data and Synoptic Survey Methods and Results

This technical memorandum summarizes historic dissolved oxygen (DO) data for County Ditch 31 and the data collection methods and results for the August 2009 Synoptic Survey. The synoptic survey was performed to obtain the data needed to construct and calibrate a River and Stream Water Quality Model (QUAL2K) to address the ditch's DO impairment during low-flow conditions.

1.0 WATERSHED DESCRIPTION

County Ditch 31 flows approximately 3.11 miles from the outlet of the Woodland Wetland System south-east of Montrose, MN, to the North Fork Crow River, an Upper Mississippi River tributary (Figure 1.1). This stretch of CD31 (AUID 07010204-527) was listed as impaired for dissolved oxygen in 2005. The system is narrow, shallow and straight with moderate channel slopes. The average slope for the whole length of CD31 is approximately 4.9 feet per mile. For the TMDL study, the CD31 watershed was considered to be the 3693 - acre watershed that drains to the Woodland Wetland and the ditch itself. Agriculture dominates the landscape: 34% of land within the watershed is cultivated for row crops while 30% is used for grassland and pasture. The Woodland Wetland System covers approximately 13% of the watershed while forests and lakes each account for less than 10%. The city of Montrose also comprises a portion of the watershed (12%).

Table 1.1 Landuse summary table for CD31 Watershed. Landuse Type	Acres	Percentage
Cultivated Land	1,253	34%
Grassland/Pasture	1,100	30%
Wetlands	496	13%
Developed	448	12%
Forest	255	7%
Lakes	141	4%
Total	3,693	100%

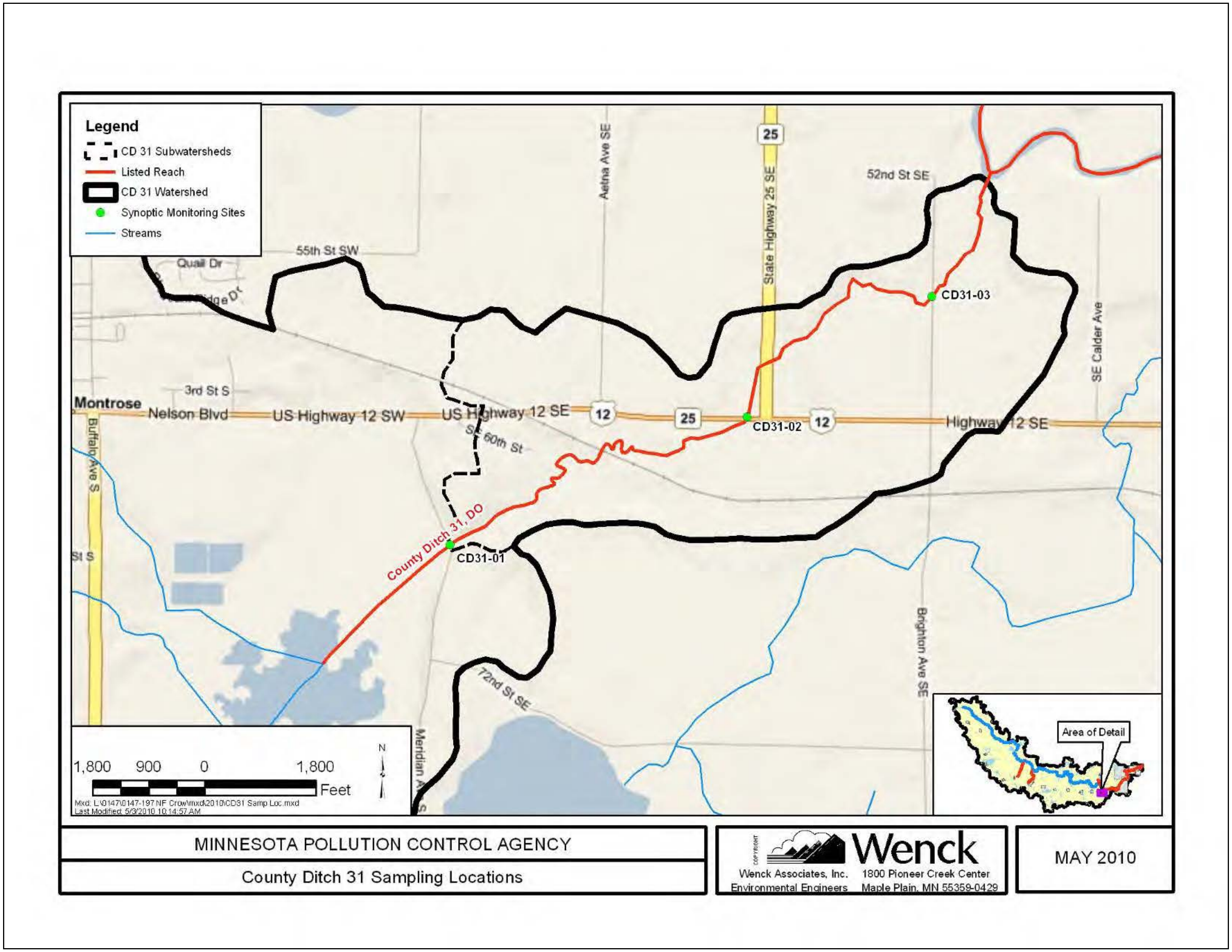


Figure 1.1 County Ditch 31 watershed and monitoring locations.

2.0 REVIEW OF COUNTY DITCH 31 HISTORIC DISSOLVED OXYGEN DATA

County Ditch 31 has four STORET water quality stations with DO measurements available through the MPCA's STORET database (Table 2.1, Figure 1.1). Station CD31-02 (S002-020) is the long-term monitoring station for the MPCA and the CROW intensive watershed monitoring program. Stations CD31-01 (S005-837) and CD31-03 (S005-839) are additional stations set-up by Wenck Associates, Inc. to sample dissolved oxygen and other water quality parameters as part of a two-day synoptic survey study that took place on August 26th and 27th, 2009 (Table 1.1). Station CD31-00 (S001-499) is located upstream of the Woodland wetland system and outside the listed reach but is included in the historic data review.

Table2.1 CD31 Water Quality Monitoring Stations and DO data available in STORET.

Station Name	STORET #	Location	River Km	DO Measurements	Violations	Years
CD31-00	S001-499	Unnamed Tributary at Armitage Ave SE crossing	7.23	22	0	08-09
CD31-01	S005-837	CD31 at Meridan Ave SE crossing	4.15	1	1	09
CD31-02	S002-020	CD31 at Highway 12 crossing	2.13	93	23	01-03; 06-09
CD31-03	S005-839	CD31 at Brighton Ave SE crossing	0.73	1	1	09

2.1 DO GRABS/FIELD MEASUREMENTS

County Ditch 31 is designated by state statute as a beneficial-use Class 2B water (cool/warm water fishery). This designation states that DO concentrations shall not fall below 5.0 mg/L as a daily minimum in order to support the aquatic life and recreation of the system. Twenty five of the 117 STORET DO field measurements collected on CD31 were below the 5.0 mg/L DO standard (Figure 2.1). All CD31 violations were recorded downstream of the Woodland wetland system at sites CD31-01 and CD31-02. Dissolved oxygen data from STORET is also plotted by month (Figure 2.2) and shows 22 of the 25 violations were recorded during summer months (June-September) when water temperatures are warmer and diurnal DO swings are typically highest. Plotting DO by time of day (Figure 2.3) indicates only 6 of the 117 DO measurements were recorded prior to 9:00 am. The MPCA now recognizes measurements taken after 9:00 am do not represent daily minimums, and thus measurements greater than 5.0 mg/L dissolved oxygen later in the day are no longer considered to be indications that a stream is meeting state standards. That said, 23 of the 111 (21%) measurements recorded after 9:00 am were in violation of the DO standard which exceeds the 10% needed for a stream to be considered impaired.

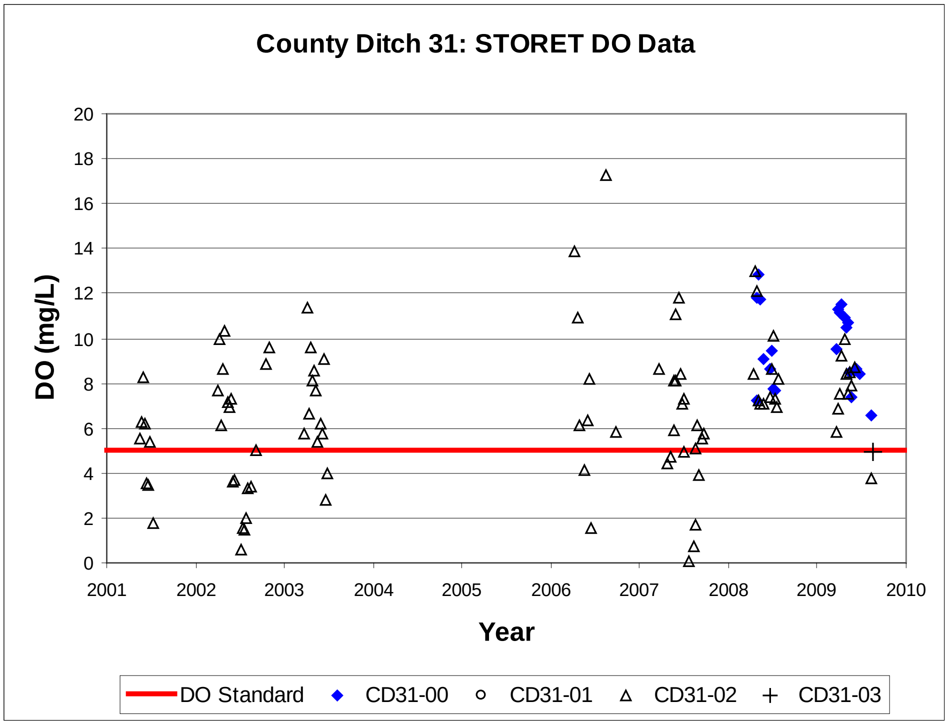


Figure 2.1 Dissolved oxygen data from STORET for all CD31 Stations.

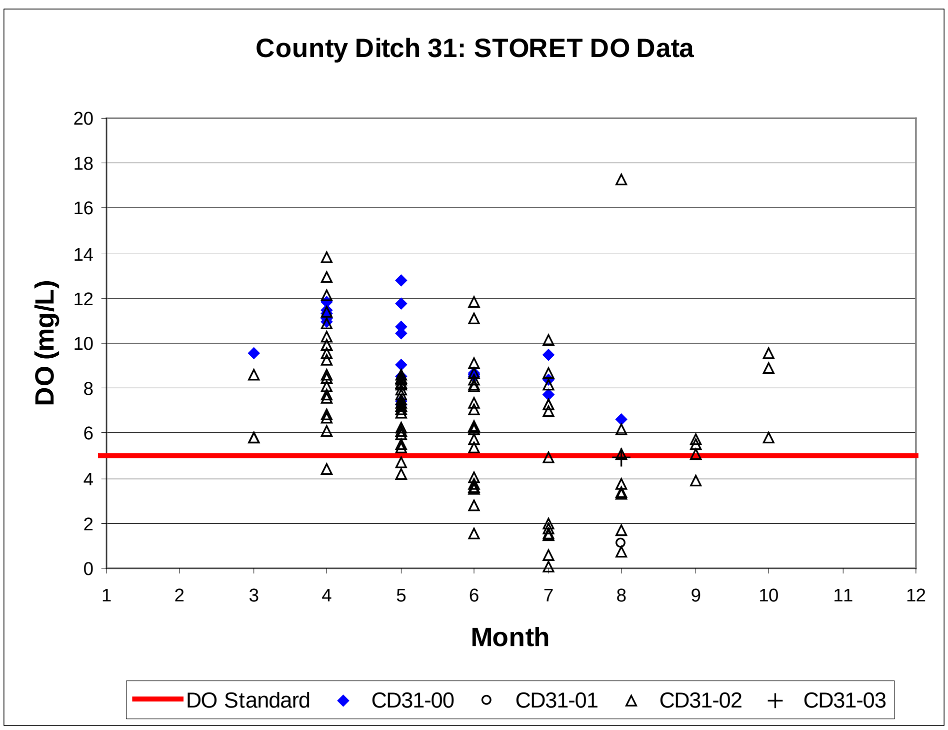


Figure 2.2 Dissolved oxygen data from STORET for all CD31 stations by month, regardless of year.

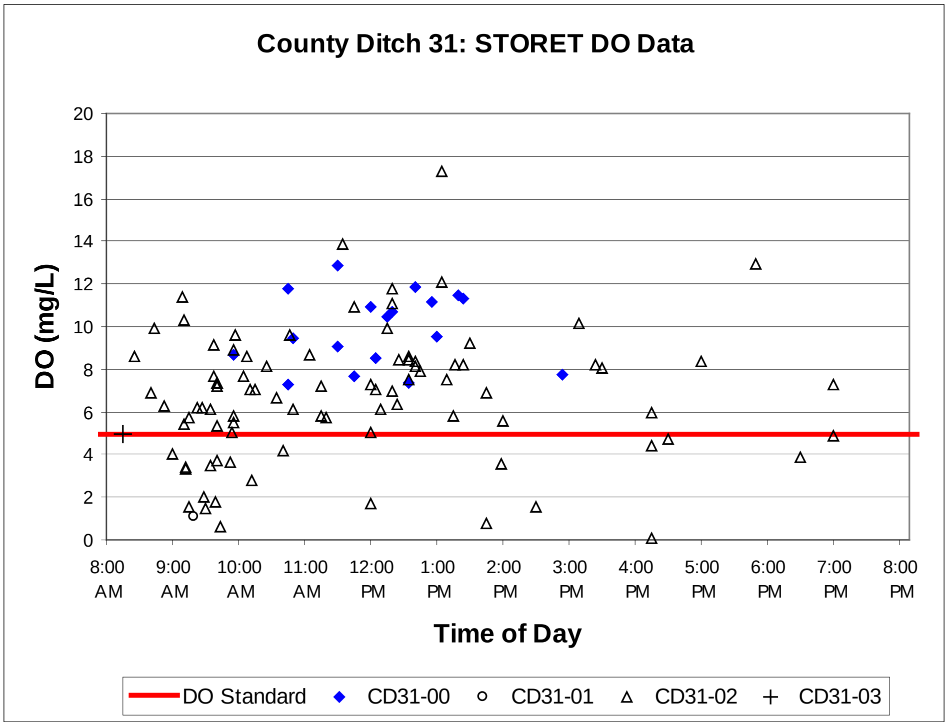


Figure 2.3 Dissolved oxygen data from STORET for all CD31 stations by hour, regardless of year and month. No measurements were reported between 8:00pm and 8:00 am.

2.2 CONTINUOUS DO MEASUREMENTS

Continuous DO data was collected in 2008 by the MPCA using data sondes at two locations along County Ditch 31. The sondes were deployed at station CD31-01 for 43 days (4/16/09 through 5/28/09) and for two separate deployments at station CD31-02 for 59 days (4/16/09 through 5/28/09 and 8/25/09 through 9/10/09). The sensors record continuous measurements of dissolved oxygen, temperature, pH and conductivity. DO was consistently below the 5.0 mg/L standard at CD31-02 when temperatures warmed and flow dropped below 1 cfs beginning early in May, 2009 (Figure 2.4).

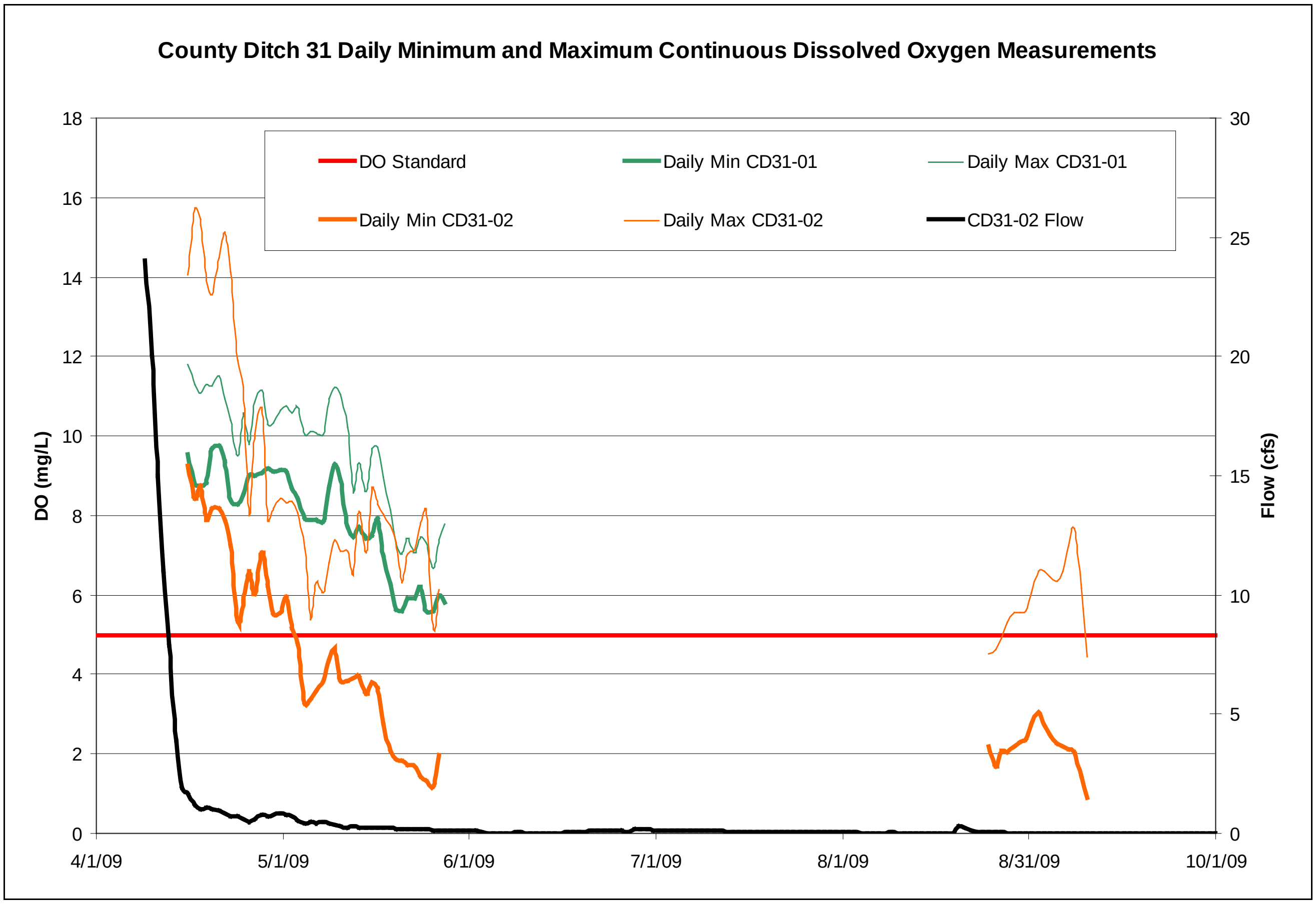


Figure 2.4 Statistics of continuous dissolved oxygen data collected in 2008.

2.3 DO RELATION TO FLOW

The nearest United States Geologic Survey (USGS) monitoring station is located at Crow River at Rockford. Average daily flows have been monitored at this station since 1906 (23 miles upstream from confluence with the Mississippi River). The mean annual flow for water years 1906 through 2002 is 826 cubic feet per second (cfs), which represents 4.25 inches of runoff from the 2,640-square mile drainage area located upstream of Rockford. Monthly average flows for this station range from 172 cfs in February to 2,243 cfs in April. The maximum average daily flow, 22,100 cfs, was recorded April 16, 1965. The minimum average daily flow, 3.8 cfs, was recorded August 4, 1934. These statistics are based on flows observed through September 2002. Table 2.2 summarizes select water year data and characterizes the year as a wet, dry or average year based on comparison to long term monitoring.

Table 2.2 Water year summary for the last ten years at USGS Crow River at Rockford.

Water Year	Average Annual Flow at Main Stem Crow USGS Station at Rockford (cfs)	Percent Variation from Average	Wet / Dry / Average
2000	275	-67%	DRY
2001	1329	59%	WET
2002	1605	93%	WET
2003	1245	49%	WET
2004	718	-14%	AVERAGE
2005	1158	39%	WET
2006	1399	68%	WET
2007	603.1	-28%	DRY
2008	640.8	-23%	DRY
2009	658.8	-21%	DRY

While there is no USGS gage on CD31, the MPCA established a continuous flow station at CD31-02 in April, 2009. There are also 21 gauged flow measurements recorded at CD31-02 from 2001-2003 available in STORET. There are a total of eight paired flow-DO measurements below the 5 mg/L DO standard. These violations occurred across both high and low flow regimes as well as both wet and dry years (Figure 2.5).

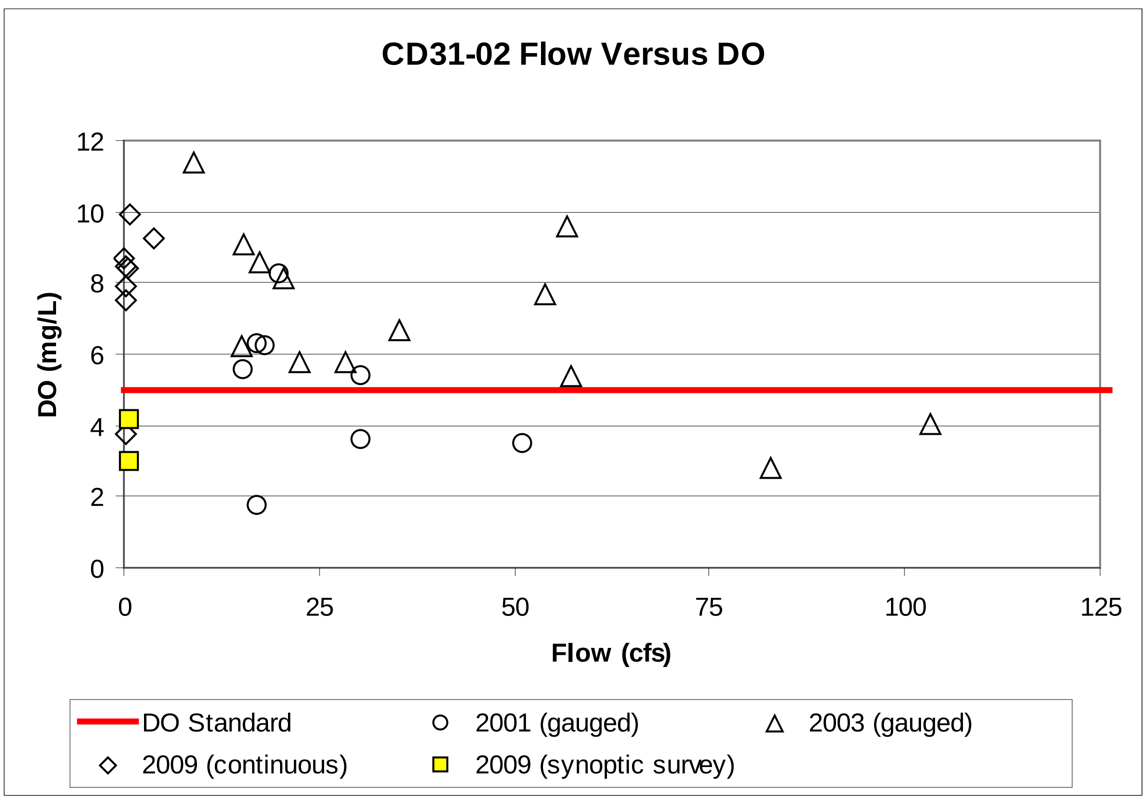


Figure 2.5 CD31-02 dissolved oxygen compared to gauged and continuous flow measurement.

3.0 SYNOPTIC SURVEY DATA COLLECTION METHODS

3.1 STUDY AREA AND LOCATIONS

The Minnesota Department of Natural Resources (DNR) stream file shows County Ditch 31 begins at the Woodland wetland system (Figure 1.1). Flow was measured downstream of this wetland where CD31 crosses Meridan Ave S (CD31-01) on August 26th, 2009. Flow at this station (~0.42 cfs) was determined suitable to initiate the dye study and represent the upstream boundary condition/headwater for the study.

3.2 DYE STUDY

A slug of a tracer (Rhodamine WT dye) was injected at CD31-01 and CD31-02 and measured downstream during the synoptic survey on August 26th, 2009. Dye was released first at the downstream most injection location to prevent dye from separate injection points "catching up" and mixing. Dye samples were collected as grabs by field personnel or ISCO automatic samplers. Fixed stations downstream of the injection point were sampled until the dye cloud passed (Table 3.1). The concentration of the dye in each sample was measured using an Aquafluor handheld fluorometer Rantz, 1982).

Table3.1 CD31 Synoptic Survey Monitoring Locations.

Site	Location (River km)	Lab WQ Grab Station	Field Parameter WQ Station	Flow Station	Dye Station
CD31-00	7.23	---	---	---	---
CD31-01	4.15	X	X	X	X
CD31-02	2.13	CBOD only	X	X	X
CD31-03	0.73	X	X	X	X

3.3 FLOW GAUGING

Stream gauging measurements were collected in conjunction with the time of travel dye study. Flow was recorded using a SonTek Flow Tracker handheld digital velocity meter with an accuracy of 0.001 cubic feet per second. Velocity measurements were taken at 60 percent of the total depth for shallow reaches (less than 2.5 feet deep) and at 20 percent and 80 percent of the total depth for deeper reaches. Horizontal spacing of velocity measurements was set so less than 10 percent of total discharge is accounted for by any single velocity measurement. Flow gauging was conducted at each dye injection and monitoring station (Table 3.1).

3.4 WATER QUALITY SAMPLING

Water quality data was collected on August 26, 2009 at three locations along CD31 (Table 3.1 and Figure 1.1). Each water sample (grab) was collected and preserved for lab analysis. The lab analyzed the samples for the following parameters: total kjeldahl nitrogen (TKN), ammonia nitrogen (NH_3-N), nitrate nitrogen (NO_2-N), 5-day and ultimate carbonaceous biochemical oxygen demand ($CBOD_{5\text{-day}}$ & $CBOD_u$), total phosphorus (TP), ortho-phosphorus (soluble reactive phosphorus), total organic carbon (TOC), and chlorophyll-*a*. A data sonde (YSI Model 6920 V2) was used at six sites in the field to collect the following additional water quality parameters: temperature, conductivity, pH, and dissolved oxygen (DO).

3.5 CONTINUOUS DISSOLVED OXYGEN MEASUREMENTS

The Minnesota Pollution Control Agency deployed one multi-parameter YSI sondes with internal logging capability to monitor continuous DO levels during the dye study and synoptic water quality survey. This instrument was deployed to monitor continuous DO concentrations at 15-minute intervals for a minimum of 72-hours before, after and during the synoptic surveys. The instrument also measured and recorded other in-situ parameters such as DO saturation, temperature, conductivity, and pH.

4.0 SYNOPTIC SURVEY RESULTS

4.1 DYE STUDY

Travel times from the dye study suggest mean velocity was significantly slower in the upper reach compared to the lower reach likely due to lower flows and channel slopes (Table 4.1, and Figures 4.1 – 4.2). Combined travel time for both reaches was just under two days indicating residence time for CD31 is fairly long during this flow regime given the ditch's length.

Table 4.1 Estimated travel times from the Grove Creek dye study. Travel times estimated by calculating the time between upstream injection and peak concentration measured downstream.

Reach Description	Reach Length (km)	Estimated Travel Time (hrs)	Mean Velocity (ft/sec)
Upper Reach: CD31-01 to CD31-02	2.02	36.5	0.05
Lower Reach: CD31-02 to CD31-03	1.40	8.8	0.14

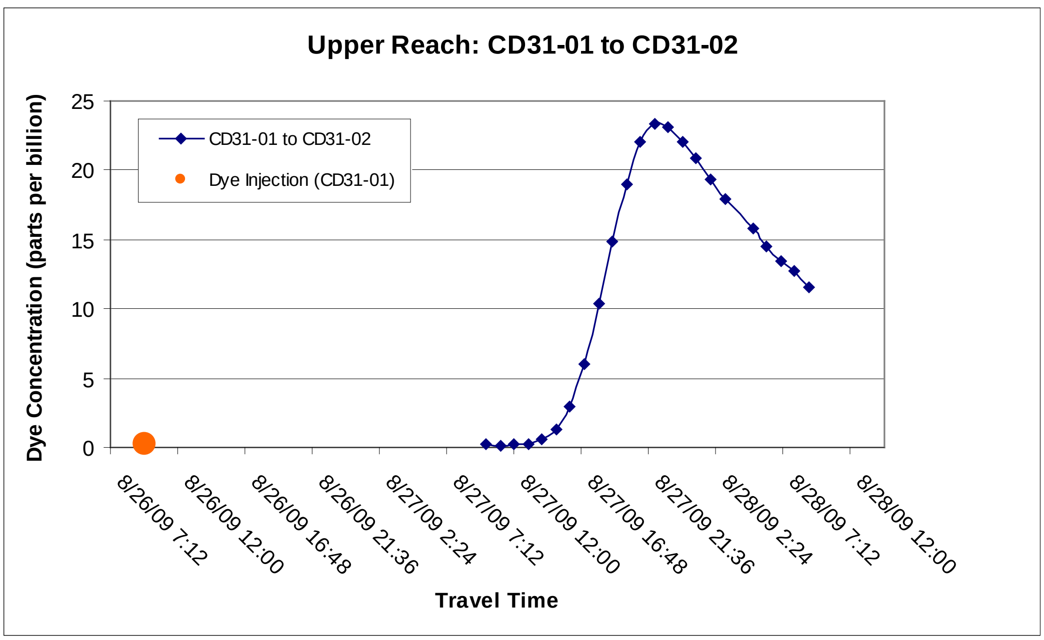


Figure 4.1 Dye concentration measurements from station CD31-02.

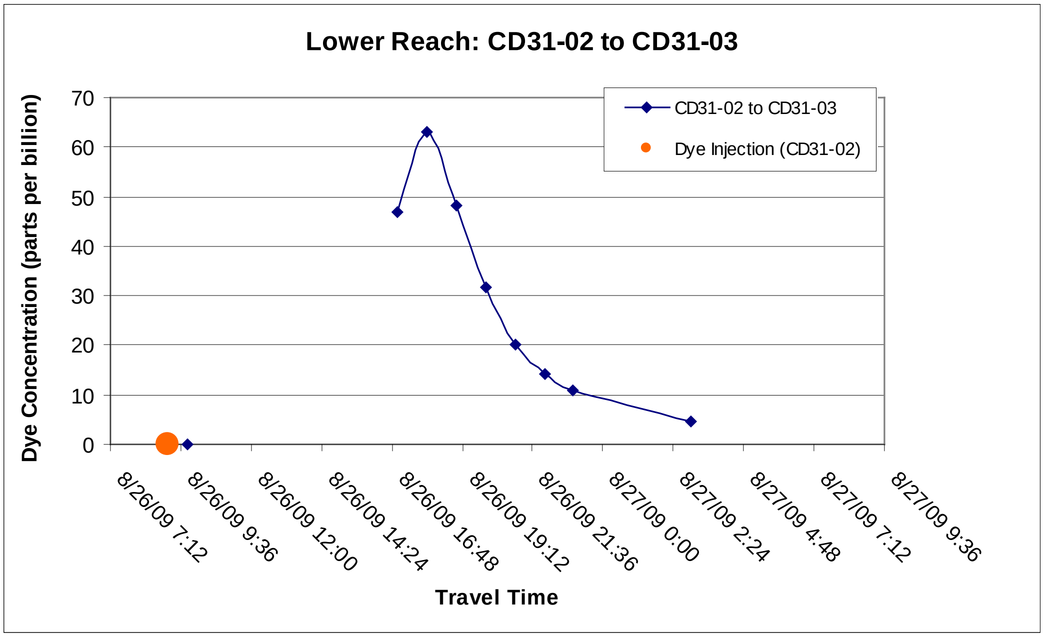


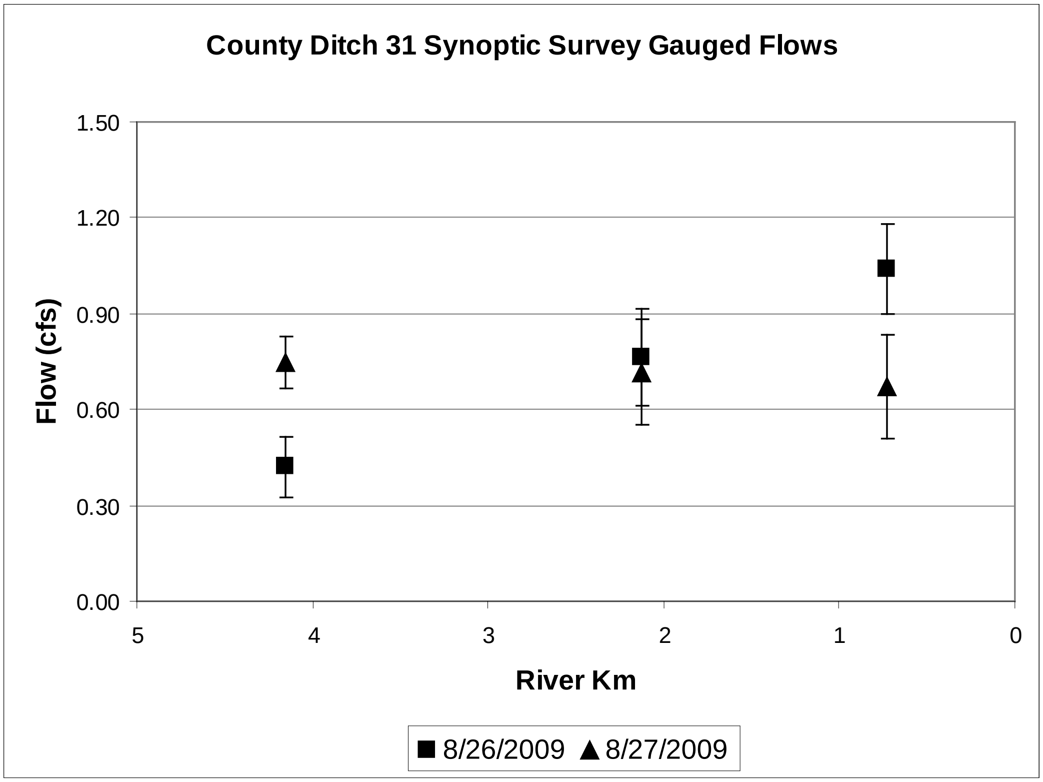
Figure 4.2 Dye concentration measurements from station CD31-03.

4.2 FLOW GAUGING

Gauged flow data suggests CD31 is a gaining stream from CD31-01 to CD31-03 during the first day of the synoptic survey (Table 4.2 and Figure 4.3). While no rain fell during the survey, approximately 2.5 inches of rainfall was recorded at a nearby weather station in the week leading up to the August 26-27 survey. As a result, gauged flows show a decrease between 8/26 and 8/27 at downstream station CD31-03.

Table 4.2: Gauged flow measurements taken during the September synoptic survey.

Station	River km	Q - 8/26 (cfs)	Q - 8/27 (cfs)
CD31-01	4.15	0.42	0.75
CD31-02	2.13	0.76	0.72
CD31-03	0.73	1.04	0.67



Figures 4.3 Gauged flows by river kilometer for the CD31 synoptic survey. Error bars represent estimated uncertainty of the Flow-Tracker field measurement.

4.3 WATER QUALITY

Lab water quality results show County Ditch 31 has higher concentrations of organic-bound nutrients, organic carbon, and CBOD near its wetland headwaters (CD31-01). In general, these parameters decrease at downstream monitoring stations as organic material is broken down by heterotrophs, settles out of the water column or diluted by incoming water (Table 4.3 and Figures 4.4 - 4.8).

Table 4.3 August 26th, 2009 water quality grab synoptic survey results.

Parameter	CD31-01 (3.45 km)	CD31-02 (2.15 km)	CD31-03 (1.15 km)
Temperature (Celsius)	16.32	17.47	15.87
DO (mg/L)	1.08	2.96	4.94
pH	7.00	7.15	7.55
Total Phosphorus (mg/L)	0.97	--	0.57
Ortho-P (mg/L)	0.85	--	0.51
TKN (mg/L)	2.68	--	2.03
NH_3 (mg/L)	0.38	--	0.24
Nitrate (mg/L)	<RL*	--	0.54
5-day CBOD (mg/L)	3.62	1.77	2.09
Ultimate CBOD (mg/L)	26.4	24.7	21.2
TOC (mg/L)	24	--	20
Chlorophyll-*a* (µg/L)	2.74	--	5.41

*Indicates below laboratory method reporting limit

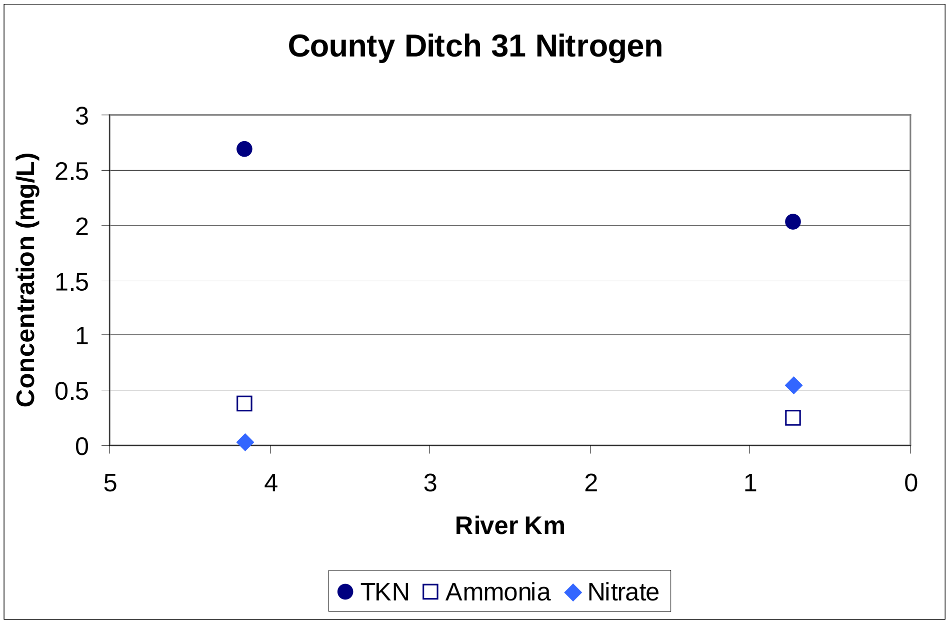


Figure 4.4 August 26, 2009 synoptic survey grab lab results for CD31.

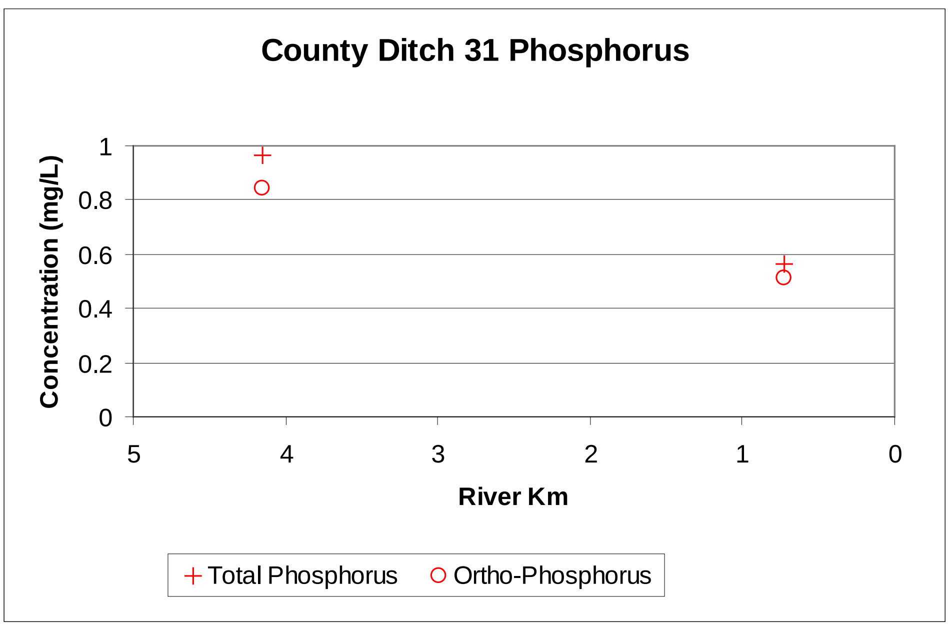


Figure 4.5 August 26, 2009 synoptic survey grab lab results for CD31.

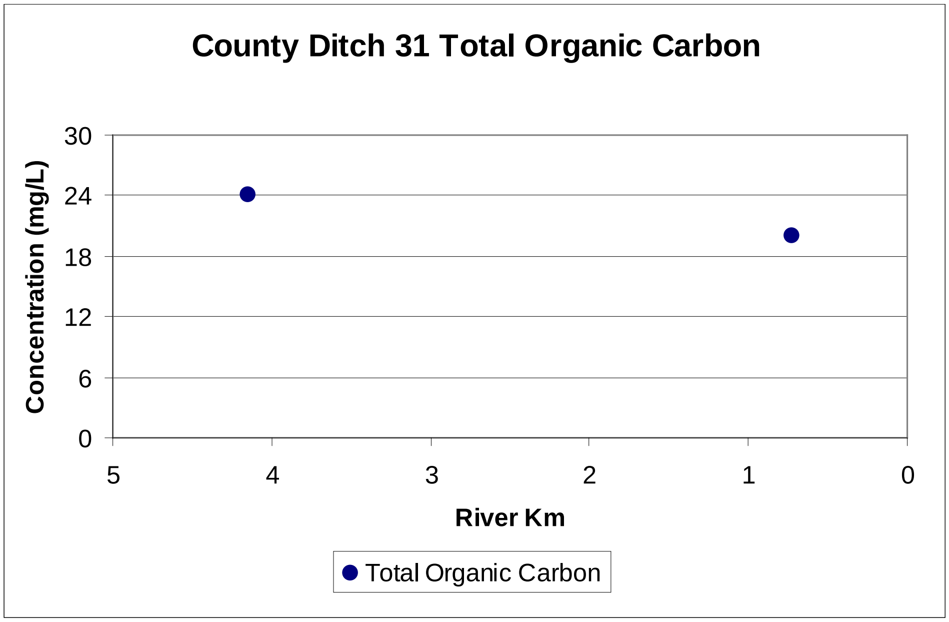


Figure 4.6 August 26, 2009 synoptic survey grab lab results for CD31.

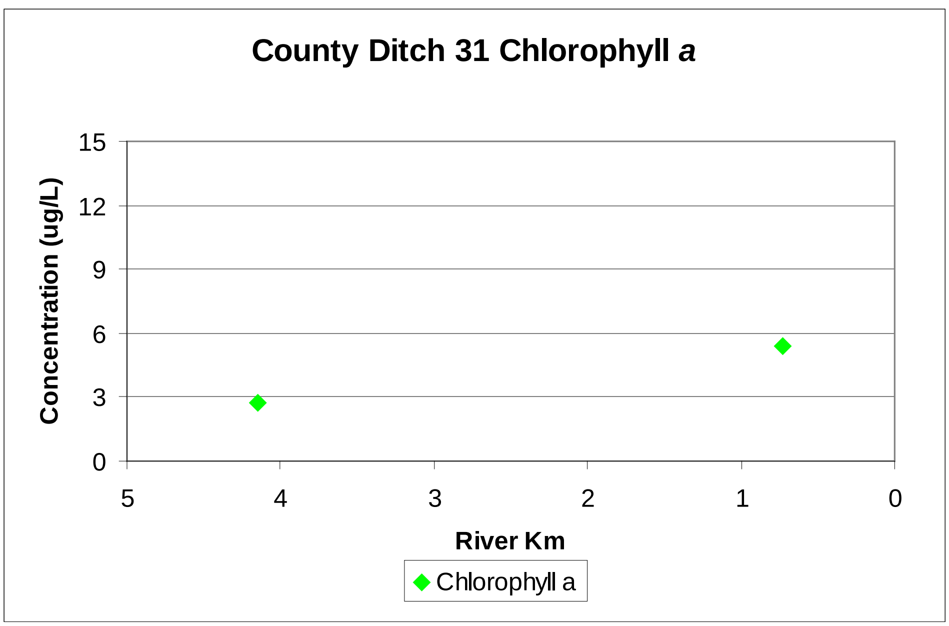


Figure 4.7 August 26, 2009 synoptic survey grab lab results for CD31.

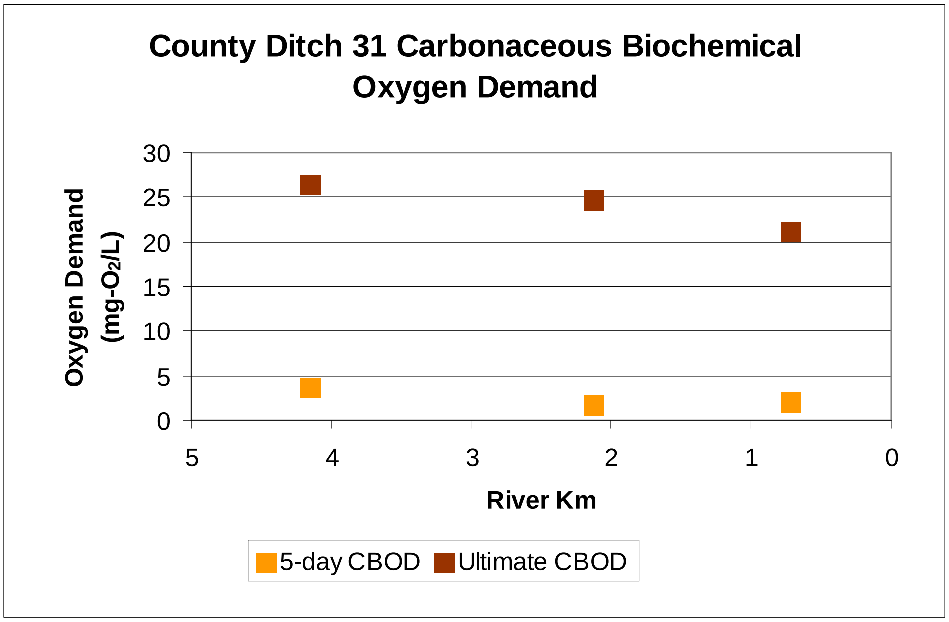


Figure 4.8 August 26, 2009 synoptic survey grab lab results for CD31.

4.4 DISSOLVED OXYGEN

4.4.1 Continuous Measurements

Continuous sonde data shows station CD31-02 was below the 5.0 mg/L dissolved oxygen standard for the entire synoptic survey (Figure 4.9). Mean DO concentrations at this station on August 26 and August 27 were 2.97 mg/L and 3.15 mg/L respectively. Diurnal DO fluctuations at this site are small over this two day period suggesting primary production was low during the synoptic survey.

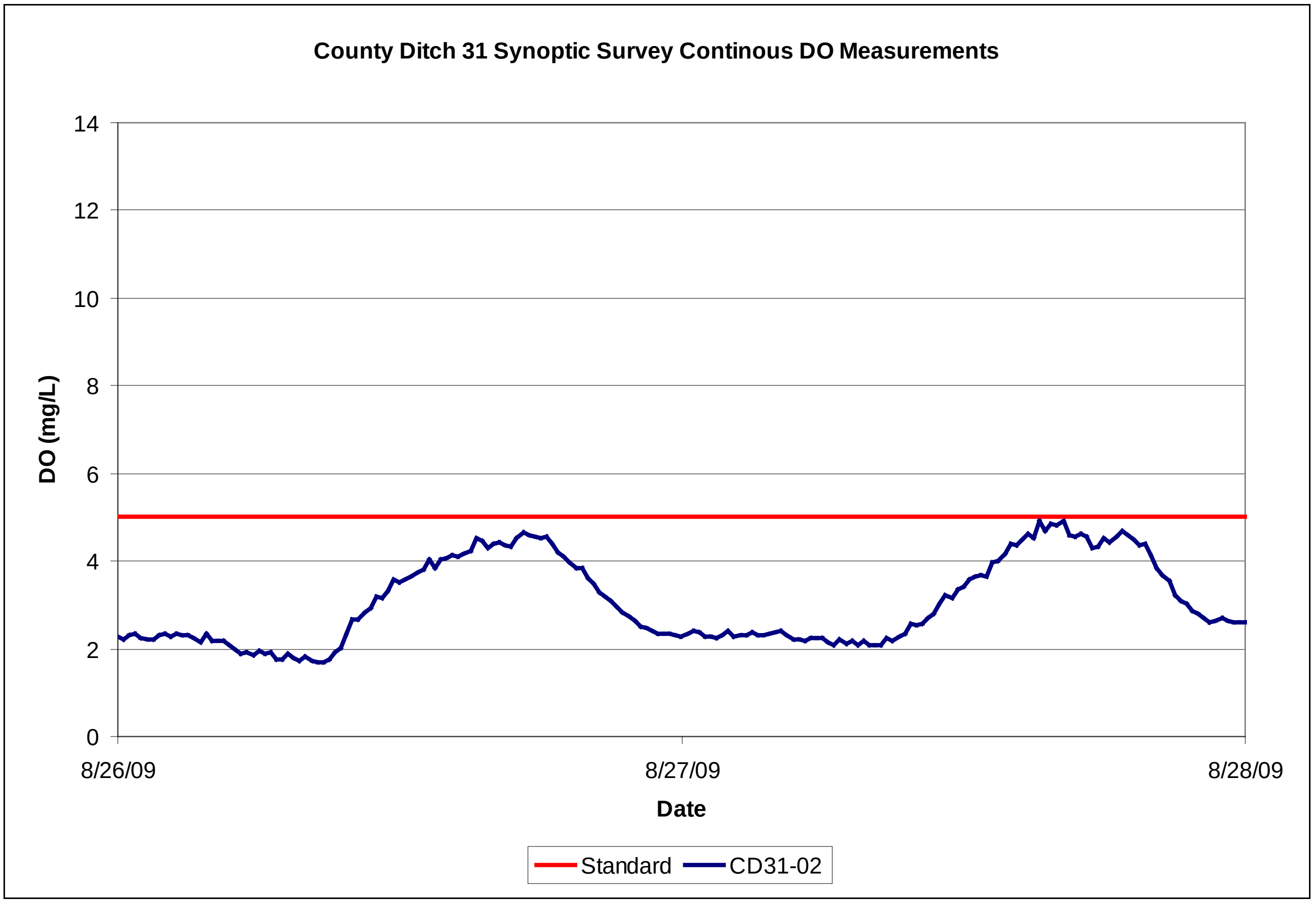


Figure 4.9 Synoptic survey continuous dissolved oxygen concentrations.

4.4.2 Longitudinal Profile

Discrete dissolved oxygen measurements were taken at the three synoptic survey monitoring locations along County Ditch 31 using a hand-held YSI probe as part of two longitudinal dissolved oxygen surveys on 8/26/09 and 8/27/09. Every effort was made to take upstream to downstream within a 1-2 hour time period in order to measure spatial variability in DO while limiting the influence of biological/diurnal patterns. These profiles show dissolved oxygen concentrations increase from approximately 1.0 mg/L near the headwaters to around 5.0 mg/L at the downstream most station on both 8/26/09 and 8/27/09 (Figure 4.10).

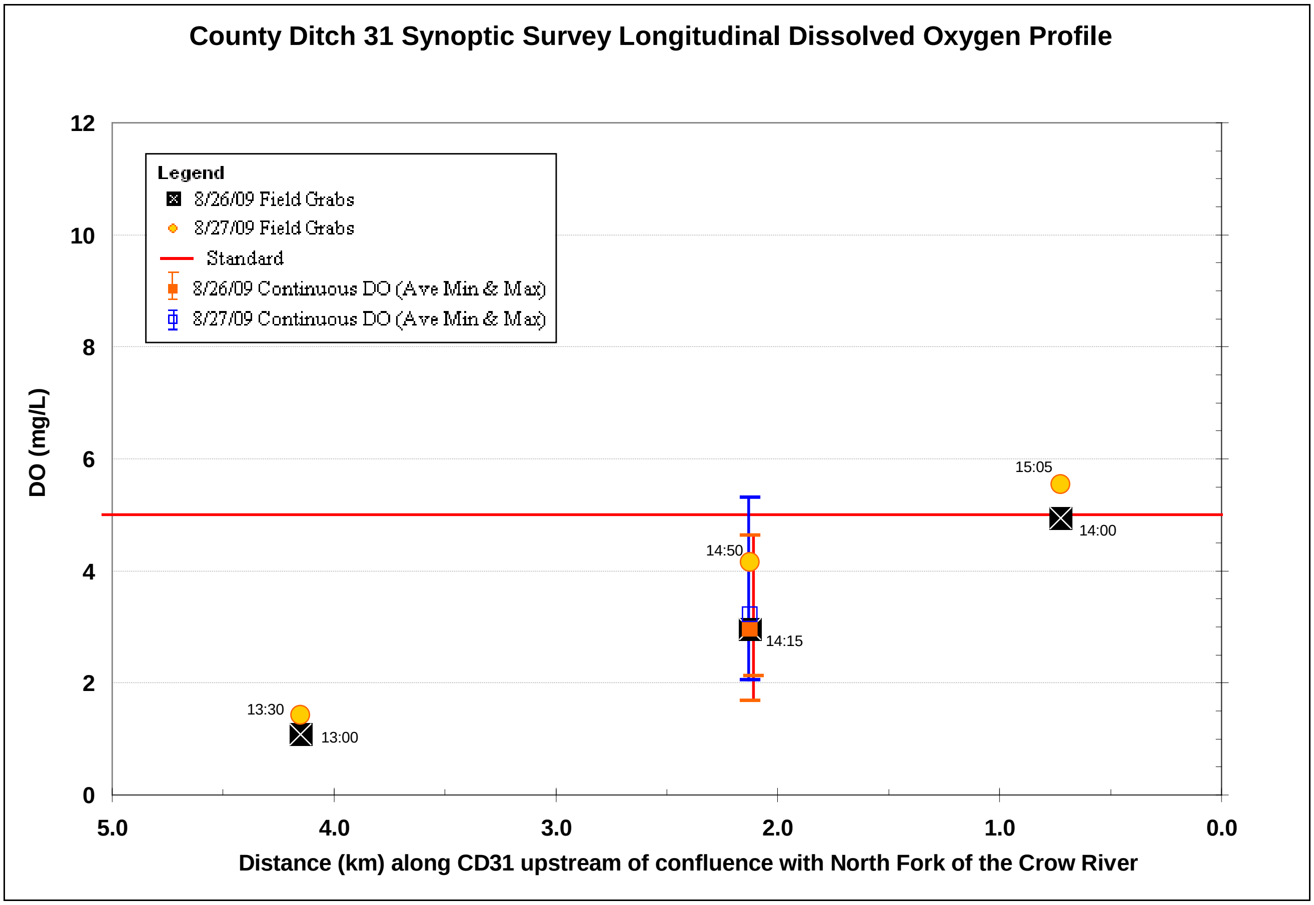


Figure 4.10 Dissolved oxygen observations during the August 2009 synoptic survey.

5.0 REFERENCES

Rantz, S.E. et al. 1982. "Measurement of Stage and Discharge", Measurement and Computation of Streamflow, Volume 1, U.S. Geologic Survey. Water Supply Paper 2175. Washington, D.C.: Governement Printing Office.

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TECHNICAL MEMORANDUM

TO: Diane Sander, Crow River Organization of Water Watershed Coordinator

CC: Maggie Leach, MPCA Regional Impaired Waters Coordinator

FROM: Joe Bischoff, Project Manager
Pamela Massaro, P.E.
Jeff Strom

DATE: April 22, 2010

SUBJECT: Grove Creek Dissolved Oxygen TMDL
Historic Data and Synoptic Survey Methods and Results

This technical memorandum summarizes historic dissolved oxygen (DO) data for Grove Creek and the data collection methods and results for the September 2008 Grove Creek Synoptic Survey. The synoptic survey was performed to obtain the data needed to construct and calibrate a River and Stream Water Quality Model (QUAL2K) to address the Grove Creek DO impairment during low-flow conditions.

1.0 WATERSHED DESCRIPTION

Grove Creek flows 10.4 miles through Meeker County, from the outlet of Long Lake to the North Fork Crow River (River Mile 117.8), an Upper Mississippi River tributary (Figure 1.1). The creek's watershed is comprised of two main subbasins: the Long Lake subwatershed to the south (8,403 acres) and the larger downstream subwatershed to the north (22,680 acres). The creek is narrow, shallow, straight, and moderately sloped. The average slope for the whole length of Grove Creek is 4.4 feet per mile. Agriculture dominates the landscape: 62% of land within the watershed is used for row and other agricultural uses while 12% of the watershed is grassland, some of which may be used as pasture (Table 1.1). The remaining watershed area is comprised of forest, open water, wetlands and urban and developed rural land. The watershed includes one municipality, Grove City, with a wastewater treatment facility considered in the TMDL study.

Table 1.1: Landuse summary table for Grove Creek Watershed.

Landuse Type	Acres	Percentage
Cultivated Land	19,224	62%
Grassland/Pasture	3,813	12%
Forest	2,640	8%
Developed	2,537	8%
Open Water	1,484	5%
Wetlands	1,385	4%
Total	31,083	100%

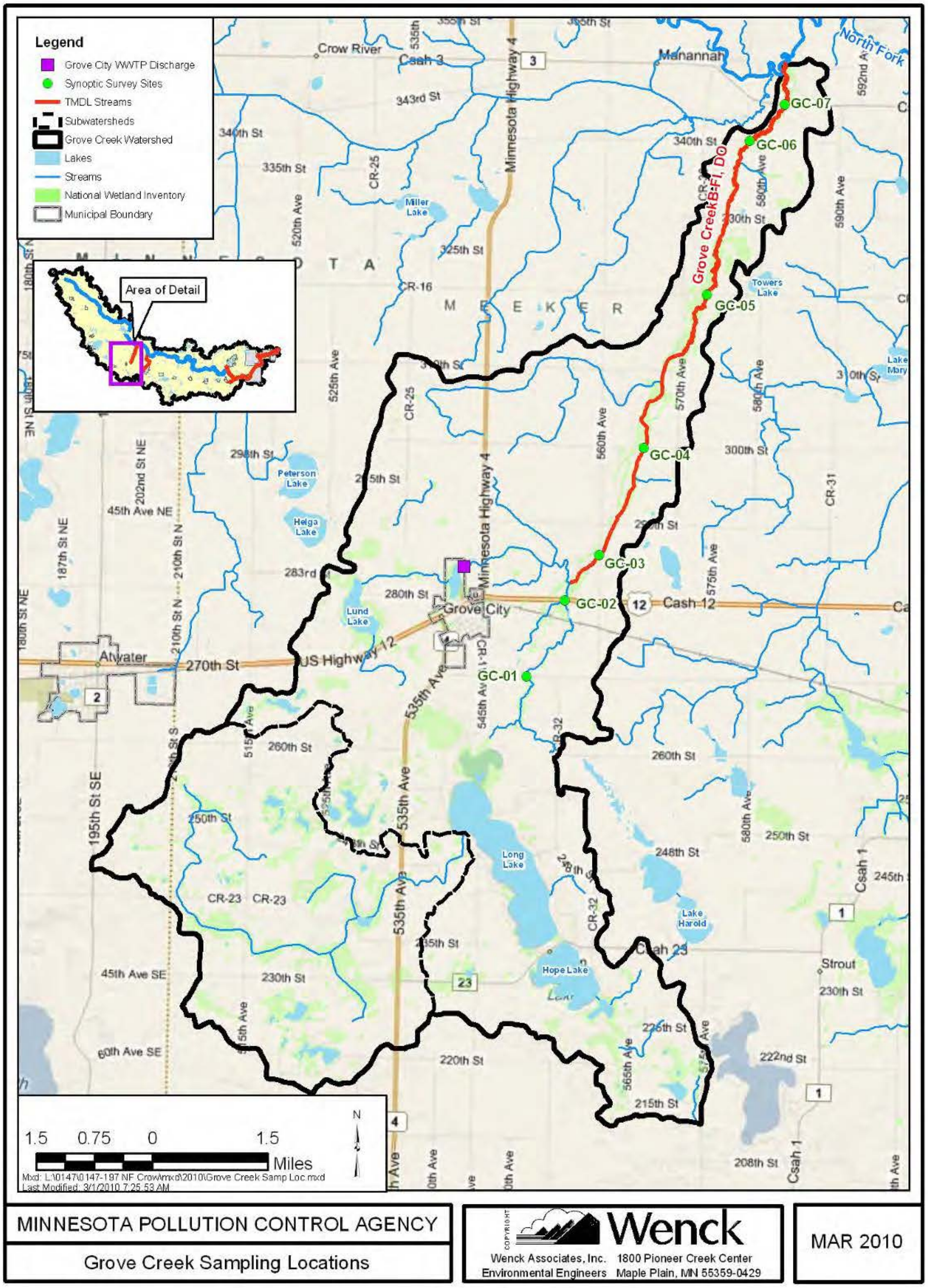


Figure 1.1 Grove Creek September 2008 synoptic survey monitoring locations.

2.0 REVIEW OF GROVE CREEK HISTORIC DISSOLVED OXYGEN DATA

Grove Creek has six STORET water quality stations with DO measurements available through the MPCA's STORET database (Table 2.1, Figure 1.1). Station GC-07 (S000-847) is the long-term monitoring station for the MPCA and the CROW's intensive watershed monitoring program.

Table 2.1. Jewitts Creek Water Quality Monitoring Stations and DO data available in STORET.

Station Name	STORET #	Location	River Km	DO Measurements	Violations	Years
GC-01	---	Grove Creek at 273rd Street	18.99	0	--	--
GC-02	S000-854	Grove Creek at US Highway 12	16.67	1	1	09
GC-03	S000-851	Grove Creek at 560th Avenue	15.37	1	0	09
GC-04	S000-850	Grove Creek at 300th Street	12.91	1	1	08
GC-05	S000-848	Grove Creek at County Road 16	8.46	1	0	08
GC-06	S000-897	Grove Creek at 340th Street	3.44	13	3	07, 09
GC-07	S000-847	Grove Creek at County Road 3	1.61	86	10	01 – 09

2.1 DISSOLVED OXYGEN GRABS/FIELD MEASUREMENTS

Grove Creek is designated by state statute as a beneficial-use Class 2B water (cool/warm water fishery). This designation states that daily minimum DO concentrations shall not fall below 5.0 mg/L to support the aquatic life and recreation of the system. Fifteen of the 113 STORET DO field measurements collected on Grove Creek were below the 5.0 mg/L DO standard (Figure 2.1). Dissolved oxygen data from STORET is also plotted by month (Figure 2.2) and shows 14 of the 15 violations were recorded during summer months (June-September) when water temperatures are warmer and diurnal DO swings are typically highest. Plotting DO by time of day (Figure 2.3) indicates only 5 of the 103 DO measurements were recorded prior to 9:00 am. The MPCA now recognizes measurements taken after 9:00 am do not represent daily minimums, and thus measurements greater than 5.0 mg/L dissolved oxygen later in the day are no longer considered to be indications that a stream is meeting state standards. That said, 14 of the 98 (14%) measurements recorded after 9:00 am were in violation of the DO standard which exceeds the 10% needed for a stream to be considered impaired.

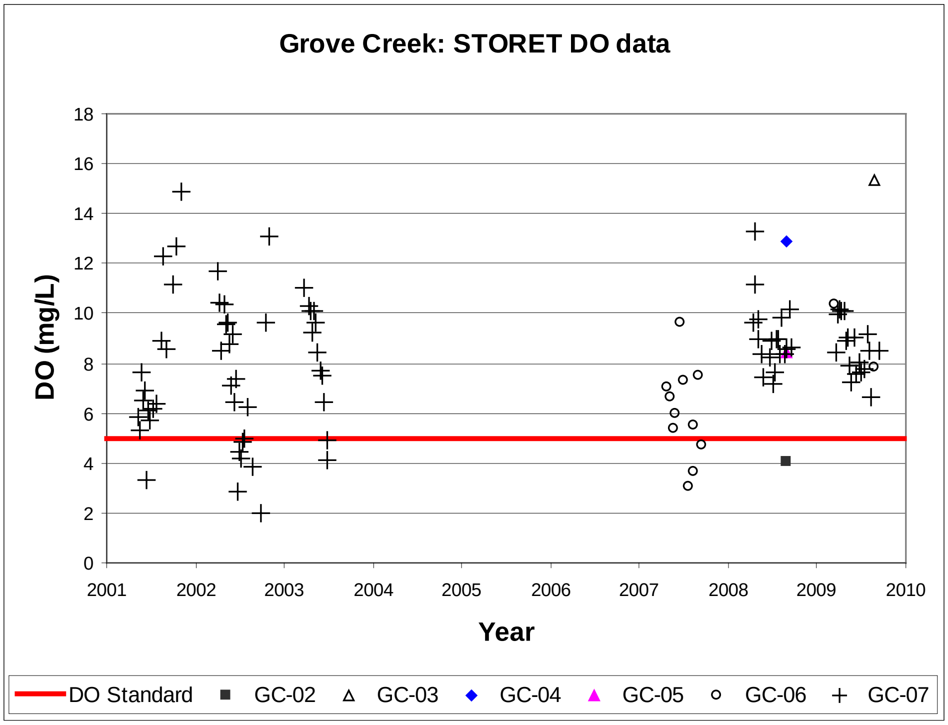


Figure 2.1: Dissolved oxygen data from STORET for all Grove Creek Stations.

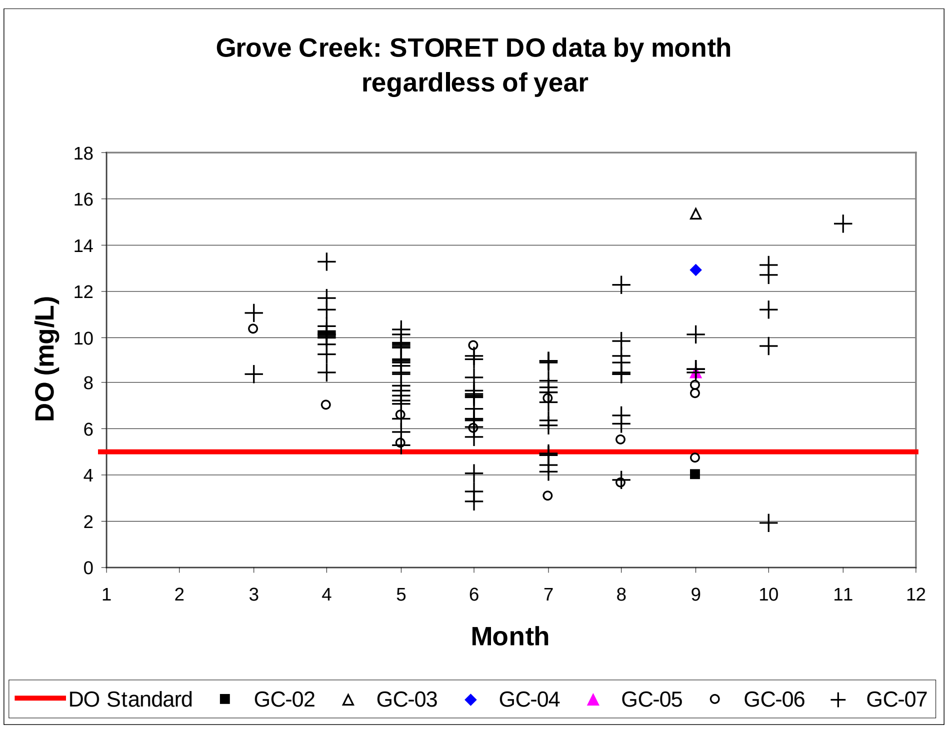


Figure 2.2: Dissolved oxygen data from STORET for all Grove Creek Stations by month, regardless of year.

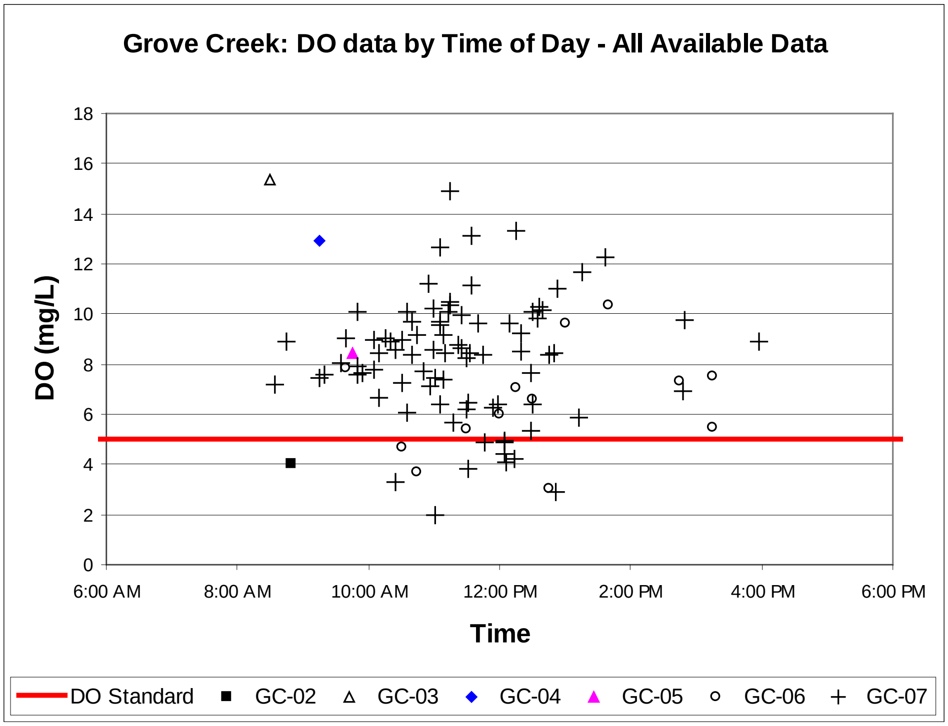


Figure 2.3: Dissolved oxygen data from STORET for all Grove Creek Stations by hour, regardless of year and month. No data was collected prior to 8:00 am or after 4:30 pm.

2.2 CONTINUOUS DISSOLVED OXYGEN MEASUREMENTS

Continuous DO data was collected in 2008 by the MPCA using data sondes at two locations along Grove Creek (GC-03 and GC-07). The sensors record continuous measurements of dissolved oxygen, temperature, pH and conductivity. DO was consistently above the 5.0 mg/L standard during the 56-day deployment (9/2/08 to 10/28/08) as shown in Figure 2.4.

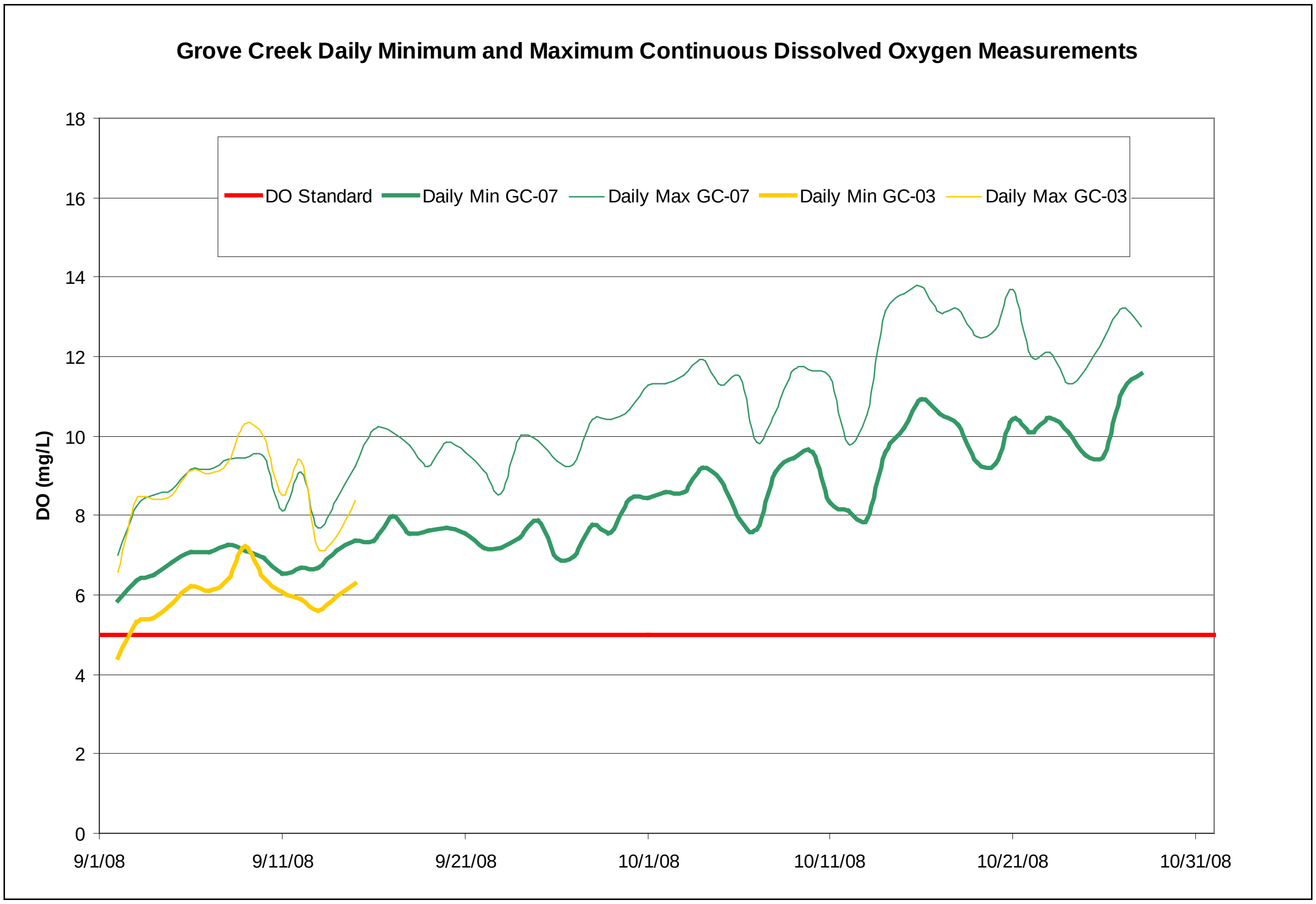


Figure 2.4: Statistics of continuous dissolved oxygen data collected in 2008.

2.3 DISSOLVED OXYGEN RELATION TO FLOW

The nearest United States Geologic Survey (USGS) monitoring station is located at Crow River at Rockford. Average daily flows have been monitored at this stations since 1906 (23 miles upstream from confluence with the Mississippi River). The mean annual flow for water years 1906 through 2002 is 826 cubic feet per second (cfs), which represents 4.25 inches of runoff from the 2,640-square mile drainage area located upstream of Rockford. Monthly average flows for this station range from 172 cfs in February to 2,243 cfs in April. The maximum average daily flow, 22,100 cfs, was recorded April 16, 1965. The minimum average daily flow, 3.8 cfs, was recorded August 4, 1934. Table 2.2 summarizes select water year data and characterizes the year as a wet, dry or average year based on comparison to long term monitoring.

Table 2.2 Water year summary for the last ten years at USGS Crow River at Rockford.

Water Year	Average Annual Flow at Main Stem Crow USGS Station at Rockford (cfs)	Percent Variation from Average	Wet / Dry / Average
2000	275	-67%	DRY
2001	1329	59%	WET
2002	1605	93%	WET
2003	1245	49%	WET
2004	718	-14%	AVERAGE
2005	1158	39%	WET
2006	1399	68%	WET
2007	603	-28%	DRY
2008	641	-23%	DRY
2009	659	-21%	DRY

While there is no USGS gage on Grove Creek, the MPCA established a continuous flow station at GC-07 in April, 2009. There are also 32 gauged flow measurements recorded at GC-07 from 2001-2003 available in STORET. There are a total of three paired flow-DO measurements below the 5 mg/L DO standard. All of these violations occurred under high flow conditions (>75 cfs) in 2001 and 2003 (Figure 2.5).

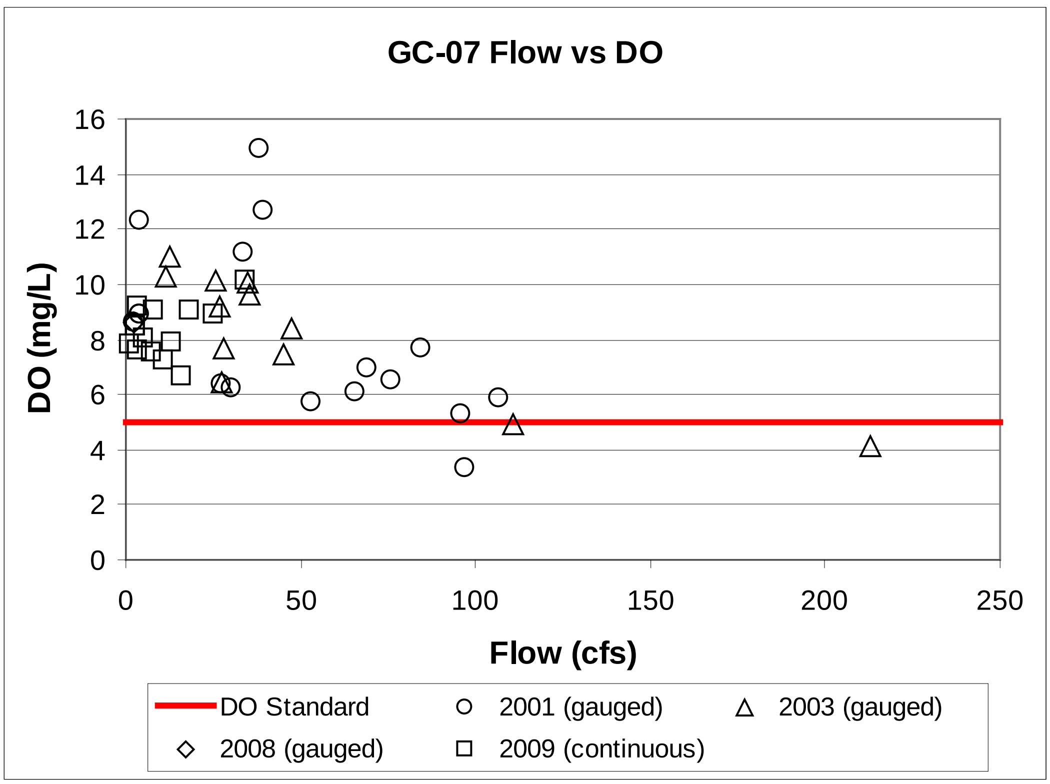


Figure 2.5 Dissolved oxygen compared to gauged and continuous flow measurement.

3.0 SYNOPTIC SURVEY DATA COLLECTION METHODS

3.1 STUDY AREA AND LOCATIONS

The Minnesota Department of Natural Resources (DNR) stream file shows Grove Creek begins at the tributary inflow downstream of the US Highway 12 crossing (Figure 1.1, Site GC-02). The MPCA has done monitoring at the 273rd Street crossing (GC-01) upstream of US Highway 12. Prior to collecting data for this study, Wenck visited the GC-01 station and observed standing water with no velocity. For the purposes of this study, the upstream boundary condition/headwater is represented by the water quality and flow data collected at station GC-02, not GC-01.

3.2 DYE STUDY

A slug of a tracer (Rhodamine WT dye) was injected at GC-02 and GC-05 and measured downstream during the synoptic survey on September 3, 2008 (Table 3.1). Dye was released first at the downstream most injection location to prevent dye from separate injection points "catching up" and mixing. Dye samples were collected as grabs by field personnel or ISCO automatic samplers. Fixed stations downstream of the injection point were sampled until the dye cloud passed (Table 3.1). The concentration of the dye in each sample was measured using an Aquafluor handheld fluorometer (Rantz, 1982).

Table 3.1 Grove Creek Synoptic Survey Monitoring Locations.

Site	Location (River km)	Lab WQ Grab Station	Field Parameter WQ Station	Flow Station	Dye Injection	Dye Monitoring
GC-01	18.99	---	---	---	---	---
GC-02	16.67	X	X	X	X	---
GC-03	15.37	---	X	X	---	---
GC-04	12.91	X	X	X	---	---
GC-05	8.46	X	X	X	X	X
GC-06	3.44	---	X	---	---	---
GC-07	1.61	X	X	X	---	X

3.3 FLOW GAUGING

Stream gauging measurements were collected in conjunction with the time of travel dye study. Flow was recorded using a SonTek Flow Tracker handheld digital velocity meter with an accuracy of 0.001 cubic feet per second. Velocity measurements were taken at 60 percent of the total depth for shallow reaches (less than 2.5 feet deep) and at 20 percent and 80 percent of the total depth for deeper reaches. Horizontal spacing of velocity measurements was set so less than 10 percent of total discharge is accounted for by any single velocity measurement. Flow gauging was conducted at each dye injection and monitoring station (Table 3.1).

3.4 WATER QUALITY SAMPLING

Water quality data was collected on September 3, 2008 at five locations along Grove Creek (Table 3.1 and Figure 1.1). Each water sample (grab) was collected and preserved for lab analysis. The lab analyzed the four samples for: total kjeldahl nitrogen (TKN), ammonia nitrogen (NH_3-N), nitrate nitrogen (NO_2-N), 5-day and ultimate biological oxygen demand ($BOD_{5\text{-day}}$ & BOD_u), total phosphorus (TP), ortho-phosphorus (soluble reactive phosphorus), total organic carbon (TOC), and chlorophyll-*a*. A data sonde (YSI Model 6920 V2) was used at six sites in the field to collect the following parameters: temperature, conductivity, pH, and dissolved oxygen (DO).

3.5 CONTINUOUS DISSOLVED OXYGEN MEASUREMENTS

The Minnesota Pollution Control Agency deployed two multi-parameter YSI sondes with internal logging capability to monitor continuous DO levels during the dye study and synoptic water quality survey. These instruments were deployed to monitor continuous DO concentrations at 15-minute intervals for a minimum of 72-hours before, after and during the synoptic surveys. The instruments also measured and recorded other in-situ parameters such as DO saturation, temperature, conductivity, and pH.

4.0 SYNOPTIC SURVEY RESULTS

4.1 DYE STUDY

Travel time and mean velocity could not be calculated for the upper reach as no concentration peak was detected at GC-05 (Table 4.1, Figures 4.1- 4.2). Grab sample collected by Wenck staff at station GC-03 upstream of GC-05 suggest the dye cloud passed this station sometime early in the morning on 9/4/2008. However, a small in-channel pond/reservoir and incoming flows downstream of GC-03 likely diluted dye concentrations below detection at GC-05. The dye moved well through the lower reach as travel time was estimated to be slightly less than one day.

Table 4.1: Estimated travel times for the Grove Creek dye study. Times were calculated by elapsed time between upstream injection and peak concentration measured downstream.

Reach Description	Reach Length (km)	Estimated Travel Time (hrs)	Mean Velocity (ft/sec)
Upper Reach: GC-02 to GC-05	8.21	Unmeasurable	Unmeasurable
Lower Reach: JC-05 to JC-07	6.85	21.0	0.30

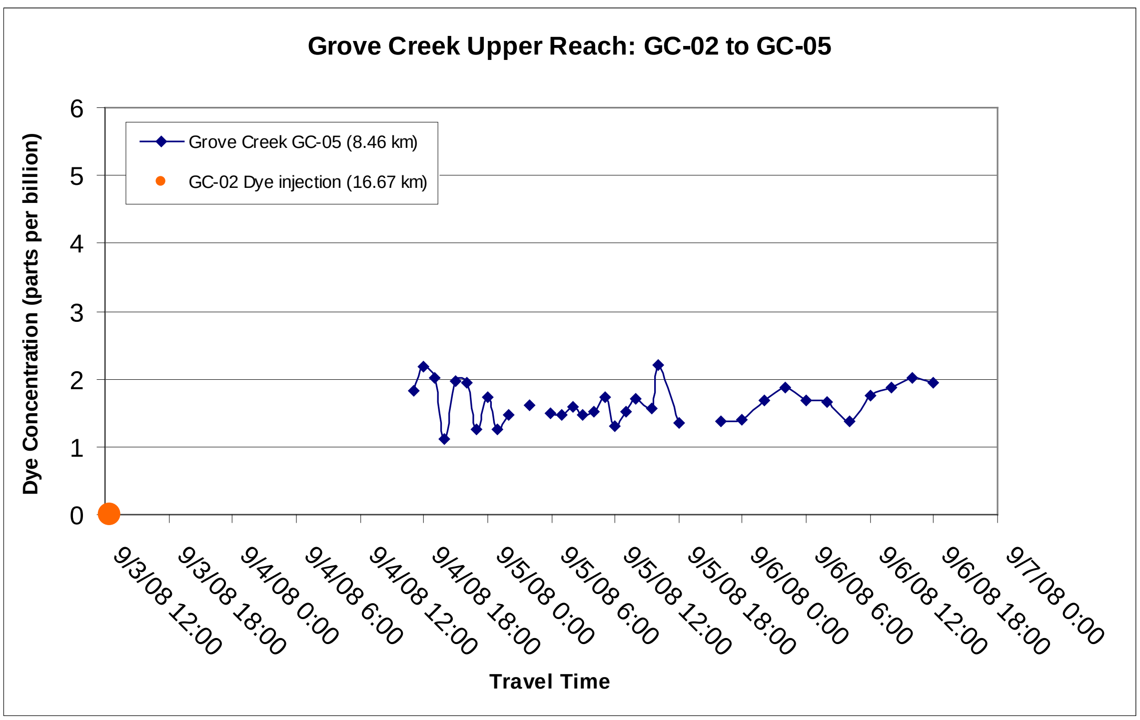


Figure 4.1: Dye concentration measurements from station GC-05.

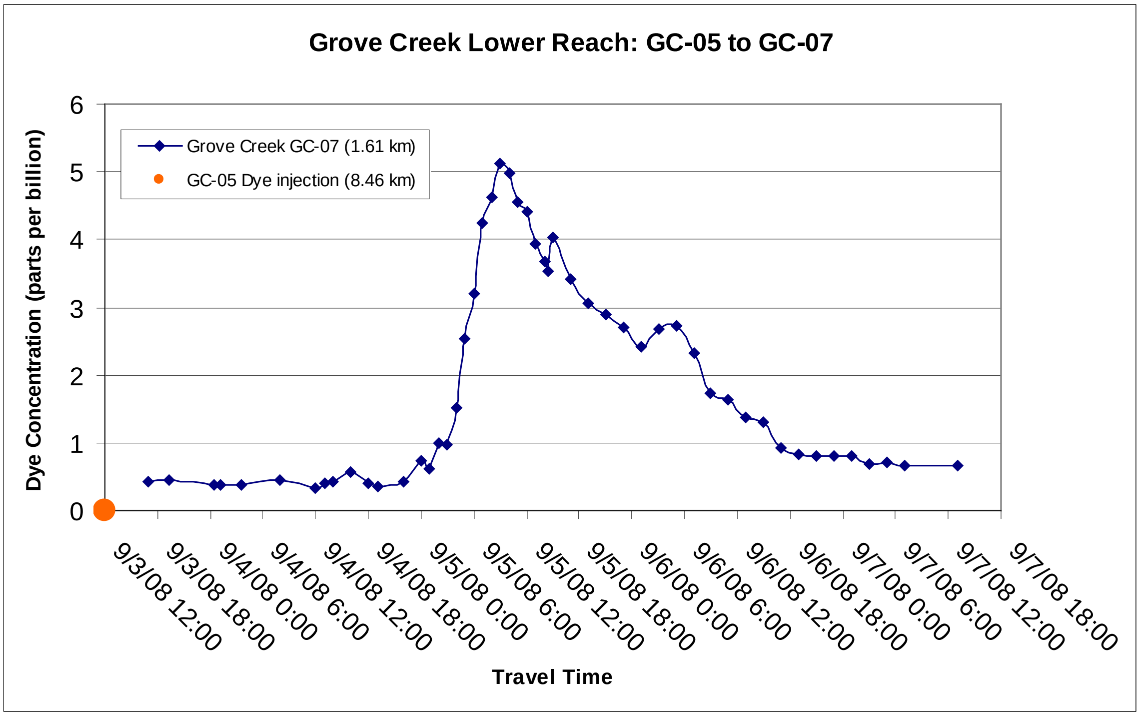


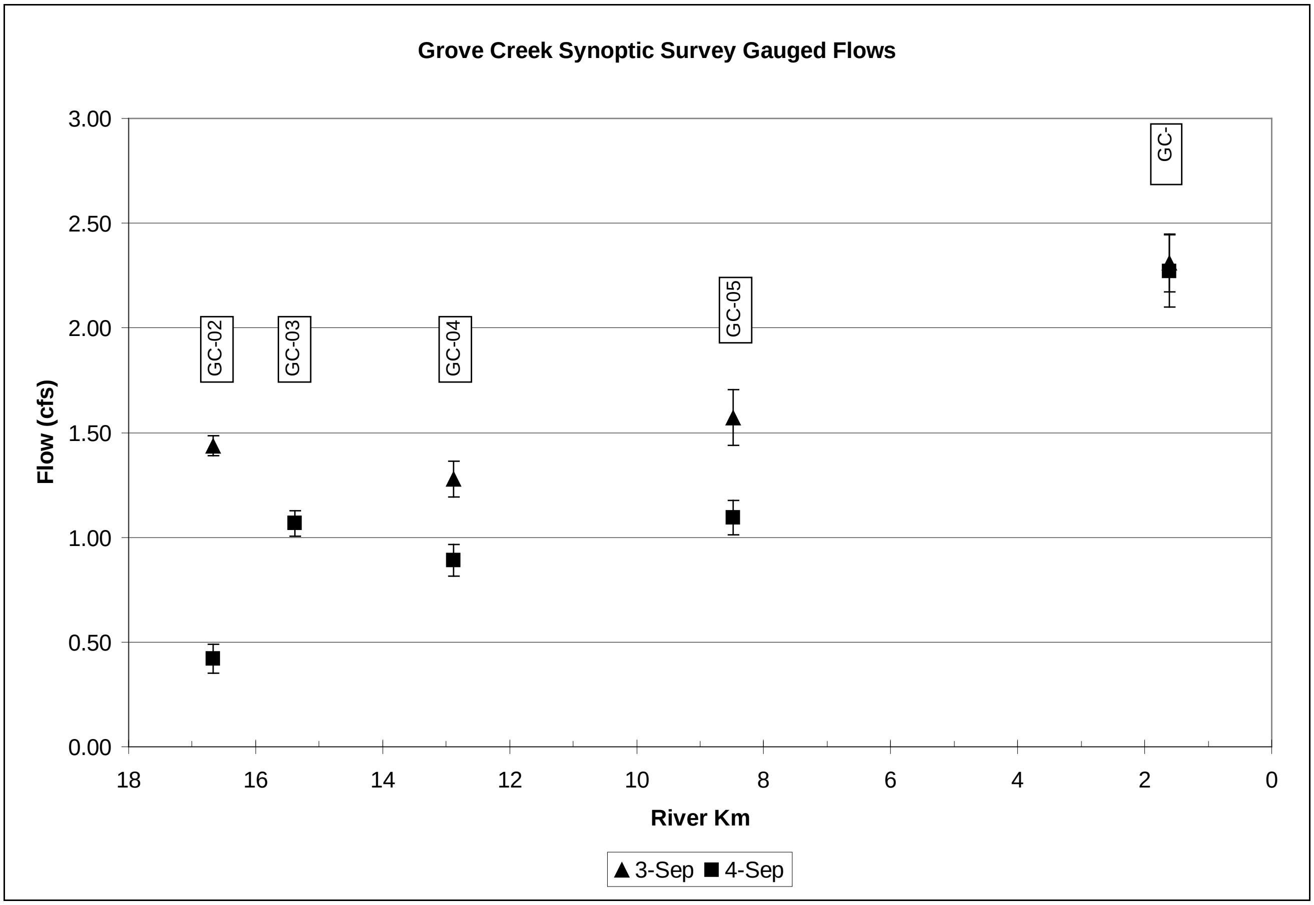
Figure 4.2 Dye concentration measurements from station GC-07.

4.2 FLOW GAUGING

Flow gauging data shows the upper reaches may be losing between GC-02 and GC-04 and gaining throughout all reaches down-stream of GC-04 (Table 4.2 and Figure 4.3). While no rain fell during the survey, approximately 1.9 inches of rainfall was recorded at the Litchfield, MN Airport in the week leading up to September 3rd. As a result, data from all sites show Grove Creek to be losing flow each day of the synoptic survey from 9/3/2008 through 9/5/2008.

Table 4.2 Gauged flow measurements taken during the September synoptic survey.

Station	River km	Q - 9/3 (cfs)	Q - 9/4 (cfs)	Q - 9/5 (cfs)
GC-02	16.67	1.44	0.42	---
GC-03	15.37	---	1.07	---
GC-04	12.91	1.28	0.89	---
GC-05	8.46	1.57	1.09	0.90
GC-06	3.44	---	---	---
GC-07	1.61	2.31	2.27	1.56



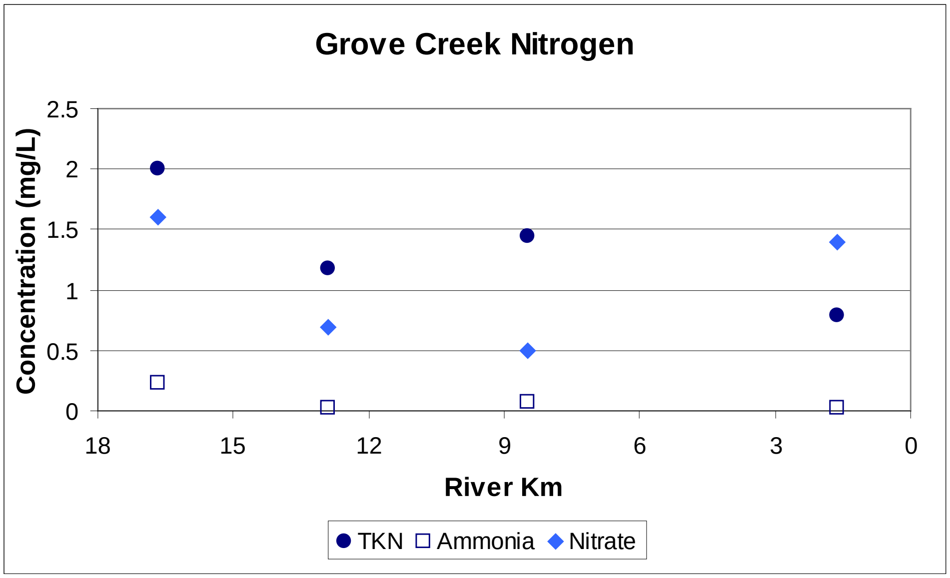
Figures 4.3 Gauged flows by river kilometer for the Grove Creek survey. Error bars represent estimated uncertainty of the Flow-Tracker field measurement.

4.3 WATER QUALITY

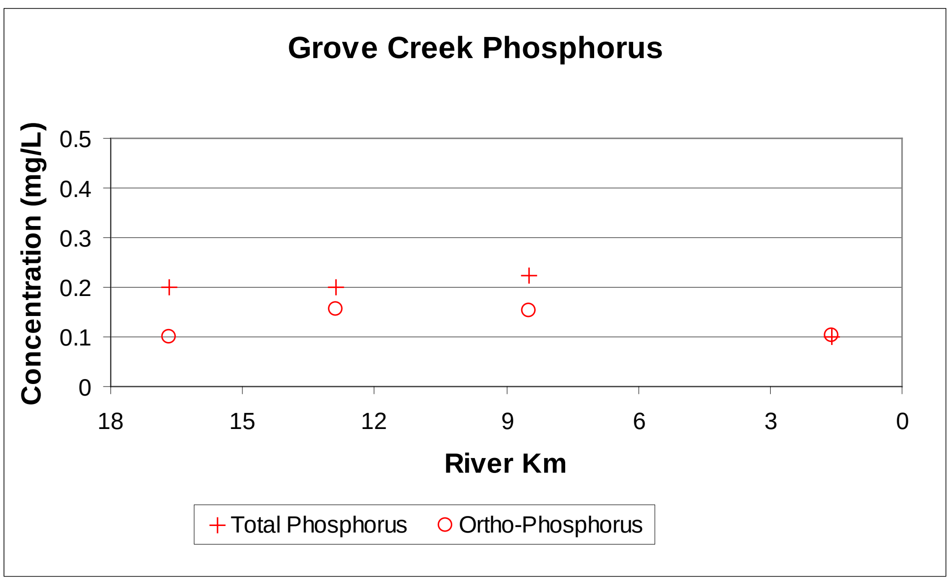
In general, Grove Creek displayed higher concentrations of organic-bound nutrients, organic carbon, chlorophyll-*a* and BOD near its headwaters (GC-02). These parameters decreased at downstream monitoring stations as the organic material was broken down by heterotrophs, settled out of the water column or diluted by incoming water (Table 4.3 and Figures 4.4 - 4.8).

Table 4.3 September 3, 2008 water quality synoptic survey sample results.

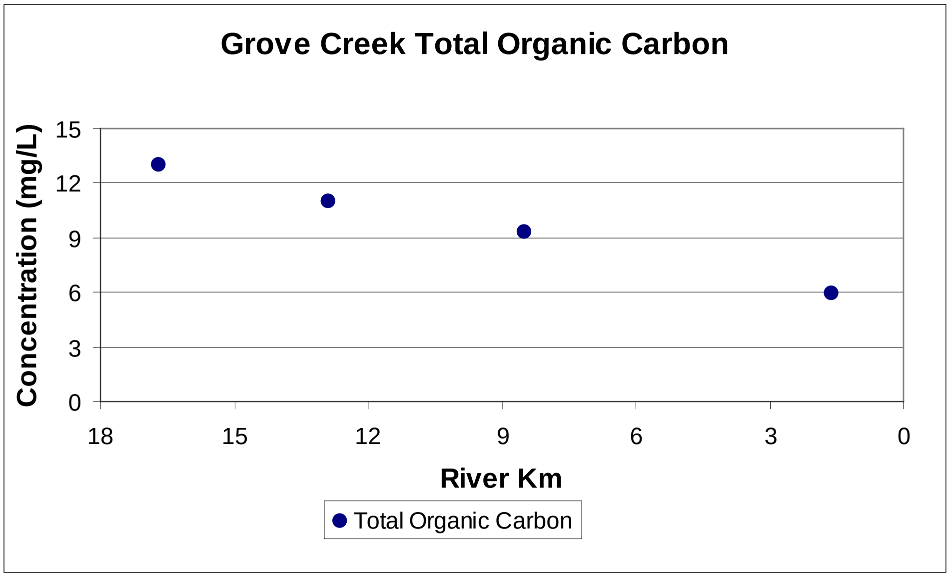
Parameter	GC-02 (16.67 km)	GC-03 (15.37 km)	GC-04 (12.91 km)	GC-05 (8.46 km)	GC-06 (3.44 km)	GC-07 (1.61 km)
Sample Time	8:50	17:15	9:25	9:50	16:35	10:25
Temperature (Celsius)	12.50	17.07	16.35	13.84	20.20	13.53
DO (mg/L)	4.03	8.37	4.29	7.23	10.42	8.59
pH	8.85	8.15	8.00	8.15	8.36	8.33
Total Phosphorus (mg/L)	0.200	---	0.201	0.223	---	0.100
Ortho-P (mg/L)	0.099	---	0.155	0.153	---	0.103
TKN (mg/L)	2.00	---	1.18	1.45	---	0.79
NH_3 (mg/L)	0.230	---	<0.050	0.070	---	<0.050
Nitrate (mg/L)	1.60	---	0.69	0.50	---	1.40
5-day BOD (mg/L)	3.52	---	<1.00	<1.00	---	<1.00
Ultimate BOD (mg/L)	10.20	---	4.55	3.45	---	2.23
TOC (mg/L)	13.00	---	11.00	9.30	---	5.90
Chlorophyll-*a* (µg/L)	11.00	---	4.40	8.91	---	2.53



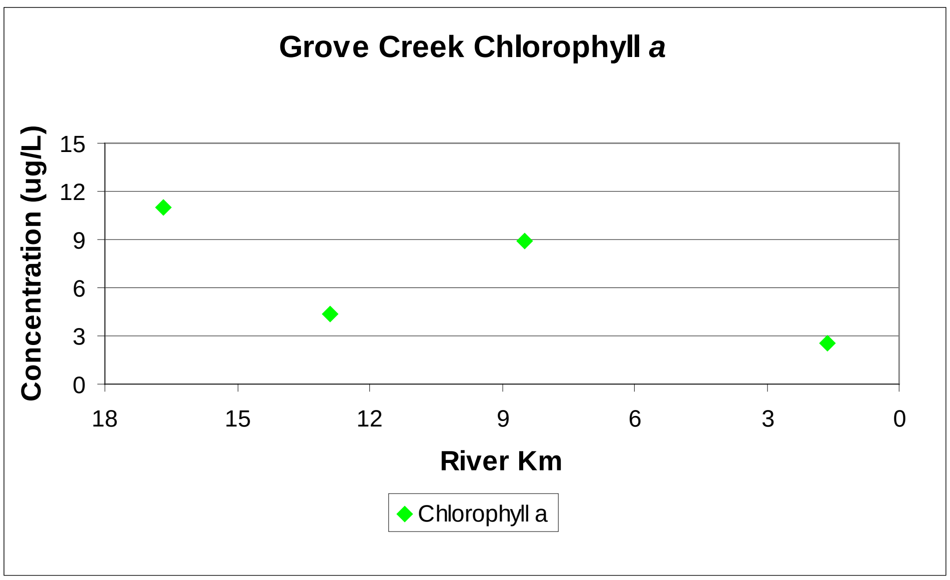
Figures 4.4 September 3, 2008 synoptic survey water quality lab results for Grove Creek.



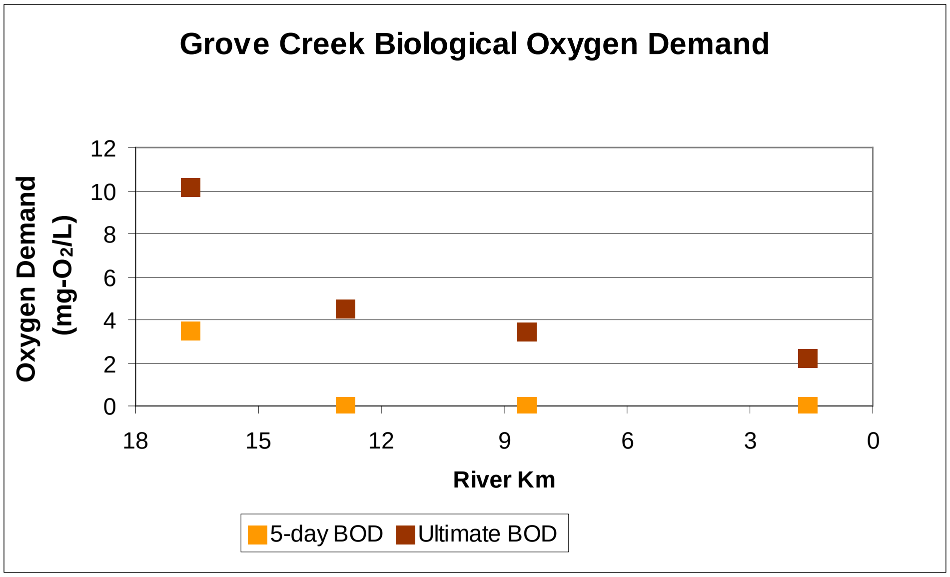
Figures 4.5 September 3, 2008 synoptic survey water quality lab results for Grove Creek.



Figures 4.6 September 3, 2008 synoptic survey water quality lab results for Grove Creek.



Figures 4.7 September 3, 2008 synoptic survey water quality lab results for Grove Creek.



Figures 4.8 September 3, 2008 synoptic survey water quality lab results for Grove Creek.

4.4 DISSOLVED OXYGEN

4.4.1 Continuous Measurements

Continuous sonde data shows neither station GC-03 or GC-07 fell below the 5.0 mg/L dissolved oxygen standard during the synoptic survey (Figure 4.9). The daily dissolved oxygen sag was slightly lower at the upstream station (GC-03) compared to the downstream station (GC-07). Mean DO concentrations at GC-03 and GC-07 from September 3 and September 4 were 6.82 mg/L and 7.23 mg/L, respectively.

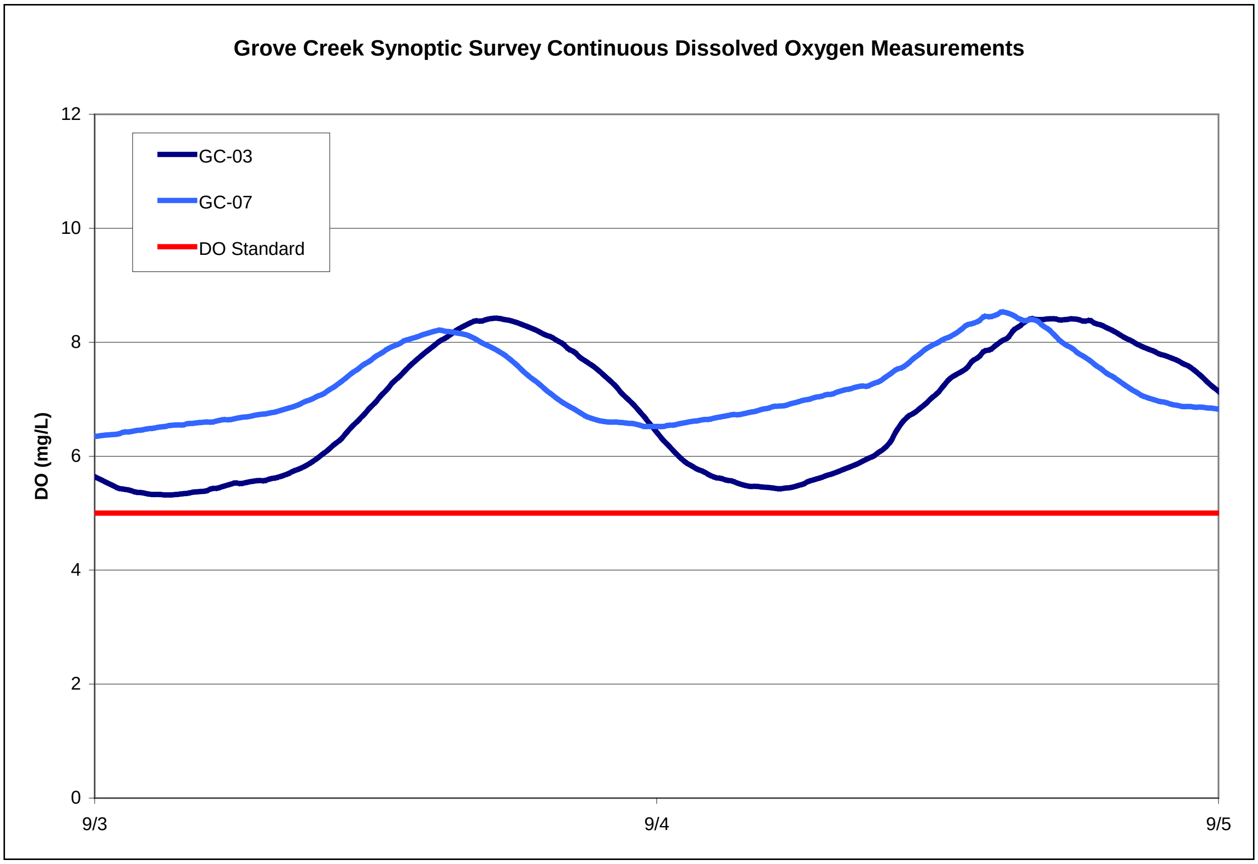


Figure 4.9 Synoptic survey continuous dissolved oxygen concentrations.

4.4.2 Longitudinal Profile

Field grabs of dissolved oxygen were taken on September 3 and September 4 using the hand-held YSI and are labeled in Figure 4.10 with the time of sample collection, if available. The minimum and maximum dissolved oxygen range from the continuous measurements are plotted in Figure 4.10 as orange and blue "I" while average daily DO is marked on the plot with an orange or blue box for September 3rd and 4th, respectively. All field grab measurements were taken by Wenck staff between 8:00 am and 10:30 am on 9/3/2008 and between 10:30 am and 4:00 pm on 9/4/2008. These profiles were consistent and show a slight sag in dissolved oxygen downstream of GC-03 followed by a general increase in dissolved oxygen between GC-04 to GC-07. The decrease in oxygen downstream of GC-03 is likely due to low reaeration and elevated breakdown of organic matter through the over-widened channel and the in-channel backwater pond located at the upstream end of this reach.

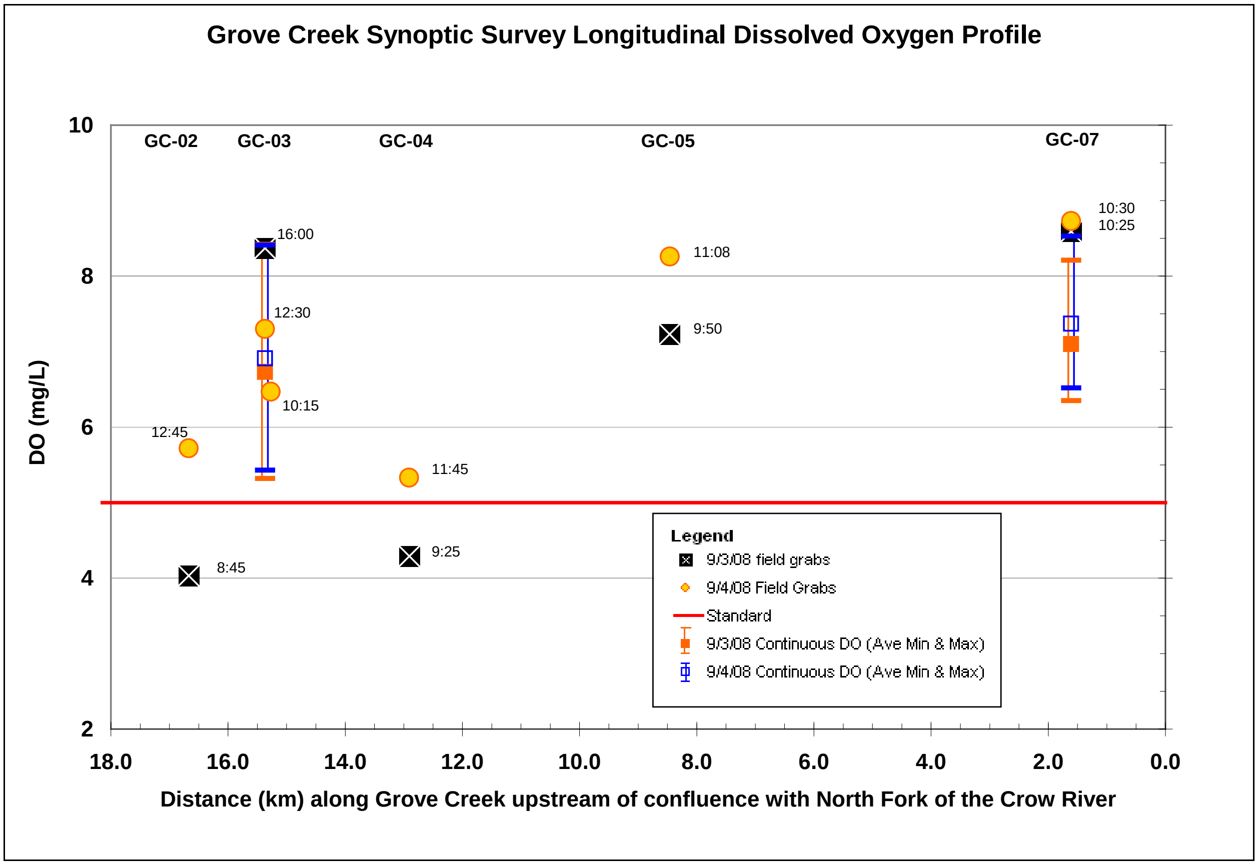


Figure 4.10 Dissolved oxygen observations during the September 2008 synoptic survey.

5.0 REFERENCES

Rantz, S.E. et al. 1982. “Measurement of Stage and Discharge”, Measurement and Computation of Streamflow, Volume 1, U.S. Geologic Survey. Water Supply Paper 2175. Washington, D.C.: Governement Printing Office.

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TECHNICAL MEMORANDUM

TO: Diane Sander, Crow River Organization of Water Watershed Coordinator

CC: Maggie Leach, MPCA Regional Impaired Waters Coordinator

FROM: Joe Bischoff, Project Manager
Pamela Massaro, P.E.
Jeff Strom

DATE: April 22, 2010

SUBJECT: Jewitts Creek Dissolved Oxygen TMDL
Historic Data and Synoptic Survey Methods and Results

This technical memorandum summarizes historic dissolved oxygen (DO) data for Jewitts Creek and the data collection methods and results of the September 2008 Jewitts Creek Synoptic Survey. The synoptic survey was done to obtain the data needed to construct and calibrate a River and Stream Water Quality Model (QUAL2K) to address the Jewitts Creek DO impairment during low-flow conditions.

1.0 WATERSHED DESCRIPTION

Jewitts Creek flows 8.6 miles through Meeker County, from the outlet of Ripley Lake through Litchfield, MN to the North Fork Crow River (River Mile 107.5), an Upper Mississippi River tributary. The creek's watershed is comprised of two main subbasins: the Ripley Lake subwatershed to the south (5,912 acres) and the larger downstream subwatershed to the north (20,252 acres). The headwater outflow from Ripley Lake, is dam controlled and of good water quality. The creek is narrow, shallow, straight, and moderately sloped. The average slope for the whole length of Jewitts Creek is 5.7 feet per mile. Between Highway 34 and 300th Street, the creek becomes channelized through a large wetland (Shultz Wetland Complex) where it also merges with outflow from Shultz Lake under higher-flow conditions (Figure 1.1).

Agriculture dominates the landscape: 45% of land within the watershed is used for row crops and other agricultural uses (Table 1.1). The remaining watershed area is comprised of grasslands, forest, open water, wetlands and urban and developed rural land. The watershed includes one municipality, Litchfield, with a wastewater treatment facility considered in the TMDL study.

Table 1.1 Landuse summary table for the entire Jewitts Creek Watershed.

Landuse Type	Acres	Percentage
Cultivated Land	11,884	45%
Grassland/Pasture	4,577	17%
Developed	3,780	14%
Wetlands	2,183	8%
Forest	1,970	8%
Open Water	1,770	7%
Total	26,164	100%

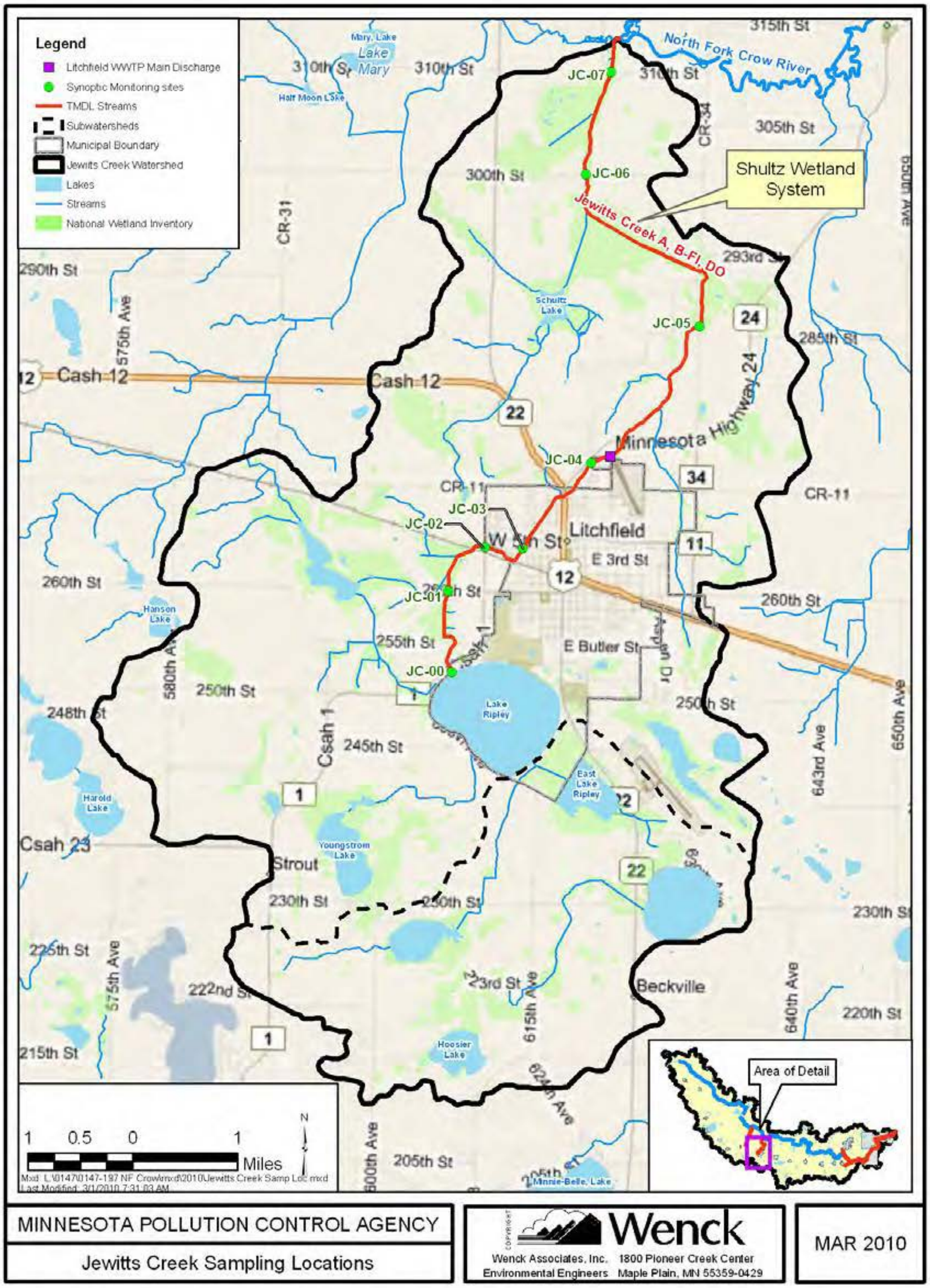


Figure 1.1 Jewitts Creek watershed and monitoring locations.

2.0 REVIEW OF HISTORIC JEWITTS CREEK DISSOLVED OXYGEN DATA

Jewitts Creek has six water quality stations with DO measurements available through the MPCA's STORET database (Table 2.1, Figure 1.1). Station JC-06 (S001-502) is the long-term monitoring station for the MPCA and the CROW's intensive watershed monitoring program.

Table 2.1 Jewitts Creek Water Quality Monitoring Stations and DO data available in STORET.

Study Station Name	STORET #	Location	River Km	DO Measurements	Violations	Years
JC-00	---	Jewitts Creek headwaters at Ripley Lake outlet	13.76	0	---	---
JC-01	---	Jewitts Creek at 260th St crossing	12.31	0	---	---
JC-02	S002-525	Jewitts Creek at CSAH 1 crossing	11.28	4	0	08 – 09
JC-03	---	Jewitts Creek at W. 4th St. Crossing in Litchfield	10.53	0	---	---
JC-04	S000-923 S001-166	Jewitts Creek at County Hwy 42 crossing	8.78	25	0	08 – 09
JC-05	S000-921	Jewitts Creek at County Highway 34 crossing	5.86	15	1	08 – 09
JC-06	S001-502	Jewitts Creek at 300th St crossing	2.30	87	32	01 – 09
JC-07	S000-294	Jewitts Creek at 310th St Crossing	0.60	1	0	08

2.1 DISSOLVED OXYGEN GRABS/FIELD MEASUREMENTS

Jewitts Creek is designated by state statute as a beneficial-use Class 2B water (cool/warm water fishery). This designation states that daily minimum DO concentrations shall not fall below 5.0 mg/L to support the aquatic life and recreation of the system. Thirty-three of the 132 STORET DO field measurements collected on Jewitts Creek were below the 5.0 mg/L DO standard (Figure 2.1). All but one of the thirty-three violations was recorded at station JC-06 downstream of the Shultz Wetland System. Dissolved oxygen data from STORET is also plotted by month (Figure 2.2) and shows 28 of the 33 violations were recorded during summer months (June-September) when water temperatures are warmer and diurnal DO swings are typically highest. Plotting DO by time of day (Figure 2.3) indicates only 7 of the 132 DO measurements were recorded prior to 9:00 am. The MPCA now recognizes measurements taken after 9:00 am do not represent daily minimums, and thus measurements greater than 5.0 mg/L dissolved oxygen later in the day are no longer considered to be indications that a stream is meeting state standards. That said, 31 of the 125 (25%) measurements recorded after 9:00 am were in violation of the DO standard which exceeds the 10% needed for a stream to be considered impaired.

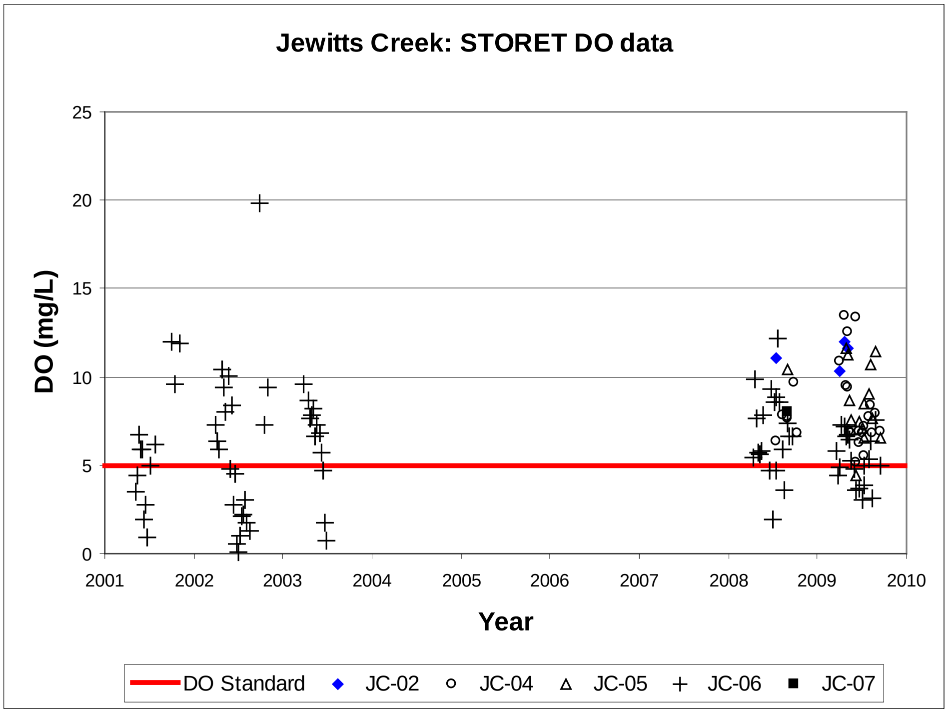


Figure 2.1 Dissolved oxygen data from STORET for all Jewitts Creek Stations.

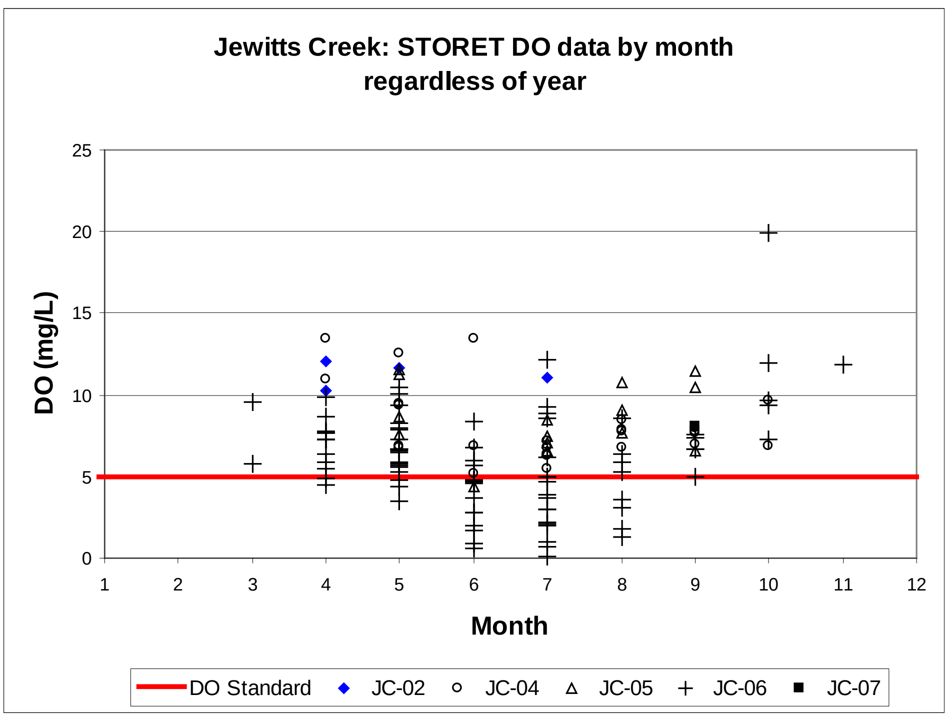


Figure 2.2 Dissolved oxygen data from STORET for all Jewitts Creek Stations by month, regardless of year.

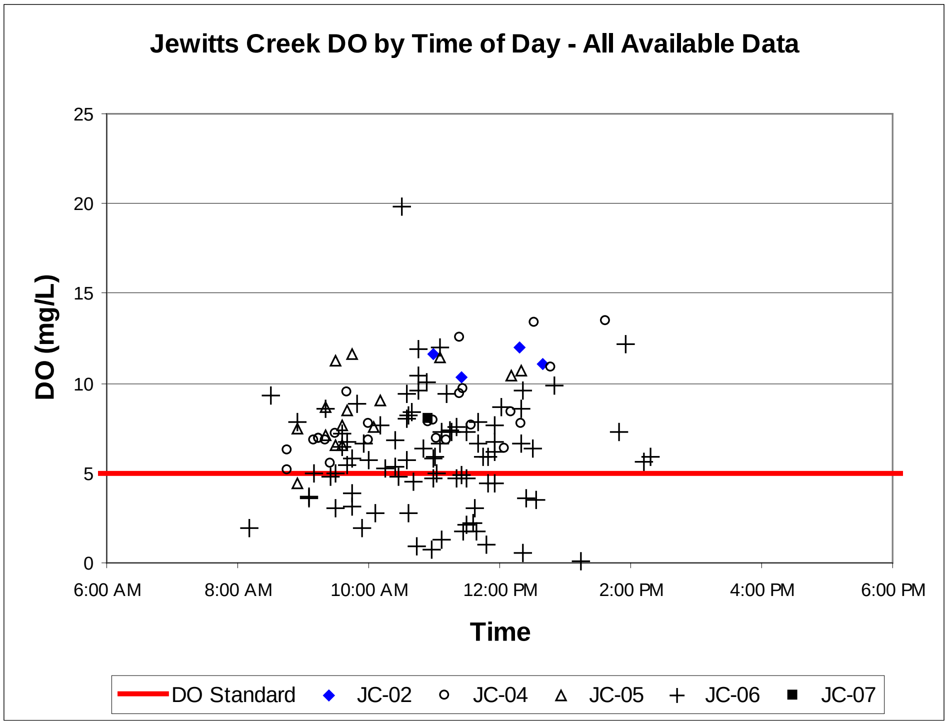


Figure 2.3 Dissolved oxygen data from STORET for all Jewitts Creek stations by time of day, regardless of year and month. No data has been collected prior to 8:00 am or later than 4:00 pm.

2.2 CONTINUOUS DISSOLVED OXYGEN MEASUREMENTS

Continuous DO data was collected in 2008 by the MPCA using data sondes at three locations along Jewitts Creek. The data sondes were deployed at station JC-04 for 57-days (9/2/08 through 10/28/08), JC-05 for 14-days (9/2/08 through 9/15/08) and JC-06 for 130-days (5/28/08 through 7/3/08, 7/22/08 through 9/23/08 and 9/30/08 through 10/28/08). The sensors record continuous measurements of dissolved oxygen, temperature, pH and conductivity. Figure 2.4 shows the daily minimum, daily average and daily maximum of the continuous DO data. The daily minimum DO for station JC-04 is below 5 mg/L for only 10 of the 50-days monitored. DO at station JC-05 was always above the 5.0 mg/L standard for the entire period of deployment in early September. Daily minimum DO was below the standard at JC-06 from 5/28/08 through 10/2/08, except for a 4-day period after a June storm event when minimum DO increased above the 5 mg/L standard. DO increased above the standard at JC-06 from 10/2/08 through 10/28/08.

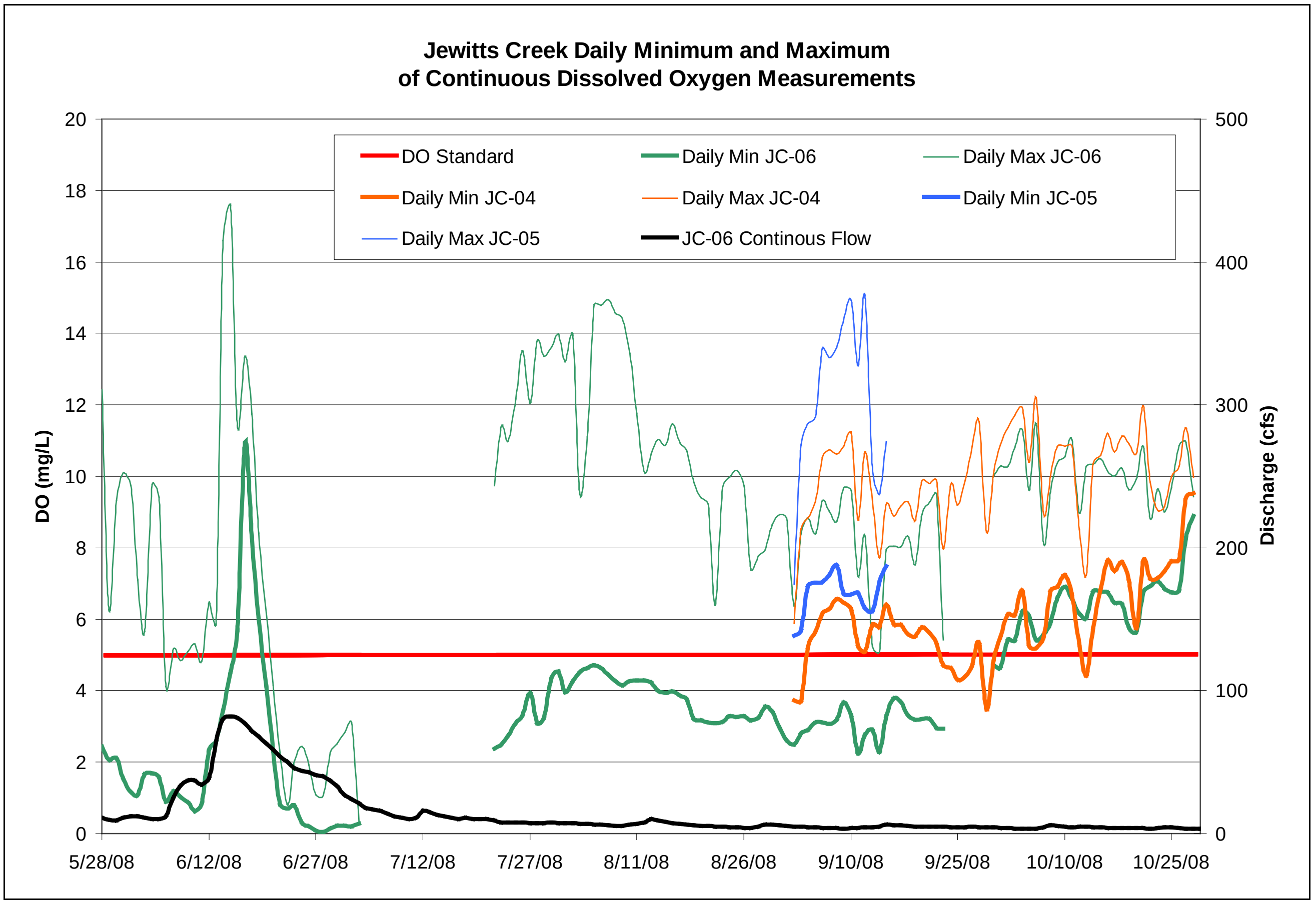


Figure 2.4 Daily statistics of continuous dissolved oxygen and flow data collected in 2008.

2.3 DISSOLVED OXYGEN RELATION TO FLOW

The nearest United States Geologic Survey (USGS) monitoring station is located on the Crow River at Rockford, MN. Average daily flows have been monitored at this station since 1906 (23 miles upstream from confluence with the Mississippi River). The mean annual flow for water years 1906 through 2002 is 826 cubic feet per second (cfs), which represents 4.25 inches of runoff from the 2,640-square mile drainage area located upstream of Rockford. Monthly average flows for this station range from 172 cfs in February to 2,243 cfs in April. The maximum average daily flow, 22,100 cfs, was recorded April 16, 1965. The minimum average daily flow, 3.8 cfs, was recorded August 4, 1934. Table 1.1 summarizes the past ten years data and characterizes the year as a wet, dry or average year based on comparison to long term monitoring.

Table 2.2 Water year summary for the last ten years at USGS Crow River at Rockford.

Water Year	Average Annual Flow at Main Stem Crow USGS Station at Rockford (cfs)	Percent Variation from Average	Wet / Dry / Average
2000	275	-67%	DRY
2001	1329	59%	WET
2002	1605	93%	WET
2003	1245	49%	WET
2004	718	-14%	AVERAGE
2005	1158	39%	WET
2006	1399	68%	WET
2007	603.1	-28%	DRY
2008	640.8	-23%	DRY
2009	658.8	-21%	DRY

While there is no USGS gage on Jewitts Creek, the MPCA established a continuous flow station at JC-06 in April, 2008. Additionally, there were 29 gauged flow measurements recorded at JC-06 from 2001-2003 available in STORET. While violations appear to occur under all flow regimes, eleven of the 21 DO violations with paired flow data occurred when flow was greater than 15 cfs (Figure 2.5).

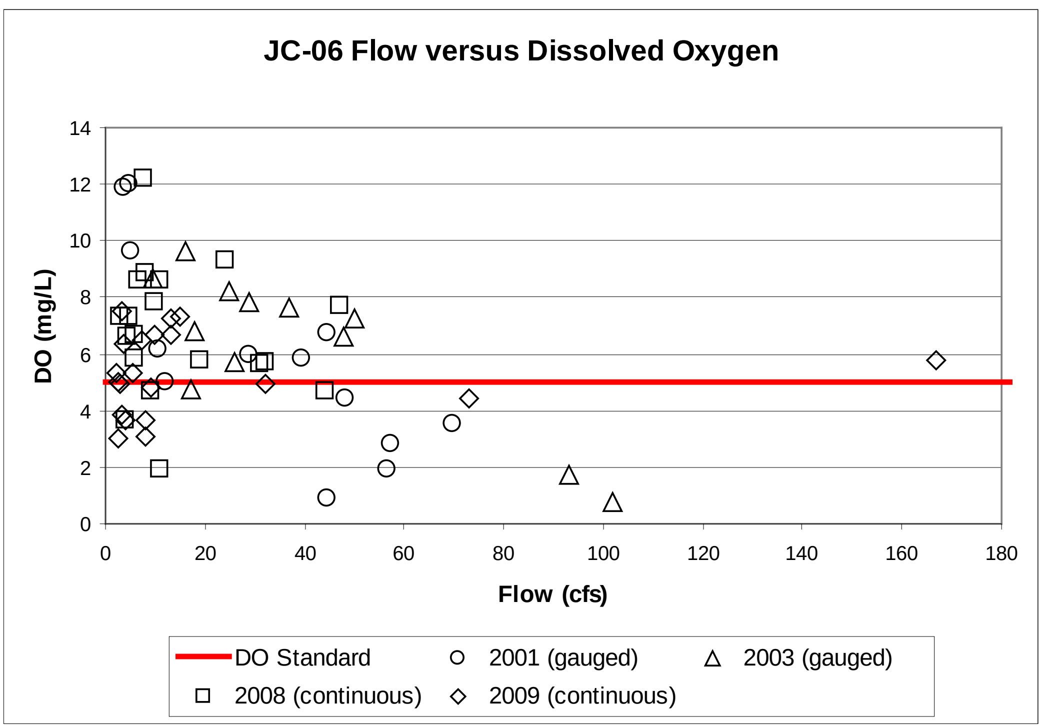


Figure 2.5 Dissolved oxygen compared to gauged and continuous flow measurements.

3.0 SYNOPTIC SURVEY DATA COLLECTION METHODS

3.1 SAMPLING LOCATIONS

The Minnesota Department of Natural Resources (DNR) stream file shows Jewitts Creek's headwaters is located at the outlet of Ripley Lake (shown on Figure 1.1 as JC-00). During the synoptic survey, JC-00 was observed to have standing water with no measurable velocity. Flow was gauged downstream at the County State Aide Highway 1 crossing (Figure 1.1, Site JC-02) west of Litchfield to be less than 0.09 cubic feet per second, which was determined too low to initiate a dye study or collect reliable water quality samples. Gauged flow at JC-03 at West 4th St near the Public Works building in Litchfield was higher (~1.21 cfs) and determined suitable to represent the upstream boundary condition/headwater for the study.

3.2 DYE STUDY

A slug of a tracer (Rhodamine WT dye) was injected at JC-03 and JC-05 and measured downstream during the synoptic survey on September 3, 2008. Dye was released first at the downstream most injection location to prevent dye from separate injection points "catching up" and mixing. Dye samples were collected as grabs by field personnel or ISCO automatic samplers. Fixed stations downstream of the injection point were sampled until the dye cloud passed. The concentration of the dye in each sample was measured using an Aquafluor handheld fluorometer (Rantz, 1982).

Table 3.1 Jewitts Creek Synoptic Survey Monitoring Locations.

Site	Location (River km)	Lab WQ Grab Station	Field Parameter WQ Station	Flow Station	Dye Injection	Dye Monitoring
JC-00	13.76	---	---	---	---	---
JC-01	12.31	---	---	---	---	---
JC-02	11.28	---	---	X	---	---
JC-03	10.53	X	X	X	X	---
JC-04	8.78	(BOD only)	X	X	---	---
JC-05	5.86	X	X	X	X	X
JC-06	2.30	X	X	X	---	---
JC-07	0.60	X	X	X	---	X

3.3 FLOW GAUGING

Stream gauging measurements were collected in conjunction with the time of travel dye study. Flow was recorded using a SonTek Flow Tracker handheld digital velocity meter with an accuracy of 0.001 cubic feet per second. Velocity measurements were taken at 60 percent of the total depth for shallow reaches (less than 2.5 feet deep) and at 20 percent and 80 percent of the total depth for deeper reaches. Horizontal spacing of velocity measurements was set so less than 10 percent of total discharge is accounted for by any single velocity measurement. Flow gauging was conducted at each dye injection and monitoring station.

3.4 WATER QUALITY SAMPLING

Water quality data was collected on September 3, 2008 at selected stations along Jewitts Creek (Table 3.1, Figure 1.1). Each water sample (grab) was collected and preserved for lab analysis. The lab analyzed four of the five samples for: total kjeldahl nitrogen (TKN), ammonia nitrogen (NH_3-N), nitrate nitrogen (NO_2-N), 5-day and ultimate biological oxygen demand ($BOD_{5\text{-day}}$ & BOD_u), total phosphorus (TP), ortho-phosphorus (soluble reactive phosphorus), total organic carbon (TOC), and chlorophyll-*a*. One grab sample (JC-04) was only analyzed for $BOD_{5\text{-day}}$ & BOD_u only. All five sites were monitored in the field using a data sonde (YSI Model 6920 V2) for the following parameters: temperature, conductivity, pH, and dissolved oxygen (DO).

3.5 CONTINUOUS DISSOLVED OXYGEN MEASUREMENTS

The Minnesota Pollution Control Agency deployed 3 multi-parameter YSI sondes with internal logging capability to monitor continuous DO levels during the dye study and synoptic water quality survey. These instruments were deployed to monitor continuous DO concentrations at 15-minute intervals for a minimum of 72-hours before, after and during the synoptic surveys. The instruments also measured and recorded other in-situ parameters such as DO saturation, temperature, conductivity, and pH.

4.0 SYNOPTIC SURVEY RESULTS

4.1 DYE STUDY

Travel times from the dye study suggest mean velocity was slower in the lower reach compared to the upper reach likely due to the Shultz Wetland System's gentle slopes and over-widened channel (Table 4.1, Figures 4.1-4.2). Combined travel time for both reaches was over two days indicating residence time for Jewitts Creek is fairly long during this low-flow regime.

Table 4.1 Estimated travel times from the Jewitts Creek dye study. Travel times estimated by calculating the time between upstream injection and peak concentration measured downstream.

Reach Description	Reach Length (km)	Estimated Travel Time (hrs)	Mean Velocity (ft/sec)
Upper Reach: JC-03 to JC-05	4.67	21.25	0.20
Lower Reach: JC-05 to JC-07	5.26	29.50	0.16

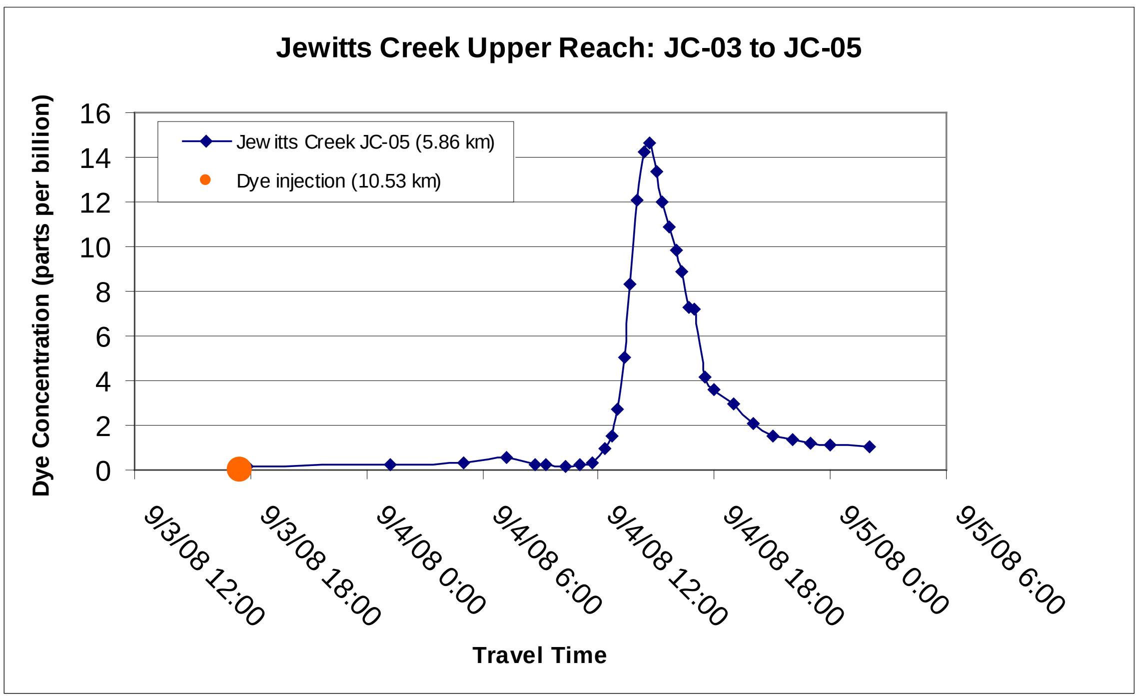


Figure 4.1 Dye concentration measurements for station JC-05.

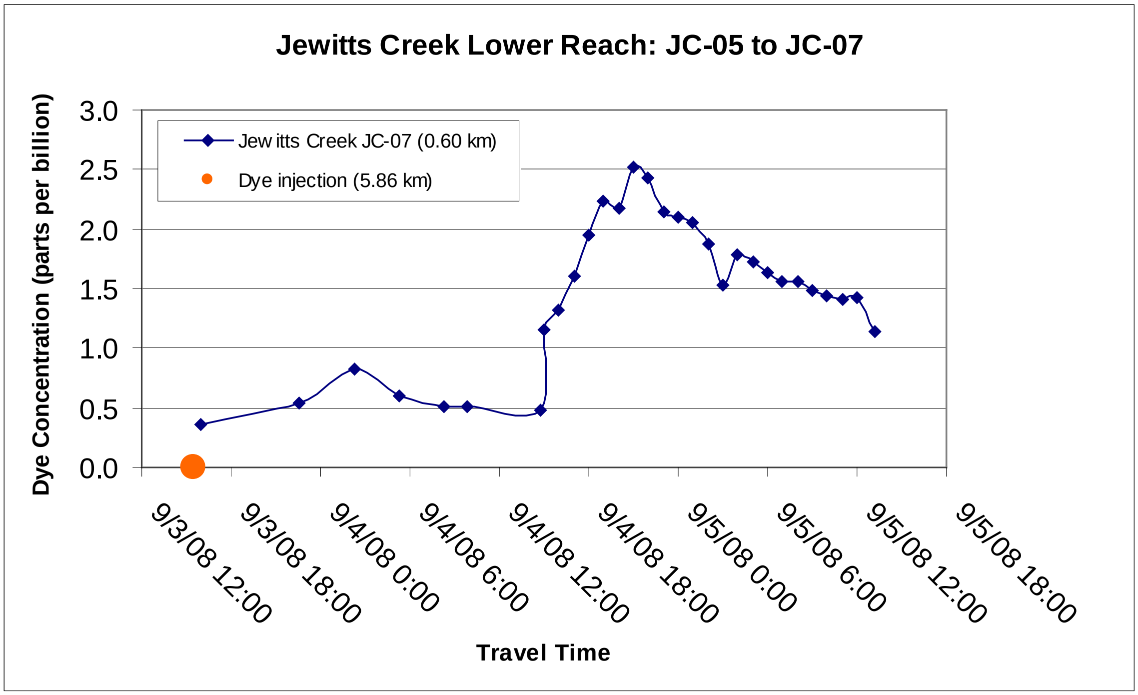


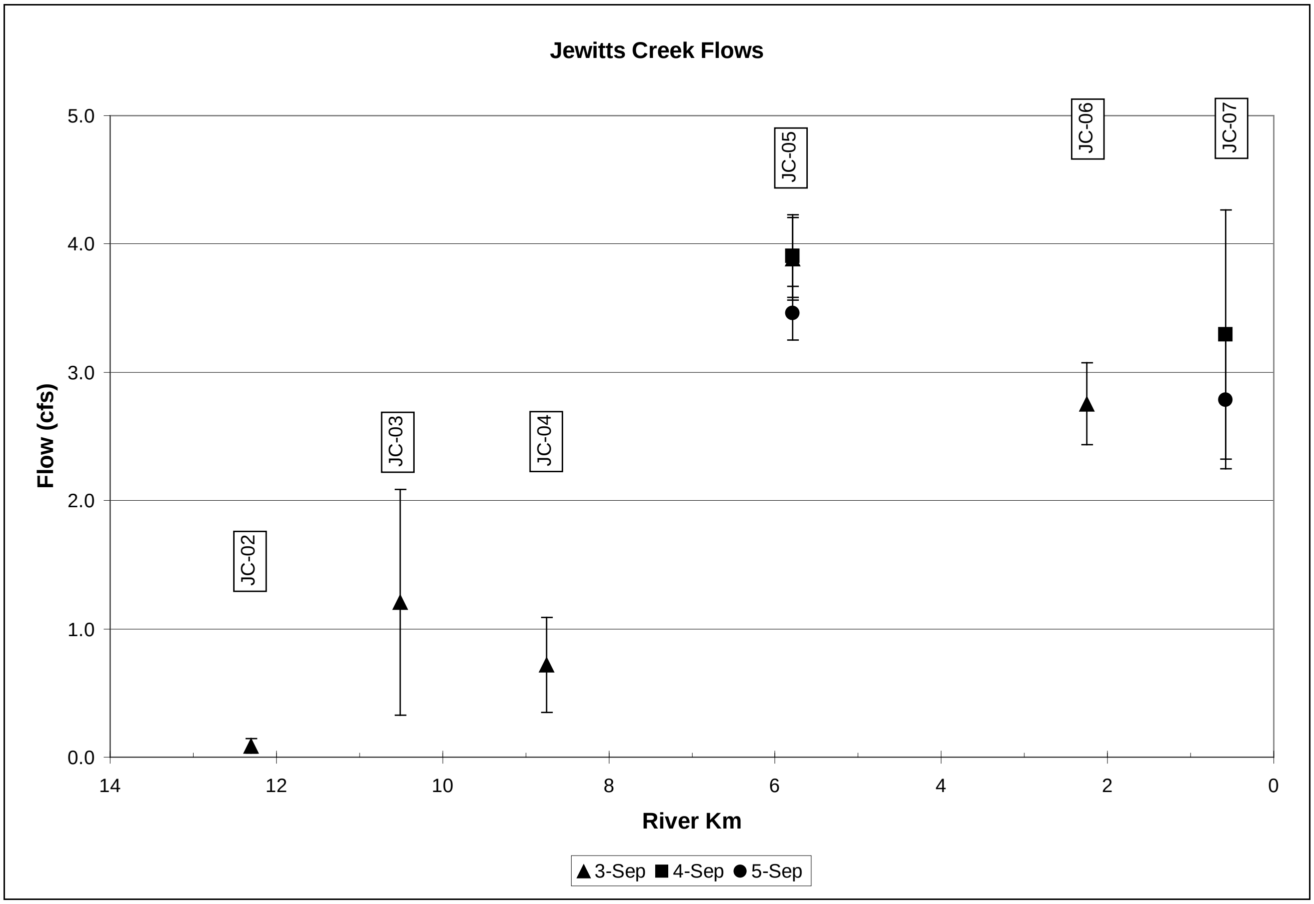
Figure 4.2 Dye concentration measurements for station JC-07

4.2 FLOW GAUGING

Synoptic survey gauged flow measurements show the upper reach is gaining between JC-04 and JC-05, and both gaining and losing through the Shultz Wetland System downstream of JC-05 (Table 4.2 and Figure 4.3). While no rain fell during the survey, approximately 1.9 inches of rainfall was recorded at the Litchfield, MN Airport in the week leading up to September 3rd. As a result, data from JC-05 and JC-07 shows Jewitts Creek to be losing flow each day of the synoptic survey from 9/3/2008 through 9/5/2008.

Table 4.2 Gauged flow measurements taken during the September synoptic survey.

Station	River km	Q - 9/3 (cfs)	Q - 9/4 (cfs)	Q - 9/5 (cfs)
JC-02	12.31	0.09	---	---
JC-03	10.53	1.21	---	---
JC-04	8.78	0.72	---	---
JC-05	5.86	3.89	3.91	3.46
JC-06	2.30	2.76	---	---
JC-07	0.60	7.00	3.30	2.78



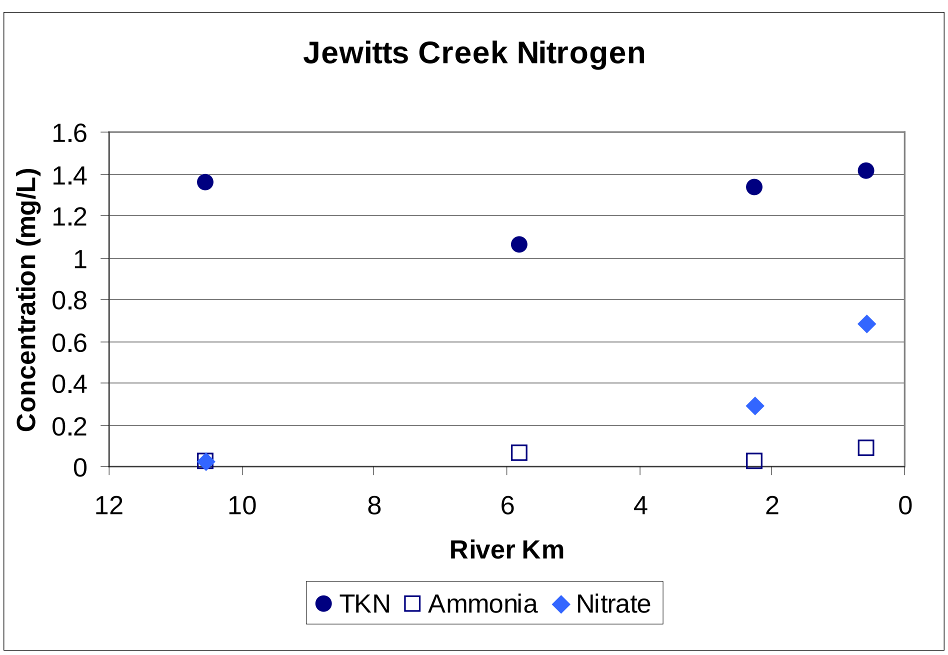
Figures 4.3 Gauged flows by river kilometer recorded during the Jewitts Creek synoptic survey. Error bars represent estimated uncertainty of the Flow-Tracker field measurement.

4.3 WATER QUALITY

Water quality results suggest Jewitts Creek displays higher concentrations of organic-bound nutrients, organic carbon, chlorophyll-*a* and BOD near its headwaters (JC-03) and coming out the Shultz Wetland System reach (Table 4.3). For the most part, these parameters decreased at downstream monitoring stations as the organic material was broken down by heterotrophs, settled out of the water column or diluted by incoming water (Table 4.3 and Figures 4.4 - 4.8).

Table 4.3 September 3, 2008 water quality grab synoptic survey results.

Parameter	JC-03 (10.53 km)	JC-04 (8.78 km)	JC-05 (5.86 km)	JC-06 (2.25 km)	JC-07 (0.60 km)
Temperature (Celsius)	16.3	15.4	20.1	18.2	19.0
DO (mg/L)	4.83	7.74	10.44	7.34	8.03
pH	7.86	7.92	8.20	7.92	8.04
Total Phosphorus (mg/L)	0.236	---	0.200	0.352	0.326
Ortho-P (mg/L)	0.175	---	0.104	0.357	0.326
TKN (mg/L)	1.36	---	1.06	1.33	1.41
NH_3 (mg/L)	<0.05	---	0.060	<0.05	0.090
Nitrate (mg/L)	<0.05	---	3.900	0.290	0.680
5-day BOD (mg/L)	2.42	<1.00	2.56	<1.00	<1.00
Ultimate BOD (mg/L)	5.24	3.73	5.47	3.01	4.03
TOC (mg/L)	8.9	---	5.7	12.0	12.0
Chlorophyll-*a* (µg/L)	11.90	---	4.92	5.15	3.84



Figures 4.4 September 3, 2008 synoptic survey water quality lab results for Jewitts Creek.

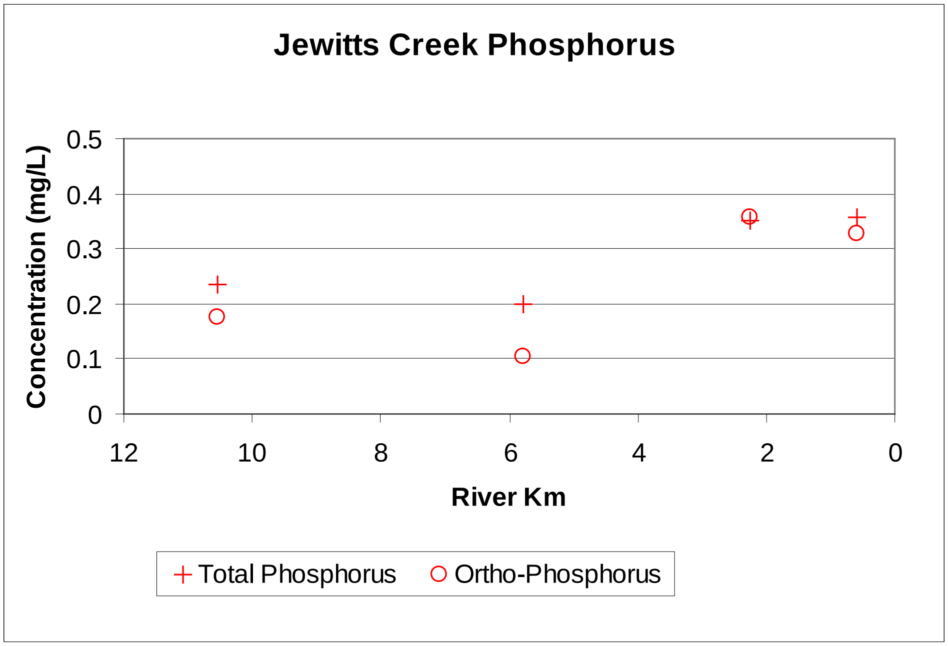
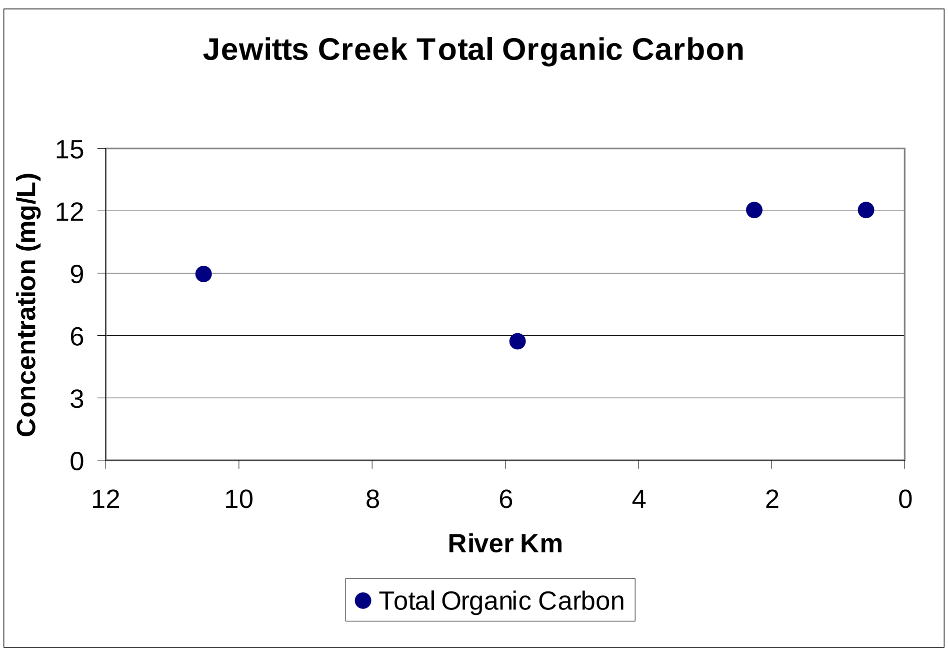
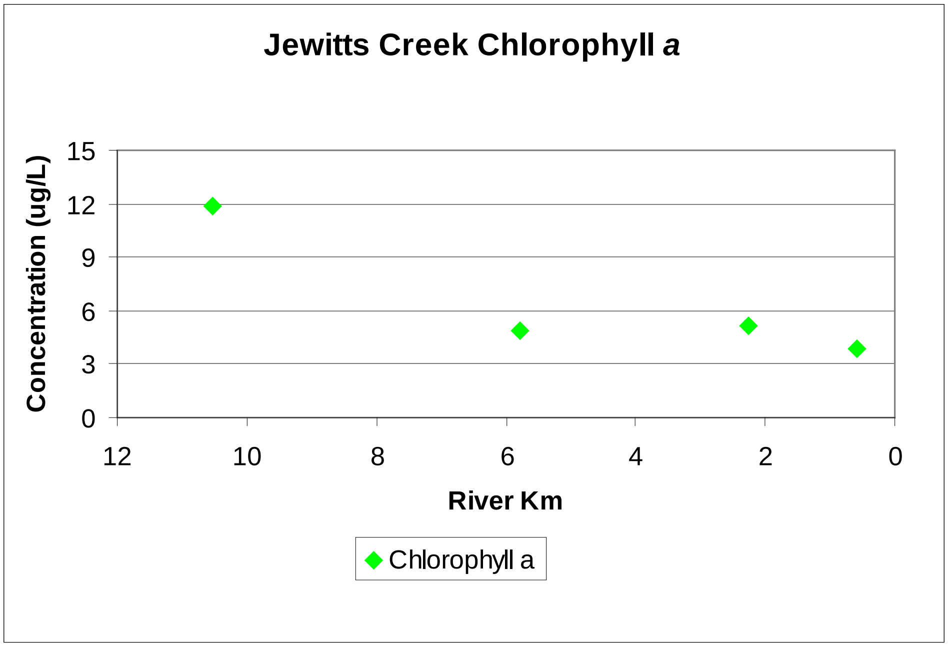


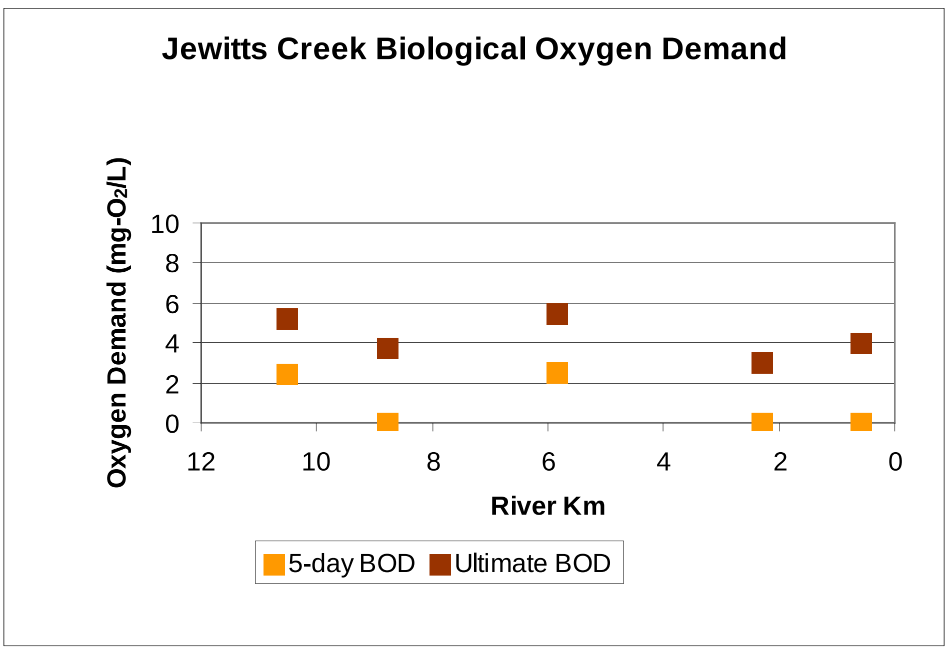
Figure 4.5 September 3, 2008 synoptic survey water quality lab results for Jewitts Creek.



Figures 4.6 September 3, 2008 synoptic survey water quality lab results for Jewitts Creek.



Figures 4.7 September 3, 2008 synoptic survey water quality lab results for Jewitts Creek.



Figures 4.8 September 3, 2008 synoptic survey water quality lab results for Jewitts Creek.

4.4 DISSOLVED OXYGEN

4.4.1 Continuous Measurements

The continuous sonde data shows dissolved oxygen dropped the lowest at station JC-06 near the downstream end of the slow-flowing Shultz Wetland System reach (Figure 4.9). Mean DO concentrations at JC-04, JC-05 and JC-06 from September 3rd through September 4th were 6.12 mg/L, 7.73 mg/L and 5.08 mg/L, respectively.

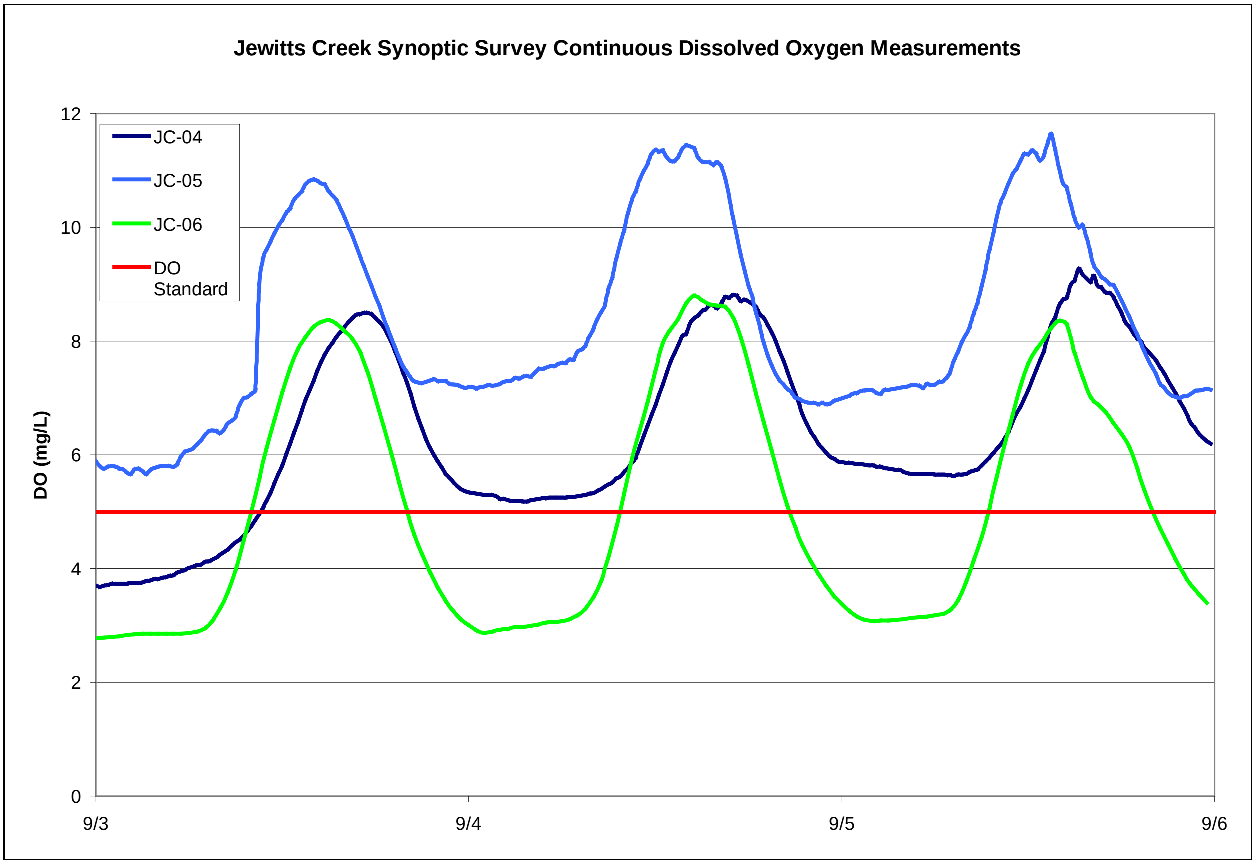


Figure 4.9 Synoptic survey continuous dissolved oxygen concentrations.

4.4.2 Longitudinal Profile

Instantaneous field measurements of dissolved oxygen were taken on September 3 and September 4 using the hand-held YSI and are labeled in Figure 4.10 with the time of sample collection, if available. The minimum and maximum dissolved oxygen range from the continuous measurements (Figure 4.10) are plotted as orange and blue "I" while average daily DO is marked on the plot with an orange or blue box for September 3rd and 4th, respectively. All field grab measurements recorded by Wenck staff on 9/3/2008 and 9/4/2008 were taken between 12:00 pm and 4:00 pm and were closer to representing daily maximums. These profiles were consistent and show an increase in dissolved oxygen between JC-04 and JC-05 followed by a decrease between JC-05 and JC-06. This decrease in oxygen is likely due to elevated breakdown of organic matter in the water column and peaty sediments in the over-widened, slow-flowing Schultz Wetland System reach between JC-05 and JC-06.

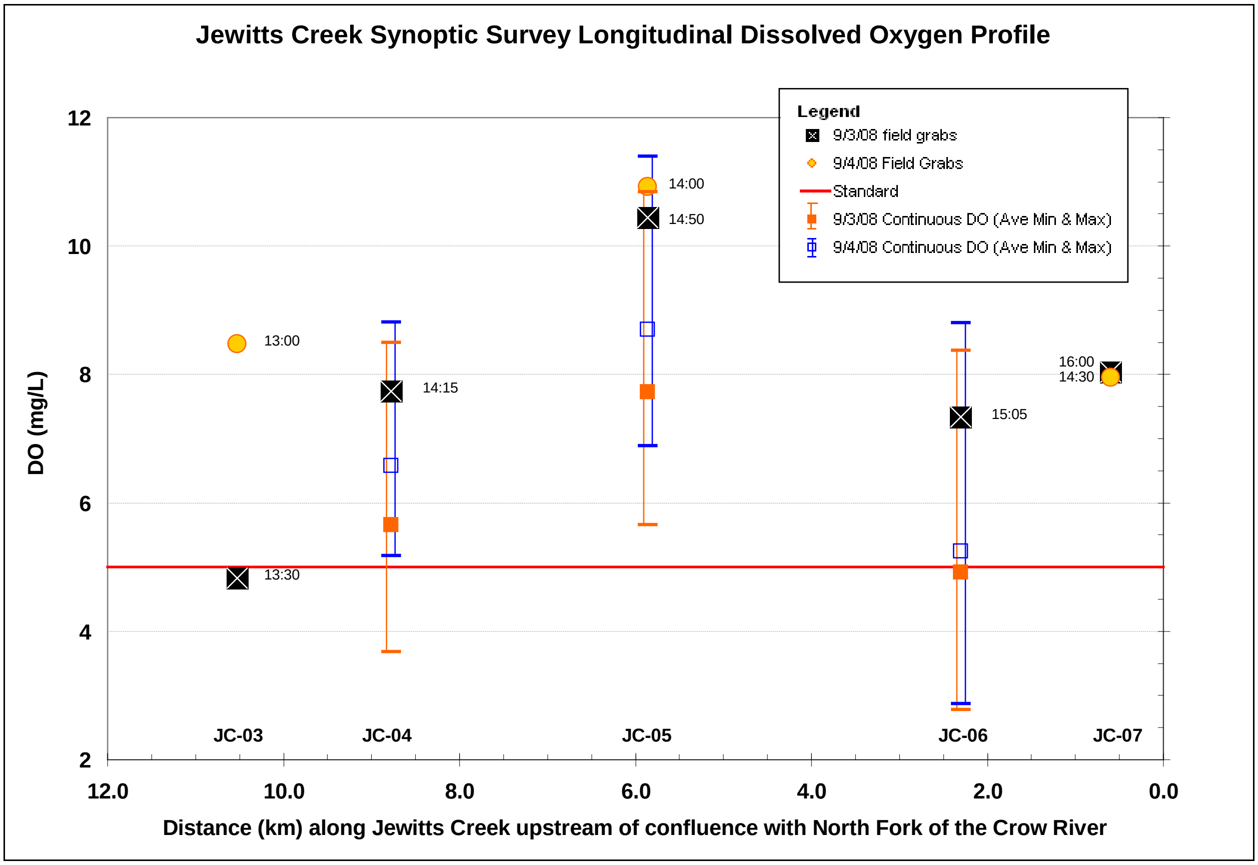


Figure 4.10 Dissolved oxygen observations during the September 2008 synoptic survey.

5.0 REFERENCES

Rantz, S.E. et al. 1982. “Measurement of Stage and Discharge”, Measurement and Computation of Streamflow, Volume 1, U.S. Geologic Survey. Water Supply Paper 2175. Washington, D.C.: Governement Printing Office.

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TECHNICAL MEMORANDUM

TO: Diane Sander, Crow River Organization of Water Watershed Coordinator

CC: Maggie Leach, MPCA Regional Impaired Waters Coordinator

FROM: Joe Bischoff, Project Manager
Pamela Massaro, P.E.
Jeff Strom

DATE: May 10, 2010

SUBJECT: Mill Creek Dissolved Oxygen TMDL
Historic Data and Synoptic Survey Methods and Results

This technical memorandum summarizes historic dissolved oxygen (DO) data for Mill Creek and the data collection methods and results for the September 2009 Synoptic Survey. The synoptic survey was performed to obtain the data needed to construct and calibrate a River and Stream Water Quality Model (QUAL2K) to address the creek's DO impairment during low-flow conditions.

1.0 WATERSHED DESCRIPTION

Mill Creek flows approximately 2.63 miles from the outlet of Deer Lake south west of Buffalo, MN, to the North Fork Crow River, an Upper Mississippi River tributary (Figure 1.1). This stretch of Mill Creek (AUID 07010204-515) was listed as impaired for dissolved oxygen in 2006. The system is wide near the Deer Lake headwaters and narrows and straightens moving downstream near its junction with the North Fork Crow River. For the TMDL study, the Mill Creek watershed was considered to be the 2,804 - acre watershed downstream of Deer Lake that drains to a wetland east of Mill Creek via an unnamed tributary that joins the main stem near river mile 1.93. Agriculture dominates the landscape: 43% is used for grassland and pasture while 15% is cultivated for row crops. The wetlands in the eastern portion of the lower sub-watershed cover approximately 20% of the landscape while forest, lakes and developed land comprise the remainder the watershed.

Table 1.1 Landuse summary table for Mill Creek Watershed.

Landuse Type	Acres	Percentage
Grassland/Pasture	1,211	43%
Wetlands	551	20%
Cultivated Land	427	15%
Forest	332	12%
Developed	219	8%
Lakes	64	2%
TOTAL	2,804	100%

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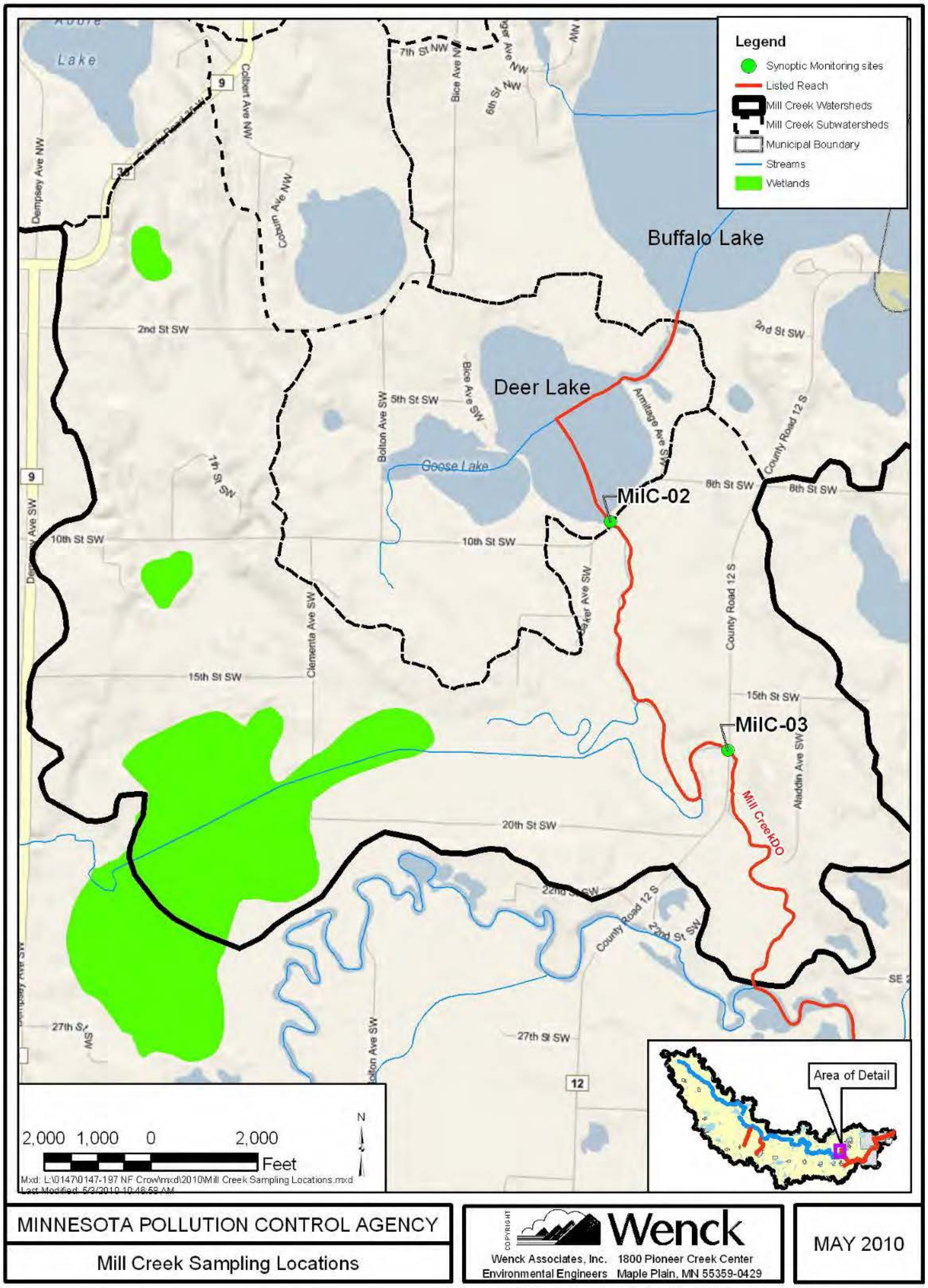


Figure 1.1 Mill Creek watershed and monitoring locations.

2.0 REVIEW OF MILL CREEK HISTORIC DISSOLVED OXYGEN DATA

Mill Creek has two STORET water quality stations with DO measurements available through the MPCA's STORET database (Table 2.1, Figure 1.1). Station MillCr-03 (S002-018) is the long-term monitoring station for the MPCA and the CROW intensive watershed monitoring program. MillCr-02 is a station established by Wenck Associates, Inc. at the outlet of Deer Lake to sample dissolved oxygen and other water quality parameters as part of a two-day synoptic survey study that took place on September 1st and 2nd, 2009 (Table 1.1).

Table2.1 Mill Creek Water Quality Monitoring Stations and DO data available in STORET.

Station Name	STORET #	Location	River Km	DO Measurements	Violations	Years
MillCr-02	S005-838	Mill Creek at 10 St SW crossing – outlet of Deer Lake	4.23	2	0	09
MillCr-03	S002-018	Mill Creek at CSAH-12 crossing	1.78	108	21	01-03; 06-09

2.1 DO GRABS/FIELD MEASUREMENTS

Mill Creek is designated by state statute as a beneficial-use Class 2B water (cool/warm water fishery). This designation states that DO concentrations shall not fall below 5.0 mg/L as a daily minimum in order to support the aquatic life and recreation of the system. Twenty one of the 110 STORET DO field measurements collected on Mill Creek were below the 5.0 mg/L DO standard (Figure 2.1). Dissolved oxygen data from STORET is also plotted by month (Figure 2.2) and shows 18 of the 21 violations were recorded during summer months (June-September) when water temperatures are warmer and diurnal DO swings are typically highest. Plotting DO by time of day (Figure 2.3) indicates only 18 of the 109 DO measurements were recorded prior to 9:00 am. The MPCA now recognizes measurements taken after 9:00 am do not represent daily minimums, and thus measurements greater than 5.0 mg/L dissolved oxygen later in the day are no longer considered to be indications that a stream is meeting state standards. That said, 16 of the 91 (18%) measurements recorded after 9:00 am were in violation of the DO standard which exceeds the 10% needed for a stream to be considered impaired.

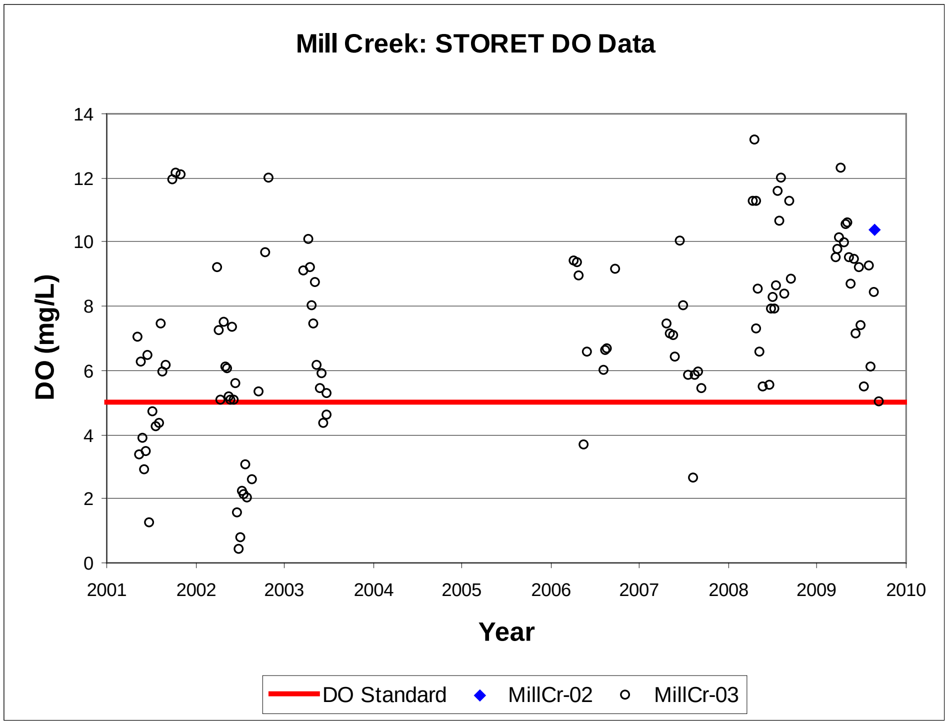


Figure 2.1 Dissolved oxygen data from STORET for all Mill Creek Stations

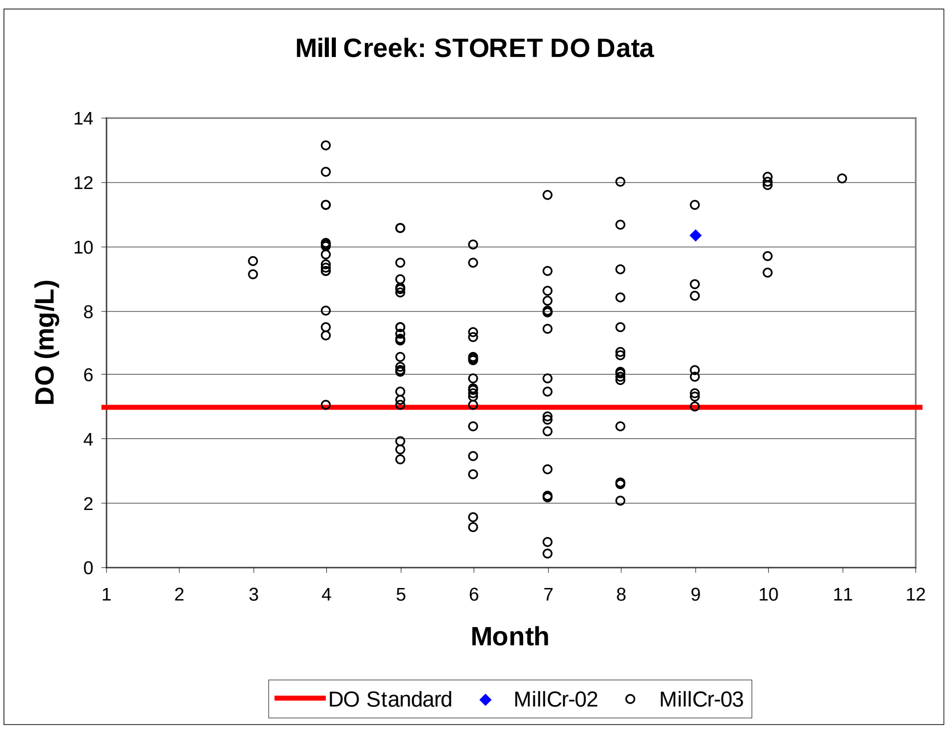


Figure 2.2 Dissolved oxygen data from STORET for all Mill Creek stations by month, regardless of year.

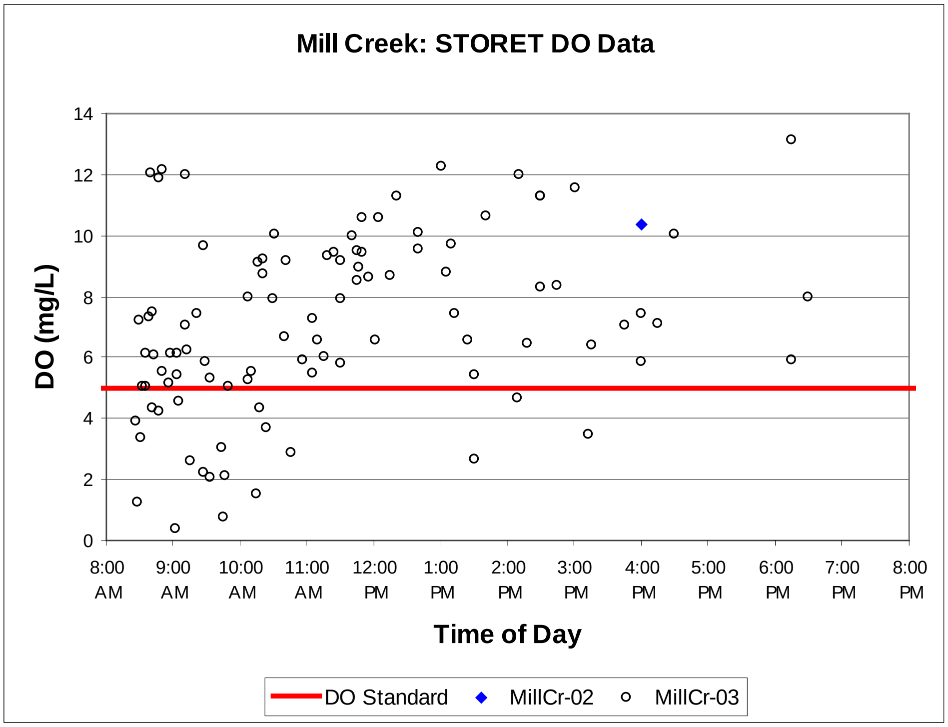


Figure 2.3 Dissolved oxygen data from STORET for all Mill Creek stations by hour, regardless of year and month. No data was collected between 8:00 pm and 8:00 am.

2.2 CONTINUOUS DO MEASUREMENTS

Continuous DO data was collected in 2009 by the MPCA using a data sonde at MillCr-03. The sensor records continuous measurements of dissolved oxygen, temperature, pH and conductivity. Daily minimum DO fell below the 5.0 mg/L standard beginning in early June through middle to late August when water temperatures warmed and stream flows were lower (Figure 2.4).

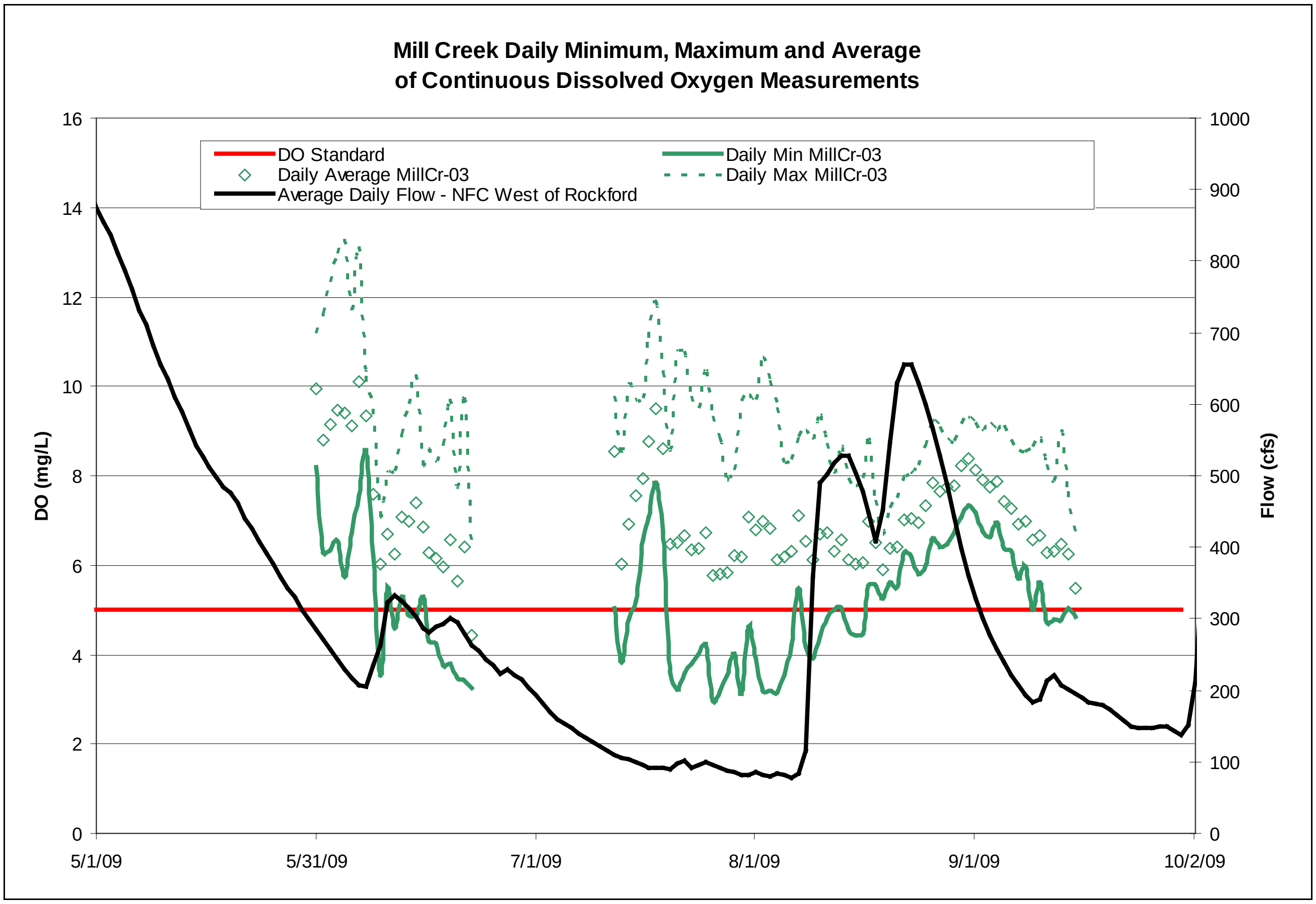


Figure 2.4 Statistics of continuous dissolved oxygen data collected in 2009.

2.3 DO RELATION TO FLOW

While there is no USGS gauge on Mill Creek,, there is continuous flow station on the North Fork Crow River west of Rockford MN (Figure 2.4). There are also 20 gauged flow measurements in STORET recorded in 2001 and 2009. A total of eight paired flow-DO measurements were below the 5 mg/L DO standard. All paired violations were recorded in 2001 and occurred across both high and low-flow regimes (Figure 2.5).

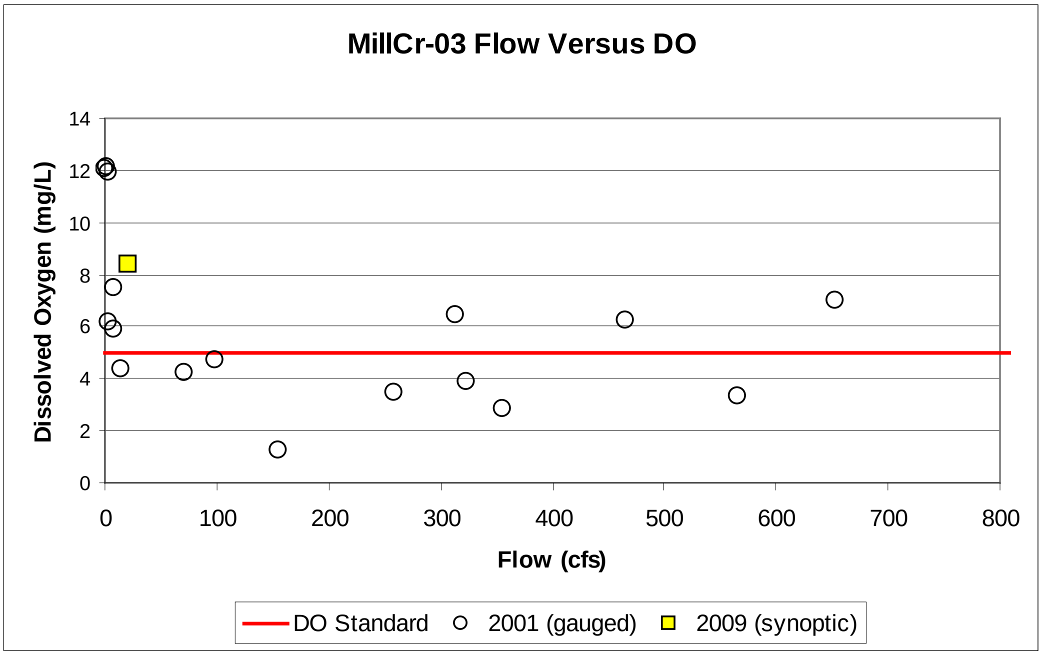


Figure 2.5 MillCr-03 dissolved oxygen compared to gauged and continuous flow measurement.

3.0 SYNOPTIC SURVEY DATA COLLECTION METHODS

3.1 STUDY AREA AND LOCATIONS

The Minnesota Department of Natural Resources (DNR) stream file shows two branches converge upstream of MillCr-03 at river kilometer 3.10 to form the main-stem of Mill Creek (Figure 1.1). These branches originate from two separate headwater waterbodies: Deer Lake to the north and an unnamed wetland system to the west. Flow was measured at the Deer Lake outlet (MillCr-02) on August 26th, 2009. Flow at this station (~ 11.90 cfs) was determined suitable to initiate the dye study and represent the upstream boundary condition/headwater for the study.

3.2 DYE STUDY

A slug of a tracer (Rhodamine WT dye) was injected at MillCr-02 and measured downstream at MillCr-03 during the synoptic survey on September 1st, 2009. Dye samples were collected as grabs by field personnel or ISCO automatic samplers. Fixed stations downstream of the injection point were sampled until the dye cloud passed (Table 3.1). The concentration of the dye in each sample was measured using an Aquafluor handheld fluorometer (Rantz, 1982).

Table3.1 Mill Creek Synoptic Survey Monitoring Locations.

Site	Location (River km)	Lab WQ Grab Station	Field Parameter WQ Station	Flow Station	Dye Station
MillCr-02	4.23	X	X	X	X
MillCr-03	1.78	X	X	X	X

3.3 FLOW GAUGING

Stream gauging measurements were collected in conjunction with the time of travel dye study. Flow was recorded using a SonTek Flow Tracker handheld digital velocity meter with an accuracy of 0.001 cubic feet per second. Velocity measurements were taken at 60 percent of the total depth for shallow reaches (less than 2.5 feet deep) and at 20 percent and 80 percent of the total depth for deeper reaches. Horizontal spacing of velocity measurements was set so less than 10 percent of total discharge is accounted for by any single velocity measurement. Flow gauging was conducted at each dye injection and monitoring station (Table 3.1).

3.4 WATER QUALITY SAMPLING

Water quality data was collected on September 1, 2009 at two locations along Mill Creek (Table 3.1 and Figure 1.1). All water samples (grab) were collected, preserved and shipped to the Minnesota Department of Health laboratory. Samples from both sites were analyzed for the following parameters: total kjeldahl nitrogen (TKN), ammonia nitrogen (NH_3-N), nitrate nitrogen (NO_2-N), 5-day and ultimate carbonaceous biochemical oxygen demand ($CBOD_{5\text{-day}}$ & $CBOD_u$), total phosphorus (TP), ortho-phosphorus (soluble reactive phosphorus), total organic carbon (TOC), and chlorophyll-*a*. A data sonde (YSI Model 6920 V2) was used at six sites in the field to collect the following additional water quality parameters: temperature, conductivity, pH, and dissolved oxygen (DO).

3.5 CONTINUOUS DISSOLVED OXYGEN MEASUREMENTS

The Minnesota Pollution Control Agency deployed one multi-parameter YSI sondes with internal logging capability to monitor continuous DO levels during the dye study and synoptic water quality survey. This instrument was deployed to monitor continuous DO concentrations at 15-minute intervals for a minimum of 72-hours before, after and during the synoptic surveys. The instrument also measured and recorded other in-situ parameters such as DO saturation, temperature, conductivity, and pH.

4.0 SYNOPTIC SURVEY RESULTS

4.1 DYE STUDY

Travel times from the dye study suggest mean velocity was relatively fast in the upper reach during the synoptic survey (Table 4.1, Figure 4.1). Travel time for the upper reach was only 8 hours indicating residence time for Mill Creek is short during this flow regime.

Table 4.1 Estimated travel times from the Mill Creek dye study. Travel times estimated by calculating the time between upstream injection and peak concentration measured downstream.

Reach Description	Reach Length (km)	Estimated Travel Time (hrs)	Mean Velocity (ft/sec)
Upper Reach: MillCr-02 to MillCr-03	2.45	8.1	0.28
Lower Reach: MillCr-03 to Outflow to Crow	1.78	Not measured	Not measured

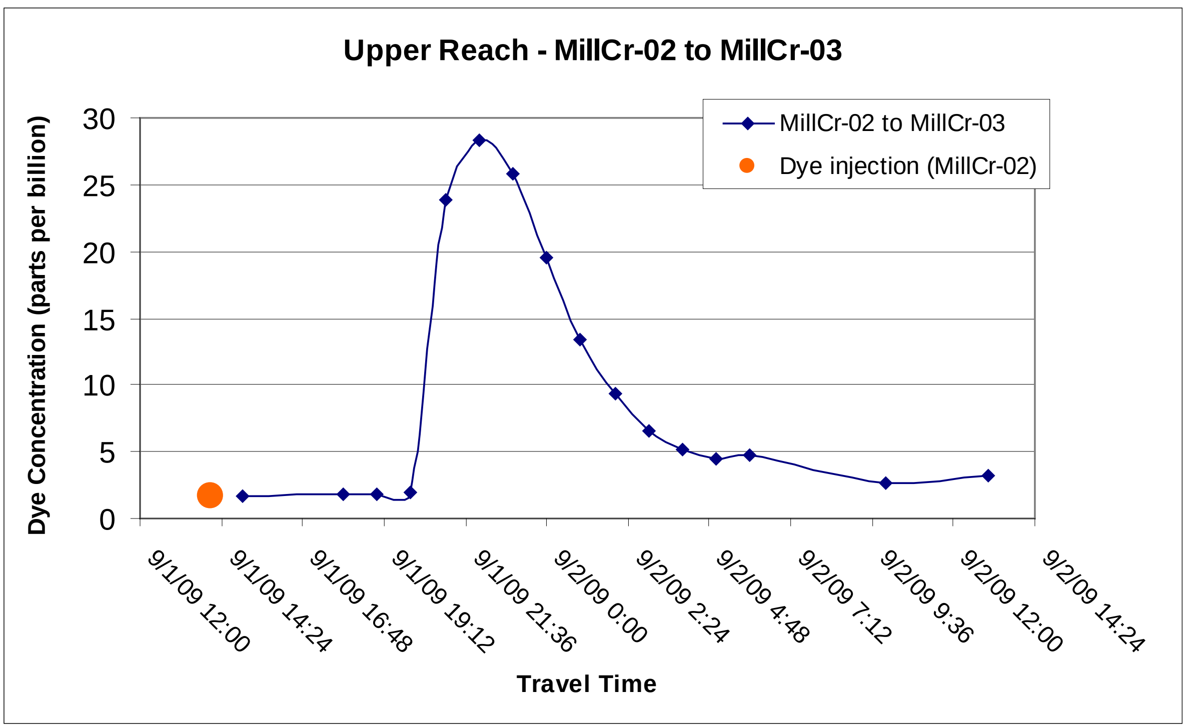


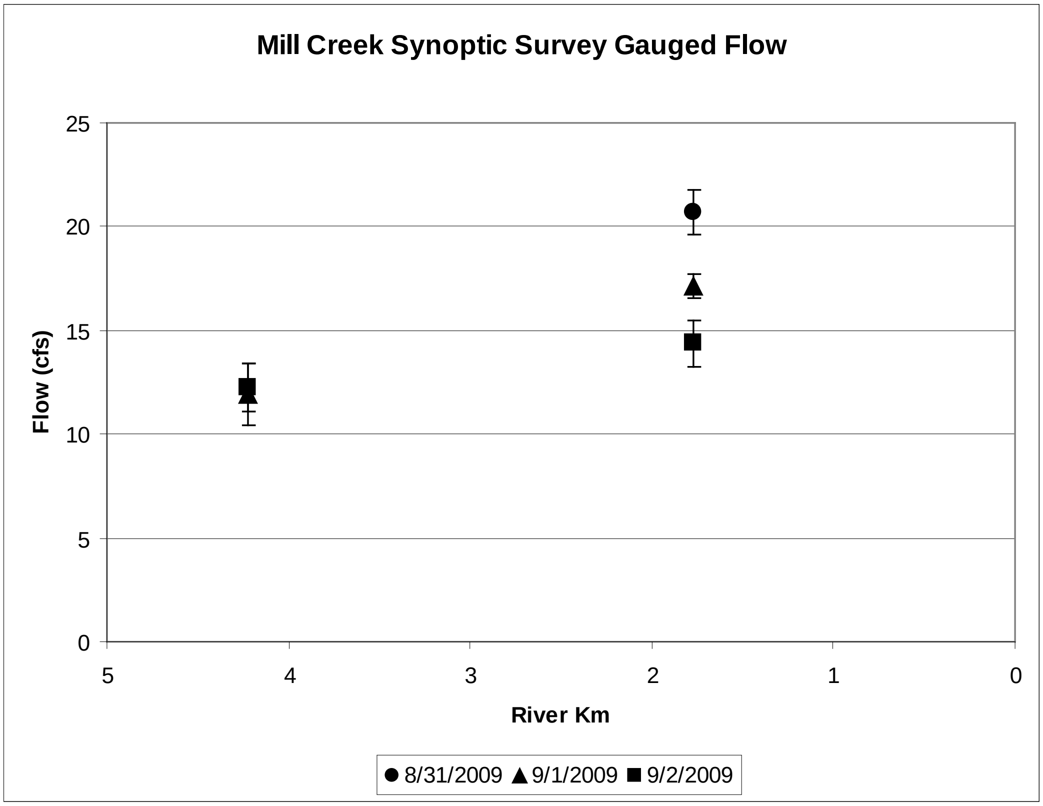
Figure 4.1 Dye concentration measurements from station MillCr-03

4.2 FLOW GAUGING

Gauged flow data suggests Mill Creek is gaining approximately 2-5 cfs of flow between the Deer Lake outlet and station MillCr-03. The most likely source of this increase is the tributary branch that drains the western half of the watershed (Figure 1.1). While no rain fell for 4 days prior to September 1st, approximately 3.3 inches of rainfall was recorded at a nearby weather station in the two weeks leading up to the survey. As a result, gauged flows show a decrease between 8/31 and 9/1 at downstream station MillCr-03.

Table 4.2 Gauged flow measurements taken during the September synoptic survey.

Station	River km	Q – 8/31 (cfs)	Q – 9/1 (cfs)	Q – 9/2 (cfs)
MillCr-02	4.23	---	11.93	12.22
MillCr-03	1.78	20.70	17.14	14.38



Figures 4.2 Gauged flows by river kilometer for the Mill Creek synoptic survey. Error bars represent estimated uncertainty of the Flow-Tracker field measurement.

4.3 WATER QUALITY

Lab water quality results show Mill Creek has slightly higher concentrations of organic nitrogen, total organic carbon, chlorophyll a and CBOD near the Deer Lake outlet headwaters (MillCr-02). In general, these parameters decrease at the downstream monitoring station as organic material is broken down by heterotrophs, settles out of the water column or diluted by incoming water (Table 4.3 and Figures 4.3 - 4.7).

Table 4.3 September 1, 2009 water quality grab synoptic survey results

Parameter	MillCr-02 (4.23 km)	MillCr-03 (1.78 km)
Temperature (Celsius)	22.3	19.2
DO (mg/L)	10.36	8.42
pH	9.03	8.34
Total Phosphorus (mg/L)	0.072	0.091
Ortho-P (mg/L)	0.014	0.022
TKN (mg/L)	1.88	1.56
NH_3 (mg/L)	<RL*	<RL*
Nitrate (mg/L)	<RL*	<RL*
5-day CBOD (mg/L)	7.21	5.5
Ultimate CBOD (mg/L)	17.9	15.5
TOC (mg/L)	11.0	9.7
Chlorophyll-*a* (µg/L)	43.1	31.4

*Indicates below laboratory method reporting limit

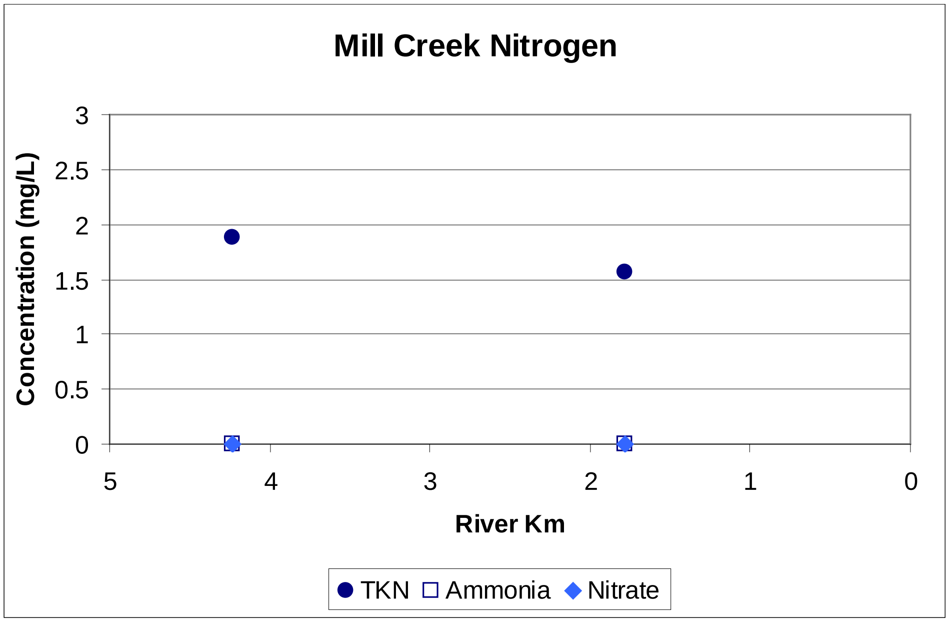


Figure 4.3 September1, 2009 synoptic survey grab lab results for Mill Creek.

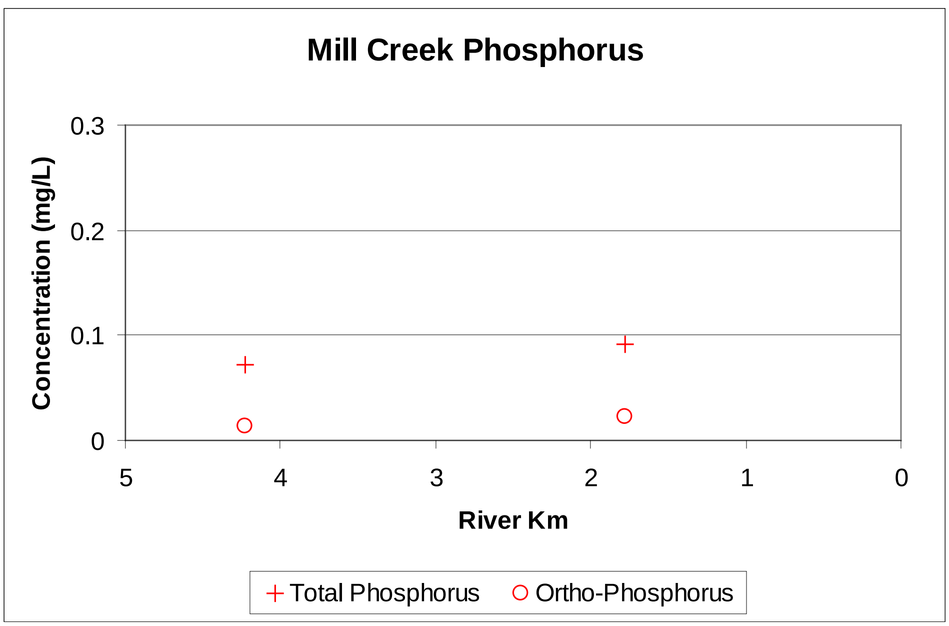


Figure 4.4 September 1, 2009 synoptic survey grab lab results for Mill Creek.

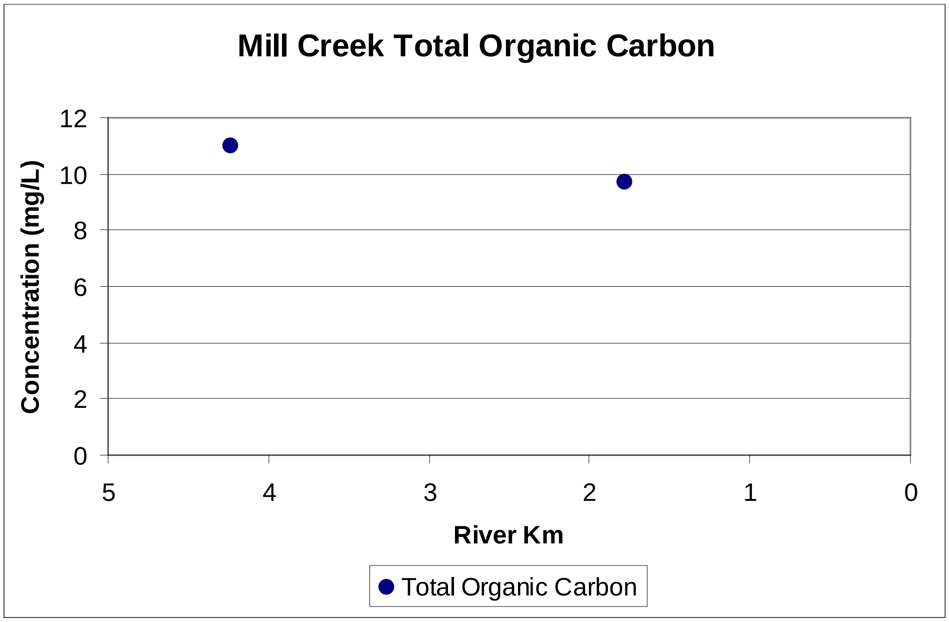


Figure 4.5 September 1, 2009 synoptic survey grab lab results for Mill Creek.

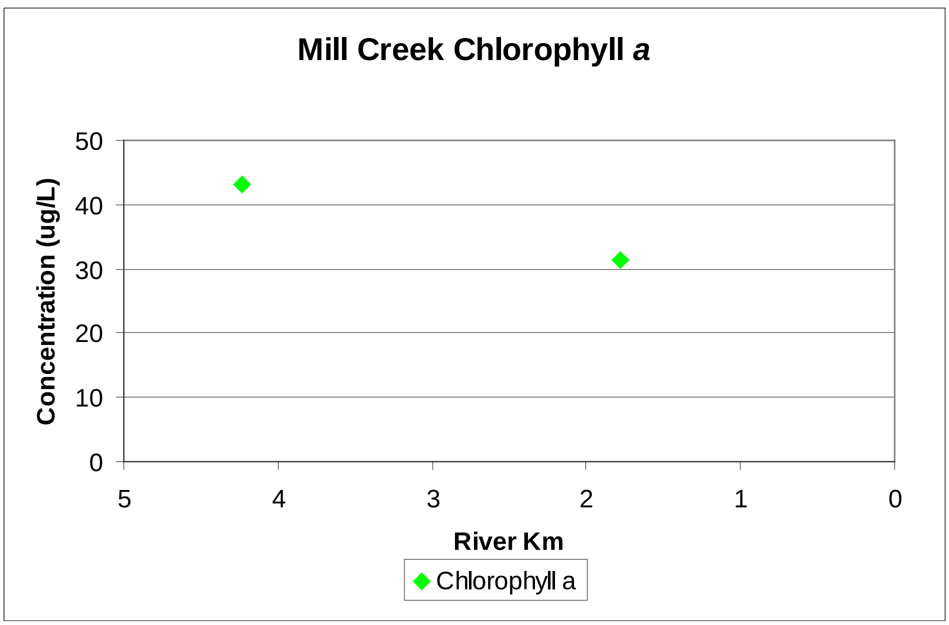


Figure 4.6 September 1, 2009 synoptic survey grab lab results for Mill Creek.

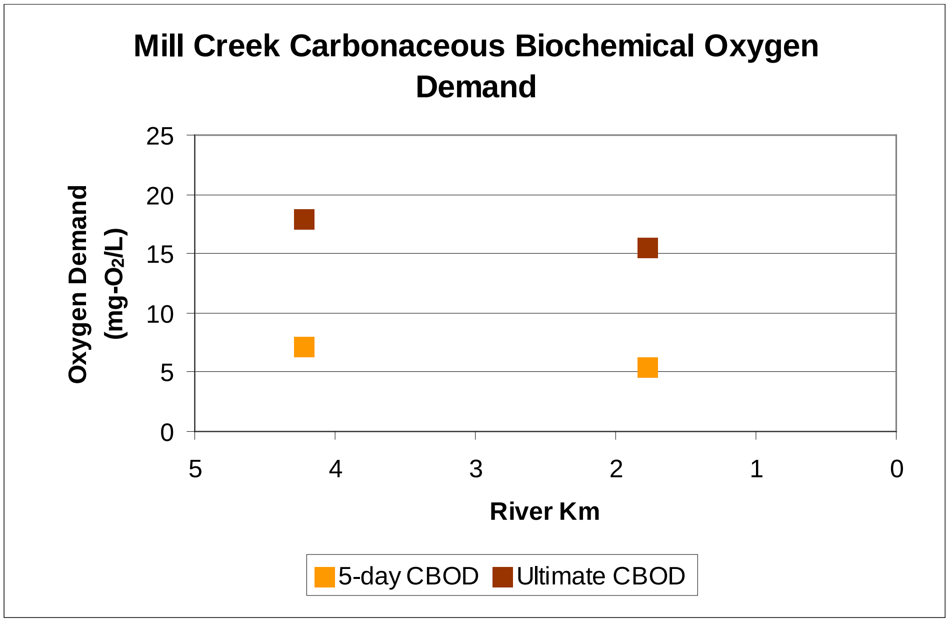


Figure 4.7 September 1, 2009 synoptic survey grab lab results for Mill Creek.

4.4 DISSOLVED OXYGEN

4.4.1 Continuous Measurements

Continuous sonde data shows station MillCr-03 was above the 5.0 mg/L dissolved oxygen standard for the entire synoptic survey (Figure 4.8). Mean DO concentrations at this station on September 1st and 2nd were 8.39 mg/L and 8.14 mg/L respectively. Diurnal DO fluctuations at this site are small over the two day survey despite relatively high chlorophyll *a* concentrations suggesting primary production was low during this time.

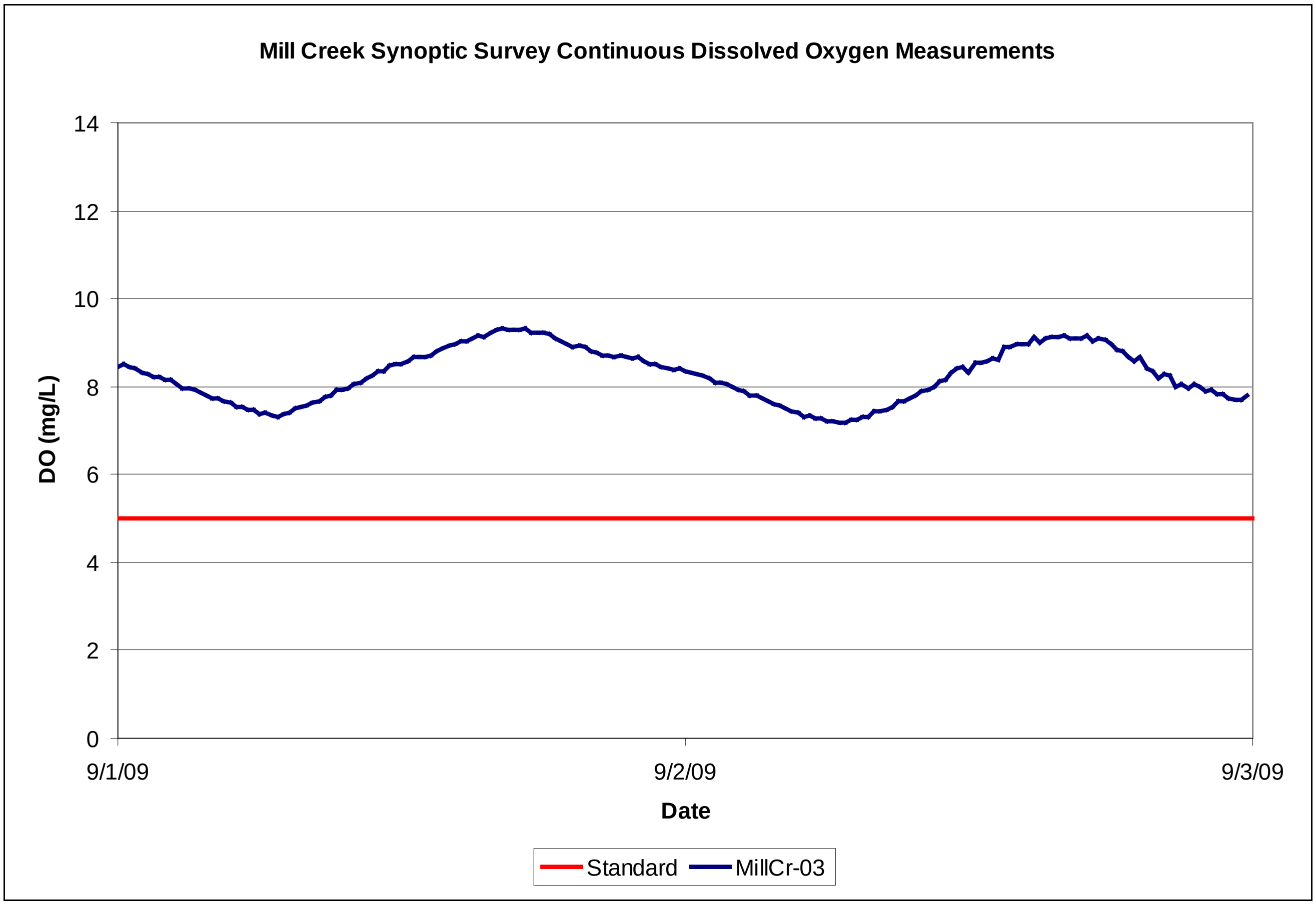


Figure 4.8 Synoptic survey continuous dissolved oxygen concentrations.

4.4.2 Longitudinal Profile

Discrete dissolved oxygen measurements were taken at the two Mill Creek monitoring station during the synoptic survey using a hand-held YSI probe to assess longitudinal variability in dissolved oxygen on 9/1/2009 and 9/2/2009. Every effort was made to take upstream to downstream within a 1-2 hour time period in order to measure spatial variability in DO while limiting the influence of biological/diurnal patterns. These profiles show dissolved oxygen concentrations decrease slightly from approximately 10 mg/L at the outlet of Deer Lake (MillCr-02) to around 8 mg/L at the downstream most monitoring station (MillCr-03) on both 9/1/09 and 9/2/09.

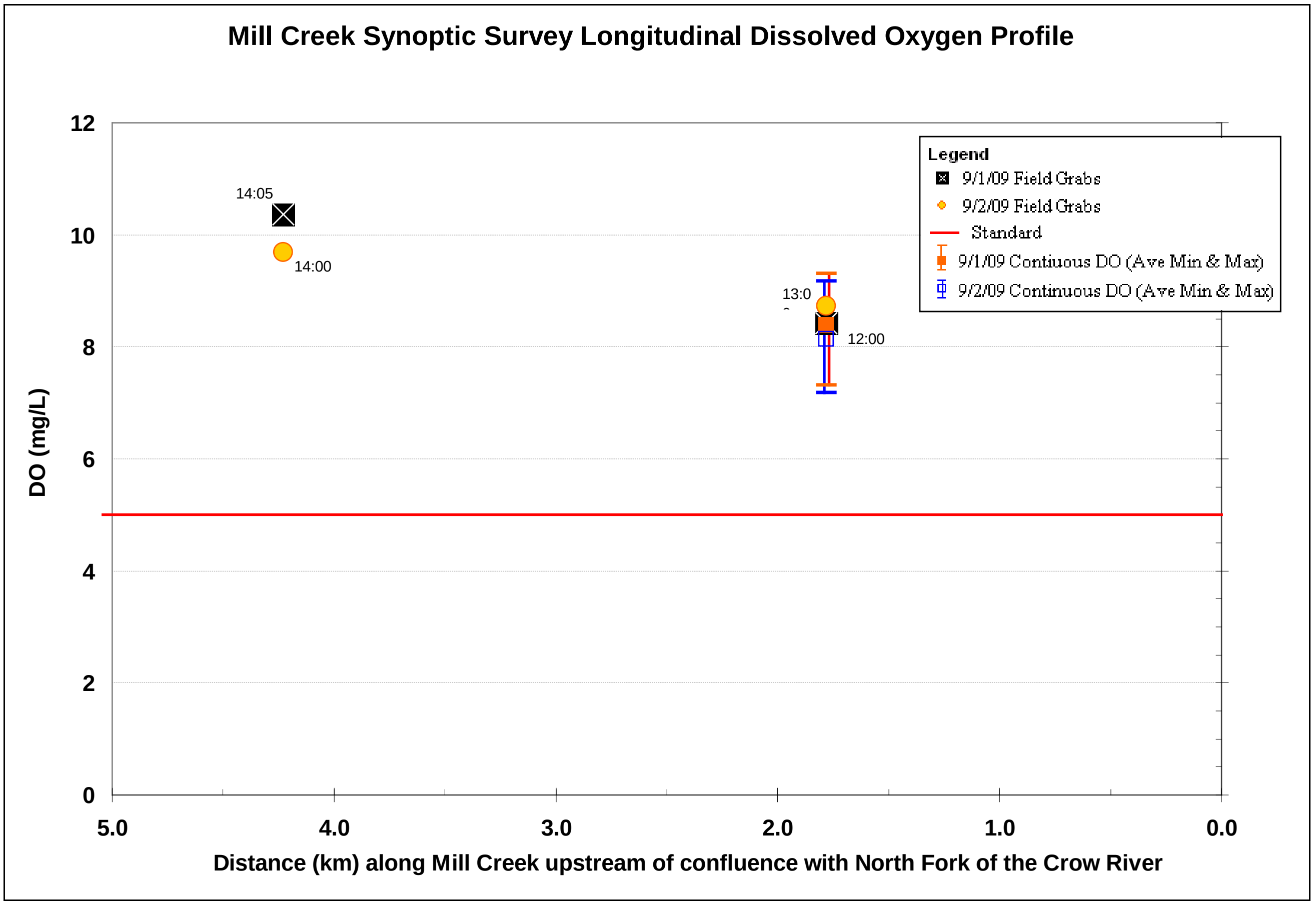


Figure 4.8 Dissolved oxygen observations during the September 2009 synoptic survey.

5.0 REFERENCES

Rantz, S.E. et al. 1982. “Measurement of Stage and Discharge”, Measurement and Computation of Streamflow, Volume 1, U.S. Geologic Survey. Water Supply Paper 2175. Washington, D.C.: Governement Printing Office.

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TECHNICAL MEMORANDUM

TO: Diane Sander, Crow River Organization of Water Watershed Coordinator

CC: Maggie Leach, MPCA Regional Impaired Waters Coordinator

FROM: Joe Bischoff, Project Manager
Pamela Massaro, P.E.
Jeff Strom

DATE: May 5, 2010

SUBJECT: ~~– DRAFT~~ Regal Creek Dissolved Oxygen TMDL

Historic Data and Synoptic Survey Methods and Results

This technical memorandum summarizes historic dissolved oxygen (DO) data for Regal Creek and the data collection methods and results for the August 2009 Regal Creek Synoptic Survey. The synoptic survey was performed to obtain the data needed to construct and calibrate a River and Stream Water Quality Model (QUAL2K) to address the Regal Creek DO impairment during low-flow conditions.

1.0 DESCRIPTION OF WATERSHED AND LISTED REACH

Regal Creek flows approximately 3.5 miles through Wright County, from its headwater wetland through St. Michael, MN to the North Fork Crow River, an Upper Mississippi River tributary (Figure 1.1). This stretch of Regal Creek (AUID 07010205-542) was listed as impaired for dissolved oxygen in 2005. The creek has a rock-sand bottom and is narrow, shallow, and moderately sloped. For the TMDL study, the Regal Creek watershed was considered to be the 7,000 - acre watershed that drains to the headwater wetland and the creek itself. Agriculture dominates the landscape: 36% of land within the watershed is used for grassland and pasture while 31% is cultivated for row crops and other agricultural uses (Table 1.1). The city of St. Michael also comprises a large portion of the watershed (22%) while forest, wetlands and lakes each account for less than 10%.

Table 1.1 Landuse summary table for Regal Creek Watershed.

Landuse Type	Acres	Percentage
Grassland/Pasture	2491	36%
Cultivated	2168	31%
Developed	1521	22%
Forest	565	8%
Wetlands	193	3%
Lakes	72	1%
Total	7009	100%

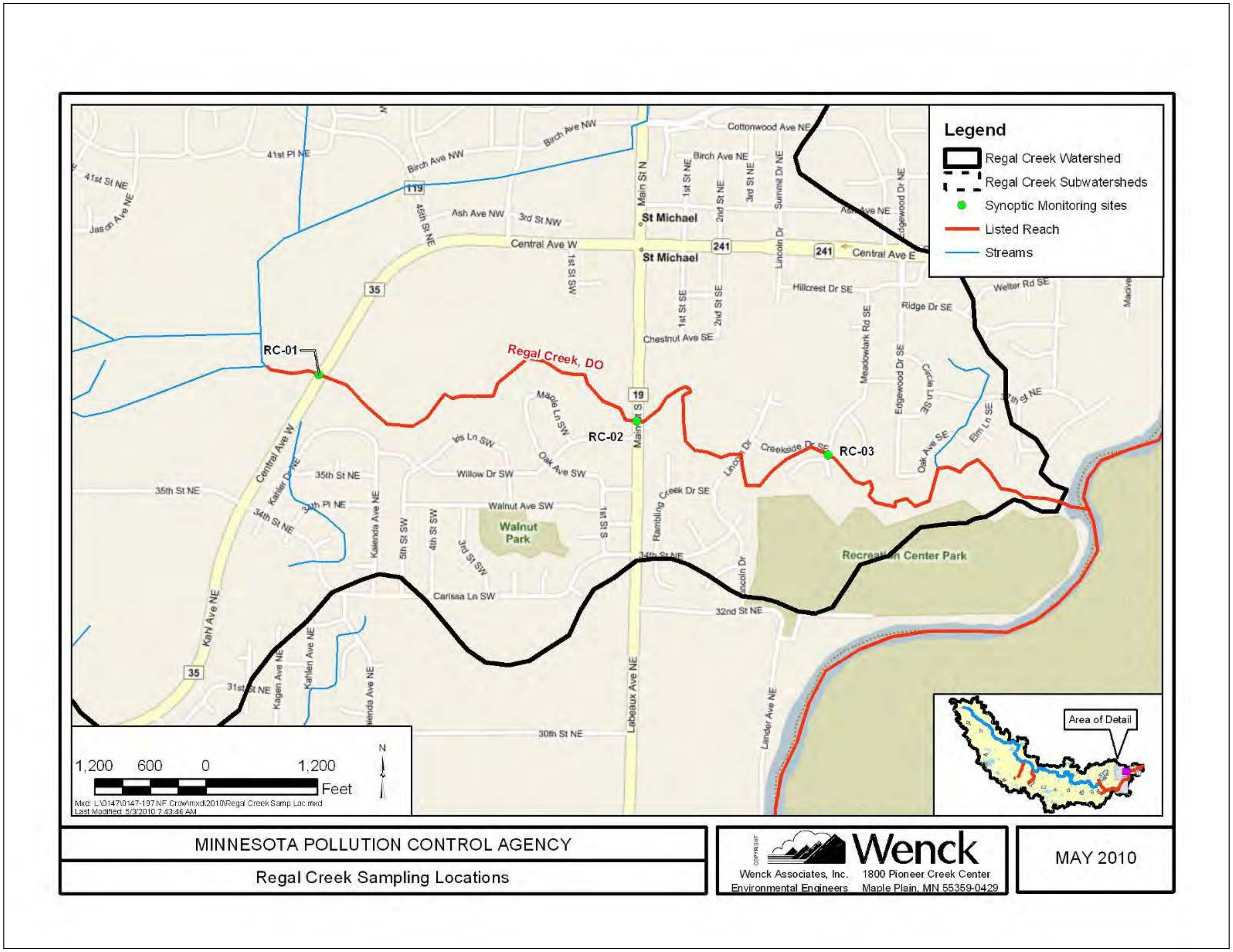


Figure1.1 Regal Creek sampling locations.

2.0 REVIEW OF REGAL CREEK DISSOLVED OXYGEN DATA

Regal Creek has three water quality stations with dissolved oxygen measurements available through the MPCA's STORET database (Figure 1.1). Station RC-02 (S002-030) was established in 2001 as the long-term monitoring station for the MPCA and the Crow River Organization of Water's intensive watershed monitoring program. Stations RC-01 (S005-834) and RC-02 (S005-835) are additional stations set-up by Wenck Associates, Inc. to sample dissolved oxygen and other water quality parameters as part of a two-day synoptic survey study that took place on August 26th and 27th, 2009 (Table 1.1).

Table2.1 Regal Creek Monitoring Stations and DO data available in STORET.

Study Station Name	STORET	Location	River Km	DO Measurements	Violations	Years
RC-01	S005-834	Regal Creek at CSAH-35 in St. Michael	3.45	2	2	09
RC-02	S002-030	Regal Creek at CSAH-19 in St. Michael	2.15	122	15	01-03; 06-09
RC-03	S005-835	Regal Creek at Meadowlark Rd in St. Michael	1.15	2	0	09

2.1 DO GRABS/FIELD MEASUREMENTS

Regal Creek is designated by state statute as a beneficial-use Class 2B water (cool/warm water fishery). This designation states that DO concentrations shall not fall below 5.0 mg/L as a daily minimum in order to support the aquatic life and recreation of the system. Seventeen of the 124 STORET DO field measurements (13%) collected on Regal Creek were below the 5.0 mg/L DO standard (Figure 2.1). Dissolved oxygen data from STORET is also plotted by month (Figure 2.2) and shows all of the violations were recorded during summer months (June-September) when water temperatures are warmer and diurnal DO swings are typically highest. Plotting DO by time of day (Figure 2.3) indicates only 44 of the 124 DO measurements were recorded prior to 9:00 am. The MPCA now recognizes measurements taken after 9:00 am do not represent daily minimums, and thus measurements greater than 5.0 mg/L dissolved oxygen later in the day are no longer considered to be indications that a stream is meeting state standards. 5 of the 80 (6%) measurements recorded after 9:00 am were in violation of the DO standard while 11 of the 44 (25%) recorded before 9:00 am were below 5.0 mg/L.

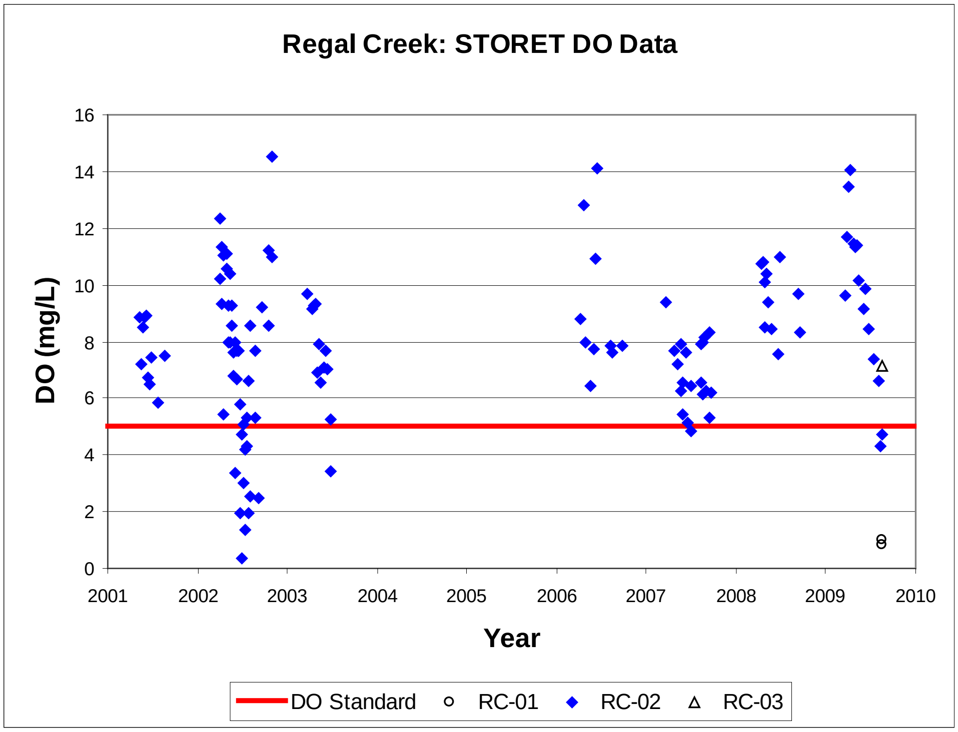


Figure 2.1 Dissolved oxygen data from STORET for all Regal Creek Stations.

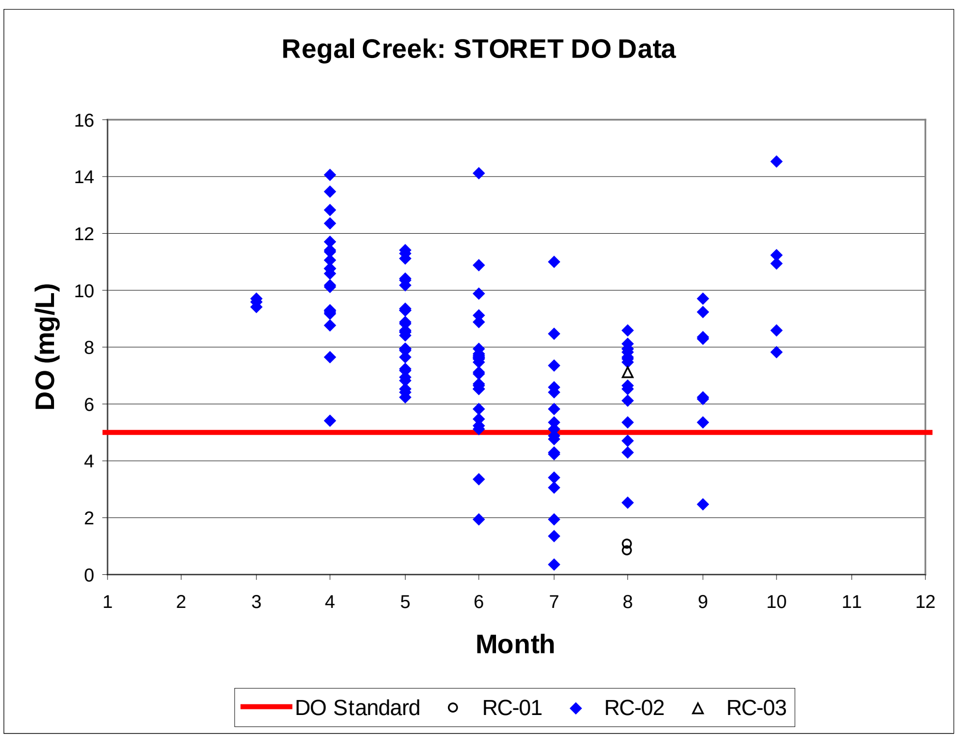


Figure 2.2 Dissolved oxygen data from STORET for all Regal Creek Stations by month, regardless of year.

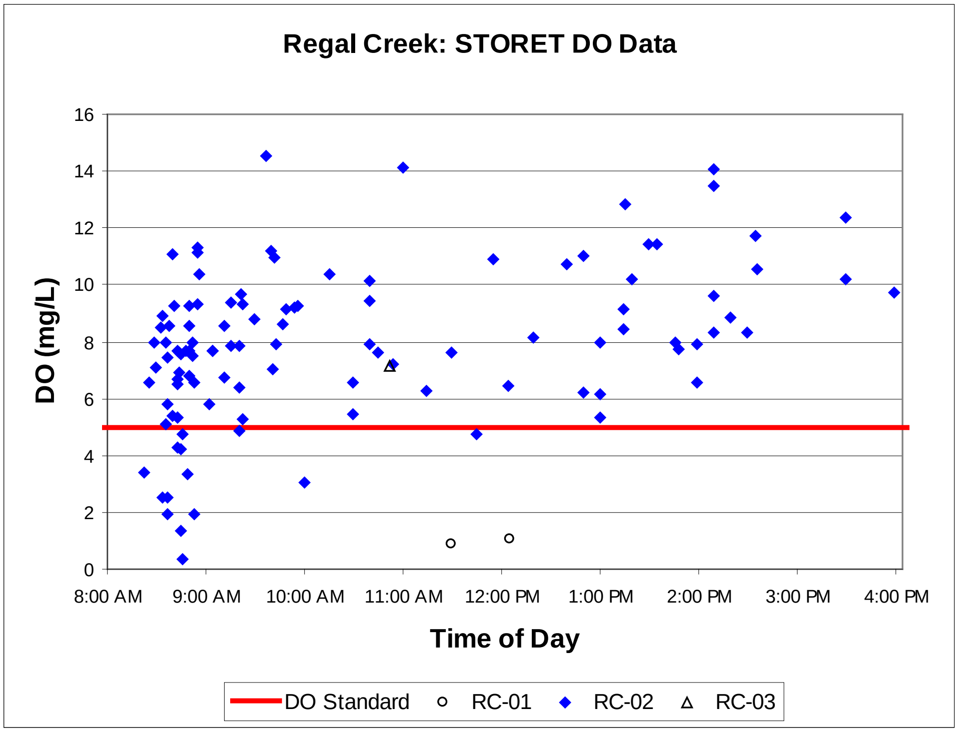


Figure 2.3 Dissolved oxygen data from STORET for all Regal Creek Stations by hour, regardless of year and month.

2.2 CONTINUOUS DO MEASUREMENTS

An in-situ YSI sensor was deployed at RC-02 (S002-030) by the MPCA during two separate time periods in 2009. This sensor records continuous measurements of dissolved oxygen, temperature, pH and conductivity. There were no violations during the first deployment (mid-April to late-May) when flows were high and water temperatures cooler thus limiting primary production (Figure 2.4). Dissolved oxygen concentrations stay at or near the 5.0 mg/L standard for the first three days of the second deployment (8/25/09 to 8/28/09) before increasing above the standard for the final 13 days of deployment (Figure 2.5).

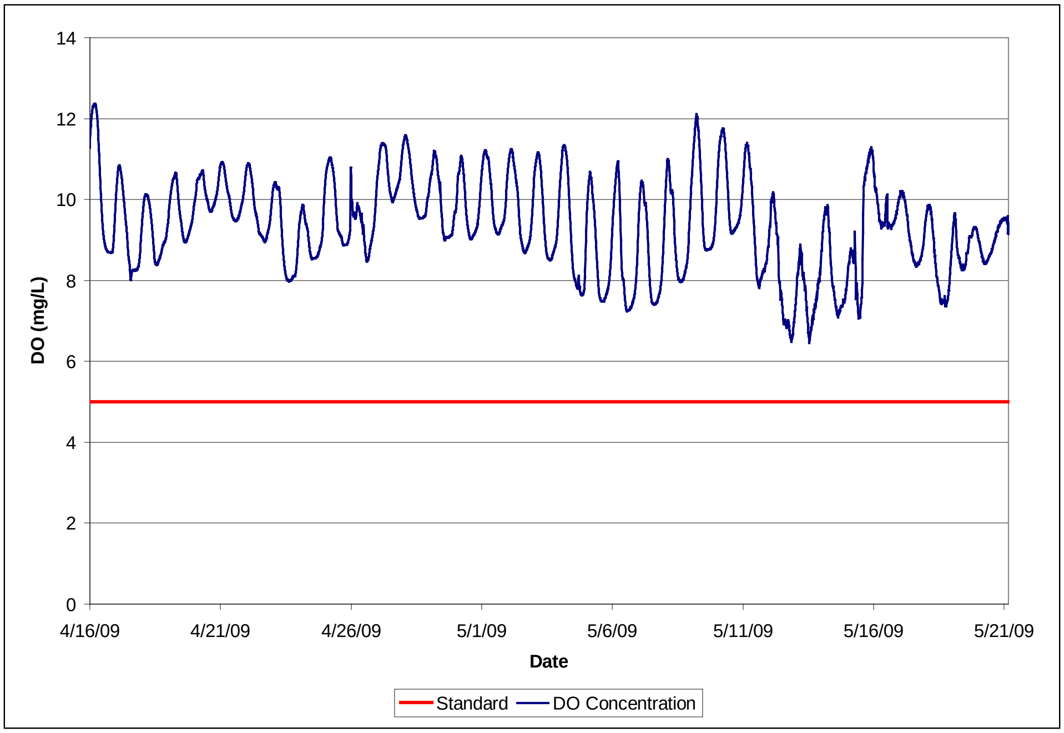


Figure 2.4 Continuous DO measurements at Station S002-030 from 4/16/09 to 5/21/2009 (preliminary data supplied by the MPCA).

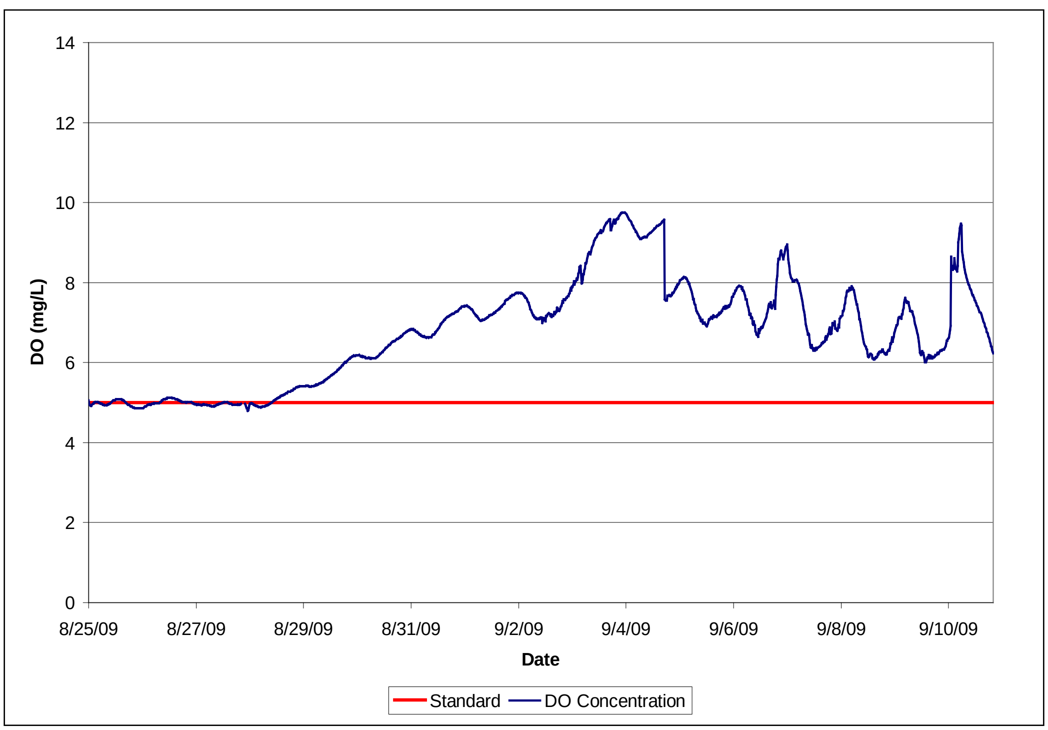


Figure 2.5 Continuous DO measurements at Station S002-030 from 8/25/09 to 9/11/2009 (preliminary data supplied by the MPCA).

3.0 SYNOPTIC SURVEY DATA COLLECTION METHODS

3.1 SAMPLING LOCATIONS

The Minnesota Department of Natural Resources (DNR) stream file shows the headwaters of Regal Creek to be the wetland system upstream of County State Aid Highway 35 (Figure 1.1). Flow was measured near the outlet of this wetland at CSAH-35 (RC-01) on August 26th, 2009. Flow at this station (~5.5 cfs) was determined suitable to represent the upstream boundary condition/headwater for the study.

Table3.1 Jewitts Creek Synoptic Survey Monitoring Locations.

Site	Location (River km)	Lab WQ Grab Station	Field Parameter WQ Station	Flow Station	Dye Station
RC-01	3.45	X	X	X	X
RC-02	2.15	CBOD only	X	X	X
RC-03	1.15	X	X	X	X

3.2 DYE STUDY

A slug of a tracer (Rhodamine WT dye) was injected at RC-01 and measured downstream at stations RC-02 and RC-03 during the synoptic survey on August 26, 2009. Dye samples were collected as grabs by field personnel or ISCO automatic samplers. Fixed stations downstream of the injection point were sampled until the dye cloud passed. The concentration of the dye in each sample was measured using an Aquafluor handheld fluorometer ("Measurement and Computation of Streamflow: Volume 1. Measurement of Stage and Discharge", p. 214).

3.3 FLOW GAUGING

Stream gauging measurements were collected in conjunction with the time of travel dye study. Flow was recorded using a SonTek Flow Tracker handheld digital velocity meter with an accuracy of 0.001 cubic feet per second. Velocity measurements were taken at 60 percent of the total depth for shallow reaches (less than 2.5 feet deep) and at 20 percent and 80 percent of the total depth for deeper reaches. Horizontal spacing of velocity measurements was set so less than 10 percent of total discharge is accounted for by any single velocity measurement. Flow gauging was conducted at each dye injection and monitoring station.

3.4 WATER QUALITY SAMPLING

Water quality data was collected on August 26, 2009 along Regal Creek (Figure 1.1). Each water sample (grab) was collected and preserved for lab analysis. The lab analyzed four of the five samples for: total kjeldahl nitrogen (TKN), ammonia nitrogen (NH_3-N), nitrate nitrogen (NO_2-N), 5-day and ultimate carbonaceous biological oxygen demand ($CBOD_{5\text{-day}}$ & $CBOD_u$), total phosphorus (TP), ortho-phosphorus (soluble reactive phosphorus), total organic carbon (TOC), and chlorophyll-*a*. One lab sample was only analyzed for $CBOD_{5\text{-day}}$ & $CBOD_u$. All five sites were monitored in the field using a data sonde (YSI Model 6920 V2) for the following additional water quality parameters: temperature, conductivity, pH, and dissolved oxygen (DO).

3.5 CONTINUOUS DISSOLVED OXYGEN MEASUREMENTS

The Minnesota Pollution Control Agency deployed one multi-parameter YSI sonde with internal logging capability to monitor continuous DO levels during the dye study and synoptic water quality survey. This instrument was deployed to monitor continuous DO concentrations at 15-minute intervals for a minimum of 72-hours before, after and during the synoptic survey. The instruments also measured and recorded other in-situ parameters such as DO saturation, temperature, conductivity, and pH.

4.0 SYNOPTIC SURVEY RESULTS

4.1 DYE STUDY

Travel times from the dye study suggest mean velocity was slower in the upper reach compared to the lower reach (Table 4.1 and Figure 4.1). Combined travel time for both reaches was less than four hours indicating residence time for Regal Creek is extremely short during this low-flow regime.

Table 4.1 Estimated travel times from the Regal Creek dye study. Travel times estimated by calculating the time between upstream injection and peak concentration measured downstream.

Reach Description	Reach Length (km)	Estimated Travel Time (hrs)	Mean Velocity (ft/sec)
Upper Reach: RC-01 to RC-02	1.30	2.33	0.51
Lower Reach: RC-02 to RC-03	1.00	1.00	0.91
Entire Reach: RC-01 to RC-03	**2.30**	**3.33**	**0.63**

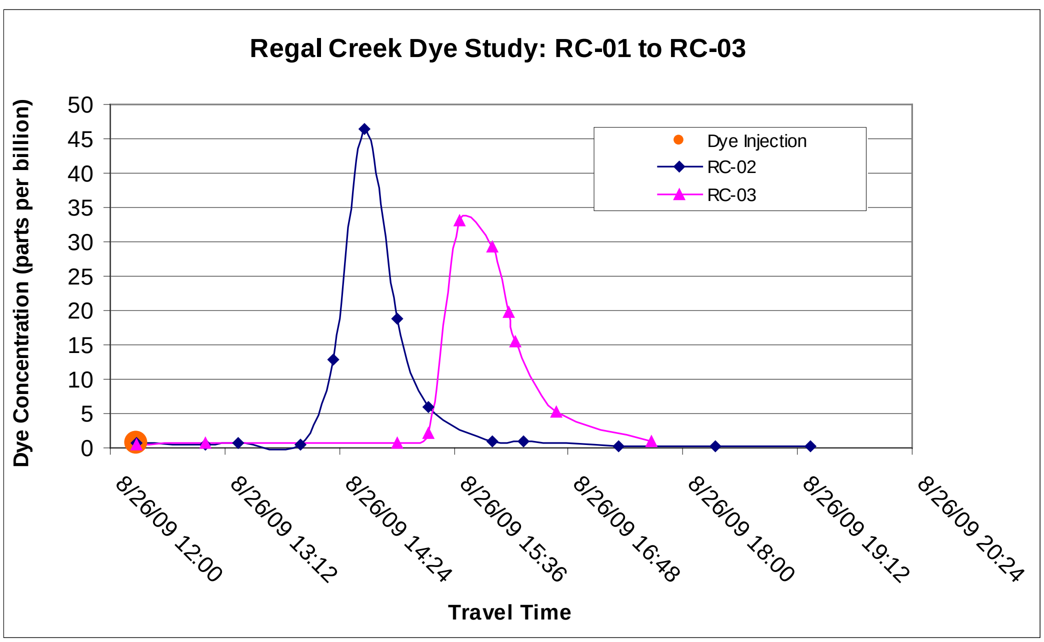


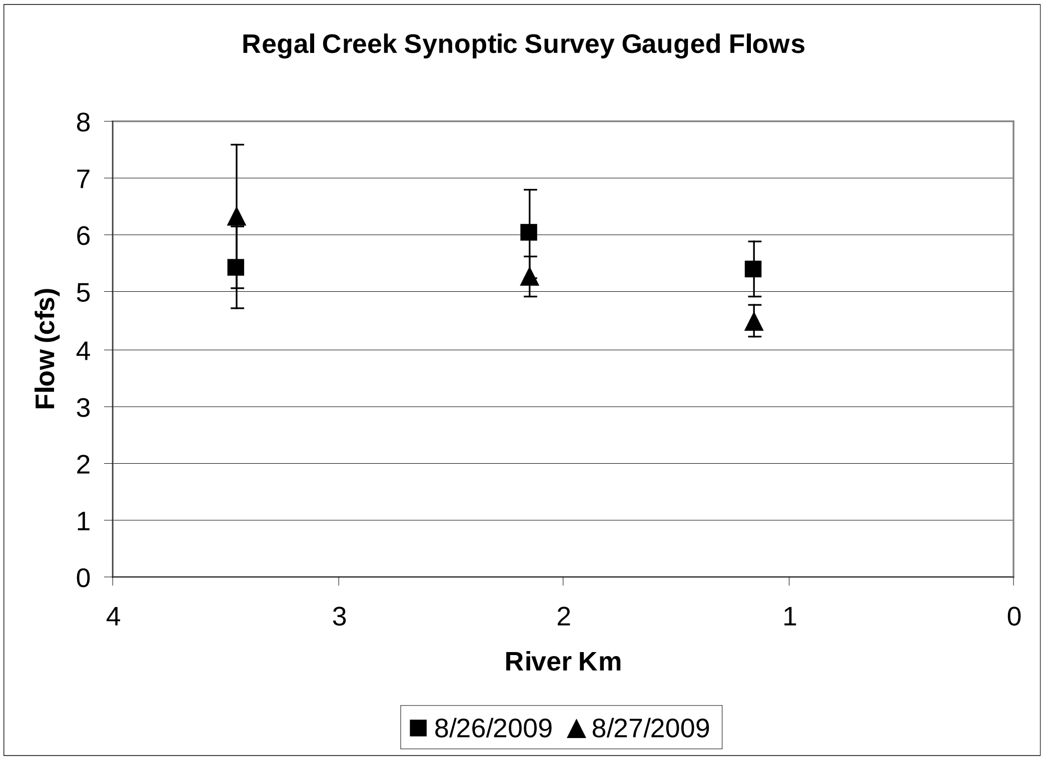
Figure 4.1 Dye concentration measurements from Regal Creek

4.2 FLOW GAUGING

Gauged flow data suggests Regal Creek may be a losing stream from RC-01 to RC-03 during this time of year. While no rain fell during the survey, approximately 2.5 inches of rainfall was recorded at a nearby weather station in the week leading up to the August 26-27 survey. As a result, gauged flows show a decrease between 8/26 and 8/27 at stations RC-02 and RC-03.

Table 4.2 Gauged flow measurements taken during the September synoptic survey.

Station	River km	Q - 8/26 (cfs)	Q - 8/27 (cfs)
RC-01	3.45	5.43	6.33
RC-02	2.15	6.03	5.28
RC-03	1.15	5.40	4.49



Figures 4.2 Gauged flows by river kilometer for the Regal Creek synoptic survey. Error bars represent estimated uncertainty of the Flow-Tracker field measurement.

4.3 WATER QUALITY

Lab water quality results show Regal Creek has slightly higher concentrations of organic-bound nutrients, organic carbon, chlorophyll-*a* and BOD near its wetland headwaters (RC-01). In general, these parameters decrease at downstream monitoring stations as organic material is broken down by heterotrophs and settles out of the water column (Table 4.3 and Figures 4.3 - 4.7).

Table 4.3 August 26th, 2009 water quality grab synoptic survey results.

Parameter	RC-01 (3.45 km)	RC-02 (2.15 km)	RC-03 (1.15 km)
Temperature (Celsius)	18.84	19.14	19.08
DO (mg/L)	0.64	4.72	7.13
pH	7.10	7.33	7.60
Total Phosphorus (mg/L)	0.52	---	0.40
Ortho-P (mg/L)	0.35	---	0.30
TKN (mg/L)	2.04	---	1.71
NH_3 (mg/L)	0.09	---	0.07
Nitrate (mg/L)	<RL*	---	0.05
5-day CBOD (mg/L)	3.64	3.26	2.90
Ultimate CBOD (mg/L)	21.0	24.2	21.1
TOC (mg/L)	18	---	17
Chlorophyll-*a* (µg/L)	10.00	---	6.89

*Indicates below laboratory method reporting limit

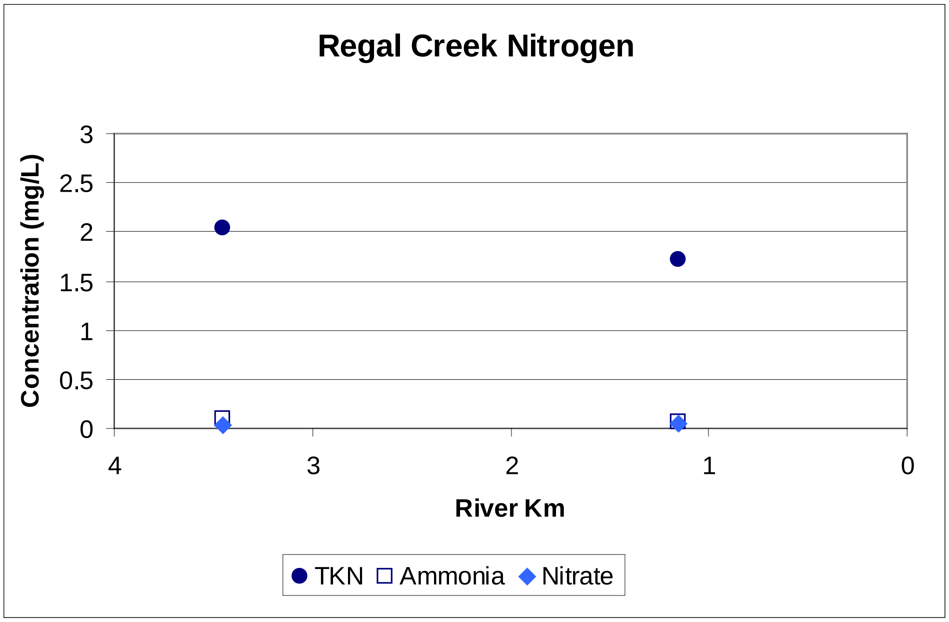


Figure 4.3 August 26, 2009 synoptic survey grab lab results for CD31.

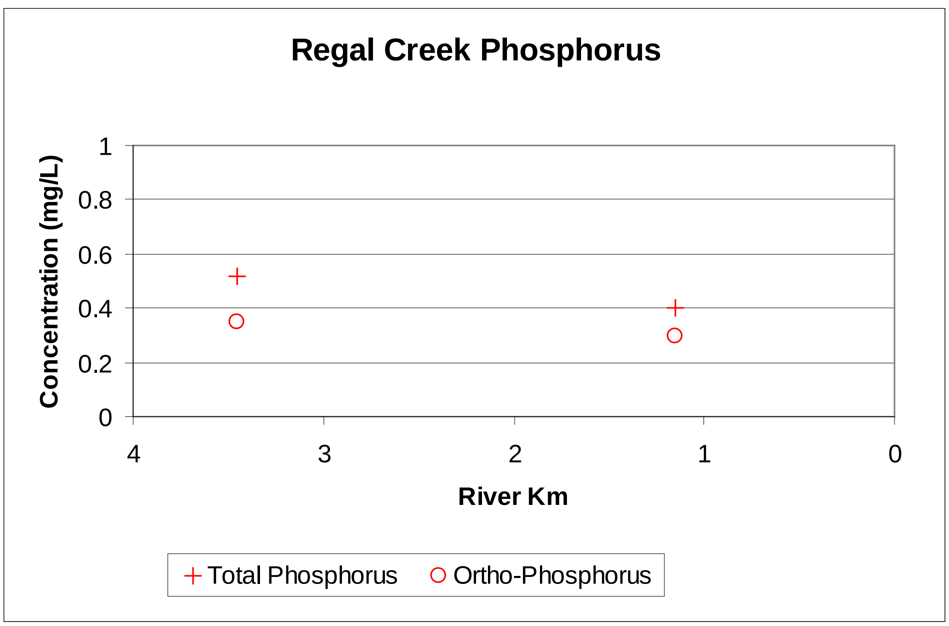
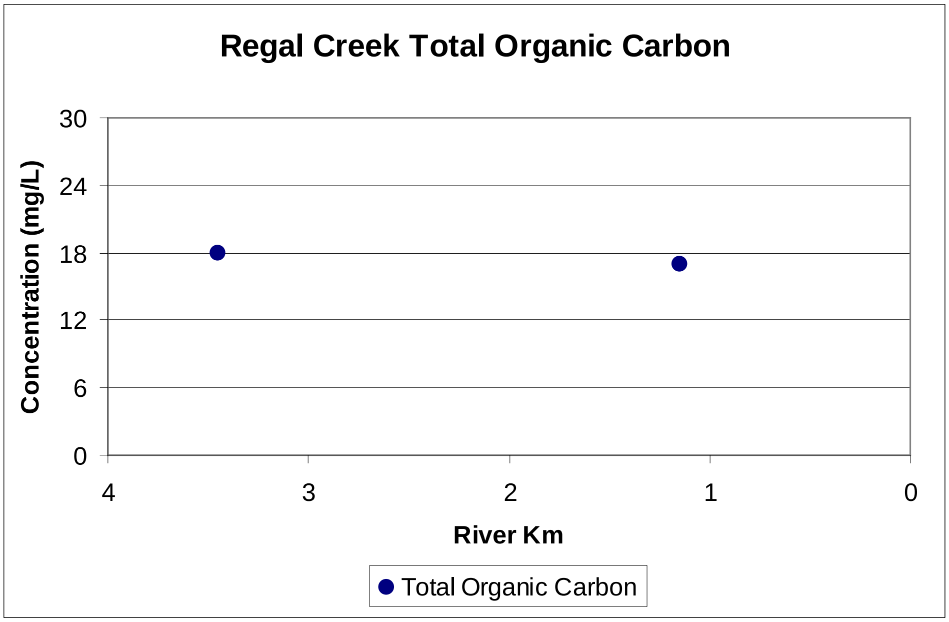
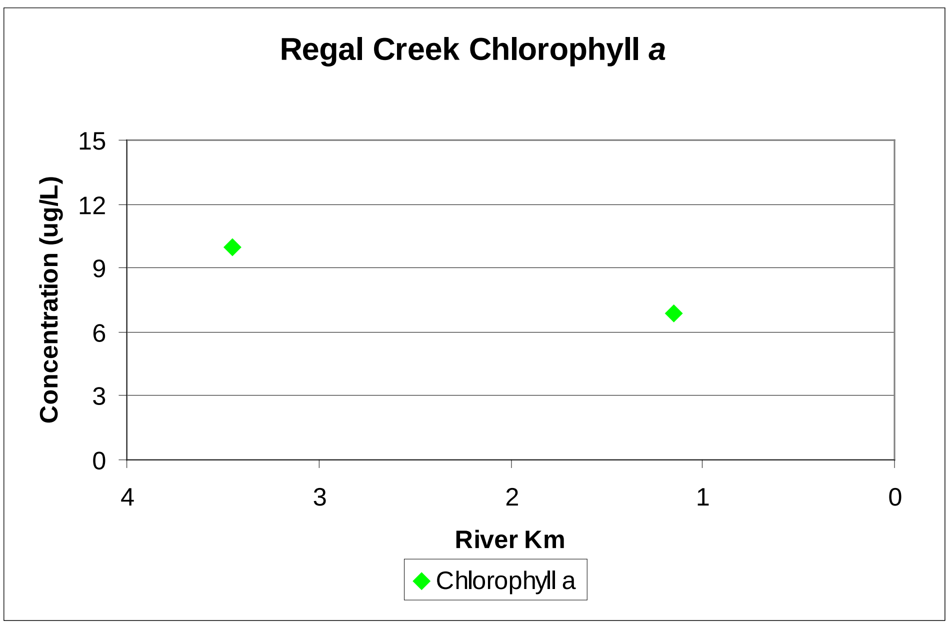


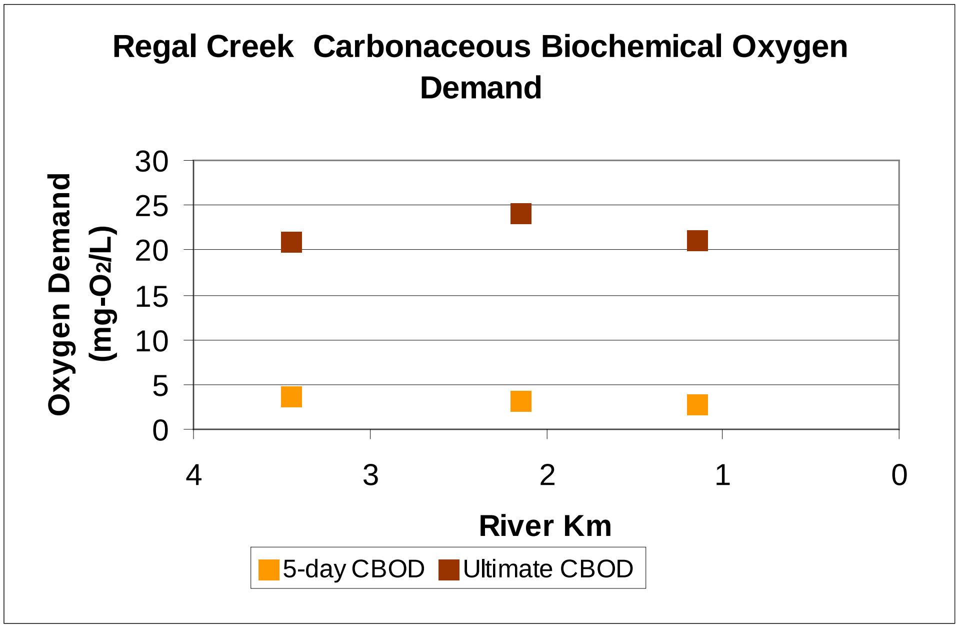
Figure 4.4 August 26, 2009 synoptic survey grab lab results for Regal Creek.



Figures 4.5 August 26, 2009 synoptic survey grab lab results for Regal Creek.



Figures 4.6 August 26, 2009 synoptic survey grab lab results for Regal Creek.



Figures 4.7 August 26, 2009 synoptic survey grab lab results for Regal Creek.

4.4 DISSOLVED OXYGEN

4.4.1 Continuous Measurements

The continuous sonde data shows no diurnal DO pattern at RC-02 during the August 26^{th} synoptic survey (Figure 2.5). Dissolved oxygen minimum on this day was 4.86 mg/L while the maximum was 5.13 mg/L suggesting there is very little in-stream primary production by algae and rooted or floating macrophytes. Diurnal DO patterns are re-established at RC-02 in early September about one week after the synoptic survey but do not fall below the 5.0 mg/L dissolved oxygen standard.

4.4.2 Longitudinal Profile

Discrete dissolved oxygen measurements were taken at three separate locations along Regal Creek using a hand-held YSI probe as part of two longitudinal dissolved oxygen surveys on 8/26/09 and 8/27/09. Every effort was made to take upstream to downstream within a 1-2 hour time period in order to measure spatial variability in DO while limiting the influence of biological/diurnal patterns. These profiles show dissolved oxygen concentrations increase from less than 1.0 mg/L near the headwaters to around 7.0 mg/L at the downstream most station on both 8/26/09 and 8/27/09. Longitudinal flow data collected at the same time as the DO measurements show no significant flow increases from upstream to downstream stations suggesting DO increases is likely driven by reaeration.

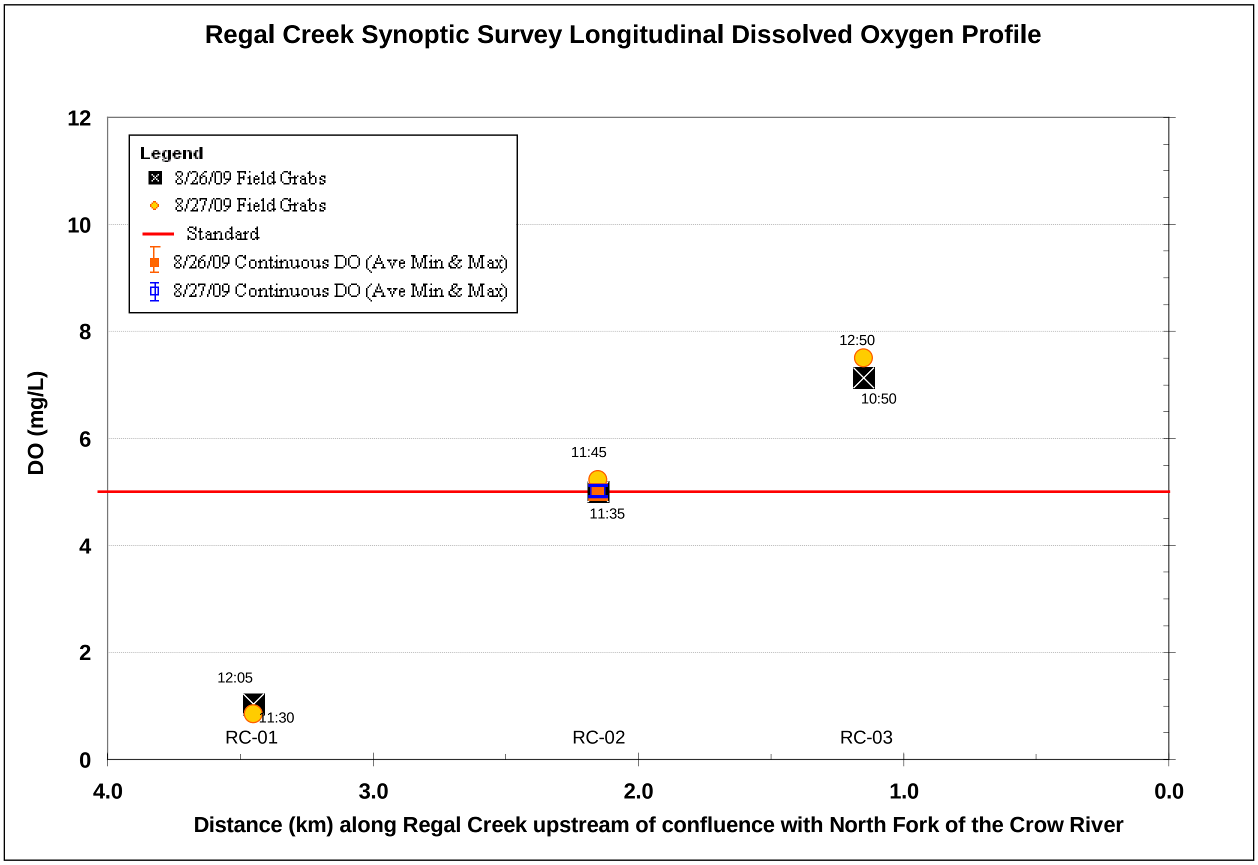


Figure 4.8 Dissolved oxygen observations during the August 2009 synoptic survey.

5.0 REFERENCES

Rantz, S.E. et al. 1982. "Measurement of Stage and Discharge", Measurement and Computation of Streamflow, Volume 1, U.S. Geologic Survey. Water Supply Paper 2175. Washington, D.C.: Governement Printing Office.

Appendix H

Dissolved Oxygen QUAL2K Model Tech Memos

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TECHNICAL MEMORANDUM

TO: Diane Sander, Crow River Organization of Water Watershed Coordinator

CC: Maggie Leach, MPCA Regional Impaired Waters Coordinator

FROM: Joe Bischoff, Project Manager
Pamela Massaro, P.E.
Jeff Strom

DATE: September, 2011

SUBJECT: County Ditch 31 Dissolved Oxygen TMDL
Description of QUAL2K Modeling Methods and Results

Wenck Associates, Inc. has developed and calibrated a QUAL2K model for County Ditch 31 from the Meridan Ave SE crossing to the Creek's confluence with the main-stem of the North Fork Crow River. The purpose of this technical memorandum is to describe the methods and assumptions used to create and calibrate the QUAL2K model.

1.0 INTRODUCTION

1.1 Model Selection

The U.S. EPA River and Stream Water Quality Model (QUAL2K) version 7 is a modernized version of the QUAL2E model developed by Dr. Steven Chapra with Tufts University and Greg Pelletier with Washington State. It was selected to analyze County Ditch 31 (CD31) because it is a relatively simple surface water quality model that can be used during steady-state conditions to model nutrient, algal and dissolved oxygen dynamics.

1.2 General Overview of Model

The model was built using late summer synoptic survey data collected on August 26^{th}-27^{th}, 2008. Stream locations and physical features were built in to the model first before proceeding to hydraulic calibration. With the diffuse flow inputs incorporated, the conservative water quality parameters (such as water temperature and conductivity) were adjusted to match monitored observations. Then, chlorophyll-*a* (phytoplankton production), nutrients (phosphorus and nitrogen components), and carbonaceous biochemical oxygen demand (CBOD) were calibrated by adjusting tributary/groundwater contributions and/or kinetic coefficients within the range of published values. In some cases, reach specific kinetic rates and in-stream nutrient fluxes were assigned to model geochemical processes believed to be unique to certain reaches. Finally, bottom algae and sediment oxygen demand were adjusted for each reach to match observed dissolved oxygen data.

2.0 MODEL SETUP AND INPUTS

The River and Stream Water Quality Model (QUAL2K version 7) covers CD31 from where it crosses Meridan Ave S near the outlet of the Woodland wetland system south-east of Montrose, MN. to its confluence with the North Fork Crow River. The stretch of the creek, explicitly modeled, represents approximately 2.58 miles (4.15 km) subdivided in to four reaches. The start of each main stem reach correlates with a monitoring station location or change in stream hydrology/morphometry (Figure 2.1, Table 2.1 and Table 2.2). There are no registered point sources that directly discharge to this stretch of CD31.

Table 2.1 Model reach characteristics.

Reach	Description	US River km	DS River km	Distance (km)	Distance (mile)
1	CD31-01 to CD31-02	4.15	2.13	2.02	1.26
2	CD31-02 to Hwy 25	2.13	1.75	0.38	0.23
3	Hwy 25 to CD31-03	1.75	0.73	1.02	0.64
4	CD31-03 to North Fork Crow	0.73	0.00	0.73	0.45

Table 2.2 Monitoring locations.

Reach	Reach Start Monitoring Location ID	Description	Data Collected
1	CD31-01	Meridan Ave SE	Q, Grab, Field
2	CD31-02	Highway 12	ToT, Q, Field, Sonde
4	CD31-03	Brighton Ave SE	ToT, Q, Grab, Field

Q = Flow gauged.
ToT = Time of Travel determined from dye study.
Grab = Water quality grab sample collected and lab analyzed for typical pollutants (total kjeldahl nitrogen (TKN), ammonia nitrogen (NH_3-N), nitrate nitrogen (NO_2-N), 5-day and ultimate carbonaceous biological oxygen demand ($CBOD_{5\text{-}day}$ & $CBOD_u$), total phosphorus (TP), ortho-phosphorus (soluble reactive phosphorus), total organic carbon (TOC), and chlorophyll-*a*).
Field = In-field measurement of temperature, conductivity, pH, and dissolved oxygen (DO).
Sonde = continuous data sonde deployed to hourly temperature, DO, pH, conductivity data

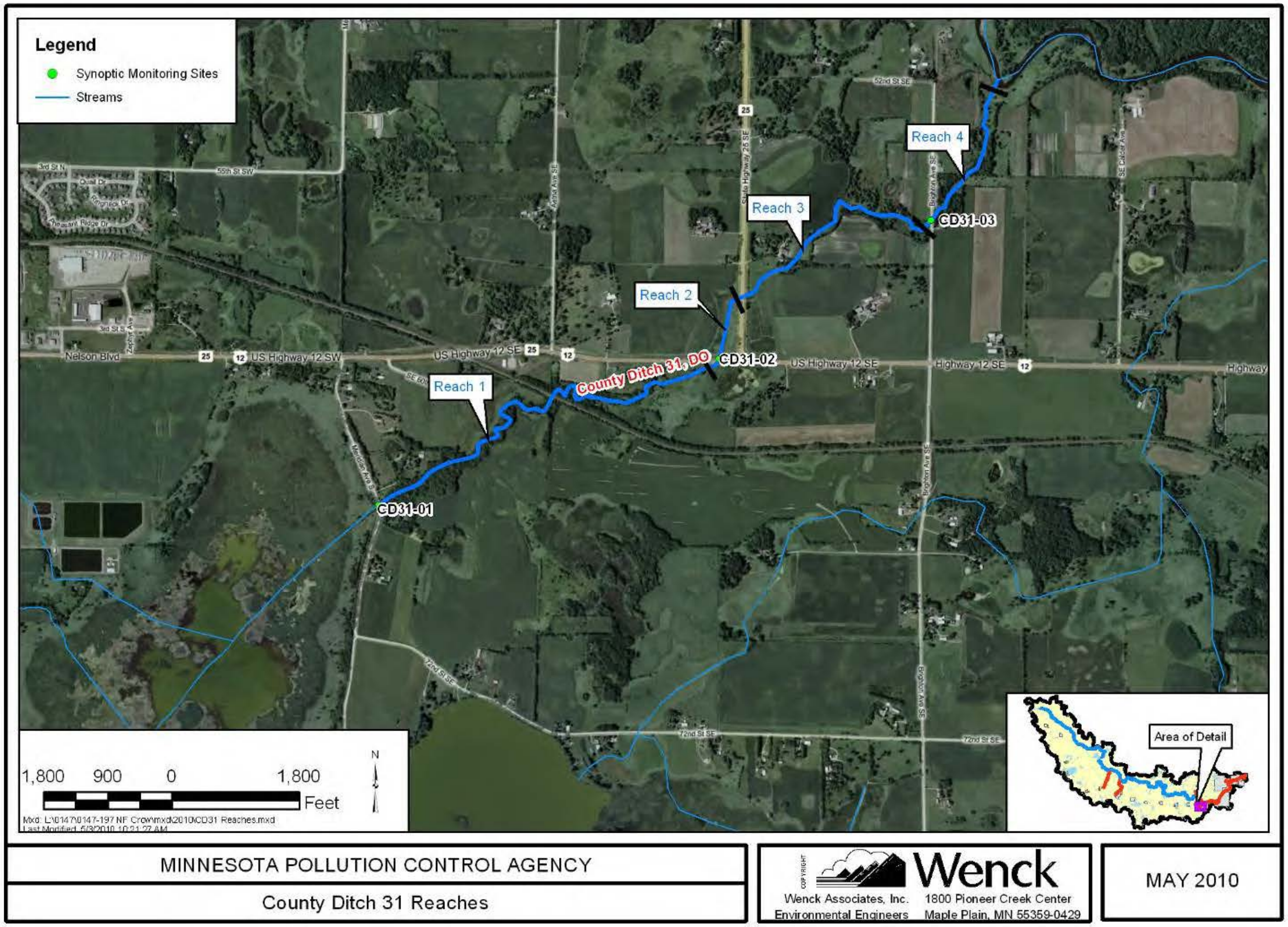

Figure 2.1 Monitoring stations and reaches on CD31.

2.1 Channel Slope

Reaeration may be prescribed by the user or calculated using one of eight hydraulic-based reaeration models built into QUAL2K. The Tsivoglou-Neal reaeration model was selected for CD31 because it is the most appropriate model to predict reaeration for flows less than 10 cfs (Tsivoglou and Neal, 1972; Thomann and Mueller, 1987). This reaeration model formula is shown below:

$K_a = 1.8 \times V \times S$ for $1 < Q < 10$ cfs

Where:
K_a = reaeration rate coefficient at 20°C (base e, day $^{-1}$)
V = average velocity (ft/s)
S = slope of energy gradient (ft/mile)

Channel slope and velocity are the variables used to calculate reaeration in each reach. Average channel slopes are based on data from an elevation survey conducted by Wenck in the fall of 2008 (Figure 2.2 and Table 2.3).

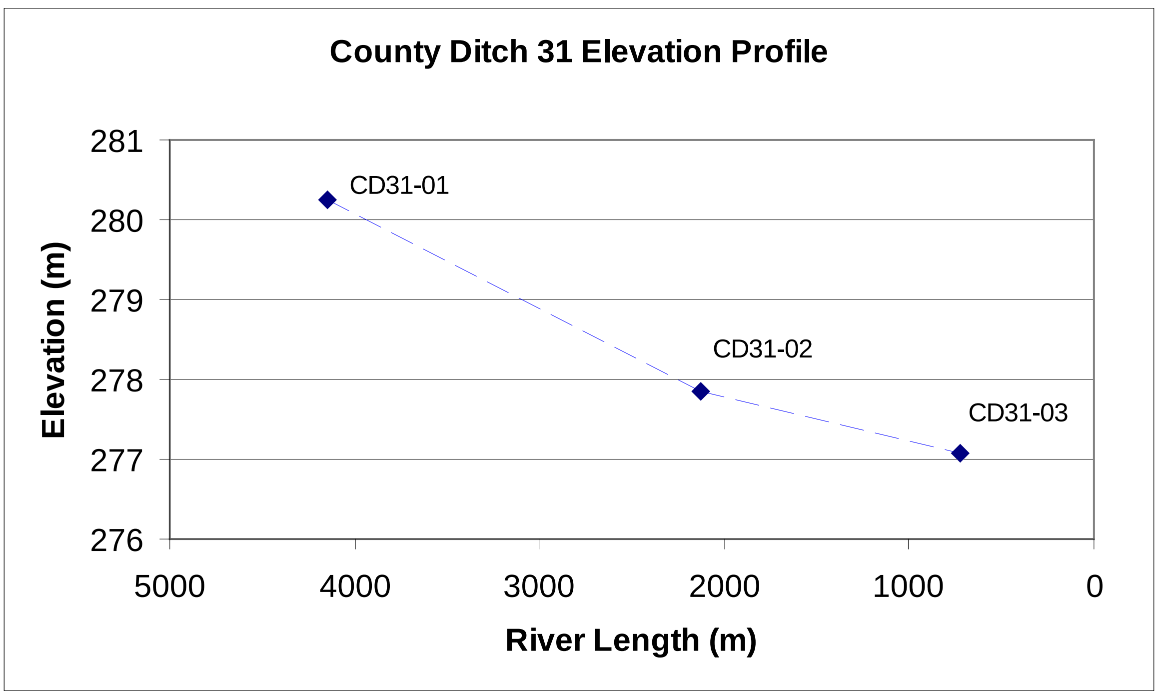

Figure 2.2 Survey elevations used to estimate reach slopes for County Ditch 31.

Table 2.3 County Ditch 31 Longitudinal Elevation Survey Summary.

Monitoring Station	River Kilometer	River Mile	Elevation (meters)	Elevation (feet)	Slope (ft/mile)
CD31-01	4.15	2.58	280.25	919.46	---
CD31-02	2.13	1.32	277.85	911.58	6.25
CD31-03	0.73	0.45	277.07	909.02	2.94
				Total Slope	4.90

2.2 Weather and Physical Processes

Hourly weather measurements of temperature, cloud conditions, relative humidity and wind speed were downloaded from the National Weather Service (NWS) NOAA Minneapolis-St. Paul Airport. Stream canopy coverage was established based on field observations and investigation of air photos in GIS (Table 2.4).

Table 2.4 County Ditch 31 canopy cover.

Reach	Description	Canopy coverage (%)
1	CD31-01 to CD31-02	40
2	CD31-02 to Hwy 25	0
3	Hwy 25 to CD31-03	15
4	CD31-03 to North Fork Crow	25

2.3 Headwaters

The Minnesota Department of Natural Resources (DNR) stream file shows County Ditch 31 headwaters to be the outflow from the Woodland wetland system south-east of Montrose, MN. Historically, the MPCA has monitored one site upstream of the Woodland wetland System (CD31-00) at Armitage Avenue. This site was visited prior to the synoptic survey and observed to be dry. Thus, all water quality and flow data collected at station CD31-01 was used to represent the upstream boundary condition/headwater in the QUAL2K model.

As noted in Table 2.2, no data sonde was deployed at the upstream boundary/headwaters (CD31-01). Field parameter data collected with the hand-held sonde at the beginning of the synoptic survey on August 26th was used to represent headwater temperature, conductivity, dissolved oxygen and pH.

2.4 Carbonaceous Biochemical Oxygen Demand (CBOD)

The old EPA model (QUAL2E) version had one type of CBOD with one decay rate. The modernized version (QUAL2K) now includes two forms of CBOD to represent organic carbon; a slowly oxidizing form (slow CBOD) and a rapidly oxidizing form (fast CBOD). This allows the model to decay CBOD at two decay rates, if deemed necessary. This model enhancement is great for waste streams with organic carbons in the form of sugar, glucose, etc.. Both 5-day CBOD ($CBOD_5$)and ultimate CBOD ($CBOD_u$)were collected at each monitoring station during the synoptic survey. $CBOD_u$ measurements were used to represent the breakdown of organic carbon over $CBOD_5$ in the model since this measurement more accurately represents total potential carbonaceous oxygen demand.

3.0 HYDRAULIC CALIBRATION

Modeled hydraulic inputs were derived from flow gauging data collected during the August 26^{th}-27^{th} synoptic survey. Total discharge was calibrated first before calibrating travel time. All hydraulic inputs and calibration adjustments are described in the following sections.

3.1 Hydraulic Rating Curves

QUAL2K hydraulics may be modeled using power function rating curves, weirs (dam/drop structures) or Manning's equations. Hydraulics for all CD31 reaches were represented using power function rating curves based on flow gauging data collected during the synoptic survey. The power function option relates mean velocity and depth to flow in each reach. QUAL2K uses five coefficients to define reach hydraulics, as follows:

- Velocity (mps) = $a\ Q^b$
- Depth (m) = $c\ Q^d + e$

in which Q is flow in cubic meters per second. Depth and velocity rating curves were constructed using gauged flow data from the time of travel study. Gauging stations with similar channel dimensions and flow characteristics were combined in to one rating curve to provide more robust velocity/depth versus flow relationships (Figures 3.1 - 3.3). Applying the principals of hydraulic geometry (Leopold and Maddock, 1953), there is on additional power function that defines channel width:

- Width (m) = $f\ Q^g$

Because the width, depth and velocity are a function of discharge, the following rules apply to the coefficients and exponents of these power functions. The sum of the exponents equal one ($b + d + g = 1.0$), and the product of the coefficients equal one ($a \times c \times f = 1.0$). The representative hydraulic rating curves for each reach was selected based on proximity to gauging stations and typical channel dimensions throughout the reach. The hydraulic coefficients and exponents for each QUAL2K reach are summarized in Table 3.1.

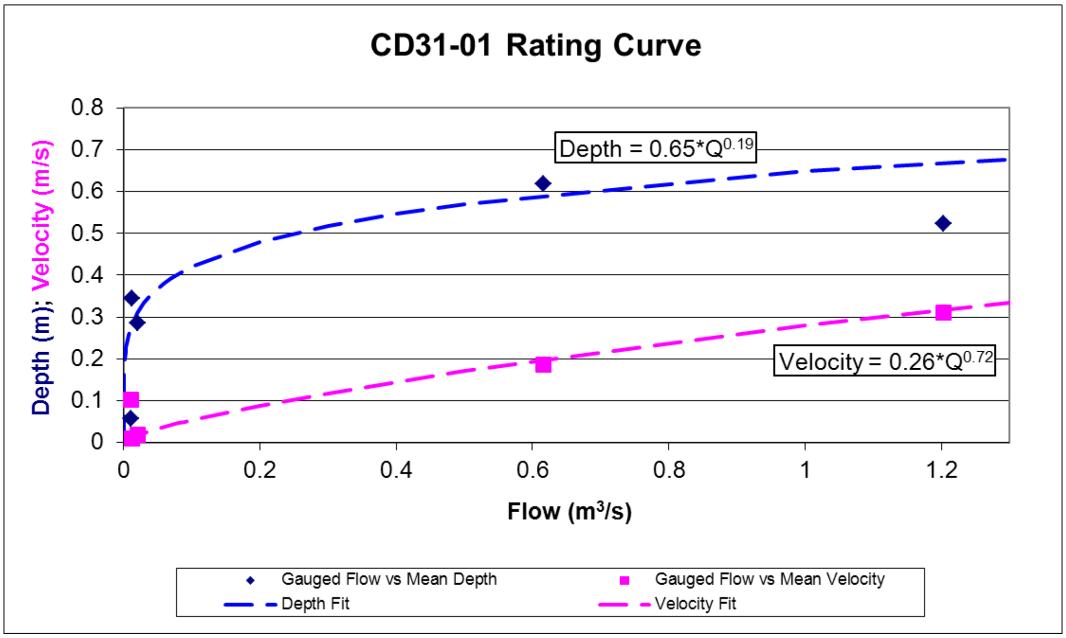

Figure 3.1 Hydraulic rating curve plot for gauging station CD31-01.

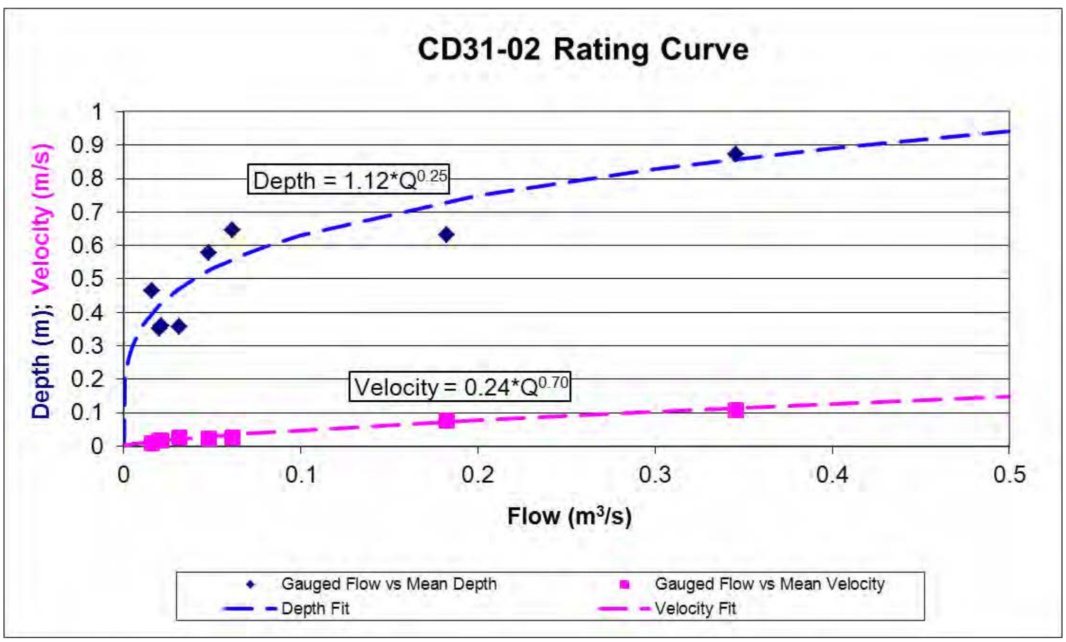

Figure 3.2 Hydraulic rating curve plot for gauging station CD31-02.

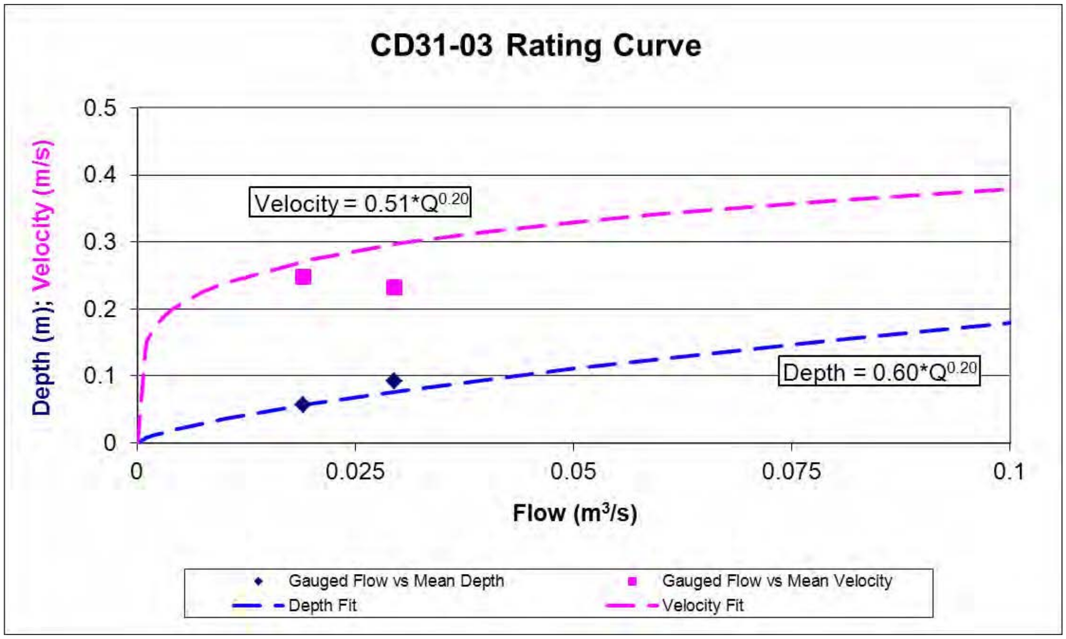

Figure 3.3 Hydraulic rating curve plot for gauging station CD31-03.

Table 3.1 Summary of hydraulic coefficients and exponents assigned to each reach.

		Velocity		Depth		
Reach	**Rating Curve used**	**Coeff.**	**Exp.**	**Coeff.**	**Exp.**	**Adjustments**
1	CD31-01*	0.26	0.72	0.65	0.19	None
2	CD31-02*	0.24	0.70	1.12	0.25	None
3	CD31-03	0.51$^{\Delta}$	0.20	0.60	0.20	Decreased velocity coefficient to match travel time
4	CD31-03*	0.51$^{\Delta}$	0.20	0.60	0.20	Decreased velocity coefficient to match travel time

* denotes that the monitoring station is at the upstream end of the reach.

Δ denotes a change in the hydraulic coefficients or exponent.

3.2 Flow Calibration

CD31 tributaries were not accessible to determine if they were contributing flow during the synoptic survey and dye study. Thus, all observed increases in flow between gauging stations were built in to the model as diffuse sources (Table 3.2). The model was deemed calibrated for total discharge once all point source and diffuse source flows were built in to the model (Figure 3.4.)

Table 3.2 Modeled diffuse source inflow for CD31.

Reach	Total Inflow throughout reach (m^3/s)	Justification
Reach 1 (CD31-01 to CD31-02)	0.004	Calculated based on flow gauging data
Reach 2+3 (CD31-02 to CD31-03)	0.003	Calculated based on flow gauging data
Reach 4 (CD31-03 to Outlet)	0.002	Calculated based on upstream flow gauging data

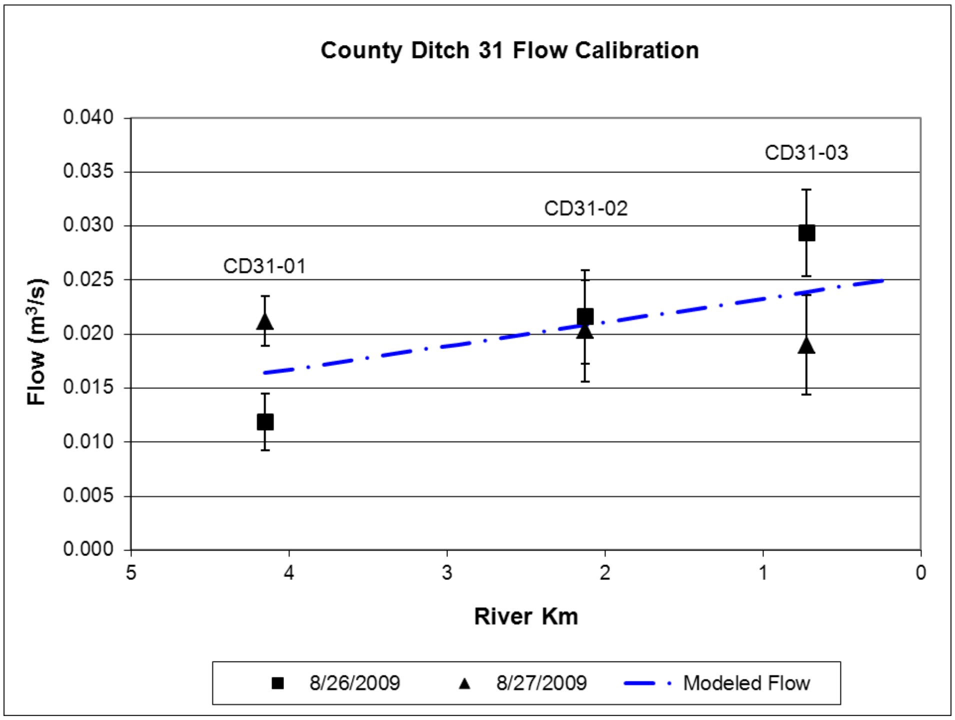

Figure 3.4 Final County Ditch 31 Flow calibration with diffuse and point source inflows.

3.3 Time of Travel Calibration

With total flow calibrated, rating curve coefficients and exponents for reaches 3 and 4 had to be adjusted slightly to lower velocity to meet time of travel measurements (Table 3.1). With total flow calibrated and the necessary hydraulic adjustments made, model predicted travel times for each reach were close to observed travel times (Figure 3.5).

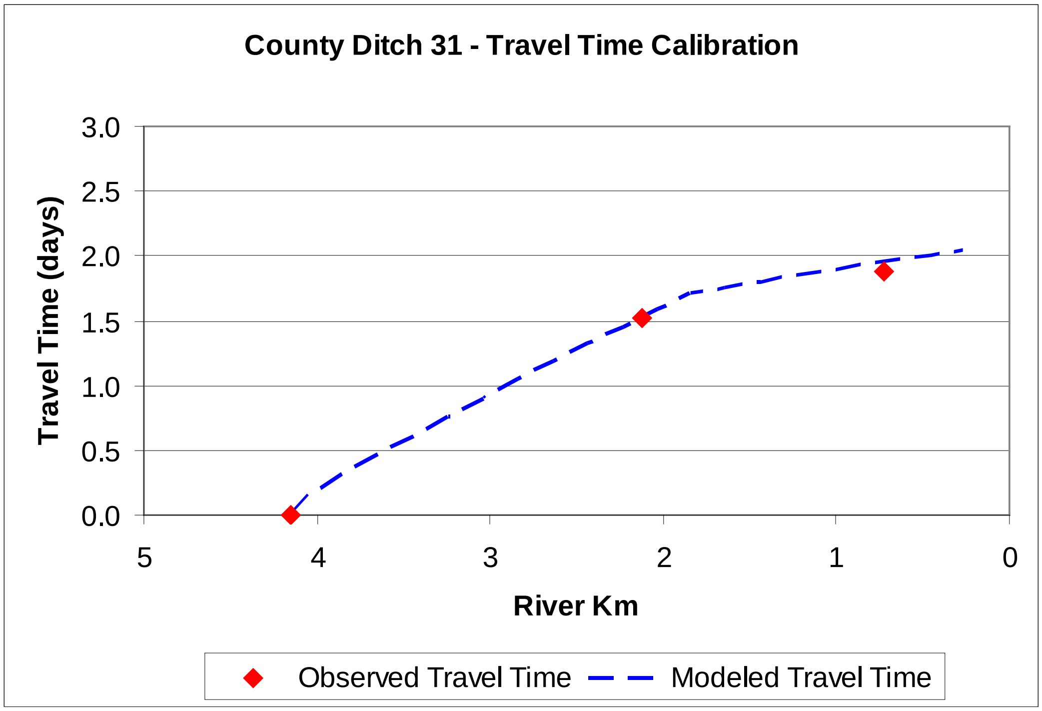

Figure 3.5 CD31 time of travel calibration.

4.0 WATER QUALITY CALIBRATION

All water quality model inputs were derived from data collected during the August 26-27, 2009 synoptic survey. Tributary and/or groundwater parameters were estimated based on literature values and calibration to in-stream water quality data. The QUAL2K model was set up to simulate temperature, flow, velocity, depth, organic nitrogen (ON), ammonia nitrogen (NH_3-N), nitrate/nitrite nitrogen (NO_2/ NO_3-N), $CBOD_u$, dissolved oxygen (DO), sediment oxygen demand (SOD), total phosphorus (TP) and chlorophyll-*a*. All model changes to global and reach specific kinetic rates as well as point source, diffuse and in-stream loadings are discussed in this section.

4.1 General Kinetic Rates

Seven kinetic rates were adjusted from model default values in order to meet longitudinal changes in observed water quality data. All kinetic rates were adjusted within the range of published values (Table 4.1).

Table 4.1 QUAL2K kinetic rates adjusted from model default values.

Rate	Calibrated Rate	Default Rate	Literature Range	Citation/Study Area
Reaeration Model	Tsivoglou and Neal	User Specified	Thomann and Mueller, 1987 cite that Tsivoglou and Neal, 1976; best for small, shallow streams (1-15 cfs)	
$CBOD_u$ oxidation rate (day^{-1})	0.23	0.23	0.02 – 0.60	Bowie et al., 1985 Table 3-17 p152 Kansas (6 rivers) Michigan (3 rivers) reported by Bansal, 1975
Organic-N Hydrolysis (day^{-1}) *The release of ammonia due to decay of organic nitrogen*	0.30	0.20	0.1 – 0.4	Baca et al., 1973
Organic-N Settling Velocity (m/d)	0.05		influenced by a material's size, shape, and density and the speed of water	
Organic-P Hydrolosis (day^{-1}) *The release of phosphate due to decay of organic phosphorus*	0.30	0.20	0.10 – 0.70	Baca et al., 1973 Baca and Arnett, 1976
Organic-P Settling Velocity (m/d)	0.05		influenced by a material's size, shape, and density and the speed of water	
Inorganic-P settling (m/d)	0.01	2.0	influenced by a material's size, shape, and density and the speed of water	
Phytoplankton Settling (m/d)	0.25	0.50	0 – 2	Bowie et al., 1985 Table 6-19 p352 Chen & Orlob, 1975 and Smith, 1978

4.2 Diffuse Source Loadings

Initially, all flow increases were assigned typical groundwater water quality values and then adjusted upward to meet in-stream water quality results (Table 4.2). All nitrogen parameters, chlorophyll *a* and $CBOD_u$ in reaches 1-4 were adjusted furthest from typical groundwater literature values. This suggests either high tributary/draintile or in-stream loading of these parameters that cannot be accounted for by adjusting model kinetic rates.

Table 4.2 Modeled diffuse source parameters for CD31.

Parameter	Reaches 1-4	Justification
Temp (C)	16	Calibrated adjustment to in-stream conditions
Sp. Cond (umhos)	900	Calibrated adjustment to in-stream conditions
DO	5.00	Calibrated adjustment to in-stream conditions
Organic- N (µg/L)	2500	Calibrated adjustment to in-stream conditions
Nitrate (µg/L)	2000	Calibrated adjustment to in-stream conditions.
Organic-P (µg/L)	11.20	Typical MN groundwater literature value (MPCA, 1999)
Inorganic-P (µg/L)	44.80	Typical MN groundwater literature value (MPCA, 1999)
$CBOD_u$ (mg O_2/L)	40 (reach 1) 20 (reach 2-3)	Calibrated adjustment to in-stream conditions.
Phytoplankton (µg/L)	30	Calibrated adjustment to in-stream conditions

4.3 Final Water Quality Calibration

$CBOD_u$, chlorophyll-*a* and all forms of nitrogen and phosphorus were calibrated once diffuse source water quality parameters and kinetic rates were properly incorporated into the model. The model performed well in predicting loads and concentrations of the primary water quality parameters that affect dissolved oxygen.

5.0 DISSOLVED OXYGEN CALIBRATION

5.1 Diurnal Oxygen Calibration

Even though water column algae was accurately depicted during water quality calibration, initial model runs predicted significantly smaller diurnal DO variability than was observed in the field. This suggests there was in-situ primary production that was not accounted for or under-represented in these model runs. QUAL2K has a bottom algae component that can simulate photosynthesis and nutrient uptake of any non-suspended algae. Bottom algae channel coverage was adjusted by reach in order to increase primary production and match the photosynthesis/respiration swings in the observed continuous DO data (Table 5.1). It is assumed that this bottom algae component represents all elements of primary production (attached algae, submerged macrophytes, rooted aquatic vegetation) that could not be measured or quantified in the field.

5.2 Sediment Oxygen Demand

Sediment oxygen demand (SOD) is calculated in QUAL2K based on the delivery and breakdown of particulate organic matter from the water column. Currently, the model does not have a macrophyte or riparian vegetation SOD component, nor does it incorporate any upland sediment transported and deposited during non-steady state storms events. The model does allow the user to assign SOD coverage (% of channel bottom) for each reach and also prescribe SOD that is added to the model predicted rate to account for SOD outside the modeling framework. SOD in streams varies depending on sediment type but is typically between 0.05 (mineral soils) and 2.00 (estuarine mud) g O_2/m^2/day (Thomann and Mueller, 1987). County Ditch 31 is a typical agricultural stream that has been ditched and straightened and, as a result, is relatively deep and slow moving during baseflow conditions. There appeared to be little or no settling/deposition during the low-flow synoptic survey as the channel sediments throughout the system were composed of soft, fine-grained particles.

Dissolved oxygen concentrations should be close to calibration as long as reasonable assumptions were made in allocating nutrient loads and adjusting kinetic rates. Model predicted dissolved oxygen concentrations for the hydraulic/phytoplankton/bottom algae/nutrient calibrated model were slightly lower than observed throughout CD31. Thus, SOD bottom coverage was decreased in each reach to ~~lower~~ increase DO concentrations to match observed values (Table 5.1).

Table 5.1 Reach specific SOD and bottom algae coverage.

Reach	Bottom SOD coverage (%)	Bottom Algae Coverage (%)	Justification
1	20	50	Wide, muddy bottomed channel, moderate rooted riparian vegetation
2	20	50	Typical muddy bottomed channel, moderate aquatic vegetation
3	20	50	Transition to channel bottoms with more sand and rock substrate
4	20	50	Transition to channel bottoms with more sand and rock substrate

5.3 Final Dissolved Oxygen Calibration

Figures 5.1 shows the final calibration results for model-predicted and observed dissolved oxygen concentrations. Field DO grabs were collected on August 26 and August 27 using the hand-held YSI and are labeled with the time of sample collection, if available. Also shown are continuous dissolved oxygen measurements for August 26th-27th (shown in plots as the range of data between minimum and maximum as orange and blue "I"). The average of the continuous DO is marked on the plot with an orange or blue box dependant on the day.

The model performs well in predicting the average daily dissolved oxygen concentration (in plot as black dashed line) at the CD31-02 monitoring station with continuous DO measurements. The model also does a good job predicting diurnal patterns (daily minimum and maximum, shown in plots as blue dashed lines).

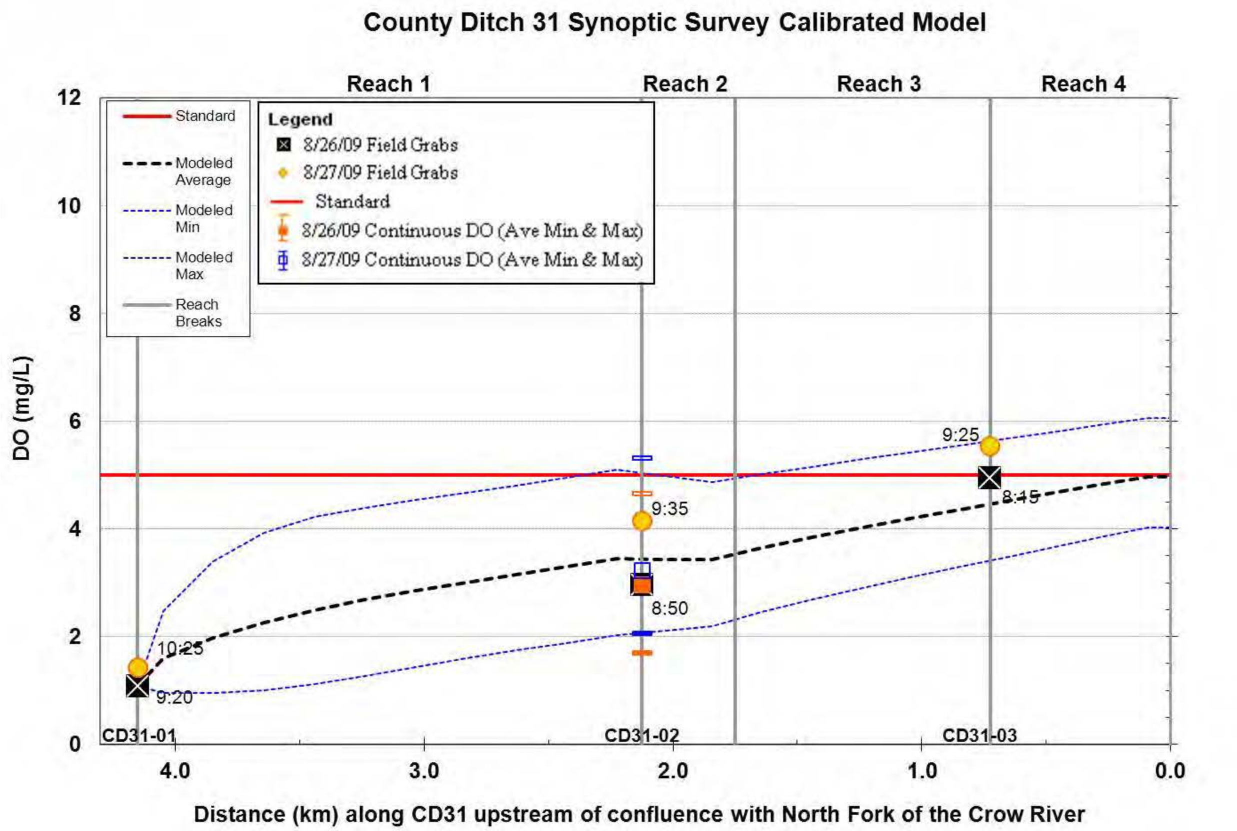

Figure 5.1 CD31 calibrated dissolved oxygen longitudinal profile.

6.0 SENSITIVITY ANALYSIS

To evaluate the sensitivity of model predicted DO to changes in model variables, seven kinetic rates (Table 6.1were adjusted by specific percentages. The following tables summarize the affect these changes have on the average model-predicted dissolved oxygen concentration for the entire modeled stretch of CD31. Results show DO throughout the system is most sensitive to the breakdown of organic carbon and nitrogen (CBOD oxidation and organic-N hydrolosis) and the kinetic rates driving SOD levels (nitrogen and phytoplankton settling). Phosphorus reactions appear to have very little affect on dissolved oxygen throughout CD31. This exercise suggests sediment processes and nitrogen transformations play the biggest role in consuming dissolved oxygen during this particular calibration/sampling event.

Table 6.1 DO sensitivity to kinetic rates.

Kinetic rate	+25%	-25%	Default
$CBOD_u$ oxidation rate (day^{-1})	-0.6%	0.9%	-0.3%
Organic-N Hydrolosis (day^{-1})	-2.8%	3.1%	4.0%
Organic-N Settling (m/d)	-1.9%	1.9%	-6.2%
Organic-P Hydrolosis (day^{-1})	0.0%	0.0%	0.0%
Organic-P Settling (m/d)	0.0%	0.0%	0.0%
Inorganic-P Settling (m/d)	0.0%	0.0%	0.0%
Phytoplankton Settling (m/d)	-0.6%	0.9%	-2.2%

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TECHNICAL MEMORANDUM

TO: Diane Sander, Crow River Organization of Water Watershed Coordinator

CC: Maggie Leach, MPCA Regional Impaired Waters Coordinator

FROM: Joe Bischoff, Project Manager
Pamela Massaro, P.E.
Jeff Strom

DATE: September, 2011

SUBJECT: Grove Creek Dissolved Oxygen TMDL
Description of QUAL2K Modeling Methods and Results

Wenck Associates, Inc. has developed and calibrated a QUAL2K model for Grove Creek from the U.S. Highway 12 crossing to the Creek's confluence with the main-stem of the North Fork Crow River just downstream of Meeker County Road 30 near Manannah, MN. The purpose of this technical memorandum is to describe the methods and assumptions used to create and calibrate the QUAL2K model.

1.0 INTRODUCTION

1.1 Model Selection

The U.S. EPA River and Stream Water Quality Model (QUAL2K) version 7 is a modernized version of the QUAL2E model developed by Dr. Steven Chapra with Tufts University and Greg Pelletier with Washington State. It was selected to analyze Grove Creek because it is a relatively simple surface water quality model that can be used during steady-state conditions to model nutrient, algal and dissolved oxygen dynamics.

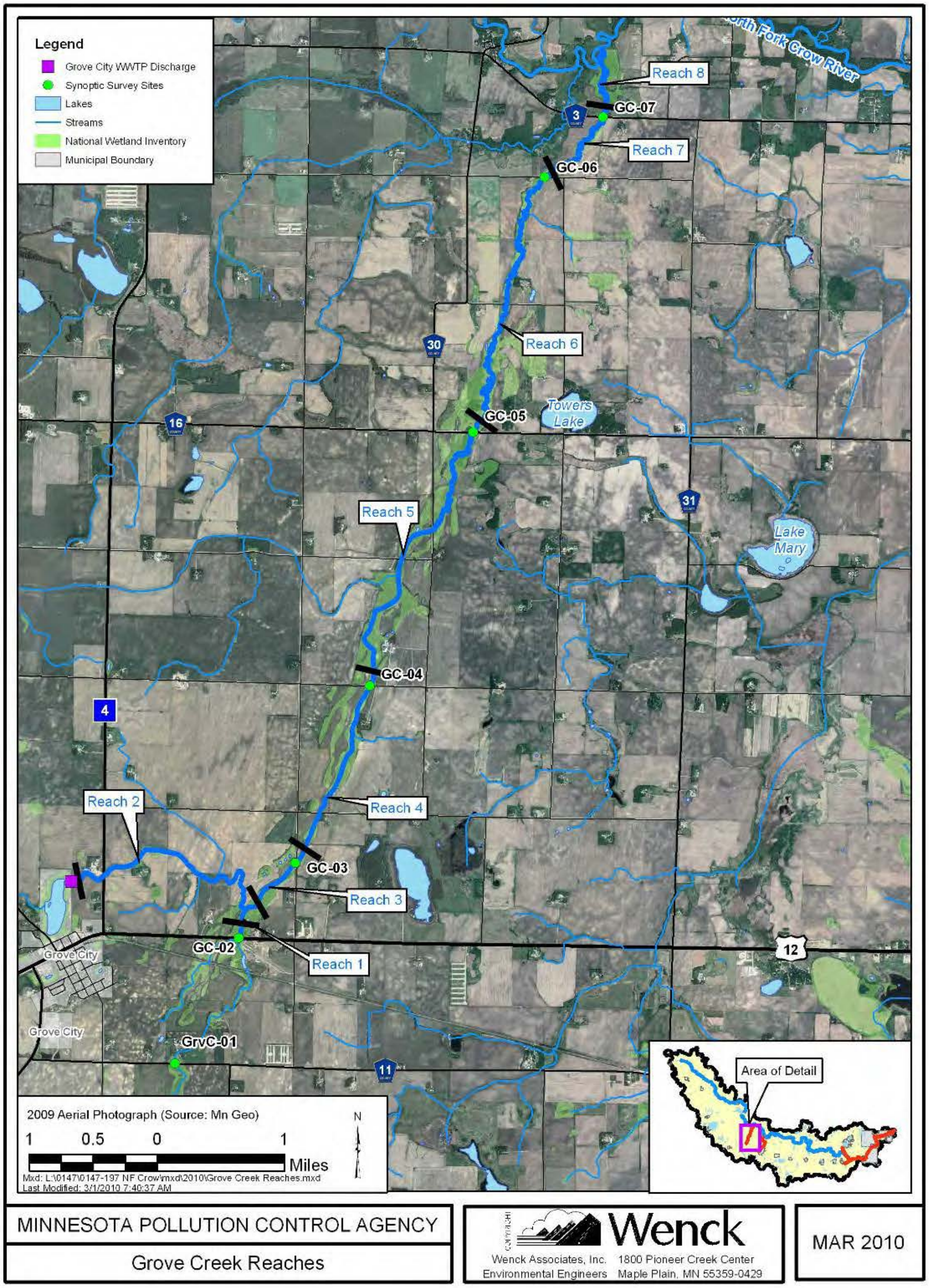

Figure 1.1 Monitoring stations and reaches on Grove Creek.

1.2 General Overview of the Model

The model was built using late summer synoptic survey data collected on September 3-4, 2008. Stream locations and physical features were built in to the model first before proceeding to hydraulic calibration. With the diffuse flow inputs incorporated, the conservative water quality parameters (such as water temperature and conductivity) were adjusted to match monitored observations. Then, chlorophyll-*a* (phytoplankton production), nutrients (phosphorus and nitrogen components), and carbonaceous biological oxygen demand (CBOD) were calibrated by adjusting tributary/groundwater contributions and/or kinetic coefficients within the range of published values. In some cases, reach specific kinetic rates and in-stream nutrient fluxes were assigned to model geochemical processes believed to be unique to certain reaches. Finally, bottom algae and sediment oxygen demand was adjusted for each reach to match observed dissolved oxygen data.

2.0 MODEL SETUP AND INPUTS

The River and Stream Water Quality Model (QUAL2K version 7) covers the main stem of Grove Creek from where it crosses US Highway 12 East of Grove City to its confluence with the North Fork Crow River. The stretch of the creek, explicitly modeled, represents approximately 10.4 main stem miles (16.67 km) subdivided in to seven reaches as well as one 2.0 mile (3.22 km) tributary reach. The start of each main stem reach correlates with a monitoring station location (Figure 1.1, Table 2.1 and Table 2.2). No data was collected for the tributary reach nor did there appear to be a large flow increase between gauging stations where this tributary enters the main-stem. Therefore, it was assumed the only source of flow in this section was the Grove City wastewater treatment facility (WWTF) located at the headwater of this reach.

Table 2.1 Model reach characteristics.

Reach	Description	US River km	DS River km	Distance (km)	Distance (mile)
1	GC-02 to tributary inflow	16.67	16.30	0.37	0.23
2 (tributary reach)	Grove City WWTF discharge to tributary outflow to Grove Creek	3.21	0.00	3.21	1.99
3	Tributary inflow to GC-03	16.30	15.37	0.93	0.58
4	GC-03 to GC-04	15.37	12.91	2.46	1.53
5	GC-04 to GC-05	12.91	8.46	4.45	2.77
6	GC-05 to GC-06	8.46	3.44	5.02	3.12
7	GC-06 to GC-07	3.44	1.61	1.83	1.14
8	GC-07 to outflow to North Fork Crow River	1.61	0.00	1.61	1.00

Table 2.2 Monitoring locations.

Reach	Reach Start Monitoring Location ID	Description	Data Collected
n/a	GC-01	273rd Street	None
1	GC-02	US Highway 12	Q, Grab, Field
4	GC-03	560th Avenue	Q, Field
5	GC-04	300th Street	Q, Grab, Field
6	GC-05	County Road 16	Q, Grab, Field, ToT
7	GC-06	340th Street	Field
8	GC-07	County Road 3	Q, Grab, Field, ToT

Q = Flow gauged.
ToT = Time of Travel determined from dye study.
Grab = Water quality grab sample collected and lab analyzed for typical pollutants (total kjeldahl nitrogen (TKN), ammonia nitrogen (NH_3-N), nitrate nitrogen (NO_2-N), 5-day and ultimate carbonaceous biological oxygen demand ($CBOD_{5\text{-day}}$ & $CBOD_u$), total phosphorus (TP), ortho-phosphorus (soluble reactive phosphorus), total organic carbon (TOC), and chlorophyll-*a*).
Field = In-field measurement of temperature, conductivity, pH, and dissolved oxygen (DO).

2.1 Channel Slope

Reaeration may be prescribed by the user or calculated using one of eight hydraulic-based reaeration models built in to QUAL2K. The Tsivoglou-Neal reaeration model was selected for Grove Creek because it is the most appropriate model to predict reaeration for flows less than 10 cfs (Tsivoglou and Neal, 1972; Thomann and Mueller, 1987). This reaeration model formula is shown below:

$$K_a = 1.8 \times V \times S \qquad \text{for} \qquad 1 < Q < 10 \text{ cfs}$$

Where:
K_a = reaeration rate coefficient at 20°C (base e, day $^{-1}$)
V = average velocity (ft/s)
S = slope of energy gradient (ft/mile)

Channel slope and velocity are the variables used to calculate reaeration in each reach. Average channel slopes are based on data from an elevation survey conducted by Wenck in the fall of 2008 (Figure 2.1 and Table 2.3).

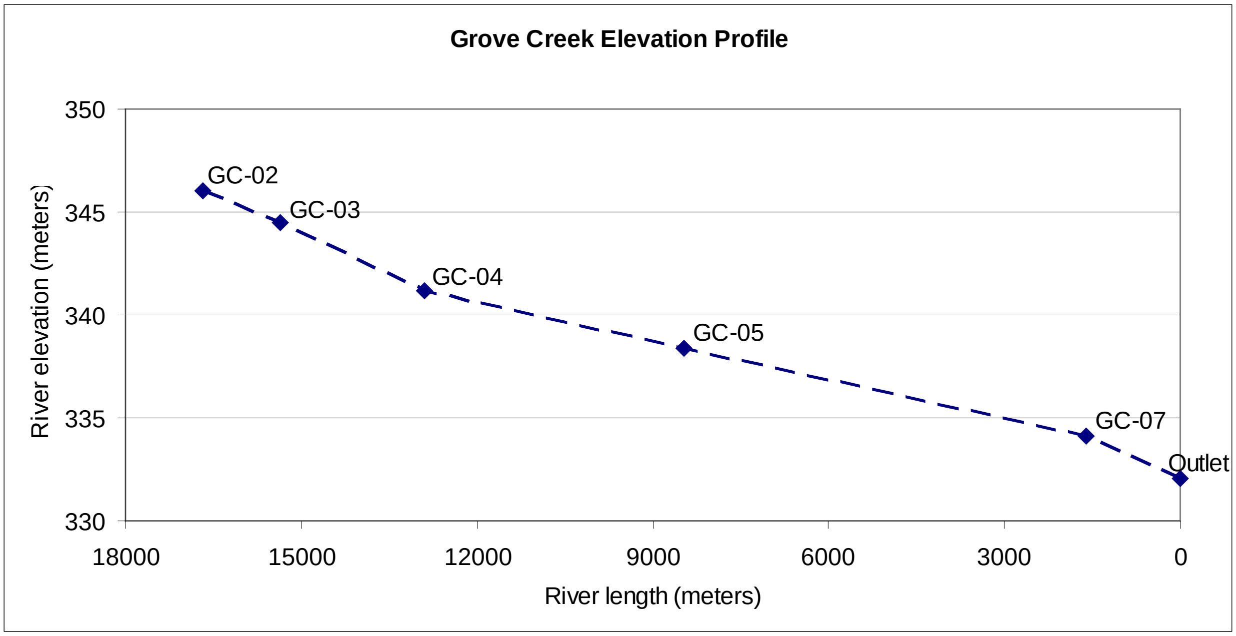

Figure 2.1 Survey elevations used to estimate reach slopes for Grove Creek.

Table 2.3 Grove Creek Longitudinal Elevation Survey Summary.

Monitoring Station	River Kilometer	River Mile	Elevation (meters)	Elevation (feet)	Slope (ft/mile)
GC-02	16.7	10.4	346.0	1135.2	---
GC-03	15.4	9.5	344.5	1130.3	6.00
GC-04	12.9	8.0	341.2	1119.4	7.13
GC-05	8.5	5.3	338.4	1110.3	3.30
GC-07	1.6	1.0	334.1	1096.1	3.33
Outlet	0.0	0.0	332.1	1089.5	6.57
				Total Slope	4.40

2.2 Weather and Physical Processes

Hourly weather measurements of temperature, cloud conditions, relative humidity and wind speed were downloaded from the National Weather Service (NWS) NOAA Litchfield Municipal Airport. Channel coverage and shading was set to 0% for all reaches due to the lack of canopy cover.

2.3 Headwaters

The Minnesota Department of Natural Resources (DNR) stream file shows Grove Creek begins at the tributary inflow downstream of the US Highway 12 crossing (GC-02). Historically, the MPCA has monitored one site upstream of GC-02 (GC-01 at 273rd Street). GC-01 was visited prior to the synoptic survey and had standing water with no observable velocity. Thus, all water quality and flow data collected at station GC-02 was used to represent the upstream boundary condition/headwater in the QUAL2K model.

As noted in Table 2.2, a data sonde was not deployed at the upstream boundary/headwaters (GC-02). Instead, hourly data from GC-03's data sonde monitored on September 3, 2008 was used to simulate temperature, conductivity, dissolved oxygen and pH at GC-02. Continuous dissolved oxygen measured by field staff at GC-02 was 30% less at 8:45 on 9/3/08 than DO recorded at the same time by the continuous data sonde at GC-03. Thus, a diurnal DO curve was simulated for the model's headwaters (GC-02) by lowering continuous DO readings at GC-03 by 30%. Temperature, conductivity and pH showed little difference between the two sampling stations as continuous measurements from GC-03 were applied to the GC-02 headwater station.

2.4 Point Sources

Grove City Waste Water Treatment Facility (WWTF) is the only National Pollutant Discharge Elimination System (NPDES) point source in the Grove Creek watershed (MN0023574). This facility is located at the eastern outflow of Grove Lake north of Grove City and has a continuous discharge (SD002) to an unnamed tributary that flows to Grove Creek downstream of GC-02. The facility also has a bypass (SD001) that has been know to discharge untreated wastewater. The permitted facility includes a collection system, lift station, bar screen, oxidation ditch, final clarifer and chlorine contact tank. The facility is designed to treat an average annual flow of 0.106 million gallons per day. Effluent monitoring data for this facility was not available for the dates of the synoptic survey and dye study. Monthly discharge monitoring reports (DMRs) from 1999-2008 were available through the MPCA. The facility's permitted average annual flow was used to model total facility discharge during the synoptic survey and time of travel study. Modeled effluent water quality parameters were set to concentrations in the September 2008 daily monitoring report. For those parameters not reported in the DMR, effluent concentrations were adjusted to meet monitored water quality data downstream of the facility discharge. All parameters calibrated to meet observed data are supported by literature values of achievable treatment levels for wastewater treatment plants (Tchobanoglous, 1991). Table 2.4 show the final values used in the calibrated model to represent Grove City WWTF.

Table 2.4 Modeled values for Grove City WWTF discharge to tributary of Grove Creek**.**

Paramter	Modeled Value	Source
Flow (m^3/s)	0.005	Permitted annual average
Temp (C)	20	Calibrated to in-stream data
Sp. Cond (umhos)	0.6	Calibrated to in-stream data
DO (mg/L)	4.5	DMR – monthly minimum
Fast CBOD (mg/L)	5.0	DMR – maximum weekly average $CBOD_5$
Ammonia (µg/L)	1000	Literature value
Nitrate (µg/L)	5000	Literature value
Organic-P (µg/L)	1105	DMR – Assumed TP was 50% Organic-P
Inorganic-P (µg/L)	1105	DMR – Assumed TP 50% Inorganic-P
pH	7.3	DMR – midpoint of monthly min/max

2.5 Carbonaceous Oxygen Demand (CBOD)

QUAL2K calculates nitrogenous oxygen demand separate from carbonaceous oxygen demand (CBOD) by requiring separate inputs of $CBOD_{ultimate}$, organic nitrogen and reduced nitrogen. $BOD_{ultimate}$, not $CBOD_{ultimate}$ was analyzed during the Grove Creek synoptic survey. Biochemical oxygen demand (BOD) is a measure of the oxygen consumed by bacteria from the decomposition of organic matter. CBOD measures oxidation of the carbon fraction of the organic matter. A $CBOD_{ultimate}$ fraction was estimated by subtracting the oxygen equivalents (4.57 mg O_2 per mg reduced nitrogen) of the reduced nitrogen in the sample according to the following equation (Thomann et al., 1987; Chapra et al., 2007):

$$CBOD_{ultimate} = BOD_{ultimate} - (4.57*TKN)$$

Resulting $CBOD_{ultimate}$ estimates were extremely low in the most upstream reach and at or below detection in downstream reaches, suggesting only one type/source of CBOD exists throughout the system.

The old EPA model (QUAL2E) version had one type of CBOD with one decay rate. The modernized version (QUAL2K) now includes two forms of CBOD to represent organic carbon; a slowly oxidizing form (slow CBOD) and a rapidly oxidizing form (fast CBOD). This allows the model to decay CBOD at two decay rates, if deemed necessary. This model enhancement is great for waste streams with organic carbons in the form of sugar, glucose, etc. Based on the CBOD data collected, it is reasonable to assume there is only one oxidizing form of CBOD. For this reason, all $CBOD_{ultimate}$ was represented in the model as fast CBOD.

3.0 HYDRAULIC CALIBRATION

Modeled hydraulic inputs were derived from flow gauging data collected during the September 3, 2008 synoptic survey. Total discharge was calibrated first before moving on to time of travel calibration. All hydraulic inputs and calibration adjustments are described in the following sections.

3.1 Hydraulic Rating Curves

QUAL2K hydraulics may be modeled using power function rating curves, weirs (dam/drop structures) or Manning's equations. Hydraulics for all Grove Creek reaches were represented using power function rating curves from flow gauging data collected during the synoptic survey. The power function option relates mean velocity and depth to flow in each reach. QUAL2K uses five coefficients to define reach hydraulics, as follows:

- Velocity (mps) = $a\ Q^b$
- Depth (m) = $c\ Q^d + e$

in which Q is flow in cubic meters per second. Depth and velocity rating curves were constructed using gauged flow data from the time of travel study. Gauging stations with similar channel dimensions and flow characteristics were combined in to one rating curve to provide more robust velocity/depth versus flow relationships (Figures 3.1 through 3.4). Applying the principals of hydraulic geometry (Leopold and Maddock, 1953), there is another power function for width:

- Width (m) = f Q^g

Because the width, depth and velocity are a function of discharge, the following rules apply to the coefficients and exponents of these power functions. The sum of the exponents equal one ($b + d + g = 1.0$), and the product of the coefficients equal one ($a \times c \times f = 1.0$). The representative hydraulic rating curves for each reach was selected based on proximity to gauging stations and typical channel dimensions throughout the reach. The hydraulic coefficients and exponents for each QUAL2K reach are summarized in Table 3.1. Table 3.1 also documents that no calibration adjustments were needed.

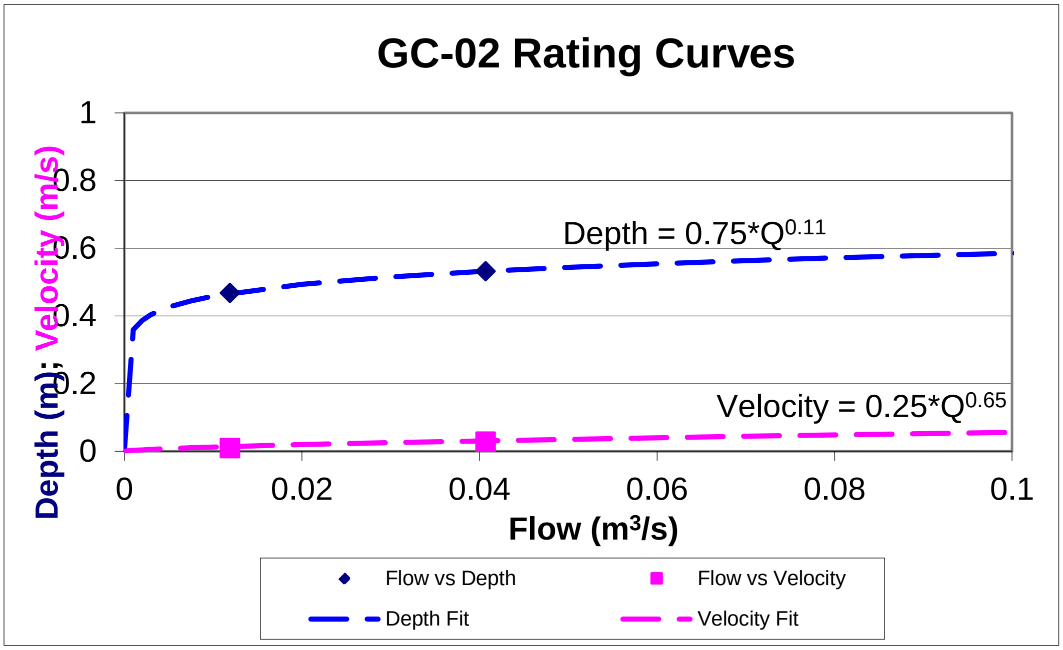

Figure 3.1 Hydraulic rating curve plot for gauging stations GC-02.

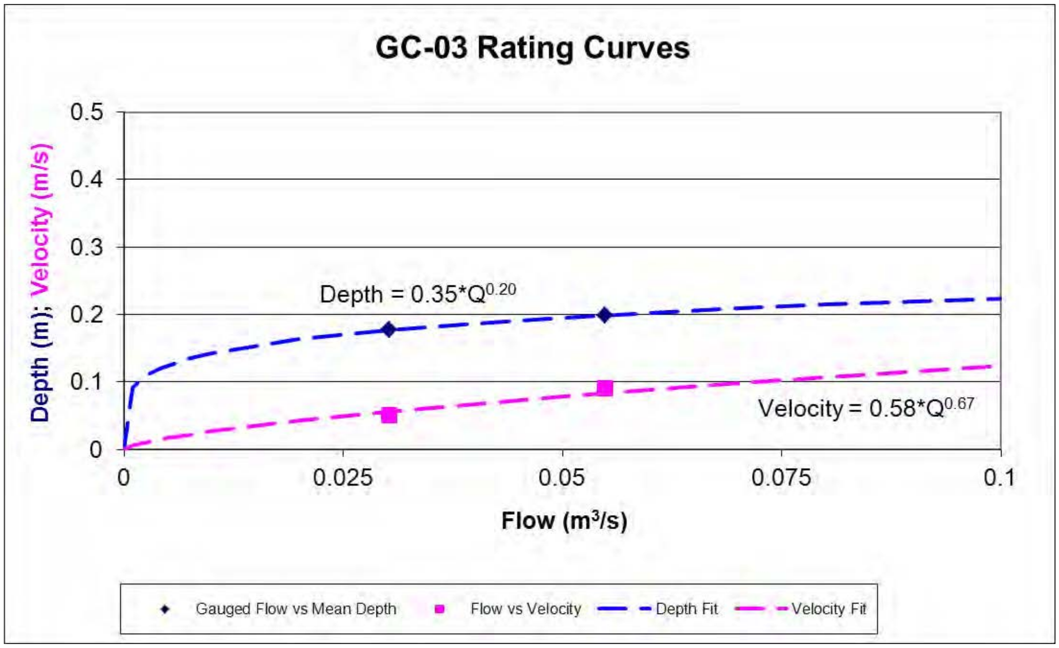

Figure 3.2 Hydraulic rating curve plot for gauging stations GC-03.

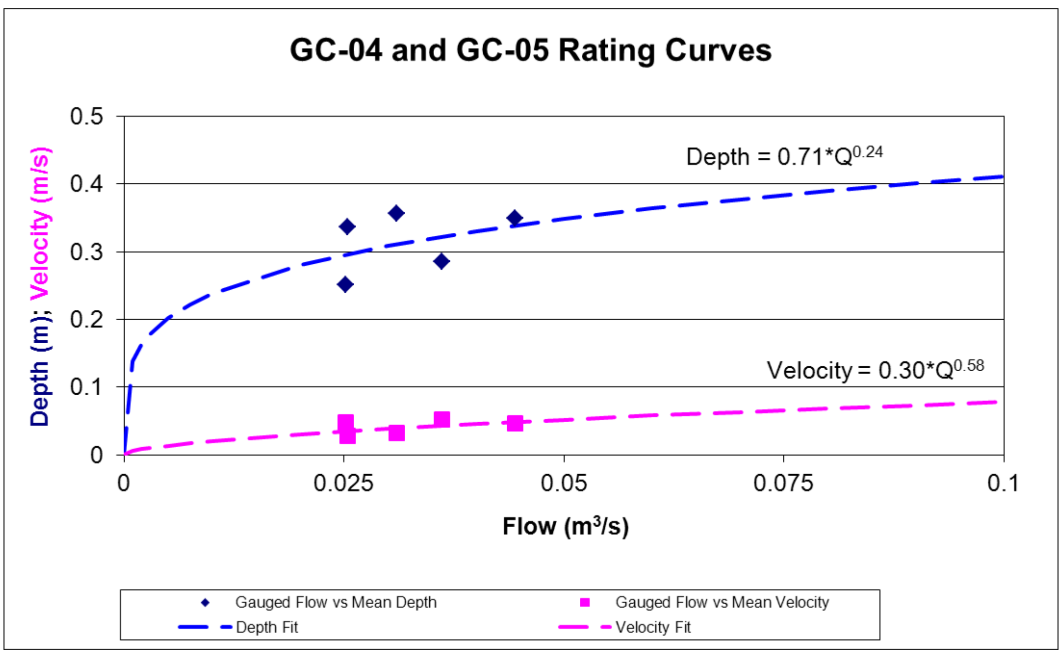

Figure 3.3 Hydraulic rating curve plot for gauging stations GC-04 and GC-05.

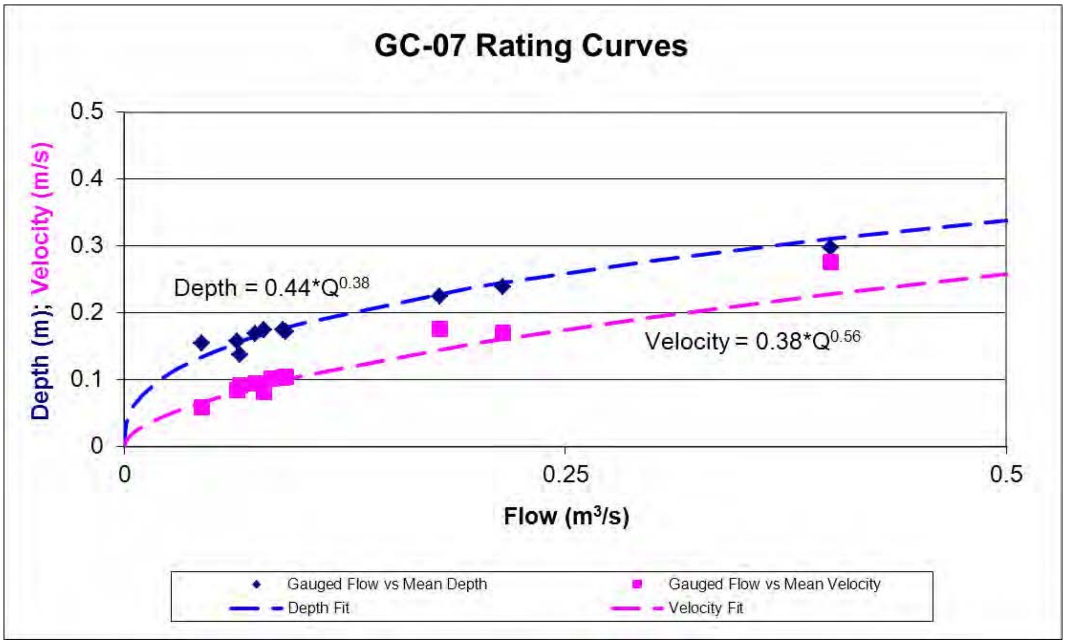

Figure 3.4 Hydraulic rating curve plot for gauging station GC-07.

Table 3.1 Summary of hydraulic coefficients and exponents assigned to each reach.

		Velocity		Depth		
Reach	**Rating Curve used**	**Coeff.**	**Exp.**	**Coeff.**	**Exp.**	**Adjustments**
1	GC-03	0.58	0.67	0.35	0.20	None
2 (trib)	GC-03	0.58	0.67	0.35	0.20	None
3	GC-03	0.58	0.67	0.35	0.20	None
4	GC-04 +GC-05	0.30	0.58	0.71	0.24	None
5	*GC-04 +GC-05	0.30	0.58	0.71	0.24	None
6	GC-07	0.38	0.56	0.44	0.38	None
7	GC-07	0.38	0.56	0.44	0.38	None
8	*GC-07	0.38	0.56	0.44	0.38	None

* denotes that the monitoring station is at the upstream end of the reach

3.2 Flow Calibration

Grove Creek tributaries were not accessible to determine if they were contributing flow during the synoptic survey and dye study. Thus, all observed increases in flow between gauging stations were built in to the model as diffuse sources (Table 3.2). The model was deemed calibrated for total discharge once all point source and diffuse source flows were built in to the model (Figure 3.5.)

Table 3.2 Modeled diffuse source inflow for Grove Creek.

Reach	Total Inflow throughout reach (m^3/s)	Justification
Reach 5 (GC-04 to GC-05)	0.008	Calculated based on flow gauging data
Reach 6+7 (GC-05 to GC-07)	0.026	Calculated based on flow gauging data
Reach 8 (GC-07 to Outlet)	0.006	Calculated based on flow gauging data

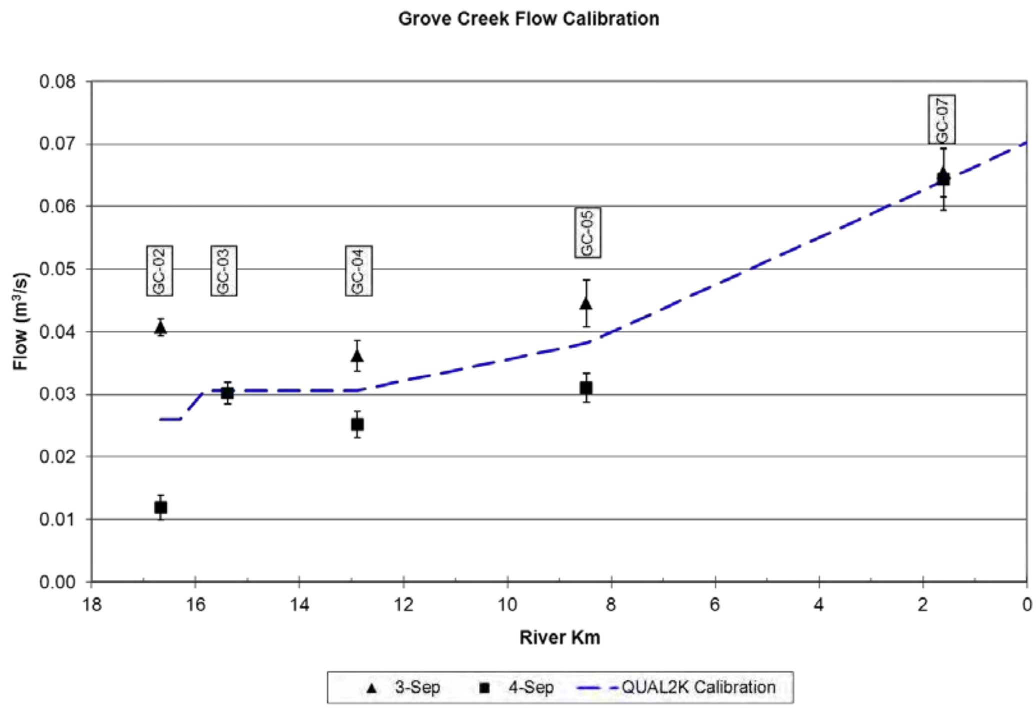

Figure 3.5 Final Grove Creek Flow calibration with diffuse and point source inflows.

3.3 Time of Travel Calibration

With total flow calibrated, the rating curve coefficients and exponents required no adjustments to meet travel times measured for the lower stretch of Grove Creek (GC-05 to GC-07). With total flow calibrated, model predicted travel times fo this reach matched observed times and support using the depth and velocity coefficients and exponents with no changes (Figure 3.6).

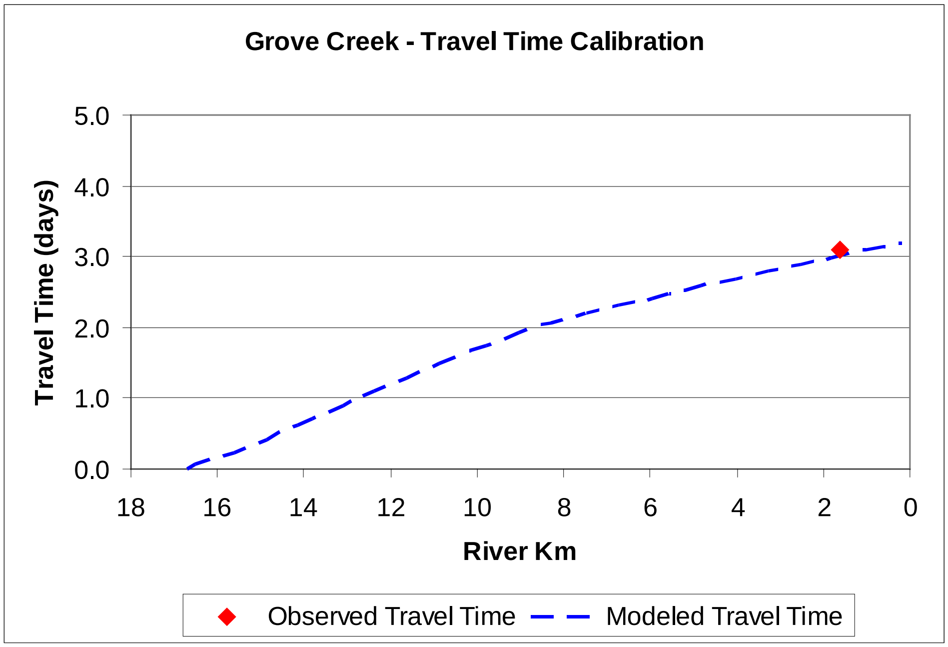

Figure 3.6 Grove Creek time of travel calibration.

4.0 WATER QUALITY CALIBRATION

All water quality model inputs were derived from data collected during the September 3-4, 2008 synoptic survey. Tributary and/or groundwater parameters were estimated based on literature values and calibration to in-stream water quality data. The QUAL2K model was set up to simulate temperature, flow, velocity, depth, chloride, organic nitrogen (ON), ammonia nitrogen (NH_3-N), nitrate/nitrite nitrogen (NO_2/ NO_3-N), ultimate carbonaceous biological oxygen demand ($CBOD_u$), dissolved oxygen (DO), sediment oxygen demand (SOD), total phosphorus (TP), chlorophyll-*a*. All model changes to global and reach specific kinetic rates as well as point source, diffuse and in-stream loadings are discussed in this section.

4.1 General Kinetic Rates

Five kinetic rates were adjusted from default values in order to meet longitudinal changes in observed water quality data. All kinetic rates were adjusted within the range of published values (Table 4.1).

Table 4.1 QUAL2K kinetic rates adjusted from model default values.

Rate	Calibrated Rate	Default Rate	Literature Range	Citation/Study Area
Reaeration Model	Tsivoglou and Neal	User Specified	Thomann and Mueller, 1987 cite that Tsivoglou and Neal, 1976; best for small, shallow streams (1-15 cfs)	
Fast CBOD oxidation rate (day^{-1})	2.0	0.23	0.02 – 0.60 0.56 – 3.37	Bowie et al., 1985 Table 3-17 p152 Kansas (6 rivers) Michigan (3 rivers) reported by Bansal, 1975
Organic-N Hydrolysis (day^{-1}) *The release of ammonia due to decay of organic nitrogen*	0.03	0.20	0.02 – 0.10 0.03 – 0.20	Bowie et al., 1985 Table 5-3 p259 Scavia, 1980 Di Toro & Matystik, 1980
Organic-P Hydrolosis (day^{-1}) *The release of phosphate due to decay of organic phosphorus*	0.80	0.20	0.50 – 0.80 0.02	Bowie et al., 1985 Table 5-5 p266 Jorgenson, 1976 Bowie et al., 1980
Inorganic-P settling (m/d)	0.2	2.0	influenced by a material's size, shape, and density and the speed of water	
Phytoplankton Settling (m/d)	0.10	0.50	0 – 2	Bowie et al., 1985 Table 6-19 p352 Chen & Orlob, 1975 and Smith, 1978

4.2 In-stream Loadings and Reach Specific Rates

In addition to global changes to kinetic rates, individual reaches required specific kinetic rate adjustments to calibrate to in-stream water quality data. Monitored data from reaches 4 and 5 display nutrient loadings and losses not predicted by the default and adjusted kinetic rates. It was noted during the synoptic survey that Grove Creek flows were obstructed creating backwater conditions and a relatively large pond (~75 m in diameter) downstream of GC-03 in reach 4.

Figure 4.1 Reach 4 pond (Source: Google Maps).


Figure 4.2 View of Pond from 560th Avenue.

During the synoptic survey, the Reach 4 pond was approximately 1-2 meters deep and contained a large carp population. Time of travel analysis for Reaches 4-5 suggest the dye did not make it out of this reach or was too mixed and diluted to be detected at the downstream monitoring station. Water quality downstream of this in-channel pond indicates mass load decreases of nitrate and a mass load increase of inorganic phosphorus. The flow increase through this reach was calculated as zero which suggests these changes can be attributed to in-stream denitrification and phosphorus loading. Table 4.2 summarizes the reach specific calibration adjustments made to Reaches 4-5 to represent the in-stream mass loads.

Table 4.2 Summary of reach specific sediment fluxes and kinetic rates.

Reach	Rate	Reach Specific Rate	Default Rate	Literature Range	Justification
4 (GC-03-GC-04)	Sediment Denitrification transfer coefficient (m/d)	1.0	0	0.0-1.0	Ponded reach with high denitrification rates supported by Bowie et al., 1985 Table 5-4 pp 262; Baca & Arnett, 1976
	Sediment Inorganic-P Flux (mg P/m^2/d)	75	Model calculated	9.6 - 95	In-channel pond/reservoir reach with high P-release rates. Carp population and unique hydrologic features justifies elevated P-release (Muddy River, Boston MA total dissolved phosphorus flux aerobic and anaerobic conditions from Fillos and Swanson 1975)
	Sediment NH_4 Flux (mg N/m^2/d)	25	Model Calculated	0-300	In-channel pond/reservoir reach with anoxic conditions and organic-rich sediments (rate supported by Thomann and Mueller, 1987)
	Phytoplankton settling (m/d)	0.50	0.50	0.04 – 0.60	In-channel pond/reservoir settles phytoplankton from inflowing waters supported by Jorgensen et al. 1978
5 (GC-04-GC-05)	Sediment Denitrification transfer coefficient (m/d)	1.0	0	0.0-1.0	Muddy reach with anaerobic conditions and high denitrification rates supported by Bowie et al., 1985 Table 5-4 pp 262; Baca & Arnett, 1976
	Sediment Inorganic-P Flux (mg P/m^2/d)	25	Model Calculated	9.6 - 95	Muddy, slow moving eutrophic reach with anaerobic conditions (Muddy River, Boston MA total dissolved phosphorus flux aerobic and anaerobic conditions from Fillos and Swanson 1975)
	Sediment NH_4 Flux (mg N/m^2/d)	50	Model Calculated	0-300	Muddy, slow moving low-DO reach with anaerobic conditions (rate supported by Thomann and Mueller, 1987).

As documented in Table 4.2 the sediment related parameters are modeled at the upper end (or above) the literature range. This is justified due to the unique geochemical effects the reservoir in Reach 4 has on the water discharged from the pond. Field staff observed carp stirring up the nutrient rich sediments within the pond shown in Figure 4.2. The water leaving the pond was noticeably more turbid than water entering the pond. A pond of this size, without carp activity, might act as a sediment trap.

4.3 Diffuse Source Loadings

Initially, all flow increases were assigned typical groundwater water quality values and then adjusted upward to meet in-stream water quality results (Table 4.3). Nitrate, organic nitrogen and inorganic phosphorus in reaches 5-8 were adjusted furthest from typical groundwater literature values. This suggests either high tributary/draintile or in-stream loading of these parameters that cannot be accounted for by adjusting model kinetic rates.

Table 4.3 Modeled diffuse source parameters for Grove Creek.

Parameter	Reach 5 (GC-04-GC-05)	Justification	Reaches 6-8 (GC-05-Outlet)	Justification
Temp (C)	9.15	Based on USGS groundwater atlas (Lindholm et al., 1974)	9.15	Based on USGS groundwater atlas (Lindholm et al., 1974)
Sp. Cond (umhos)	0.60	Calibrated adjustment to in-stream conditions	0.60	Calibrated adjustment to in-stream conditions
DO	1.6	Mean of published groundwater data	1.6	Mean of published groundwater data
Organic- N (µg/L)	4000	Calibrated adjustment to in-stream conditions	224	Calibrated adjustment to in-stream conditions
Nitrate (µg/L)	5000	Calibrated adjustment to in-stream conditions. Within Range of USGS groundwater atlas (Lindholm et al., 1974)	5000	Calibrated adjustment to in-stream conditions Within Range of USGS groundwater atlas (Lindholm et al., 1974)
Organic-P (µg/L)	300	Calibrated adjustment to in-stream conditions	11.20	Typical MN groundwater literature value (MPCA, 1999)
Inorganic-P (µg/L)	400	Calibrated adjustment to in-stream conditions	400	Calibrated adjustment to in-stream conditions
Phytoplankton (µg/L)	30	Calibrated adjustment to in-stream conditions	---	Typical MN groundwater value

4.4 Final Water Quality Calibration

$CBOD_{fast}$, chlorophyll-*a* and all forms of nitrogen and phosphorus were calibrated once diffuse source water quality parameters and kinetic rates were properly incorporated into the model. The model performed well in predicting loads and concentrations of the primary water quality parameters that affect dissolved oxygen.

5.0 DISSOLVED OXYGEN CALIBRATION

5.1 Diurnal Oxygen Calibration

The Grove model applies the Half Saturation formulations defining the relationship between light penetration and resulting photosynthesis. Though water column algae is accurately predicted in the model, additional modeling adjustments were needed to better predict the daily minimum and maximum DO observations. This suggests there was in-situ primary production not accounted for or under-represented in the initial model runs. In the QUAL2K model, the bottom algae component simulates photosynthesis and nutrient uptake of any non-suspended algae. In the Grove model, the bottom algae channel coverage was adjusted by reach to match the photosynthesis/respiration swings in the observed continuous DO data (Table 5.1). It is assumed that this bottom algae component defined in QUAL2K represents all elements of primary production (attached algae, submerged macrophytes, rooted aquatic vegetation) that could not be measured or quantified in the field.

5.2 Sediment Oxygen Demand

Sediment oxygen demand (SOD) is calculated in QUAL2K based on the delivery and breakdown of particulate organic matter from the water column. Currently, the model does not have a macrophyte or riparian vegetation SOD component, nor does it incorporate any upland sediment transported and deposited during non-steady state storms events. The model does allow the user to prescribe SOD to specific reaches that is added to the model predicted rate to account for SOD outside the modeling framework. SOD in streams varies depending on sediment type but is typically between 0.05 (mineral soils) and 2.00 (estuarine mud) g O_2/m^2/day (Thomann and Mueller, 1987). Grove Creek is a typical agricultural stream that has been ditched and straightened and, as a result, is relatively deep and slow moving during baseflow conditions. While there appeared to be little or no settling/deposition during the low-flow synoptic survey, channel sediments throughout Grove Creek are extremely muddy and composed of soft, fine-grained particles.

Dissolved oxygen concentrations should be close to calibration as long as reasonable assumptions were made in allocating nutrient loads and adjusting kinetic rates. Model predicted dissolved oxygen concentrations for the hydraulic/phytoplankton/bottom algae/nutrient calibrated model were slightly higher than observed throughout Grove Creek. Additional SOD was assigned to each reach to lower mean oxygen concentrations to match observed values (Table 5.1).

Table 5.1 Reach specific SOD and bottom algae coverage.

Reach	**SOD** g O_2/m^2/day	**Bottom Algae Coverage** (%)	**Justification**
1	0.00	25	Typical muddy bottomed channel, moderate aquatic vegetation
2	0.00	25	Typical muddy bottomed channel, moderate aquatic vegetation
3	0.00	25	Typical muddy bottomed channel, moderate aquatic vegetation
4	2.50	60	Typical muddy bottomed channel, in-stream pond/reservoir with more rooted riparian vegetation
5	1.00	60	Wide, muddy bottomed channel, more rooted riparian vegetation
6	0.60	25	Typical muddy bottomed channel, moderate aquatic vegetation
7	0.60	25	Typical muddy bottomed channel, moderate aquatic vegetation
8	0.60	25	Typical muddy bottomed channel, moderate aquatic vegetation

5.3 Final Dissolved Oxygen Calibration

Figures 5.1 shows the final calibration results for model-predicted and observed dissolved oxygen concentrations. Field grabs of dissolved oxygen were taken on September 3 and September 4 using the hand-held YSI. The field grabs are labeled with the time of sample collection, if available. Also shown are continuous dissolved oxygen measurements for September 3rd and September 4th (shown in plots as the range of data between minimum and maximum as orange and blue “I”). The average of the continuous DO is marked on the plot with an orange or blue box dependant on the day. All field grab measurements were taken by Wenck staff between 8:00 am and 10:30 am on 9/3/2008 and between 10:30 am and 4:00 pm on 9/4/2008.

The model performs well in predicting average daily dissolved oxygen concentrations (in plot as black dashed line) at the two monitoring stations with continuous DO measurements (GC-03 and GC-07). The model also does a good job predicting diurnal patterns (daily minimum and maximum, shown in plots as blue dashed lines).

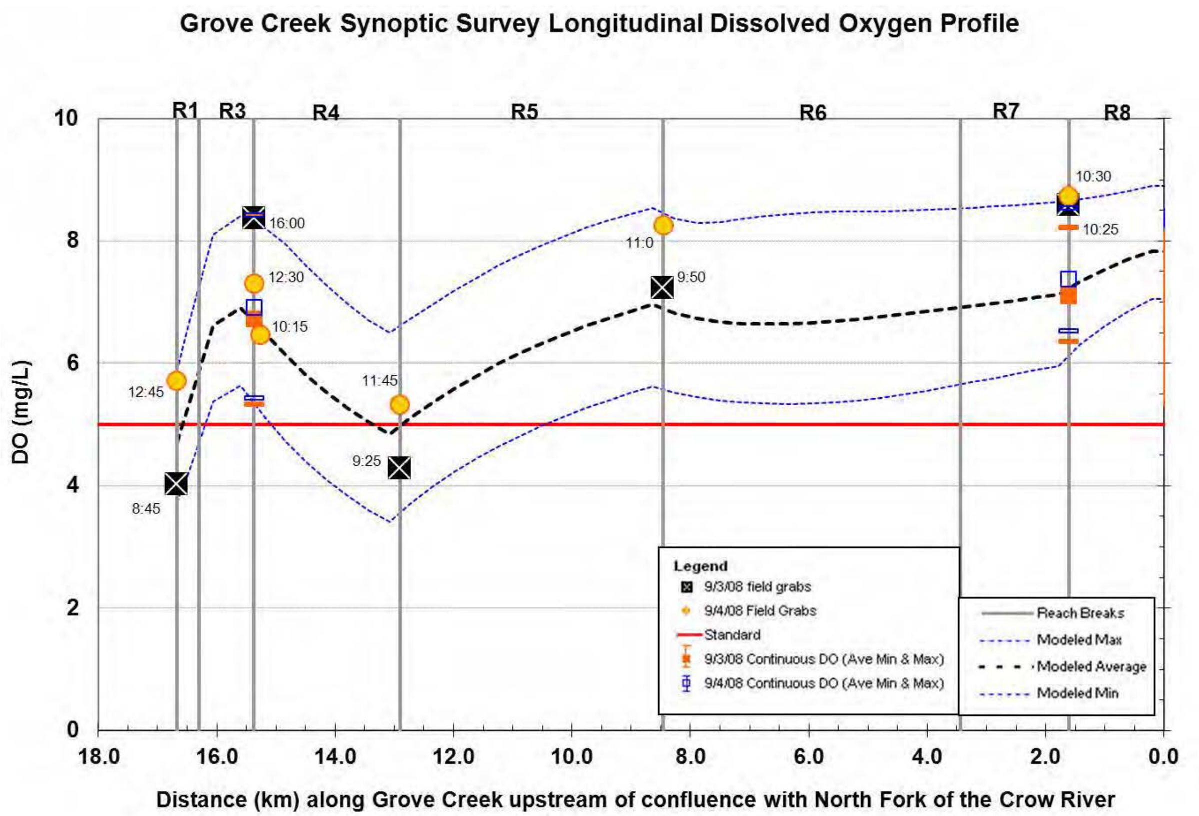

Figure 5.1 Grove Creek calibrated dissolved oxygen longitudinal profile.

6.0 SENSITIVITY ANALYSIS

To evaluate the sensitivity of model predicted dissolved oxygen to changes in model variables, seven kinetic rates (Table 6.1), four reach specific rates (Table 6.2), and channel slopes (Table 6.3) were removed or adjusted by specific percentages. The following tables summarize the affect these changes have on the average model-predicted dissolved oxygen concentration for the entire modeled stretch of Grove Creek. Results show DO throughout the system is most sensitive to the kinetic rates driving SOD levels (nitrogen and phytoplankton settling), as well as the SOD settings themselves. CBOD oxidation and nutrient hydrolysis rates are less sensitive to dissolved oxygen throughout Grove Creek. This exercise suggests sediment processes play a bigger role than water column processes in consuming dissolved oxygen during this particular calibration/sampling event.

Table 6.1 DO sensitivity to kinetic rates.

Kinetic rate	+25%	-25%	Default
$CBOD_u$ oxidation rate (day^{-1})	-0.3%	0.2%	2.6%
Organic-N Hydrolosis (day^{-1})	-0.2%	0.0%	-1.9%
Organic-N Settling (m/d)	-1.7%	2.2%	--
Organic-P Hydrolosis (day^{-1})	0.0%	-0.2%	-0.2%
Organic-P Settling (m/d)	-0.2%	0.0%	--
Inorganic-P Settling (m/d)	-0.3%	0.2%	-6.4%
Phytoplankton Settling (m/d)	-0.5%	0.3%	-2.8%

Table 6.2 DO sensitivity to reach rates.

Action	DO Sensitivity
Remove Sediment Denitrification Transfer Coefficient in reaches 4-5	1.7%
Remove reach specific phytoplankton settling rate in reach 4	2.6%
Remove prescribed NH_4 flux in reaches 4-5	2.2%
Remove prescribed Inorganic-P flux in reaches 4-6	-1.4%
Remove prescribed SOD in all reaches	44.0%
Remove all SOD by setting SOD channel coverage to 0%	74.4%

Table 6.3 DO sensitivity to channel slope.

Channel Slope	DO Sensitivity
Increased by 25%	6.5%
Decreased by 25%	-8.5%

7.0 REFERENCES

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TECHNICAL MEMORANDUM

TO: Diane Sander, Crow River Organization of Water Watershed Coordinator

CC: Maggie Leach, MPCA Regional Impaired Waters Coordinator

FROM: Joe Bischoff, Project Manager
Pamela Massaro, P.E.
Jeff Strom

DATE: September, 2011

SUBJECT: Jewitts Creek Dissolved Oxygen TMDL
Description of QUAL2K Modeling Methods and Results

Wenck Associates, Inc. has developed and calibrated a QUAL2K model for Jewitts Creek from West 4th Street in Litchfield to the Creek's confluence with the main-stem of the North Fork Crow River upstream of Meeker County Road 34. The purpose of this technical memorandum is to describe the methods and assumptions used to create and calibrate the QUAL2K model.

1.0 INTRODUCTION

1.1 Model Selection

The U.S. EPA River and Stream Water Quality Model (QUAL2K) version 7 is a modernized version of the QUAL2E model developed by Dr. Steven Chapra with Tufts University and Greg Pelletier with Washington State. It was selected to analyze Jewitts Creek because it is a relatively simple surface water quality model that can be used during steady-state conditions to model nutrient, algal and dissolved oxygen dynamics.

1.2 General Overview of the Model

The model was built using late summer synoptic survey data collected on September 3-4, 2008. Stream locations and physical features were built in to the model first before proceeding to hydraulic calibration. With the diffuse flow inputs incorporated, the conservative water quality parameters (such as water temperature and conductivity) were adjusted to match monitored observations. Then, chlorophyll-*a* (phytoplankton production), nutrients (phosphorus and nitrogen components), and carbonaceous biological oxygen demand (CBOD) were calibrated by adjusting tributary/groundwater contributions and/or kinetic coefficients within the range of published values. In some cases, reach specific kinetic rates and in-stream nutrient fluxes were assigned to model geochemical processes believed to be unique to certain reaches. Finally, bottom algae and sediment oxygen demand were adjusted for each reach to match observed dissolved oxygen data.

2.0 MODEL SETUP AND INPUTS

The QUAL2K model covers the main stem of Jewitts Creek from where it crosses West 4th Street in Litchfield, MN to its confluence with North Fork Crow River upstream of Meeker County Road 34. This stretch of Jewitts Creek, explicitly modeled, represents approximately 1.1 miles (1.75 km) as five individual reaches. The start of each reach correlates with a monitoring station location, road crossing, or physical change in stream hydrology (Figure 2.1, Table 2.1 and Table 2.2).

Table 2.1 Model reach characteristics.

Reach	Description	Upstream River km	Downstream River km	Distance (km)	Distance (mile)	Slope (m/m)
1	West 4th Street (JC-03) to MN Hwy 24 (JC-04)	10.53	8.78	1.75	1.1	0.0016
2	MN Hwy 42 (JC-04) to County Hwy 34 (JC-05)	8.78	5.86	2.92	1.8	0.0017
3	County Hwy 34 (JC-05) to 300th Street (JC-06)	5.86	2.30	3.56	2.2	0.0009
4	300th Street (JC-06) to 310th Street (JC-07)	2.30	0.60	1.70	1.1	0.0007
5	310th St. (JC-07) to Outflow to North Fork Crow River	0.60	0	0.60	0.4	0.0008

Table 2.2 Monitoring locations.

Reach	Reach Start Monitoring Location ID	Description	Data Collected
None	JC-00	Jewitts Creek at Lake Ripley outlet	None
None	JC-01	Jewitts Creek at 260th Street crossing	None
None	JC-02	Jewitts Creek at CSAH 1 crossing	Q
1	JC-03	Jewitts Creek at W. 4th Street Crossing in Litchfield	Q, Grab, Field
2	JC-04	Jewitts Creek at MN Highway 42 crossing	Q, BOD, Field, DO
3	JC-05	Jewitts Creek at County Highway 34 crossing	Q, Grab, Field, ToT, DO
4	JC-06	Jewitts Creek at 300th Street crossing	Q, Grab, Field, DO
5	JC-07	Jewitts Creek at 310th Street Crossing	Q, Grab, Field, ToT

Q = Flow gauged.
ToT = Time of Travel determined from dye study.
Grab = Water quality grab sample collected and lab analyzed for typical pollutants (total kjeldahl nitrogen (TKN), ammonia nitrogen (NH_3-N), nitrate nitrogen (NO_2-N), 5-day and ultimate carbonaceous biological oxygen demand ($CBOD_{5\text{-day}}$ & $CBOD_u$), total phosphorus (TP), ortho-phosphorus (soluble reactive phosphorus), total organic carbon (TOC), and chlorophyll-*a*).
BOD = Water quality grab sample collected and lab analyzed for $CBOD_{5\text{-day}}$ & $CBOD_u$.
Field = In-field measurement of temperature, conductivity, pH, and dissolved oxygen (DO).
DO = Data sondes deployed to collect continuous measurements of dissolved oxygen, temperature, pH and conductivity.

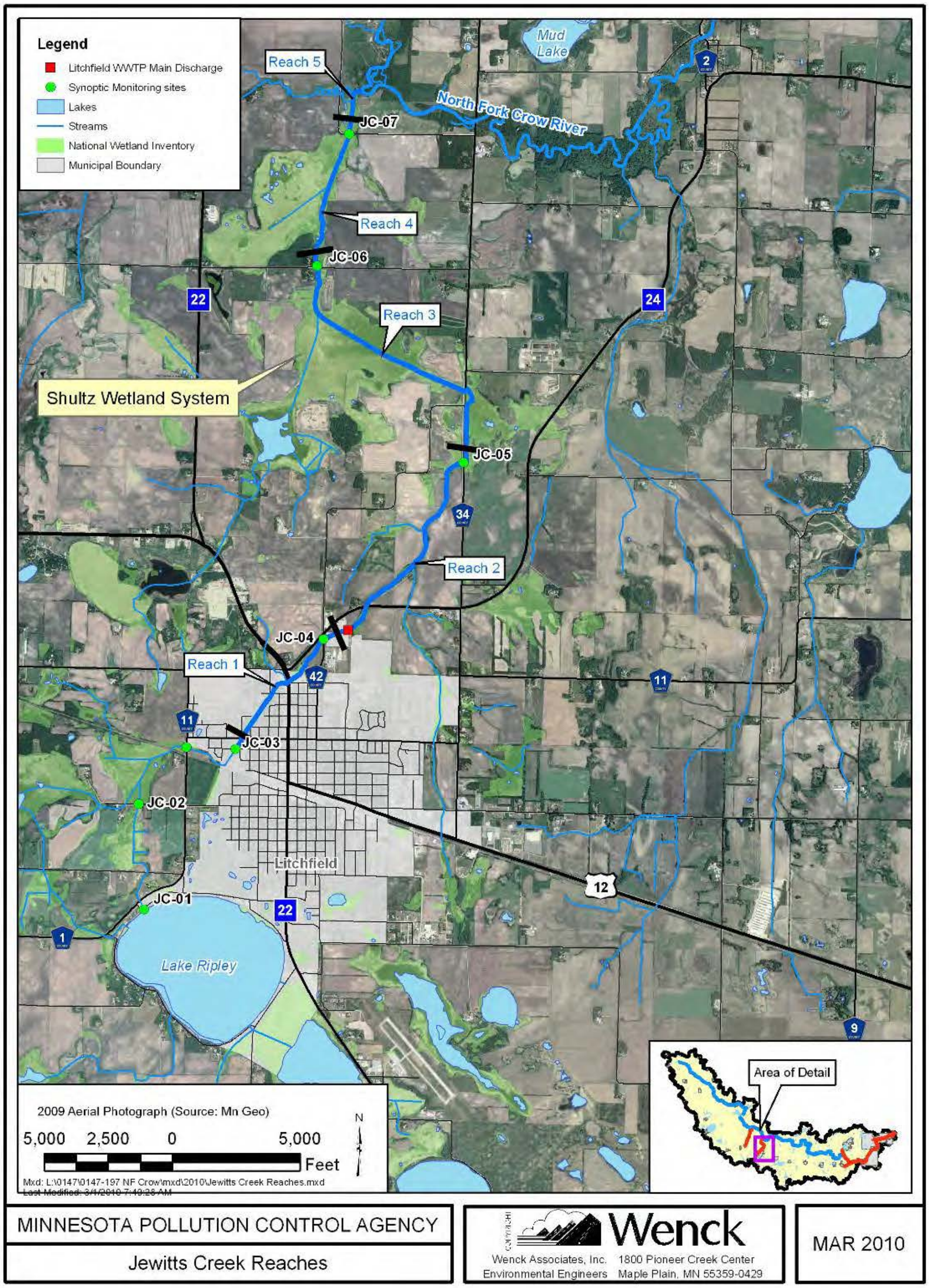

Figure 2.1 Monitoring stations and reaches on Jewitts Creek.

2.1 Channel Slope

Reaeration in QUAL2K may be prescribed by the user or calculated using one of eight hydraulic-based reaeration formulas built into the model. The Tsivoglou-Neal reaeration model was selected for Jewitts Creek because it is the most appropriate to calculate reaeration when flow is below 10 cfs (Tsivoglou and Neal, 1976; Thomann and Mueller, 1987). This reaeration model formula is shown below:

$K_a = 1.8 \times V \times S$ for $1 < Q < 10$ cfs

Where:
K_a = reaeration rate coefficient at 20°C (base e, day $^{-1}$)
V = average velocity (ft/s)
S = slope of energy gradient (ft/mile)

The channel slope and velocity are the variables in calculating reaeration in each reach. Average channel slopes were calculated based on data from an elevation survey conducted by Wenck in the fall of 2008 (Figure 2.2 and Table 2.3).

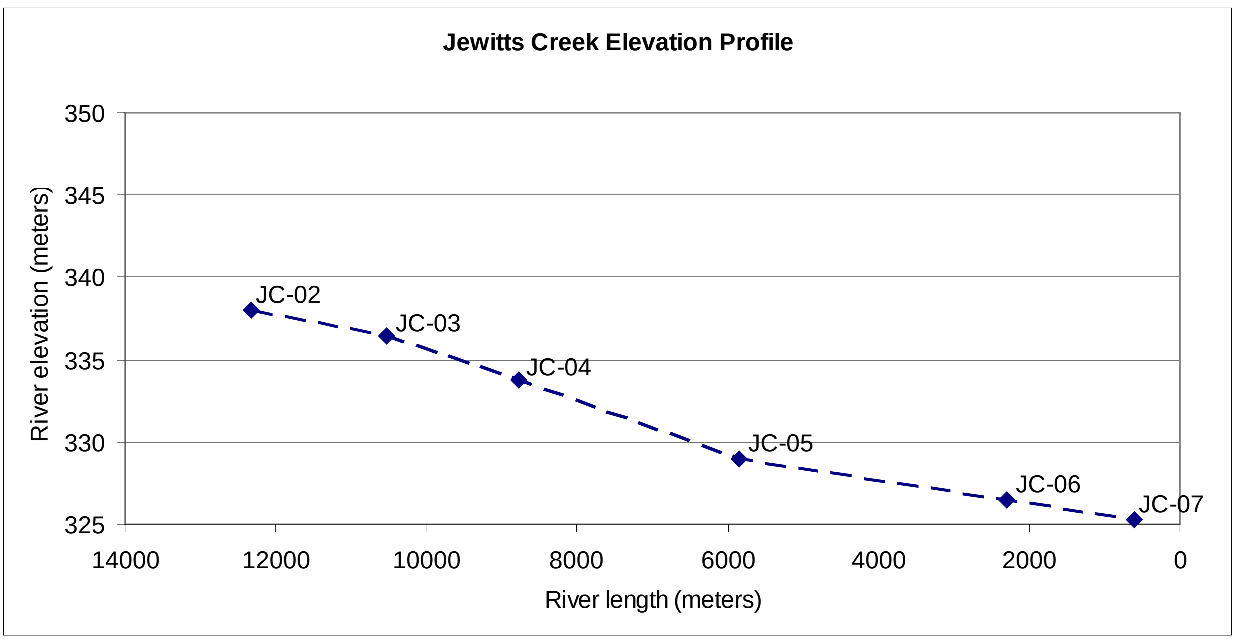

Figure 2.2 Longitudinal elevation survey and modeled reach slopes for Jewitts Creek.

Table 2.3: Jewitts Creek Longitudinal Elevation Survey Summary

Reach Start Monitoring Location ID	River Kilometer	River Mile	Elevation (meters)	Elevation (feet)	Slope (ft/mile)
JC-02	12.3	7.7	338.0	1109.0	---
JC-03	10.5	6.5	336.4	1103.7	4.68
JC-04	8.8	5.5	333.7	1094.9	8.11
JC-05	5.9	3.6	328.9	1079.2	8.63
JC-06	2.3	1.4	326.5	1071.3	3.60
JC-07	0.6	0.4	325.3	1067.3	3.74
				Total Slope	5.71

2.2 Weather and Physical Processes

Hourly weather measurements of temperature, cloud conditions, relative humidity and wind speed were downloaded from the National Weather Service (NWS) NOAA Litchfield Municipal Airport. Channel coverage and shading was set to 0 percent for all reaches due to the lack of canopy cover.

2.3 Headwaters

The Minnesota Department of Natural Resources (DNR) stream file shows Jewitts Creek headwaters to be located at the outlet of Ripley Lake (shown on Figure 1.1 as JC-00). During the synoptic survey, JC-00 contained standing water but no velocity. Flow was gauged downstream at the 260th Street crossing (JC-01) west of Litchfield but there was not enough (less than 0.09 cfs) to initiate a dye study or collect reliable water quality samples. Gauged flow at JC-03 at West 4th Street near the Public Works building in Litchfield was higher (~1.21 cfs) and more suitable for monitoring. Thus, all water quality data collected at this station on September 3-4, 2008 was used to represent the upstream boundary condition/headwater in the model. As noted in Table 2.2, a data sonde was not deployed at the JC-03 headwater station. Hourly data from JC-04's data sonde monitored on September 3, 2008 was used to represent the upstream boundary condition (JC-03). Dissolved oxygen, pH and conductivity data were used as monitored. The hourly temperature data had to be uniformly adjusted by a factor of 0.8, so that the model predicted temperature at JC-04 matched monitored values.

2.4 Point Sources

Litchfield Waste Water Treatment Facility (WWTF) is the only National Pollutant Discharge Elimination System (NPDES) point source located in the Jewitts Creek watershed (MN0023973). This continuously discharging facility is located just north of the Meeker County Fairgrounds and is designed to treat an average wet weather flow of 2.37 million gallons per day. The facility includes processes to removes both nitrogen and phosphorus, the effluent is aerated before the discharge reaches Jewitts Creek through outfall SD001. Effluent monitoring data for this facility was not available for the dates of the synoptic survey and dye study. Daily flow data from 1999-2006 and monthly flow data from 1999-2008 were available through the Minnesota Pollution Control Agency (MPCA) NPDES Discharge Monitoring Reports (DMRs). Modeled facility discharge was estimated by taking the average discharge on September 3 for the last five years in which daily flow data was available (2002-2006). Modeled effluent water quality parameters were set to concentrations in the September 2008 daily monitoring report (Table 2.4).

Table 2.4 Modeled values for Litchfield WWTP discharge to Jewitts Creek.

Paramter	Modeled Value	Source
Flow (m^3/s)	0.064	Mean of monitored daily effluent on 9/3 (2002-2006)
Temp (C)	20.00	Calibrated to in-stream data
Sp. Cond (umhos)	2.00	Calibrated to in-stream data
Dissolved Oxygen	7.00	DMR – monthly minimum
Fast CBOD (mg/L)	2.00	DMR – maximum weekly average
Organic-N (µg/L)	1000	Calibrated to in-stream data
Ammonia (µg/L)	200	DMR – monthly average
Nitrate (µg/L)	5000	Calibrated to in-stream data
Organic-P (µg/L)	300	DMR – Assumed TP was all Organic-P
Inorganic-P (µg/L)	0	DMR – Assumed TP was all Organic-P
pH	7.5	DMR – midpoint of monthly min/max

2.5 Carbonaceous Oxygen Demand (CBOD)

QUAL2K calculates nitrogenous oxygen demand separate from carbonaceous oxygen demand (CBOD) by requiring separate inputs of $CBOD_{ultimate}$, organic nitrogen and reduced nitrogen. $BOD_{ultimate}$, not $CBOD_{ultimate}$ was analyzed during the Jewitts Creek synoptic survey. Biochemical oxygen demand (BOD) is a measure of the oxygen consumed by bacteria from the decomposition of organic matter. CBOD measures oxidation of the carbon fraction of organic mater. This $CBOD_{ultimate}$ fraction was estimated by subtracting the oxygen equivalents (4.57 mg O_2 per mg reduced nitrogen) of the reduced nitrogen in the sample according to the following equation (Thomann et al., 1987; Chapra et al., 2007):

$$CBOD_{ultimate} = BOD_{ultimate} - (4.57*TKN)$$

Resulting $CBOD_{ultimate}$ estimates were extremely low in the most upstream reach and at or below detection in downstream reaches, suggesting only one type/source of CBOD exists throughout the system.

The old EPA model (QUAL2E) version had one type of CBOD with one decay rate. The modernized version (QUAL2K) now includes two forms of CBOD to represent organic carbon; a slowly oxidizing form (slow CBOD) and a rapidly oxidizing form (fast CBOD). This allows the model to decay CBOD at two decay rates, if deemed necessary. This model enhancement is great for waste streams with organic carbons in the form of sugar, glucose, etc. Based on the CBOD data collected, it is reasonable to assume there is only one oxidizing form of CBOD. For this reason, all $CBOD_{ultimate}$ was represented in the model as fast CBOD.

3.0 HYDRAULIC CALIBRATION

Modeled hydraulic inputs were derived from the flow gauging data collected during the September 3, 2008 synoptic survey. Total discharge was calibrated first before moving on to time of travel calibration. All hydraulic inputs and calibration adjustments are described in the following sections.

3.1 Hydraulic Rating Curves

QUAL2K hydraulics may be modeled using power function rating curves, weirs (dam/drop structures) or Manning's equations. Hydraulics for all Jewitts Creek reaches were represented using power function rating curves from flow gauging data collected during the synoptic survey. The power function option relates mean velocity and depth to flow in each reach. QUAL2K uses five coefficients to define reach hydraulics, as follows:

- Velocity (m/sec) = $a\ Q^b$
- Depth (m) = $c\ Q^d + e$

in which Q is flow in cubic meters per second. Depth and velocity rating curves were constructed using gauged flow data from the time of travel study. Gauging stations with similar channel dimensions and flow characteristics were combined in to one rating curve to provide more robust velocity/depth versus flow relationships (Figures 3.1 through 3.3). Applying the principals of hydraulic geometry (Leopold and Maddock, 1953), there is another power function for width.

- Width (m) = $f\ Q^g$

Because the width, depth and velocity are a function of discharge, the following rules apply to the coefficients and exponents of these power functions. The sum of the exponents equal one ($b + d + g = 1.0$), and the product of the coefficients equal one ($a \times c \times f = 1.0$). The representative hydraulic rating curves for each reach was selected based on proximity to gauging stations and typical channel dimensions throughout the reach. The hydraulic coefficients and exponents for each QUAL2K reach are summarized in Table 3.1 Along with adjustments made during calibration.

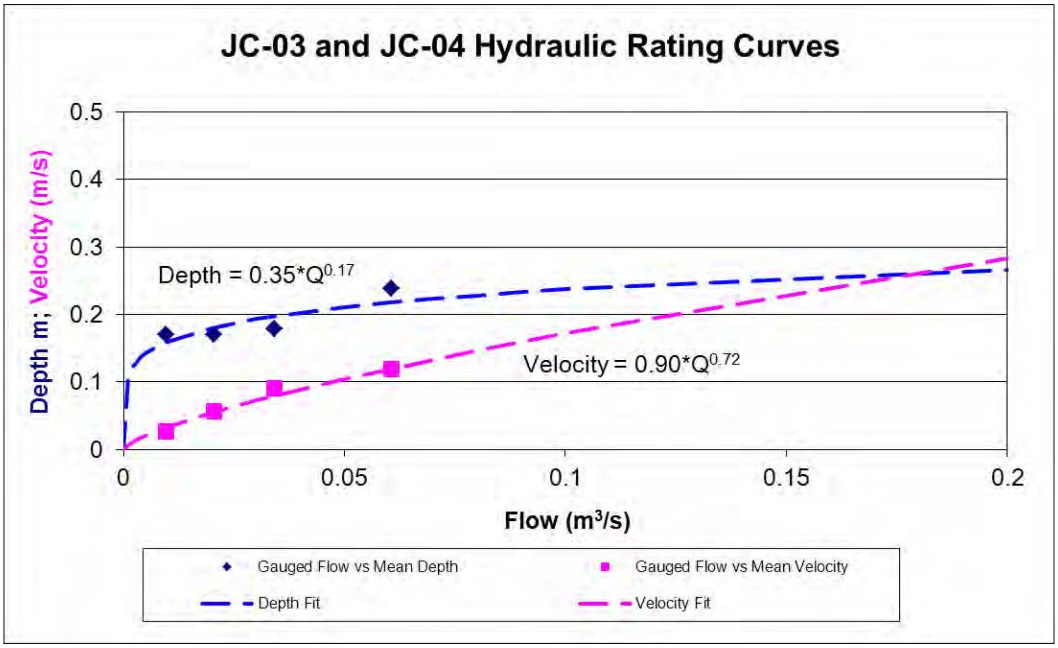

Figure 3.1 Hydraulic rating curve plot for gauging stations JC-03 and JC-04.

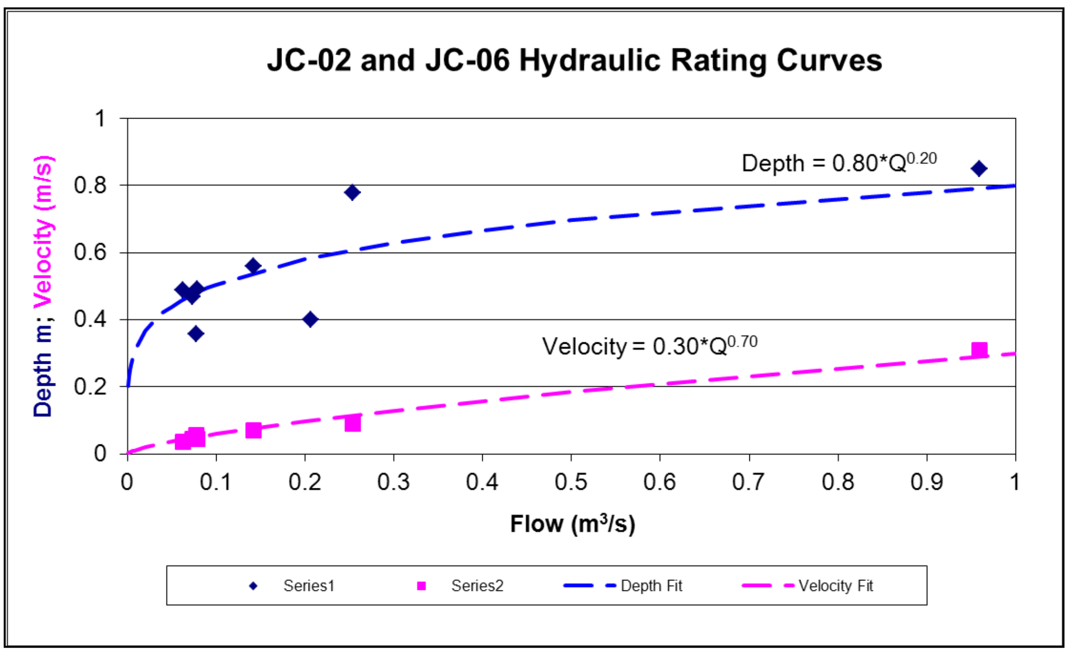

Figure 3.2 Hydraulic rating curve plot for gauging stations JC-02 and JC-06.

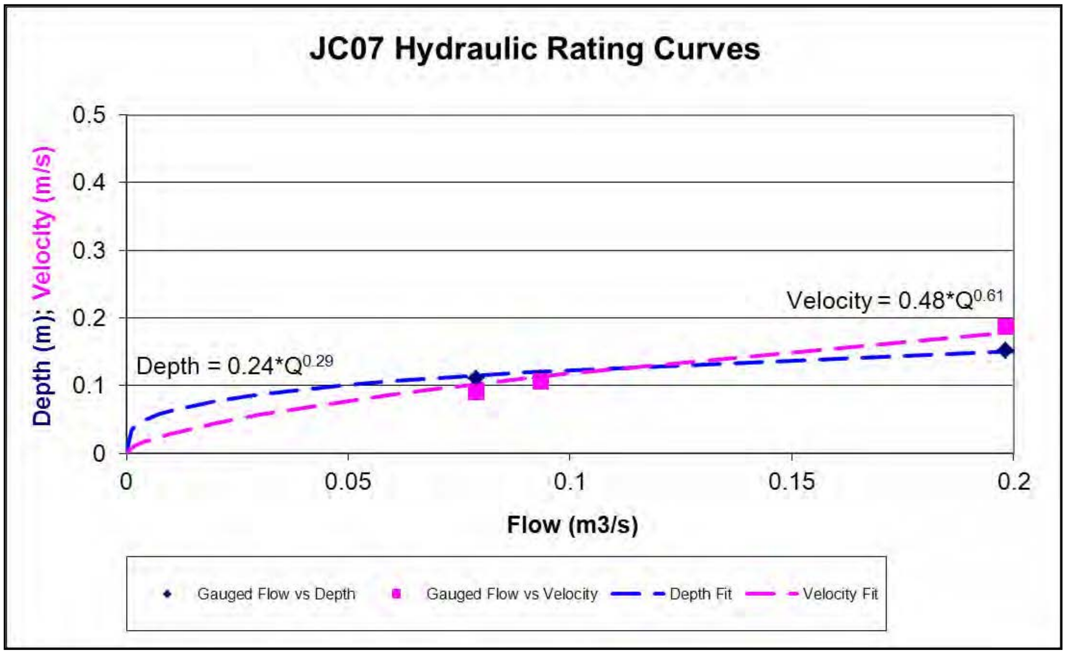

Figure 3.3 Hydraulic rating curve plot for gauging stations JC-07

Table 3.1 Summary of the hydraulic coefficients and exponents assigned to each reach.

Reach	Rating Curve Used	Velocity		Depth		Adjustments
		Coeff.	Exp.	Coeff.	Exp.	
1	JC-03*+JC-04	0.90	0.72	0.35	0.17	None
2	JC-02+JC-06	0.30	0.70	0.80	0.20	None
3	JC-02+JC-06	0.18 Δ	0.70	0.80	0.20	Wetland reach - lowered velocity coefficient
4	JC-07	0.48	0.61	0.24	0.29	None
5	JC-07*	0.48	0.61	0.24	0.29	None

* denotes that the monitoring station is at the upstream end of the reach.

Δ denotes a change in the hydraulic coefficients or exponent.

3.2 Flow Calibration

Jewitts Creek tributaries were not accessible to determine if they were contributing flow during the synoptic survey and dye study. Thus, monitored changes in flow between gauging stations were built in to the model as diffuse sources. All diffuse source flow inputs are described in Table 3.2. Reaches 3-5 were modeled as both flow abstractions and diffuse inflows in order to capture observed nutrient loading through the Shultz Wetland System. It should be noted that the wetland system was modeled as a net flow loss to match observed data. The model was deemed calibrated for total discharge once all point source and diffuse source flows were built in to the model (Figure 3.4.). The model predicted flow is within the error bars of the monitored flows.

Table 3.2 Modeled diffuse source inflow for Jewitts Creek

Reach	Total flow throughout reach (m^3/s)
Reach 1 (JC-03 to JC-05)	-0.01*
Reach 2 (JC-04 to JC-05)	0.02
Reaches 3-5 (JC-05 to Outlet)	0.04
Reaches 3-5 (JC-05 to Outlet)	-0.06*

* denotes that negative flow values are abstractions (outflows), while positive flow values are inflows.

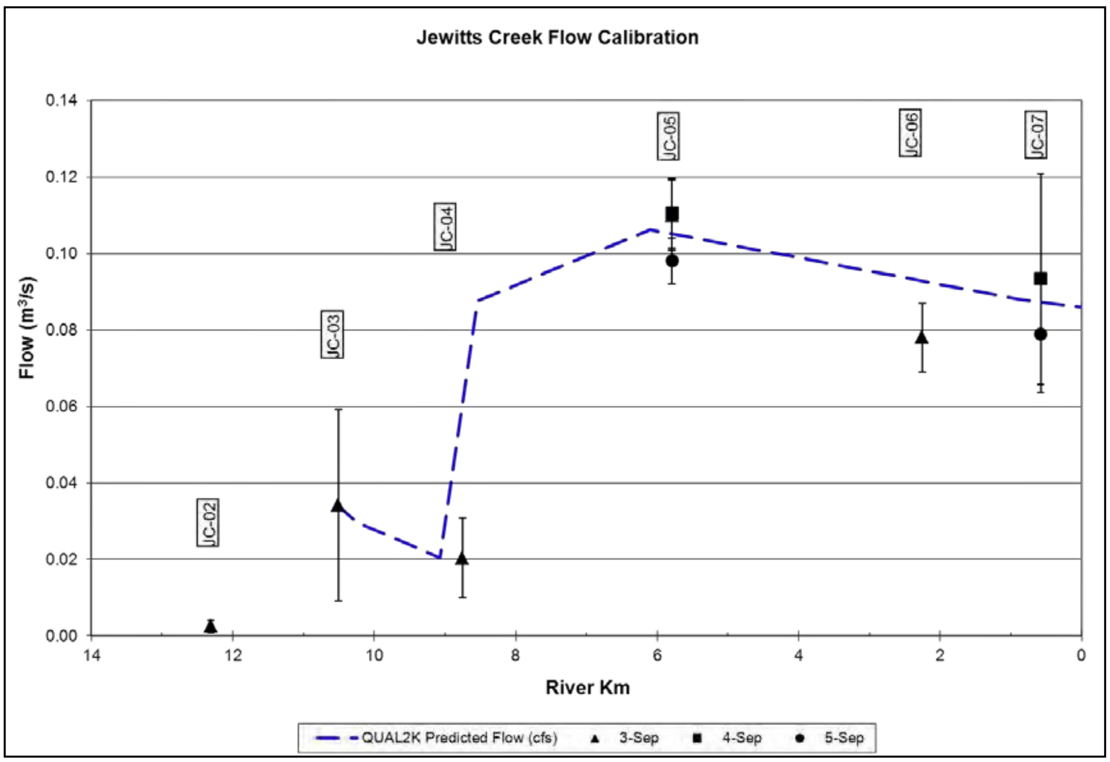

Figure 3.4 Final Jewitts Creek Flow calibration with diffuse and point source inflows.

3.3 Time of Travel Calibration

With total flow calibrated, rating curve coefficients and exponents were adjusted to meet travel times calculated during the dye study portion of the synoptic survey. Reach 3 was the only reach where travel time could not be modeled using gauging station rating curves. Reach 3 represents a large, channelized lake/wetland (Schultz Wetland System), west of MN Highway 24 and south of 300th Street. Dye study results supported adjusting the gauged hydraulic coefficient (velocity) to represent a slower than gauged velocity for the main channel thus increasing the hydraulic residence time. The velocity coefficient for this reach had to be lowered by one-half in order to meet time of travel results (Table 3.1 and Figure 3.5).

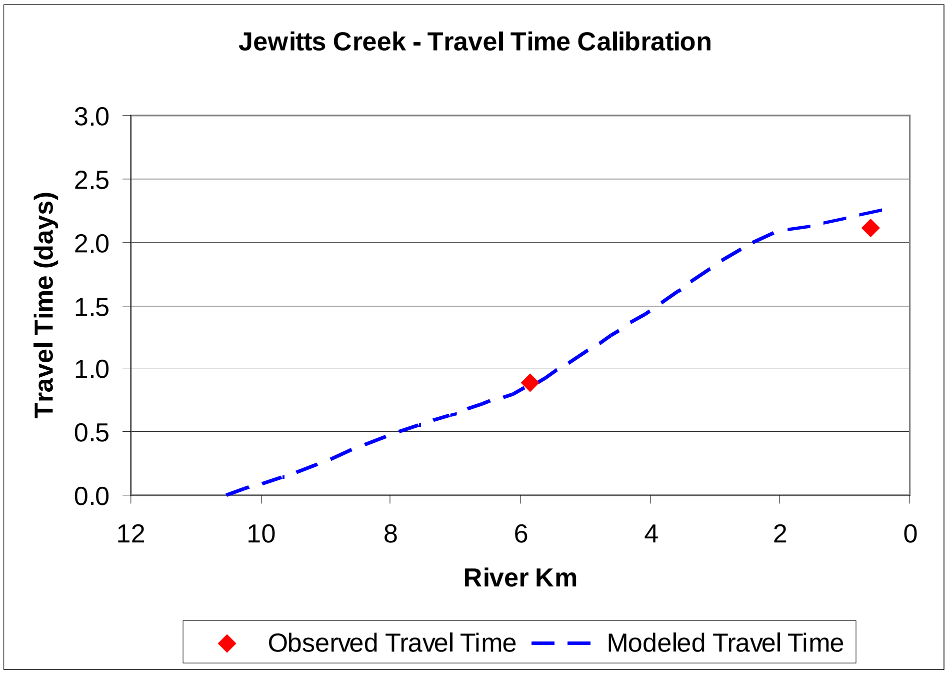

Figure 3.5 Jewitts Creek time of travel calibration.

4.0 WATER QUALITY CALIBRATION

All water quality model inputs were derived from data collected during the September 3, 2008 synoptic survey. Tributary and/or groundwater parameters were estimated based on literature values and calibration to in-stream water quality data. The QUAL2K model was set up to simulate temperature, flow, velocity, depth, chloride, organic nitrogen (ON), ammonia nitrogen (NH_3-N), nitrate/nitrite nitrogen (NO_2/ NO_3-N), ultimate carbonaceous biological oxygen demand ($CBOD_u$), dissolved oxygen (DO), sediment oxygen demand (SOD), total phosphorus (TP), chlorophyll-*a*. All model changes to global and reach specific kinetic rates as well as point source, diffuse and in-stream loadings to calibrate water quality are discussed in this section.

4.1 General Kinetic Rates

Five kinetic rates were adjusted from default values in order to meet longitudinal changes in observed water quality data. All kinetic rates were adjusted within the range of published values (Table 4.1).

Table 4.1 QUAL2K kinetic rates adjusted from model default values.

Rate	Calibrated Rate	Default Rate	Literature Range	Citation/Study Area
Reaeration Model	Tsivoglou and Neal	User Specified	Thomann and Mueller, 1987 cite that Tsivoglou and Neal, 1976; best for small, shallow streams (1-15 cfs)	
Fast CBOD oxidation rate (day^{-1})	2.0	0.23	0.02 – 0.60 0.56 – 3.37	Bowie et al., 1985 Table 3-17 p152 Kansas (6 rivers) Michigan (3 rivers) reported by Bansal, 1975
Organic-N Hydrolysis (day^{-1}) *The release of ammonia due to decay of organic nitrogen*	0.03	0.20	0.02 – 0.10 0.03 – 0.20	Bowie et al., 1985 Table 5-3 p259 Scavia, 1980 Di Toro & Matystik, 1980
Organic-P Hydrolysis (day^{-1}) *The release of phosphate due to decay of organic phosphorus*	0.80	0.20	0.50 – 0.80 0.02	Bowie et al., 1985 Table 5-5 p266 Jorgenson, 1976 Bowie et al., 1980
Inorganic-P settling (m/d)	0.25	2.0	influenced by a material's size, shape, and density and the speed of water	
Phytoplankton Settling (m/d)	0.10	0.50	0 – 2	Bowie et al., 1985 Table 6-19 p352 Chen & Orlob, 1975 and Smith, 1978

4.2 In-stream Loadings and Reach Specific Rates

In addition to global changes to kinetic rates, individual reaches required specific kinetic rate adjustments to calibrate to in-stream water quality data. Water quality data from Reaches 3 and 4-5 display nutrient loadings and losses not predicted by the default and adjusted kinetic rates. Reach 3 flows through a 346 acre lake/wetland complex referred to as the Schultz Wetland System. While flow through this wetland is relatively channelized, air photos suggest the channel widens and interacts with varying fractions of the wetland depending on flow regime. Geochemical samples upstream (JC-05) and downstream (JC-06) of the wetland indicate significant reductions in nitrate and mass loading of inorganic phosphorus. Flow increase through this reach is small which suggests these changes are attributed to stream interactions/exchanges with the larger wetland resulting in denitrification and phosphorus loading.

QUAL2K predicts nutrient release from sediments based on the delivery and breakdown of suspended organic material during steady state conditions. It is not suited to model nutrient release from sediment delivered during non-steady state conditions (storm events or previous conditions) or the breakdown of rooted and floating macrophytes. Previous studies have indicated that significant amounts of total phosphorus have accumulated in the Schultz Wetland System (Magner, 2005). While steps have been taken to reduce water column total phosphorus concentrations upstream of the Schultz Wetland System, the wetland still appears to be a major source of nutrients and eutrophication downstream. Reach specific nutrient fluxes were applied to reaches 3-6 in order to calibrate to the observed nutrient concentrations in the Schultz Wetland System (Table 4.3).

Table 4.3 Summary of reach specific sediment fluxes and kinetic rates.

Reach	**Rate**	**Reach Specific Rate**	**Default Rate**	**Literature Range**	**Justification**
3 (JC-05-JC-06)	Sediment denitrification transfer coefficient (m/d)	1.0	0	0.0-1.0	Wide, slow moving Schultz Wetland System reach with muddy bottom and wetland vegetation. Evidence of anaerobic conditions and high denitrification rates supported by Bowie et al., 1985 Table 5-4 pp 262; Baca & Arnett, 1976
	Prescribed Inorganic-P Flux (mg P/m^2/d)	200	Model calculated	9.6 - 95	Eutrophic Schultz Wetland System reach that accumulated TP under previous conditions supported by Magner, 2005. The flux occurs over the entire wetland system and the surface area of the wetland is much larger than the surface area of the modeled reach (Muddy River, Boston, MA total dissolved phosphorus flux aerobic and anaerobic conditions from Fillos and Swanson 1975)
4-5 (JC-06 - Outlet)	Prescribed Inorganic-P Flux (mg P/m^2/d)	60	Model calculated	9.6 – 95	Muddy bottom reach downstream of eutrophic Schultz Wetland System reach (Muddy River, Boston, MA total dissolved phosphorus flux aerobic and anaerobic conditions from Fillos and Swanson 1975)
4-5 (JC-06 – Outlet)	Prescribed NH_4 Flux (mg N/m^2/d)	75	Model calculated	20 - 325	Wide, slow moving reach downstream of wetland system containing sediment with high organic matter content (rate supported by Thormann and Mueller, 1987)

4.3 Point Source Loadings

For water quality parameters not reported in the Litchfield wastewater treatment facility discharge monitoring report, effluent concentrations were adjusted to meet monitored water quality data downstream of the facility discharge (Table 2.4). All parameters calibrated to meet observed data were supported by literature values for achievable treatment levels for wastewater treatment plants (EPA, 1995).

4.4 Diffuse Source Loadings

It is assumed changes in flow across Jewitts Creek (modeled as diffuse sources) are some combination of tributary, draintile and groundwater inflow/outflow. Modeled abstractions (outflows) are removals at the water quality concentrations predicted in the reach. Diffuse source inflows were initially assigned typical groundwater water quality values in QUAL2K and then adjusted upward to meet in-stream water quality results (Table 4.4). Nitrate in Reach 2 and Organic nitrogen in Reaches 2-5 were adjusted furthest from groundwater literature values. This suggests high tributary or in-stream loading of nitrate and organic nitrogen that cannot be accounted for by adjusting model kinetic rates.

Table 4.4 Modeled diffuse source water quality parameters.

Parameter	Reach 2 (JC-04-JC-05)	Justification	Reaches 3-5 (JC-05-Outlet)	Justification
Temp (C)	18.92	Calibrated adjustment to in-stream conditions. Value equal to daily average for 9/3/08 temperature monitored at JC-05.	14.70	Calibrated adjustment to in-stream conditions. Value equal to daily average for 9/3/08 temperature monitored at JC-04.
Sp. Cond (umhos)	0.60	Calibrated adjustment to in-stream conditions	0.60	Calibrated adjustment to in-stream conditions
DO	1.6	Mean of published groundwater data	1.6	Mean of published groundwater data
Organic- N (µg/L)	1000	Calibrated adjustment to in-stream conditions	2700	Calibrated adjustment to in-stream conditions
Nitrate (µg/L)	5000	Calibrated adjustment to in-stream conditions. Within range of USGS groundwater atlas (Lindholm et al., 1974)	1500	Typical MN groundwater literature value and within range of USGS groundwater atlas (MPCA, 1998; Lindholm et al., 1974)
Organic-P (µg/L)	11.20	Typical MN groundwater literature value (MPCA, 1999)	11.20	Typical MN groundwater literature value (MPCA, 1999)
Inorganic-P (µg/L)	44.80	Typical MN groundwater literature value (MPCA, 1999)	44.80	Typical MN groundwater literature value (MPCA, 1999)
Phytoplankton (µg A/L)	75	Calibrated adjustment to in-stream conditions	55	Calibrated adjustment to in-stream conditions

4.5 Final Water Quality Calibration

$CBOD_{fast}$, chlorophyll-*a* and all forms of nitrogen and phosphorus were calibrated once all diffuse source water quality parameters and kinetic rates were properly incorporated into the model. The model performed well in predicting loads and concentrations of the primary water quality parameters that affect dissolved oxygen.

5.0 DISSOLVED OXYGEN CALIBRATION

5.1 Diurnal Oxygen Calibration

The Jewitts Creek model applies the Half Saturation formulations defining the relationship light penetrates the water column and effects algae and the resulting photosynthesis. Though water column algae is accurately predicted in the model (Figure 4.4), additional modeling adjustments were needed to better predict the daily minimum and maximum DO observations. This suggests there was in-situ primary production not accounted for or under-represented in the initial model runs. In the QUAL2K model, the bottom algae component simulates photosynthesis and nutrient uptake of any non-suspended algae. In the Jewitts model, the bottom algae channel coverage was adjusted by reach to match the photosynthesis/respiration swings in the observed continuous DO data (Table 5.1). It is assumed that this bottom algae component defined in QUAL2K represents all elements of primary production (attached algae, submerged macrophytes, rooted aquatic vegetation) that could not be measured or quantified in the field.

5.2 Sediment Oxygen Demand

Sediment oxygen demand (SOD) is calculated in QUAL2K based on the delivery and breakdown of particulate organic matter from the water column. Currently, the model does not have a macrophyte or riparian vegetation SOD component, nor does it incorporate any sediment re-suspended or delivered to the stream channel during non-steady state storms events. The model does allow the user to prescribe SOD to each reach that is added to the model predicted rate to account for SOD outside the modeling framework. SOD in streams varies depending on sediment type but is typically between 0.05 (mineral soils) and 2.00 (estuarine mud) g O_2/m^2/day (Thomann and Mueller, 1987).

Dissolved oxygen concentrations should be close to calibration once diurnal variability is calibrated and reasonable assumptions have been made in allocating nutrient loads and adjusting kinetic rates. Model predicted dissolved oxygen concentrations for the hydraulic/phytoplankton/nutrient calibrated model were slightly higher than the average continuous DO monitored values. Additional SOD was assigned to each reach to lower mean oxygen concentrations to match observed values (Table 5.1).

Table 5.1 SOD prescribed to each reach that is added to the model-predicted SOD under steady state conditions.

Reach	SOD $g\ O_2/m^2/day$	Bottom Algae Coverage (%)	Justification
1	2.5	50	Necessary to lower the upstream boundary condition/headwater DO (as described in Section 2.3) to match JC-04 DO monitored DO data. This could be the result of slow water upstream, or a calibration artifact because of lack of continuous DO data at JC-03.
2	1.0	75	Typical muddy bottomed channel
3	3.1	65	Schultz Wetland System influenced reach
4	2.0	35	Typical muddy bottomed channel
5	1.5	35	Typical muddy bottomed channel

5.3 Final Dissolved Oxygen Calibration

Figure 5.1 shows the final calibration results for model-predicted and observed dissolved oxygen concentrations. Field grabs of dissolved oxygen were taken on September 3 and September 4 using the hand-held YSI. The field grabs are labeled with the time of sample collection, if available. Also shown is the continuous dissolved oxygen data recorded during the September 3rd and September 4th survey (shown in plot as the range of data between minimum and maximum as orange and blue "I"). The average of the continuous DO is marked on the plot with an orange or blue box dependant on the day. All field grab measurements taken by Wenck staff on September 3-4, 2008 were collected between 12:00 pm and 4:00 pm and were closer to representing daily maximums.

The model performs well in predicting average daily dissolved oxygen concentrations (in plot as black dashed line) and diurnal patterns (daily minimum and maximum, shown in plots as blue dashed lines) at the three monitoring stations with continuous DO measurements.

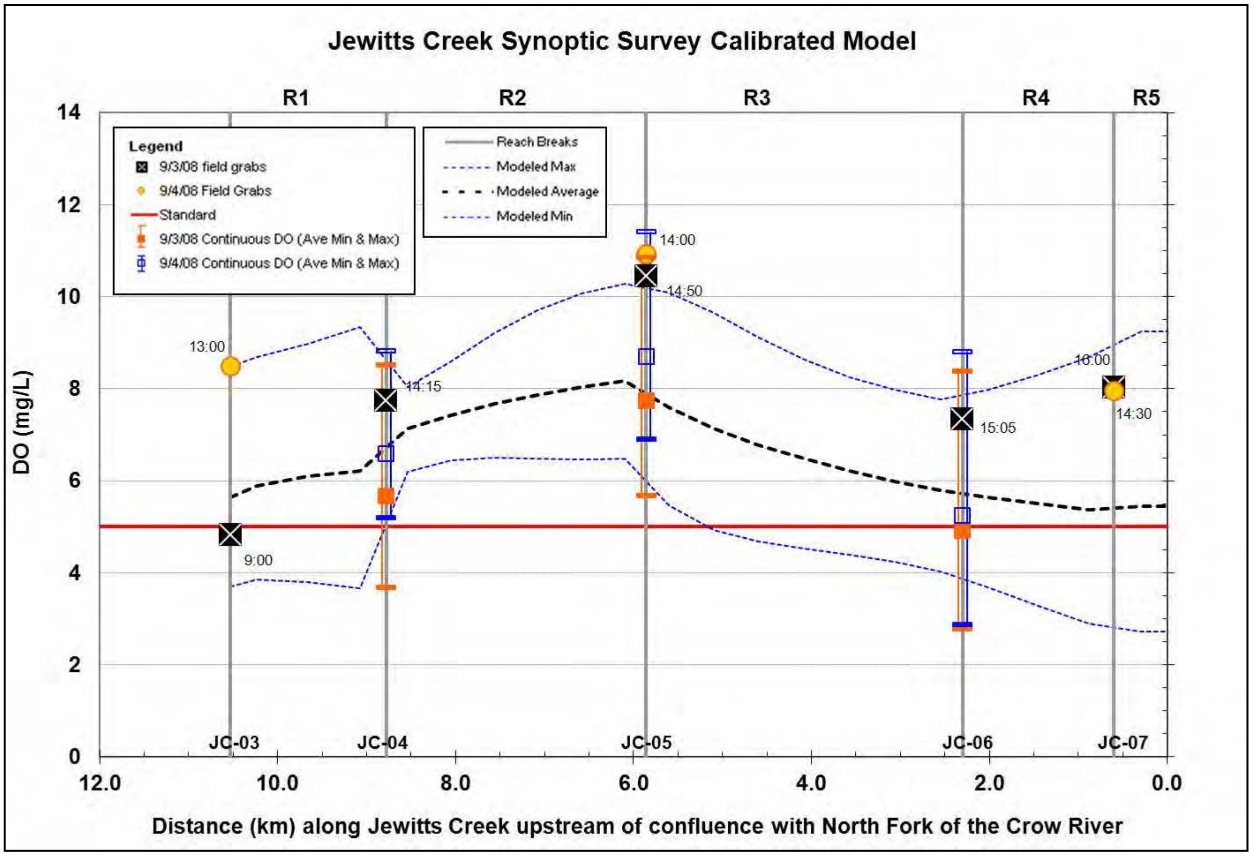

Figure 5.1 Jewitts Creek calibrated dissolved oxygen longitudinal profile.

6.0 SENSITIVITY ANALYSIS

To evaluate the sensitivity of model predicted dissolved oxygen to changes in model variables, seven kinetic rates (Table 6.1), four reach specific rates (Table 6.2), and channel slopes (Table 6.3) were removed or adjusted by specific percentages. The following tables summarize the affect these changes have on the average model-predicted dissolved oxygen concentration for the entire modeled stretch of Jewitts Creek. Results show DO throughout the system is most sensitive to the kinetic rates driving SOD levels (nitrogen and phytoplankton settling) as well as the SOD settings themselves. CBOD oxidation and nutrient hydrolysis rates are less sensitive to dissolved oxygen throughout Jewitts Creek. This exercise suggests sediment processes play a bigger role than water column processes in consuming dissolved oxygen during this particular calibration/sampling event.

Table 6.1 DO sensitivity to kinetic rates.

Kinetic rate	+25%	-25%	Default
$CBOD_u$ oxidation rate (day^{-1})	-0.3%	0.3%	2.8%
Organic-N Hydrolysis (day^{-1})	-0.2%	0.0%	-1.4%
Organic-N Settling (m/d)	-0.9%	1.1%	--
Organic-P Hydrolysis (day^{-1})	0.0%	-0.2%	-0.3%
Organic-P Settling (m/d)	0.0%	0.0%	--
Inorganic-P Settling (m/d)	-0.2%	0.0%	-1.1%
Phytoplankton Settling (m/d)	0.0%	-0.2%	0.9%

Table 6.2 DO sensitivity to reach rates.

Action	DO Sensitivity
Remove sediment denitrification transfer coefficient in reach 3	0.5%
Remove prescribed sediment inorganic-P flux in reaches 3-5	-2.0%
Remove prescribed SOD in all reaches	41.7%
Remove all SOD from model by setting SOD channel coverage to 0%	48.2%

Table 6.3 DO sensitivity to channel slope.

Channel Slope	DO Sensitivity
Increased by 25 percent	5.1%
Decreased by 25 percent	-6.7%

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TECHNICAL MEMORANDUM

TO: Diane Sander, Crow River Organization of Water Watershed Coordinator

CC: Maggie Leach, MPCA Regional Impaired Waters Coordinator

FROM: Joe Bischoff, Project Manager
Pamela Massaro, P.E.
Jeff Strom

DATE: September, 2011

SUBJECT: Mill Creek Dissolved Oxygen TMDL
Description of QUAL2K Modeling Methods and Results

Wenck Associates, Inc. has developed and calibrated a QUAL2K model for Mill Creek from the outlet of Deer Lake to the creek's confluence with the main-stem of the North Fork Crow River. The purpose of this technical memorandum is to describe the methods and assumptions used to create and calibrate the QUAL2K model.

1.0 INTRODUCTION

1.1 Model Selection

The U.S. EPA River and Stream Water Quality Model (QUAL2K) version 7 is a modernized version of the QUAL2E model developed by Dr. Steven Chapra with Tufts University and Greg Pelletier with Washington State. It was selected to analyze Mill Creek because it is a relatively simple surface water quality model that can be used during steady-state conditions to model nutrient, algal and dissolved oxygen dynamics.

1.2 General Overview of Model

First, a QUAL2K model was built and calibrated for Mill Creek using late summer synoptic survey data collected on September 1st-2nd, 2009. Then, using the synoptic survey calibrated model, a scenario was setup to model Mill Creek oxygen dynamics on August 3rd, 2009 when DO violations were recorded and stream flow was close to 7Q10 conditions. Stream locations and physical features were built in to the late summer synoptic survey model first before proceeding to hydraulic calibration. With the diffuse flow inputs incorporated, the conservative water quality parameters (such as water temperature and conductivity) were adjusted to match monitored observations. Then, chlorophyll-*a* (phytoplankton production), nutrients (phosphorus and nitrogen components), and carbonaceous biochemical oxygen demand (CBOD) were calibrated by adjusting tributary/groundwater contributions and/or kinetic coefficients within the range of published values. Finally, bottom algae and sediment oxygen demand were adjusted for each reach to match observed dissolved oxygen data.

2.0 MODEL SETUP AND INPUTS

The River and Stream Water Quality Model (QUAL2K version 7) covers Mill Creek from its outlet of Deer Lake at 10th Street SW to its confluence with the North Fork Crow River. This stretch of Mill Creek, explicitly modeled, represents approximately 4.23 kilometers (2.63 miles) subdivided in to four reaches. The start of each reach coincides with a monitoring station location or change in stream hydrology/morphometry (Figure 2.1, Table 2.1 and Table 2.2). There are no registered point sources that directly discharge to this stretch of Mill Creek.

Table 2.1 Model reach characteristics.

Reach	Description	US River km	DS River km	Distance (km)
1	MilC-02 to River km 3.85	4.23	3.85	0.38
2	River km 3.85 to Unnamed Trib	3.85	3.10	0.75
3	Unnamed Trib to MilCr-03	3.10	1.78	1.32
4	MilC-03 to Outflow to NFC	1.78	0.00	1.78

Table 2.2 Synoptic survey monitoring station data collection.

Reach	Monitoring Location ID	Description	Data Collected
1	MilCr-02	10th Street SW Crossing	ToT, Q, Grab, Field, Sonde
4	MilCr-03	Co Rd 12 Crossing	ToT, Q, Grab, Field

Q = Flow gauged.
ToT = Time of Travel determined from dye study.
Grab = Water quality grab sample collected and lab analyzed for typical pollutants (total kjeldahl nitrogen (TKN), ammonia nitrogen (NH_3-N), nitrate nitrogen (NO_2-N), 5-day and ultimate carbonaceous biological oxygen demand ($CBOD_{5\text{-day}}$ & $CBOD_u$), total phosphorus (TP), ortho-phosphorus (soluble reactive phosphorus), total organic carbon (TOC), and chlorophyll-*a*).
Field = In-field measurement of temperature, conductivity, pH, and dissolved oxygen (DO).
Sonde = continuous data sonde deployed to hourly temperature, DO, pH, conductivity data

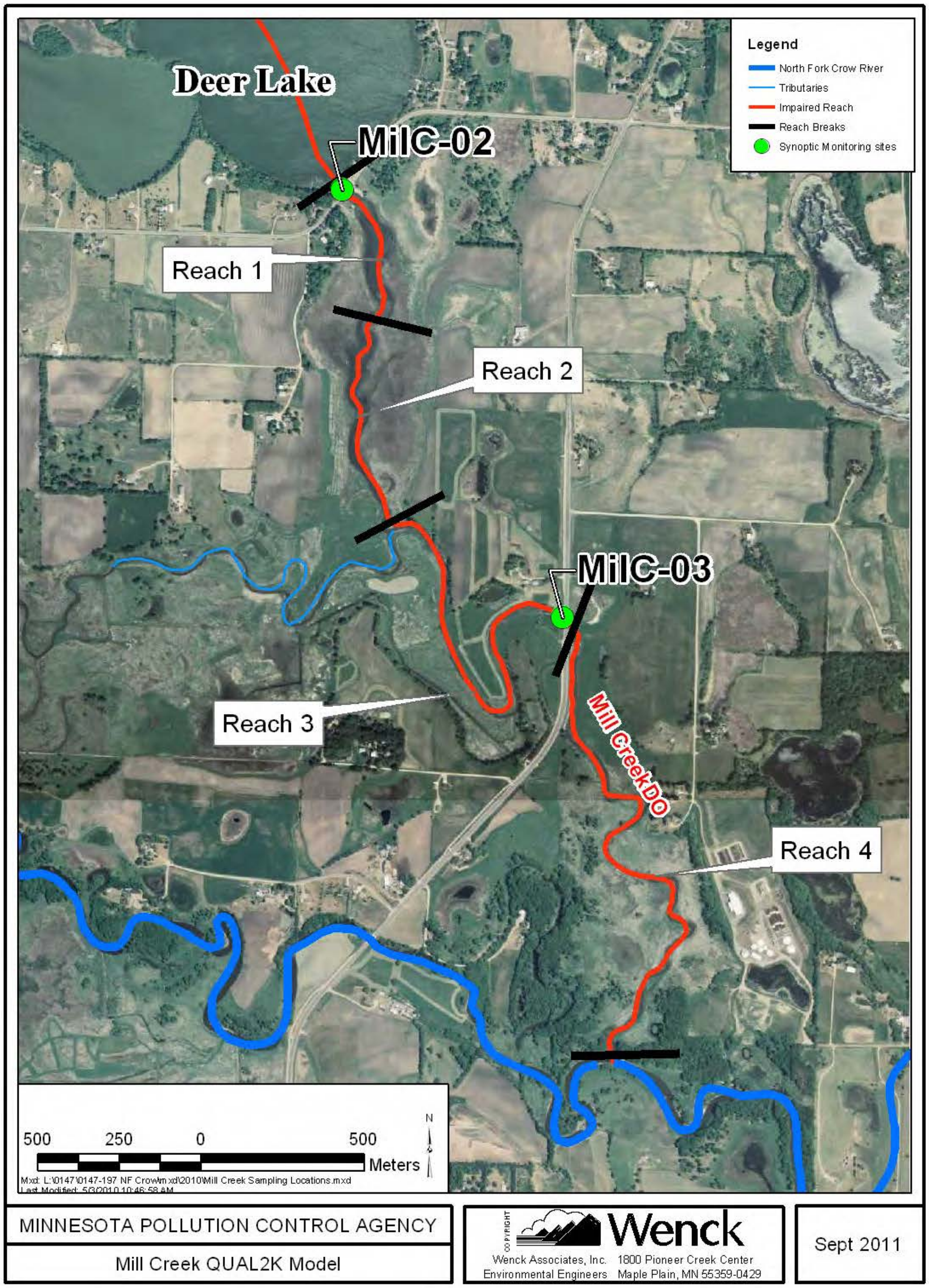

Figure 2.1 Monitoring stations and reaches on Mill Creek.

2.1 Channel Slope

Reaeration may be prescribed by the user or calculated using one of eight hydraulic-based reaeration models built into QUAL2K. The Tsivoglou-Neal reaeration model was selected for Mill Creek because it is the most appropriate model to predict reaeration for flows less than 20 cfs (Tsivoglou and Neal, 1972; Thomann and Mueller, 1987). This reaeration model formula is shown below:

$K_a = 1.8 \times V \times S$ for $1 < Q < 10$ cfs

Where:
K_a = reaeration rate coefficient at 20°C (base e, day $^{-1}$)
V = average velocity (ft/s)
S = slope of energy gradient (ft/mile)

Channel slope and velocity are the variables used to calculate reaeration in each reach. Average channel slopes are based on data from an elevation survey conducted by Wenck in the fall of 2008 (Table 2.3).

Table 2.3 Mill Creek Longitudinal Elevation Survey Summary.

Monitoring Station	River Kilometer	Elevation (meters)	Slope
MilC-02	4.23	277.31	0.00035
MilC-03	1.78	276.44	
NFC Outflow	0	275.81	

2.2 Weather and Physical Processes

Hourly weather measurements of temperature, cloud conditions, relative humidity and wind speed were downloaded from the National Weather Service (NWS) NOAA Minneapolis-St. Paul Airport. Stream canopy coverage was set to zero percent based on field observations and investigation of air photos in GIS.

2.3 Headwaters

The Minnesota Department of Natural Resources (DNR) stream file shows Mill Creek headwaters to be the outflow from Deer Lake south-west of Buffalo, MN. Thus, all water quality and flow data collected at station MilC-02 was used to represent the upstream boundary condition/headwater in the QUAL2K model. As noted in Table 2.2, no data sonde was deployed at MilC-02 to record continuous DO during the September 1st-2nd synoptic survey. Instead, only individual field DO measurements were made in the middle of the afternoon on both days using a hand-held data sonde. However, continuous data sondes were deployed at MilC-02, MilC-03 and in the Unnamed Tributary from August 24th-30th, 2010 as part of the North Fork Crow River Watershed Phase II monitoring plan. Results from this sampling event indicate average daily dissolved oxygen leaving Deer Lake (MilC-02) was approximately 25% higher than the average daily dissolved oxygen recorded at MilC-03. Thus, headwater dissolved oxygen in the QUAL2K model was set 25% higher than the average daily DO recorded on September 1^{st} at MilC-03.

2.4 Carbonaceous Biochemical Oxygen Demand (CBOD)

The old EPA model (QUAL2E) version had one type of CBOD with one decay rate. The modernized version (QUAL2K) now includes two forms of CBOD to represent organic carbon; a slowly oxidizing form (slow CBOD) and a rapidly oxidizing form (fast CBOD). This allows the model to decay CBOD at two decay rates, if deemed necessary. This model enhancement is great for waste streams with organic carbons in the form of sugar, glucose, etc.. Both 5-day CBOD ($CBOD_5$) and ultimate CBOD ($CBOD_u$) were collected at each monitoring station during the synoptic survey. $CBOD_u$ measurements were used to represent the breakdown of organic carbon over $CBOD_5$ in the model since this measurement more accurately represents total potential carbonaceous oxygen demand.

3.0 HYDRAULIC CALIBRATION

Modeled hydraulic inputs were derived from flow gauging data collected during the September 1^{st}-2^{nd} 2009 synoptic survey. Total discharge was calibrated first before calibrating travel time. All hydraulic inputs and calibration adjustments are described in the following sections.

3.1 Hydraulic Rating Curves

QUAL2K hydraulics may be modeled using power function rating curves, weirs (dam/drop structures) or Manning's equations. Hydraulics for all Mill Creek reaches were represented using power function rating curves based on flow gauging data collected during the synoptic survey. The power function option relates mean velocity and depth to flow in each reach. QUAL2K uses five coefficients to define reach hydraulics, as follows:

- Velocity (mps) = $a\ Q^b$
- Depth (m) = $c\ Q^d + e$

in which Q is flow in cubic meters per second. Depth and velocity rating curves were constructed using gauged flow data from the time of travel study. Gauging stations with similar channel dimensions and flow characteristics were combined in to one rating curve to provide more robust velocity/depth versus flow relationships (Figures 3.1 - 3.2). Applying the principals of hydraulic geometry (Leopold and Maddock, 1953), there is one additional power function that defines channel width:

- Width (m) = $f\ Q^g$

Because the width, depth and velocity are a function of discharge, the following rules apply to the coefficients and exponents of these power functions. The sum of the exponents equal one ($b + d + g = 1.0$), and the product of the coefficients equal one ($a \times c \times f = 1.0$). The representative hydraulic rating curves for each reach was selected based on proximity to gauging stations and typical channel dimensions throughout the reach. The hydraulic coefficients and exponents for each QUAL2K reach are summarized in Table 3.1.

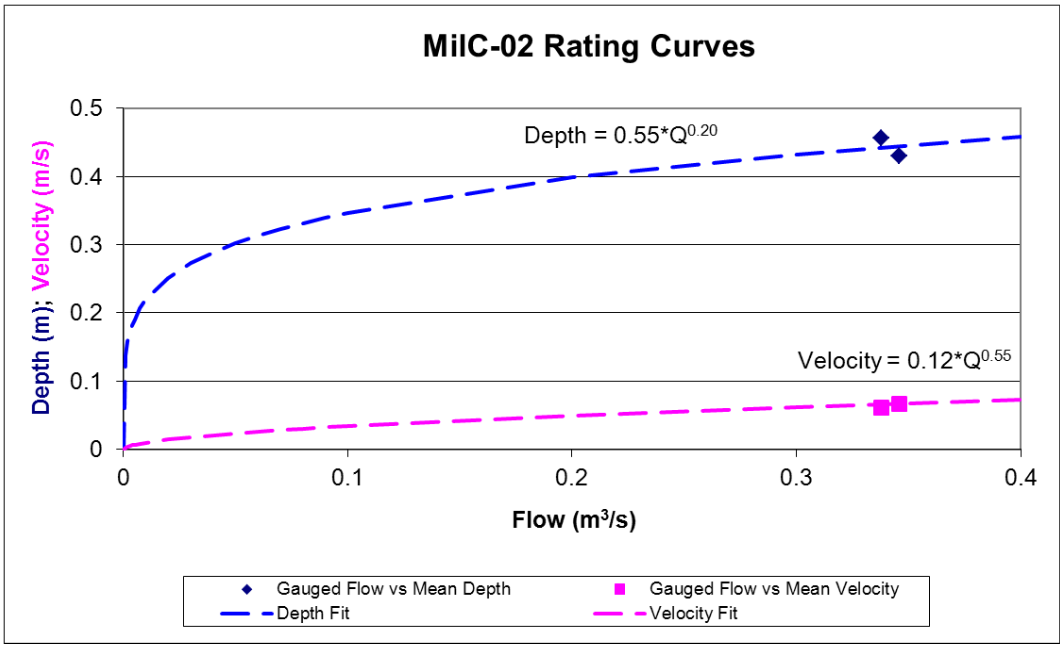

Figure 3.1 Hydraulic rating curve plot for gauging station MilC-02.

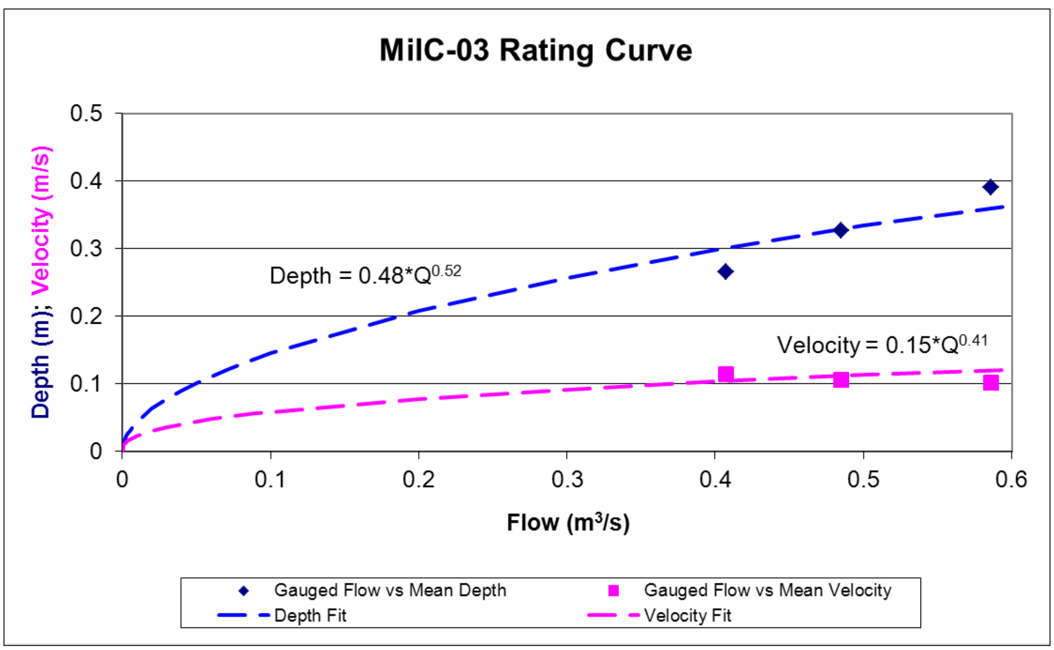

Figure 3.2 Hydraulic rating curve plot for gauging station MilC-03.

Table 3.1 Summary of hydraulic coefficients and exponents assigned to each reach.

Reach	Rating Curve used	Velocity Coeff.	Velocity Exp.	Depth Coeff.	Depth Exp.	Adjustments
1	MilC-03	0.07	0.41	0.48	0.52	Decreased velocity coefficient to match travel time
2	MilC-03	0.15	0.41	0.48	0.52	None
3	MilC-03	0.15	0.41	0.48	0.52	None
4	MilC-03	0.15	0.41	0.48	0.52	None

3.2 Flow Calibration

Mill Creek tributaries were not accessible to measure flow and water quality during the synoptic survey and dye study. It was assumed all flow increases between the MilC-02 and MilC-03 monitoring stations were from the Unnamed Tributary that drains the western portion of the Mill Creek watershed and dischargers to Mill Creek at river kilometer 3.10. This tributary was built in to the model as a tributary point source inflow. Tributary flow was set to 0.10 m^3/s (3.67 cfs) to match modeled flow and observed flow during the September 1st-2nd synoptic survey (Figure 3.3).

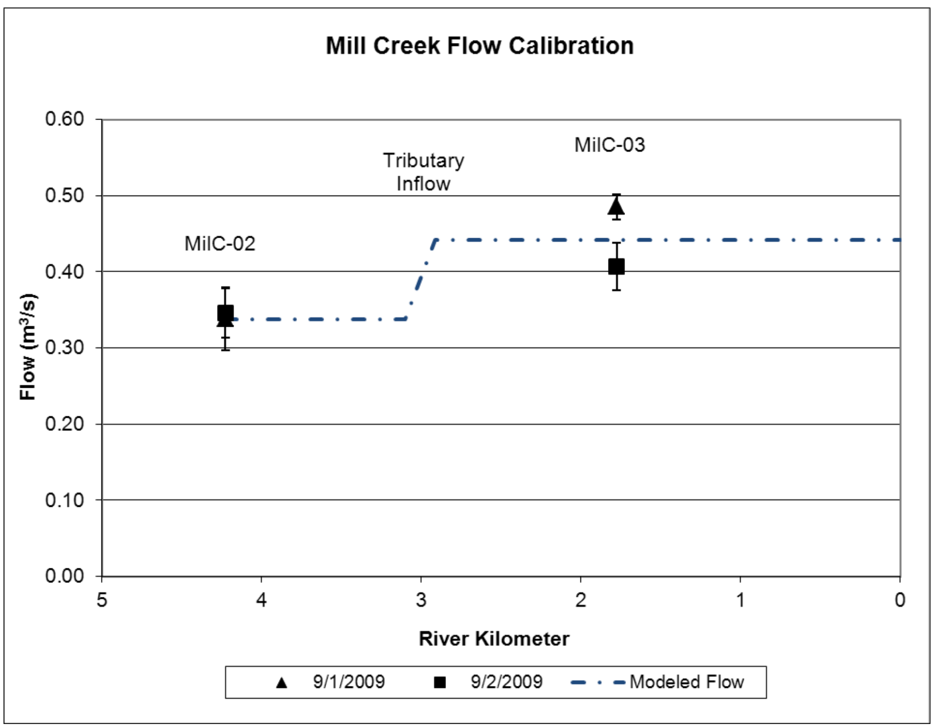

Figure 3.3 Final Mill Creek flow calibration with tributary inflow.

3.3 Time of Travel Calibration

With total flow calibrated, the rating curve coefficient reach 1 had to be adjusted slightly to lower velocity to meet time of travel measurements (Table 3.1). With total flow calibrated and the necessary hydraulic adjustments made, model predicted travel times for each reach were close to observed travel times (Figure 3.4).

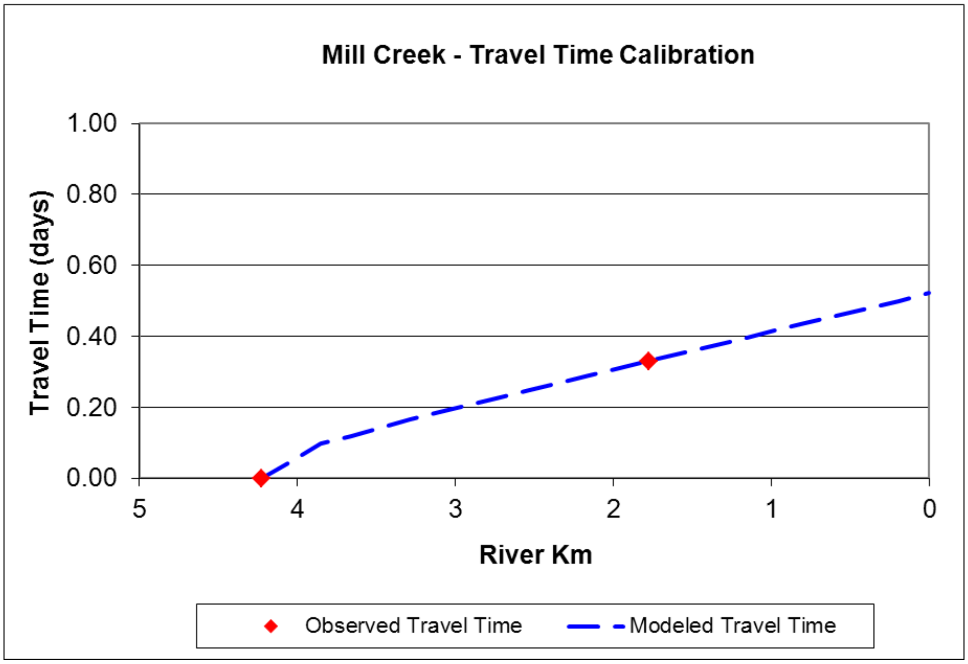

Figure 3.4 Mill Creek travel time calibration.

4.0 WATER QUALITY CALIBRATION

All water quality model inputs were derived from data collected during the September 1-2, 2009 synoptic survey. Tributary parameters were estimated based on literature values and calibration to in-stream water quality data. The QUAL2K model was set up to simulate temperature, flow, velocity, depth, organic nitrogen (ON), ammonia nitrogen (NH_3-N), nitrate/nitrite nitrogen (NO_2/ NO_3-N), $CBOD_u$, dissolved oxygen (DO), sediment oxygen demand (SOD), total phosphorus (TP) and chlorophyll-*a*. All model changes to global and reach specific kinetic rates as well as point source, diffuse and in-stream loadings are discussed in this section.

4.1 General Kinetic Rates

Eight model settings and kinetic rates were adjusted from model default values in order to meet longitudinal changes in observed water quality data. All kinetic rates were adjusted within the range of published values (Table 4.1).

Table 4.1 QUAL2K kinetic rates adjusted from model default values.

Rate	Calibrated Rate	Default Rate	Literature Range	Citation/Study Area
Reaeration Model	Tsivoglou and Neal	User Specified	Thomann and Mueller, 1987 cite that Tsivoglou and Neal, 1976; best for small, shallow streams (1-15 cfs)	
$CBOD_u$ oxidation rate (day^{-1})	0.30	0.23	0.02 – 0.60	Bowie et al., 1985 Table 3-17 p152 Kansas (6 rivers) Michigan (3 rivers) reported by Bansal, 1975
Organic-N Hydrolysis (day^{-1}) *The release of ammonia due to decay of organic nitrogen*	<0.01	0.20	0.1 – 0.4	Baca et al., 1973 Ammonia levels do not indicate significant Organic-N hydrolysis
Organic-N Settling Velocity (m/d)	0.01		influenced by a material's size, shape, and density and the speed of water	
Organic-P Hydrolosis (day^{-1}) *The release of phosphate due to decay of organic phosphorus*	0.05	0.20	0.10 – 0.70	Baca et al., 1973 Baca and Arnett, 1976
Organic-P Settling Velocity (m/d)	0.2		influenced by a material's size, shape, and density and the speed of water	
Inorganic-P settling (m/d)	0.25	2.0	influenced by a material's size, shape, and density and the speed of water	
Phytoplankton Settling (m/d)	0.1	0.50	0 – 2	Bowie et al., 1985 Table 6-19 p352 Chen & Orlob, 1975 and Smith, 1978

4.2 Tributary Inflow Water Quality

Initially, all flow increases were set to headwater water quality conditions and then adjusted upward or downward to meet in-stream water quality at MilC-03 (Table 4.2). Nitrogen and phytoplankton parameters were set lower than the Deer Lake headwater conditions while organic and inorganic phosphorus were higher. This suggests the Unnamed Tributary flowing to Mill Creek is not heavily influenced by lake discharge and displays similar water quality conditions to other small streams in the North Fork Crow River watershed.

Table 4.2 Modeled diffuse source parameters for Mill Creek.

Parameter	Reaches 1-4	Justification
Temp (C)	23	Calibrated adjustment to in-stream conditions
Sp. Cond (umhos)	516	Calibrated adjustment to in-stream conditions
DO	9.24	Calibrated adjustment to in-stream conditions
Organic- N (µg/L)	1000	Calibrated adjustment to in-stream conditions
Nitrate (µg/L)	<5	Calibrated adjustment to in-stream conditions
Organic-P (µg/L)	120	Calibrated adjustment to in-stream conditions
Inorganic-P (µg/L)	50	Calibrated adjustment to in-stream conditions
$CBOD_u$ (mg O_2/L)	5	Calibrated adjustment to in-stream conditions
Phytoplankton (µg-A/L)	5	Calibrated adjustment to in-stream conditions

4.3 Final Water Quality Calibration

$CBOD_u$, chlorophyll-*a* and all forms of nitrogen and phosphorus were calibrated once diffuse source water quality parameters and kinetic rates were properly incorporated into the model. The model performed well in predicting loads and concentrations of the primary water quality parameters that affect dissolved oxygen.

5.0 DISSOLVED OXYGEN CALIBRATION

5.1 Diurnal Oxygen Calibration

Even though water column algae was accurately depicted during water quality calibration, initial model runs predicted significantly smaller diurnal DO variability than was observed in the field. This suggests there was in-situ primary production that was not accounted for or under-represented in these model runs. QUAL2K has a bottom algae component that can simulate photosynthesis and nutrient uptake of any non-suspended algae. Bottom algae channel coverage was adjusted by reach in order to increase primary production and match the photosynthesis/respiration swings in the observed continuous DO data (Table 5.1). It is assumed that this bottom algae component represents all elements of primary production (attached algae, submerged macrophytes, rooted aquatic vegetation) that could not be measured or quantified in the field.

5.2 Sediment Oxygen Demand

Sediment oxygen demand (SOD) is calculated in QUAL2K based on the delivery and breakdown of particulate organic matter from the water column. Currently, the model does not have a macrophyte or riparian vegetation SOD component, nor does it incorporate any upland sediment transported and deposited during non-steady state storms events. The model does allow the user to assign SOD coverage (% of channel bottom) for each reach and also prescribe SOD that is added to the model predicted rate to account for SOD outside the modeling framework. SOD in streams varies depending on sediment type but is typically between 0.05 (mineral soils) and 2.00 (estuarine mud) g O_2/m^2/day (Thomann and Mueller, 1987). Mill Creek is a typical agricultural stream that has been ditched, straightened and/or widened in some areas. As a result, the stream is relatively deep and slow moving during baseflow conditions. There appeared to be minimal settling/deposition during the low-flow synoptic survey as the channel sediments throughout the system were composed of a mixture of larger rocks and soft, fine-grained particles.

Dissolved oxygen concentrations should be close to calibration as long as reasonable assumptions were made in allocating nutrient loads and adjusting kinetic rates. Model predicted dissolved oxygen concentrations for the hydraulic/phytoplankton/bottom algae/nutrient calibrated model were slightly lower than observed throughout Mill Creek. Thus, SOD bottom coverage was decreased in each reach to increase DO concentrations to match observed values (Table 5.1).

Table 5.1 Reach specific SOD and bottom algae coverage.

Reach	Bottom SOD coverage (%)	Bottom Algae Coverage (%)	Description
1	10	100	Over-widened channel, mixture of mud and hard bottom substrate, moderate rooted riparian vegetation
2	10	100	Over-widened channel, mixture of mud and hard bottom substrate, moderate rooted riparian vegetation
3	10	100	Over-widened channel, mixture of mud and hard bottom substrate, moderate rooted riparian vegetation
4	10	100	Over-widened channel, mixture of mud and hard bottom substrate, moderate rooted riparian vegetation

5.3 Final Dissolved Oxygen Calibration

Figure 5.1 shows the final calibration results for model-predicted and observed dissolved oxygen concentrations. Field DO grabs were collected on September 1st and 2nd using the hand-held YSI and are labeled with the time of sample collection, if available. Also shown are continuous dissolved oxygen measurements during the synoptic survey (shown in plots as the range of data between minimum and maximum as orange and blue “I”). The average of the continuous DO is marked on the plot with an orange or blue box dependant on the day.

The model performs well in predicting the average daily dissolved oxygen concentration (in plot as black dashed line) at the MilC-03 monitoring station with continuous DO measurements. The model also performs relatively well in predicting diurnal DO (daily minimum and maximum, shown in plots as blue dashed lines).

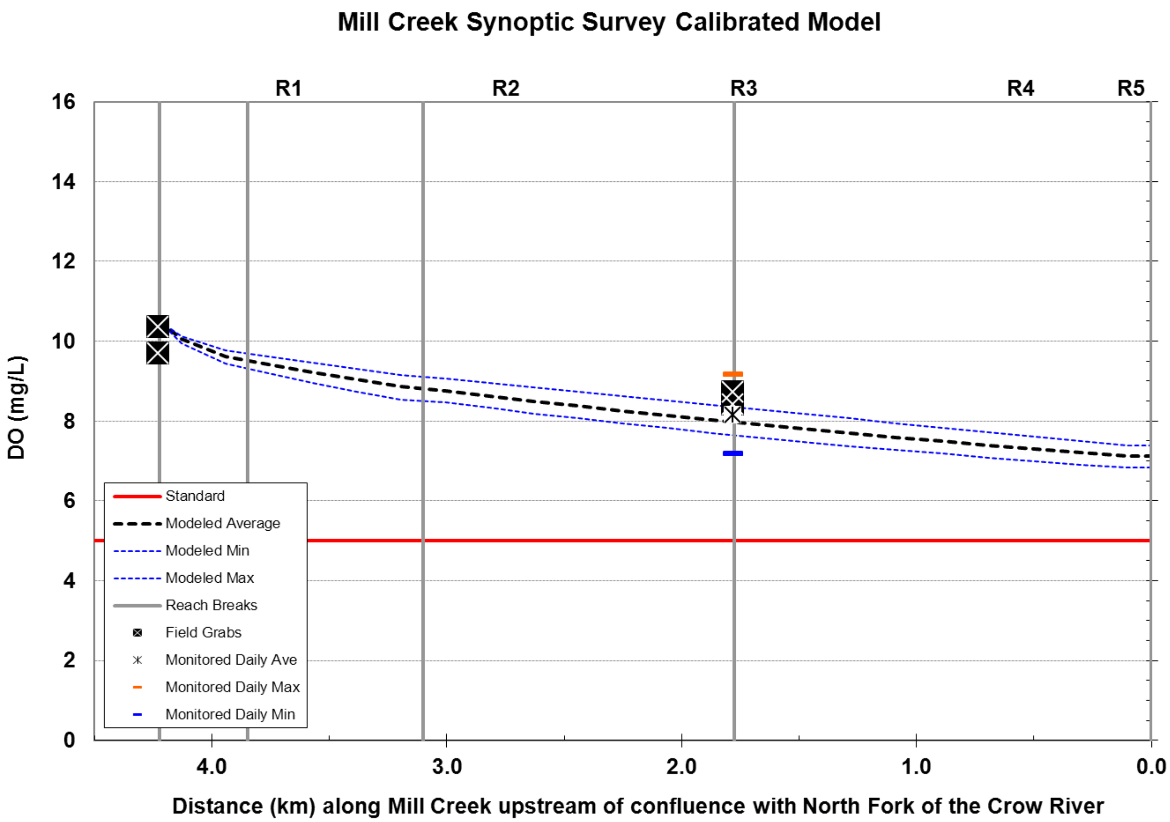

Figure 5.1 Mill Creek calibrated dissolved oxygen longitudinal profile.

6.0 AUGUST 3RD 2009 LOW-FLOW MODEL SIMULATION

There were no dissolved oxygen violations recorded throughout Mill Creek during the September 1st-2nd 2009 synoptic survey. In order to analyze low-flow DO violations in the system, the synoptic survey calibrated model was used to simulate a different summer low-flow event when DO violations were recorded. Continuous DO monitoring in 2009 indicated minimum DO at the MilC-03 monitoring station dropped well below the 5.0 mg/L DO standard during low-flow conditions on August 3rd (Figure 2.4 in the Mill Creek Historic Data and Synoptic Survey Methods and Results Memo). Average daily flow at MilC-03 on August 3rd, 2009 was 0.03 m^3/s (1.02 cfs) or approximately 93% less than the flow (15.00 cfs) recorded during the September 1-2, 2009 synoptic survey. Thus, August 3rd model simulation headwater (MilC-02) and Unnamed Tributary inflow were set 93% less than synoptic survey flow conditions. Besides one chlorophyll-a grab sample on 8/11/2009, there was no other summer water quality monitoring in Mill Creek in 2009. As a result, headwater and tributary water quality conditions for the August 3rd simulation were initially set equal to September 1st-2nd synoptic survey measurements and then adjusted upward or downward during DO model calibration.

Table 6.1 September 1-2nd synoptic survey and August 3rd low-flow simulation QUAL2K headwater and tributary water quality inputs/adjustments.

Parameter	Date	Headwater	Justification	Unnamed Tributary	Justification
DO	9/1/2009	10.50 (ave)	[1] Simulated	9.24 (ave)	[1] Simulated
(mg/L)	8/3/2009	24.66 (ave)	[2] Simulated	23.95 (ave)	[2] Simulated
CBODu	9/1/2009	17.90	Measured	5.00	[3] Adjustment
(mg/L)	8/3/2009	11.00	[4] Adjustment	5.00	[3] Adjustement
Organic Nitrogen	9/1/2009	1570	Measured	1000	[3] Adjustment
(µg/L)	8/3/2009	1570	No change	1000	[3] Adjustement
Ammonia	9/1/2009	0	Measured	0	[3] Adjustrment
(µg/L)	8/3/2009	5	[4] Adjustment	5	[4] Adjustment
Organic-P	9/1/2009	15	Measured	120	[3] Adjustment
(µg/L)	8/3/2009	58	[5] Estimated	120	[3] Adjustment
Inorganic-P	9/1/2009	14	Measured	50	[3] Adjustment
(µg/L)	8/3/2009	14	No change	50	[3] Adjustment
Phytoplankton	9/1/2009	43	Measured	5	[3] Adjustment
(µg-A/L)	8/3/2009	60	[5] Estimated	30	[4] Adjustement

[1] Simulated using continuous YSI measurements at MilC-03 on 9/1/2009. Value was estimated using relationships from continuous YSI data collected at MilC-03, MilC-02 on August 24th-30th, 2010.
[2] Simulated using continuous YSI measurements at MilC-03 on 8/3/2009. Value was estimated using relationships from continuous YSI data collected at MilC-03, MilC-02 on August 24th-30th, 2010.
[3] Calibration adjustment to meet in-stream water quality conditions on 9/1/2009.
[4] Calibration adjustment to meet in-stream continuous DO measurements at MilC-03 on 8/3/2009.
[5] Estimated value based on Mill Creek water quality sampling on 8/11/2009.

Figure 6.1 compares model predicted DO for the August 3rd low-flow QUAL2K model simulation to observed conditions at the MilC-03 monitoring station. The model performs reasonably well in predicting the average daily dissolved oxygen concentration and diurnal DO patterns

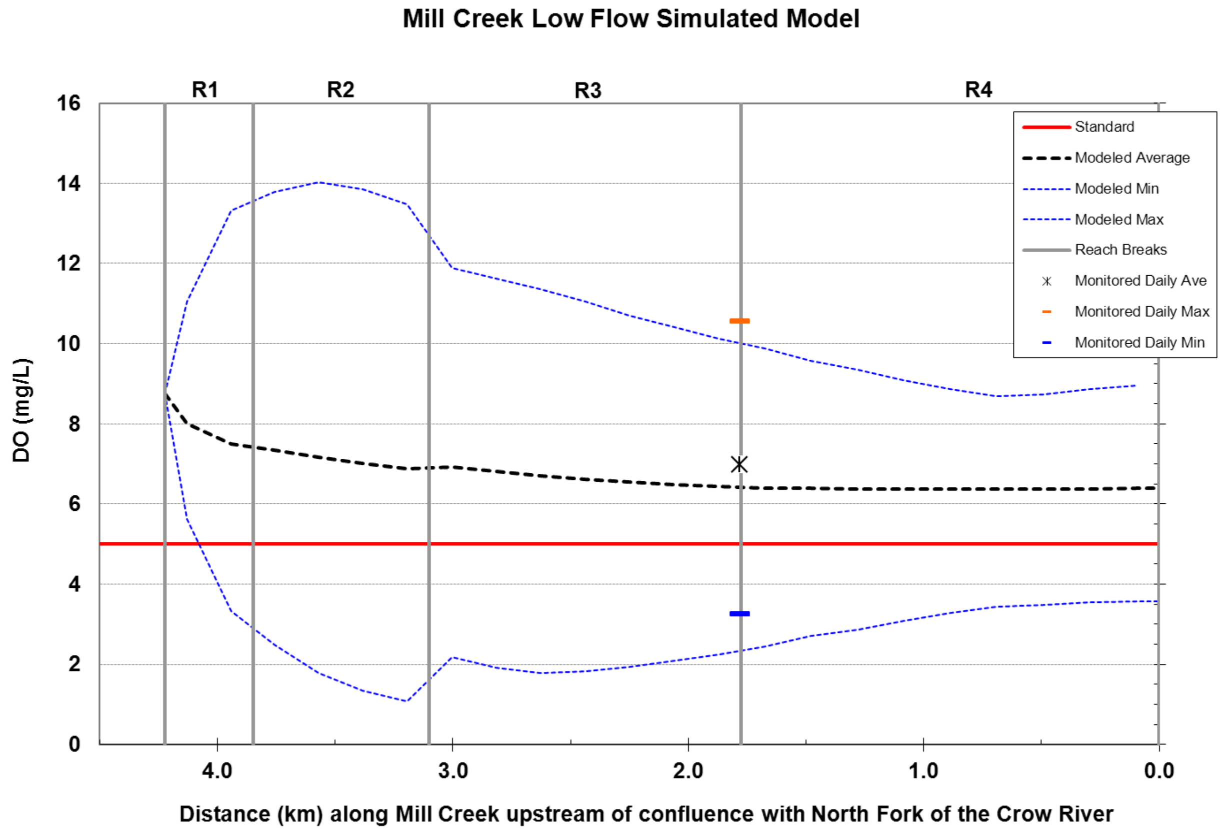

Figure 6.1 Mill Creek August 3rd low-flow model simulation dissolved oxygen longitudinal profile.

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TECHNICAL MEMORANDUM

TO: Diane Sander, Crow River Organization of Water Watershed Coordinator

CC: Maggie Leach, MPCA Regional Impaired Waters Coordinator

FROM: Joe Bischoff, Project Manager
Pamela Massaro, P.E.
Jeff Strom

DATE: September, 2011

SUBJECT: Regal Creek Dissolved Oxygen TMDL
Description of QUAL2K Modeling Methods and Results

Wenck Associates, Inc. has developed and calibrated a QUAL2K model for Regal Creek from County State Aide Highway 35 in St. Michael, MN to the Creek's confluence with the main-stem of the North Fork Crow River. The purpose of this technical memorandum is to describe the methods and assumptions used to create and calibrate the QUAL2K model.

1.0 INTRODUCTION

1.1 Model Selection

The U.S. EPA River and Stream Water Quality Model (QUAL2K) version 7 is a modernized version of the QUAL2E model developed by Dr. Steven Chapra with Tufts University and Greg Pelletier with Washington State. It was selected to analyze Regal Creek because it is a relatively simple surface water quality model that can be used during steady-state conditions to model nutrient, algal and dissolved oxygen dynamics.

1.2 General Overview of the Model

The model was built using late summer synoptic survey data collected on August 26-27, 2009. Stream locations and physical features were built in to the model first before proceeding to hydraulic calibration. With the diffuse flow inputs incorporated, the conservative water quality parameters (such as water temperature and conductivity) were adjusted to match monitored observations. Then, chlorophyll-*a* (phytoplankton production), nutrients (phosphorus and nitrogen components), and 5-day carbonaceous biological oxygen demand ($CBOD_5$) were calibrated by adjusting tributary/groundwater contributions and/or kinetic coefficients within the range of published values. In some cases, reach specific kinetic rates and in-stream nutrient fluxes were assigned to model geochemical processes believed to be unique to certain reaches. Finally, bottom algae and sediment oxygen demand were adjusted for each reach to match observed dissolved oxygen data.

2.0 MODEL SETUP AND INPUTS

The QUAL2K model covers the main stem of Regal Creek from where it crosses CSAH-35 in St. Michael, MN to its confluence with North Fork Crow River. This stretch of Regal Creek, explicitly modeled, represents approximately 2.14 miles (3.45 km) as three individual reaches. The start of each reach correlates with a monitoring station location (Figure 2.1, Table 2.1 and Table 2.2).

Table 2.1 Model reach characteristics.

Reach	Description	Upstream River km	Downstream River km	Distance (km)	Distance (miles)	Slope (m/m)
1	CSAH 35 (RC-01) to CSAH 19 (RC-02)	3.45	2.15	1.30	0.81	0.004
2	CSAH 19 (RC-02) to Meadowlark Rd (RC-03)	2.15	1.15	1.00	0.62	0.005
3	Meadowlark Rd (RC-03) to North Fork Crow	1.15	0.00	1.15	0.71	0.007

Table 2.2 Monitoring locations.

Reach	Reach Start Monitoring Location ID	Description	Data Collected
1	RC-01	Regal Creek at CSAH 35 Crossing	Q, Grab, BOD, Field
2	RC-02	Regal Creek at CSAH 19 Crossing	Q, BOD, Field, ToT, DO
3	RC-03	Regal Creek at Meadowlark Rd	Q, Grab, BOD, Field, ToT

Q = Flow gauged.
ToT = Time of Travel determined from dye study.
Grab = Water quality grab sample collected and lab analyzed for typical pollutants (total kjeldahl nitrogen (TKN), ammonia nitrogen (NH_3-N), nitrate nitrogen (NO_2-N), 5-day and ultimate carbonaceous biological oxygen demand ($CBOD_{5\text{-day}}$ & $CBOD_u$), total phosphorus (TP), ortho-phosphorus (soluble reactive phosphorus), total organic carbon (TOC), and chlorophyll-*a*).
BOD = Water quality grab sample collected and lab analyzed for $CBOD_{5\text{-day}}$ & $CBOD_u$.
Field = In-field measurement of temperature, conductivity, pH, and dissolved oxygen (DO).
DO = Data sondes deployed to collect continuous measurements of dissolved oxygen, temperature, pH and conductivity.

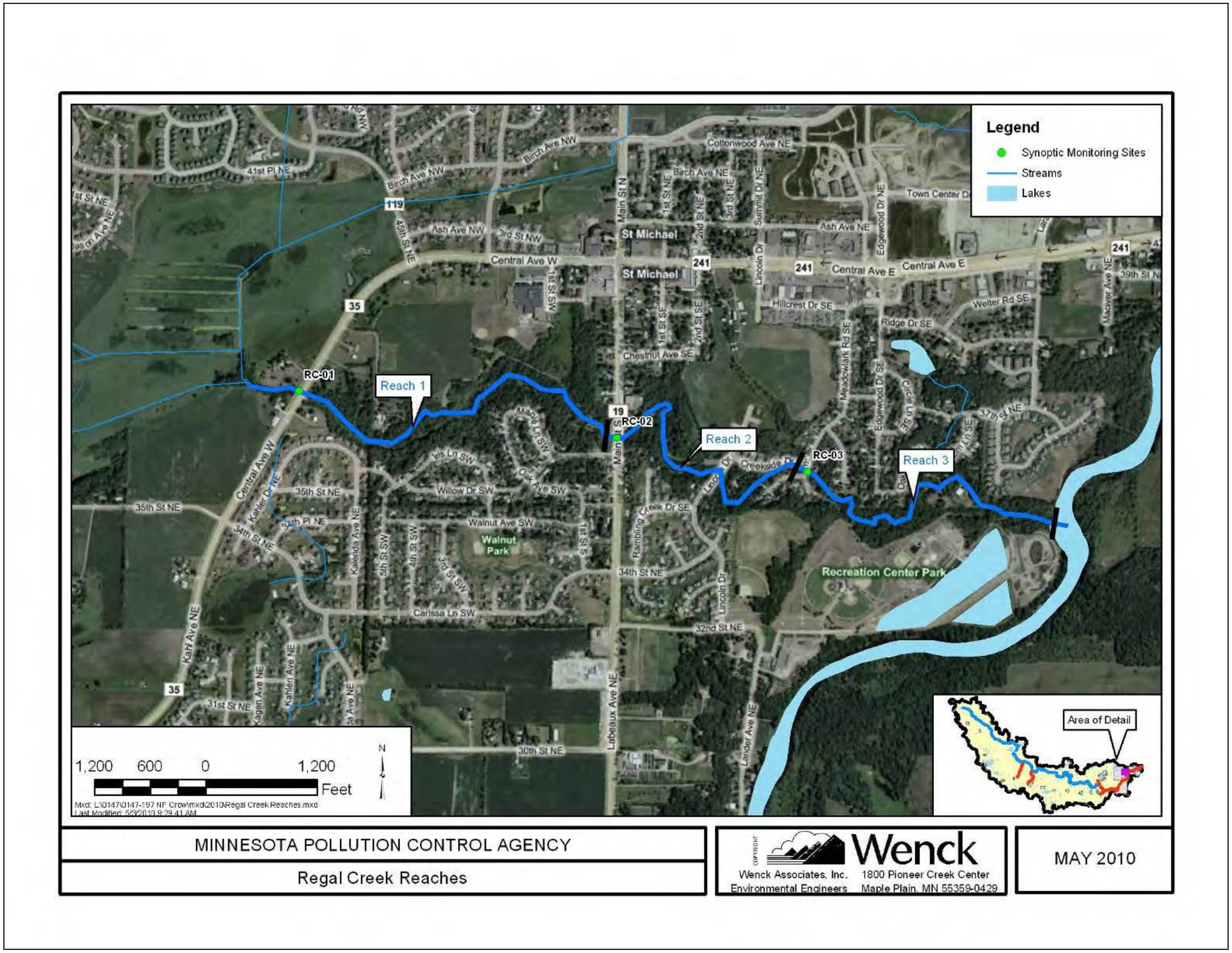

Figure 2.1 Monitoring stations and reaches on Regal Creek

2.1 Weather and Physical Processes

Hourly weather measurements of temperature, cloud conditions, relative humidity and wind speed were downloaded from the National Weather Service (NWS) NOAA Minneapolis-St. Paul Airport. Stream canopy coverage and shading was set to 75 percent for all reaches based on field observations and GIS air photos.

2.2 Headwaters

The Minnesota Department of Natural Resources (DNR) stream file shows Regal Creek headwaters to be located at the wetland upstream of CSAH-35 in St. Michael, MN. During the synoptic survey, flow was gauged downstream of the CSAH-35 (RC-01) culvert and deemed suitable to initiate the dye study and collect water quality samples. All flow and water quality data collected at the RC-01 station on August 26-27 was used to represent the upstream boundary condition/headwater for the Regal Creek QUAL2K model. As noted in Table 2.2, a data sonde was not deployed at the RC-01 station. Field dissolved oxygen measurements collected at this station in the late-morning/early-afternoon were extremely low (<1.0 mg/L). It is assumed there was virtually no diurnal DO swing at this site since these measurements were collected when photosynthesis is highest and DO should be closer to daily maximums. Thus, the DO, temperature, pH and conductivity measured in the field on 8/26/09 were used to represent model headwater conditions.

2.3 Carbonaceous Biochemical Oxygen Demand (CBOD)

The old EPA model (QUAL2E) version had one type of CBOD with one decay rate. The modernized version (QUAL2K) now includes two forms of CBOD to represent organic carbon; a slowly oxidizing form (slow CBOD) and a rapidly oxidizing form (fast CBOD). This allows the model to decay CBOD at two decay rates, if deemed necessary. This model enhancement is great for waste streams with organic carbons in the form of sugar, glucose, etc.. Both 5-day CBOD ($CBOD_5$) and ultimate CBOD ($CBOD_u$)were collected at each monitoring station during the synoptic survey. $CBOD_u$ measurements were used so that all potential carbonaceous oxygen consumption is represented in the model.

3.0 HYDRAULIC CALIBRATION

Modeled hydraulic inputs were derived from the flow gauging data collected during the August 26th and 27th synoptic survey. Total discharge was calibrated prior to calibrating travel time. All hydraulic inputs and calibration adjustments are described in the following sections.

3.1 Hydraulic Rating Curves

QUAL2K hydraulics may be modeled using power function rating curves, weirs (dam/drop structures) or Manning's equations. Hydraulics for all Regal Creek reaches were represented using power function rating curves based on flow gauging data collected during the synoptic survey. The rating curve option relates mean velocity and depth to flow in each reach. QUAL2K uses five coefficients to define reach hydraulics, as follows:

- Velocity (m/sec) = a Q^b
- Depth (m) = c Q^d + e

in which Q is flow in cubic meters per second. Depth and velocity rating curves were constructed using gauged flow data from the time of travel study. Gauging stations with similar channel dimensions and flow characteristics were combined in to one rating curve to provide more robust velocity/depth versus flow relationships (Figures 3.1 - 3.3). Applying the principals of hydraulic geometry (Leopold and Maddock, 1953), there is one additional power function that defines width:

- Width (m) = f Q^g

Because the width, depth and velocity are a function of discharge, the following rules apply to the coefficients and exponents of these power functions. The sum of the exponents equal one ($b + d + g = 1.0$), and the product of the coefficients equal one ($a \times c \times f = 1.0$). The representative hydraulic rating curves for each reach were selected based on proximity to gauging stations and typical channel dimensions throughout the reach. The hydraulic coefficients and exponents for each QUAL2K reach are summarized in Table 3.1 along with adjustments made during calibration.

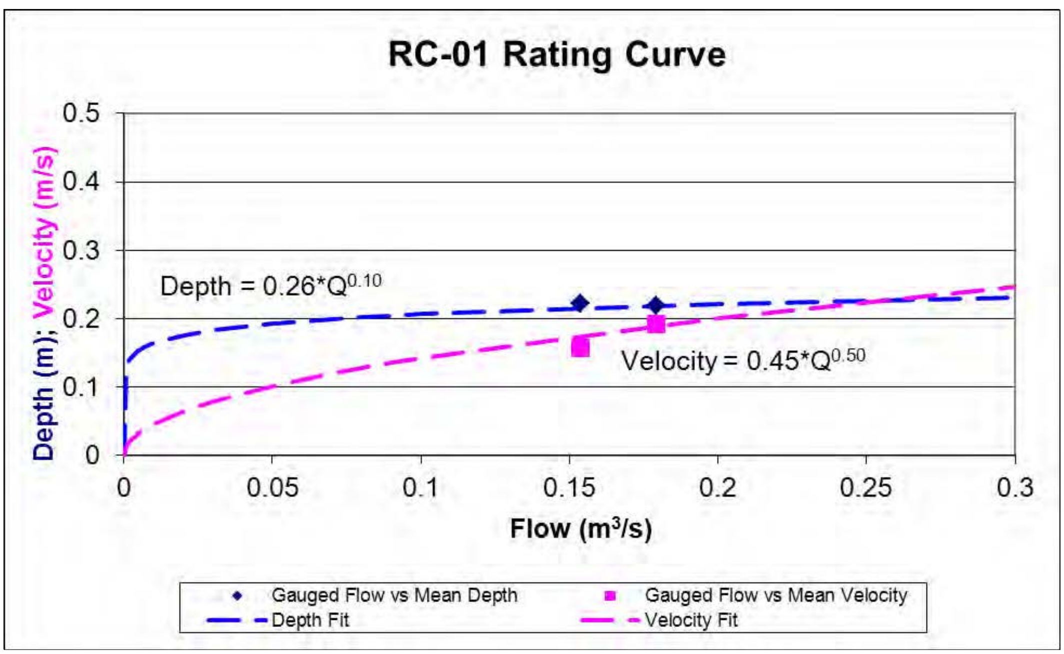

Figure 3.1 Hydraulic rating curve plot for gauging station RC-01.

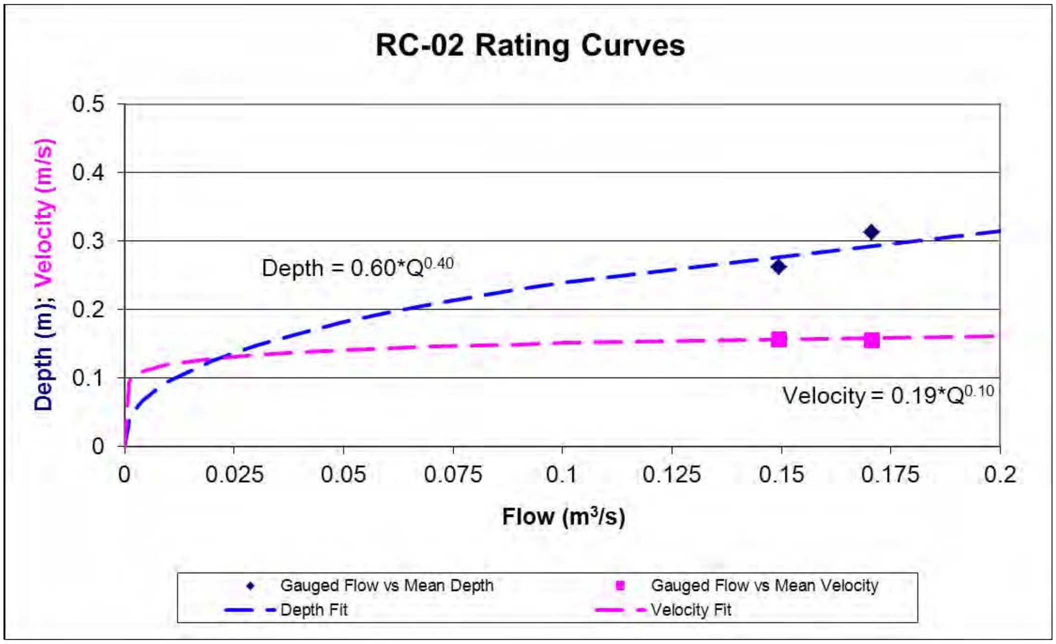

Figure 3.2 Hydraulic rating curve plot for gauging station RC-02.

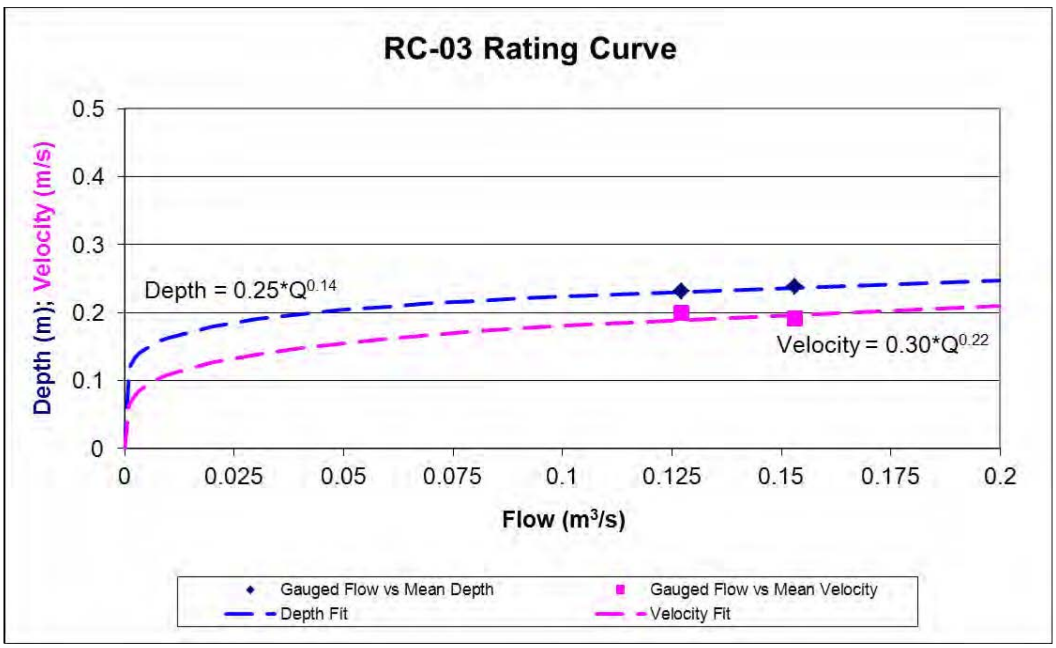

Figure 3.3 Hydraulic rating curve plot for gauging station RC-03.

Table 3.1 Summary of the hydraulic coefficients and exponents assigned to each reach.

Reach	Rating Curve Used	Velocity		Depth		Adjustments
		Coeff.	Exp.	Coeff.	Exp.	
1	RC-02	0.19	0.10	0.60	0.40	
2	RC-03	0.40$^{\Delta}$	0.22	0.25	0.14	Velocity coefficient increased to match travel time measurements
3	RC-03	0.40$^{\Delta}$	0.22	0.25	0.14	Velocity coefficient increased to match travel time measurements

* denotes that the monitoring station is at the upstream end of the reach.

$^{\Delta}$ denotes a change in the hydraulic coefficients or exponent.

3.2 Flow Calibration

Regal Creek tributaries and inflows were not accessible to determine if they were contributing flow during the synoptic survey and dye study. Thus, monitored changes in flow between gauging stations were built in to the model as diffuse inflows or abstractions. All diffuse sources are described in Table 3.2. Flow gauging data suggests Regal Creek was a losing stream between RC-01 and RC-03 during the August synoptic survey (Figure 3.4).

Table 3.2 Modeled diffuse source inflow/abstractions for Regal Creek

Reach	Total flow throughout reach (m^3/s)*	Flow Rate (m^3 per River kilometer)*
Reach 1 (RC-01 to RC-02)	-0.008*	-0.006*
Reach 2 (RC-02 to RC-03)	-0.023*	-0.023*

* denotes that negative flow values are abstractions (outflows), while positive flow values are inflows.

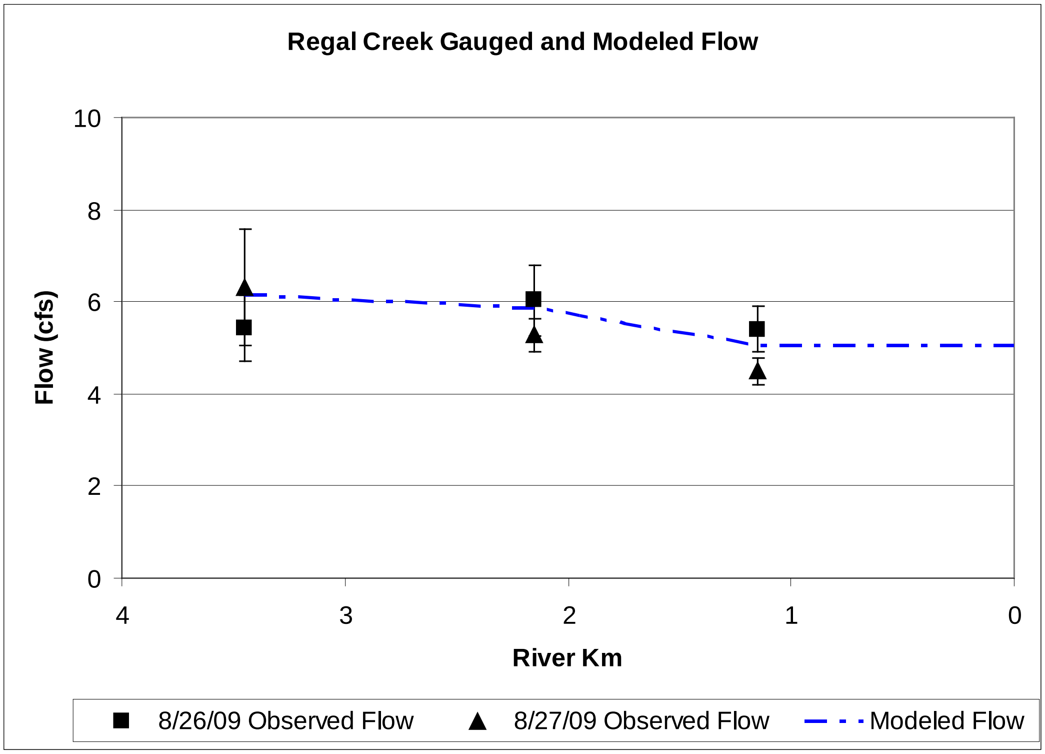

Figure 3.4 Final Regal Creek Flow calibration with diffuse inflows/abstractions. Error bars on observed measurements represent estimated uncertainty of the Flow-Tracker field measurement.

3.3 Time of Travel Calibration

With total flow calibrated, rating curve coefficients and exponents were adjusted to meet travel times calculated during the dye study portion of the synoptic survey. Reaches 2 and 3 (RC-03 rating curve) were the only reaches where travel time did not match observed using the assigned gauging station rating curves. Observed travel times support adjusting RC-03's hydraulic velocity coefficient to represent faster velocities for reaches 2 and 3 than were measured at the downstream station. This adjustment effectively matched model and observed travel time (Figure 3.5).

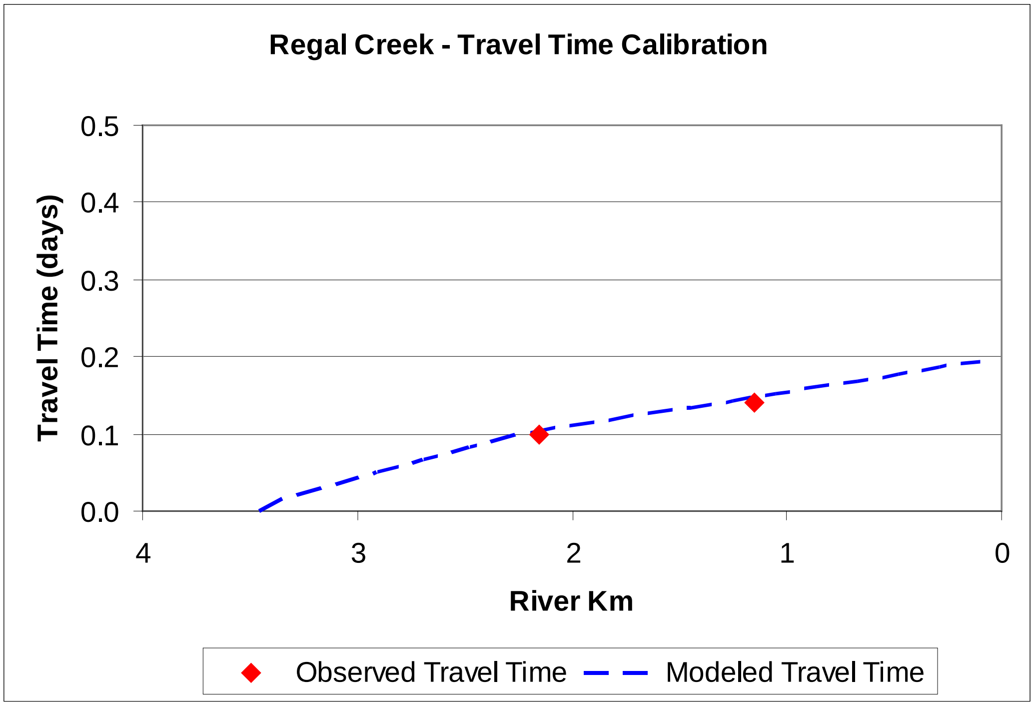

Figure 3.5 Regal Creek time of travel calibration.

4.0 WATER QUALITY CALIBRATION

All water quality model inputs were derived from data collected during the August 26-27, 2009 synoptic survey. The QUAL2K model was set up to simulate temperature, flow, velocity, depth, organic nitrogen (ON), ammonia nitrogen (NH_3-N), nitrate/nitrite nitrogen (NO_2/ NO_3-N), $CBOD_u$, DO, sediment oxygen demand (SOD), total phosphorus (TP), chlorophyll-*a*. All model changes to global and reach specific kinetic rates to calibrate water quality are discussed in this section.

4.1 Reaeration Formula

Reaeration in QUAL2K may be prescribed by the user or calculated using one of eight hydraulic-based reaeration formulas built into the model. The O'Connor-Dobbins reaeration model was selected for Regal Creek because it is the most appropriate to calculate reaeration when stream velocity is 0.5 - 1.6 feet per second (O'Connor and Dobbins, 1958). Regal Creek velocities were 0.5 – 0.6 feet per second during the August 26-27 synoptic survey. The O'Connor-Dobbins reaeration model formula is shown below:

$$K_{ah}(20) = 3.93(U^{0.5}/H^{1.5})$$

Where:
K_a = reaeration rate coefficient at 20°C (base e, day $^{-1}$)

U = mean water velocity (m/s)
H = mean water depth (m)

Flow velocity and water depth are the variables used to calculate reaeration in each reach. These variables were measured in the field at each monitoring station during flow gauging and represented in the model using hydraulic rating curves (Section 3.1).

4.2 General Kinetic Rates

Seven kinetic rates were adjusted from model default values in order to meet longitudinal changes in observed water quality data. All kinetic rates were adjusted within the range of published values (Table 4.1).

Table 4.1 QUAL2K kinetic rates adjusted from model default values.

Rate	Calibrated Rate	Default Rate	Literature Range	Citation/Study Area
Reaeration Model	O'Connor-Dobbins	User Specified	Most appropriate for stream velocities 0.5 to 1.5 feet per second (O'Connor and Dobbins, 1958)	
$CBOD_u$ oxidation rate (day^{-1})	0.3	0.23	0.02 – 0.60 0.56 – 3.37	Bowie et al., 1985 Table 3-17 p152 Kansas (6 rivers) Michigan (3 rivers) reported by Bansal, 1975
Organic-N Settling Velocity (m/d)	1.0	0.10	influenced by a material's size, shape, and density and the speed of water	
Ammonium Nitrification (day^{-1})	4	1	0.5 – 9.0 3.1 – 6.2	Koltz, 1982 Wezernak et al., 1968
Organic-P Settling Velocity (m/d)	1.0	0.10	influenced by a material's size, shape, and density and the speed of water	
Inorganic-P settling (m/d)	1.0	2.0	influenced by a material's size, shape, and density and the speed of water	

4.3 Final Water Quality Calibration

$CBOD_{ultimate}$, chlorophyll-*a* and all forms of nitrogen and phosphorus were calibrated once global and reach specific kinetic rates were properly adjusted. The model performed well in predicting loads and concentrations of the primary water quality parameters that affect dissolved oxygen.

5.0 DISSOLVED OXYGEN CALIBRATION

5.1 Diurnal Oxygen Calibration

Continuous DO data recorded at RC-02 suggest DO varied no more than 0.3 mg/L between daily minimum and maximum during the August 26 and 27 synoptic survey. Once water column algae was accurately predicted in the model (Figure 4.4), no additional model adjustments were needed to calibrate diurnal DO (Figure 5.1). This implies non-suspended photosynthesis (attached algae, submerged macrophytes, rooted aquatic vegetation) does not play a significant role in the DO dynamics of Regal Creek under these flow conditions.

5.2 Sediment Oxygen Demand

Sediment oxygen demand (SOD) is calculated in QUAL2K based on the delivery and breakdown of particulate organic matter from the water column. Currently, the model does not have a macrophyte or riparian vegetation SOD component, nor does it incorporate any upland sediment transported and deposited during non-steady state storms events. The model does allow the user to assign SOD coverage (% of channel bottom) for each reach and also prescribe SOD that is added to the model predicted rate to account for SOD outside the modeling framework. SOD in streams varies depending on sediment type but is typically between 0.05 (mineral soils) and 2.00 (estuarine mud) g O^2/m^2/day (Thomann and Mueller, 1987). For the most part, Regal Creek sediments appeared to contain very little organic matter as the channel bottom was comprised of large rocks and fine sand.

Dissolved oxygen concentrations should be close to calibration as long as reasonable assumptions were made in allocating nutrient loads and adjusting kinetic rates. Model predicted dissolved oxygen concentrations for the hydraulic/phytoplankton/bottom algae/nutrient calibrated model were slightly lower than observed throughout CD31. Thus, SOD bottom coverage was decreased in each reach to increase DO concentrations to match observed values (Table 5.1).

Table 5.1 SOD prescribed to each reach that is added to model-predicted SOD under steady state conditions.

Reach	Bottom SOD Coverage (%)	Bottom Algae Coverage (%)	Description
1	0	100	Reach displays muddier sediments near wetland headwaters (RC-01) and larger sediment particles moving downstream
2	0	100	Rock and sandy bottom reach with very little organic matter
3	0	100	Rock and sandy bottom reach with very little organic matter

5.3 Final Dissolved Oxygen Calibration

Figure 5.1 shows the final calibration results for model-predicted and observed DO concentrations. Field grabs of dissolved oxygen were taken on August 26 and August 27 using the hand-held YSI. The field grabs are labeled with the sample collection time, if available. Also shown is the continuous dissolved oxygen data recorded during the synoptic survey (shown in plot as the range of data between minimum and maximum as orange and blue "I"). The average of the continuous DO is marked on the plot with an orange or blue box dependant on the day. The model performs well in predicting average daily DO concentrations (in plot as black dashed line) and the diurnal pattern (daily minimum and maximum, shown in plots as blue dashed lines) at the RC-02 monitoring stations with continuous DO measurements.

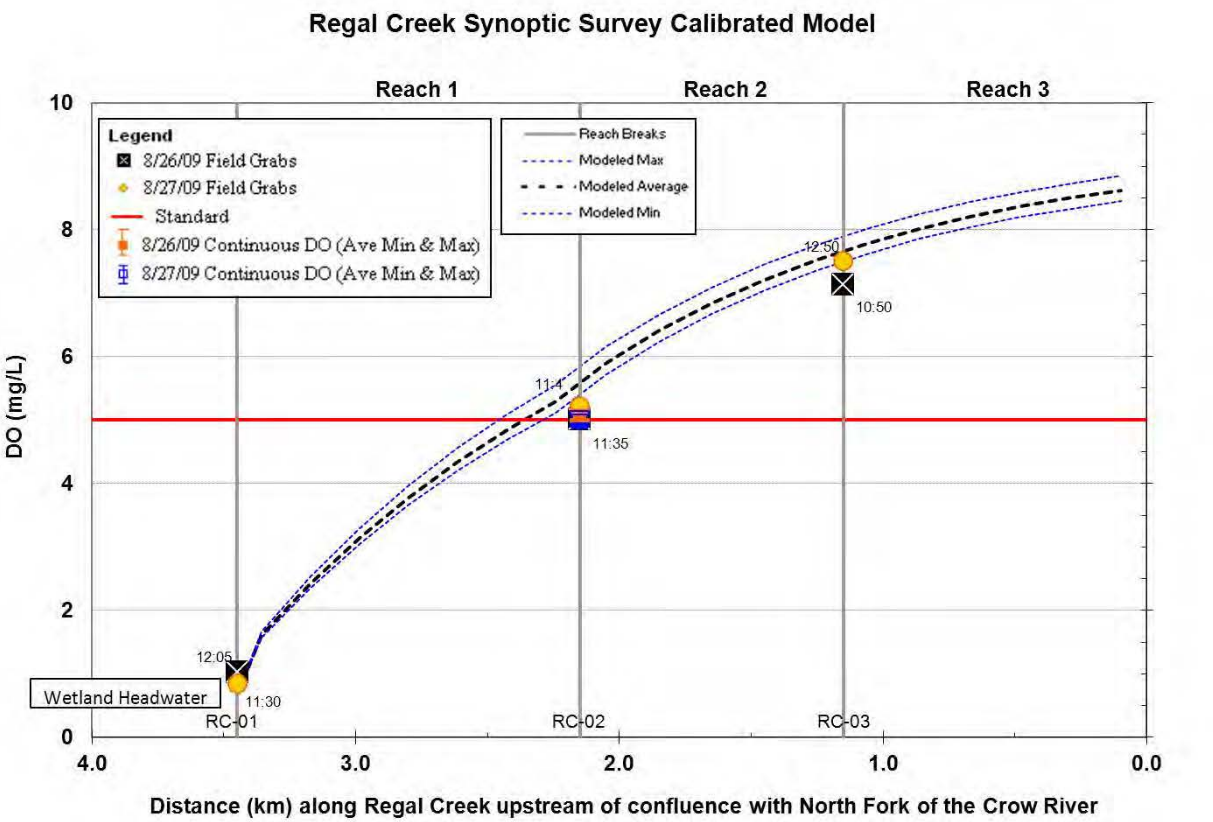

Figure 5.1 Regal Creek calibrated dissolved oxygen longitudinal profile.

6.0 SENSITIVITY ANALYSIS

To evaluate the sensitivity of model predicted DO to changes in model variables, eight kinetic rates (Table 6.1) were removed or adjusted by specific percentages. Table 6.1 summarizes the affect these changes have on the average model-predicted DO concentration for the entire modeled stretch of Regal Creek. Results show DO throughout the system is only slightly sensitive to CBOD oxidation and ammonium nitrification rates. This exercise suggests headwater conditions and stream hydrology play a bigger role than water column processes in dissolved oxygen dynamics under these flow conditions.

Table 6.1 DO sensitivity to kinetic rates.

Kinetic rate	**+25%**	**-25%**	**Default**
$CBOD_u$ oxidation rate (day^{-1})	-0.7%	0.7%	2.5%
Organic-N Hydrolysis (day^{-1})	0.0%	0.2%	---
Organic-N Settling (m/d)	0.0%	0.0%	0.0%
Ammonium Nitrification (day^{-1})	-0.2%	0.3%	0.8%
Organic-P Hydrolysis (day^{-1})	0.0%	0.0%	0.0%
Organic-P Settling (m/d)	0.0%	0.0%	0.0%
Inorganic-P Settling (m/d)	0.0%	0.0%	0.0%
Phytoplankton Settling (m/d)	0.0%	0.0%	---

7.0 REFERENCES

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Appendix H

Dissolved Oxygen QUAL2K Model Tech Memos

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TECHNICAL MEMORANDUM

TO: Diane Sander, Crow River Organization of Water Watershed Coordinator

CC: Maggie Leach, MPCA Regional Impaired Waters Coordinator

FROM: Joe Bischoff, Project Manager
Pamela Massaro, P.E.
Jeff Strom

DATE: September, 2011

SUBJECT: County Ditch 31 Dissolved Oxygen TMDL
Description of QUAL2K Modeling Methods and Results

Wenck Associates, Inc. has developed and calibrated a QUAL2K model for County Ditch 31 from the Meridan Ave SE crossing to the Creek's confluence with the main-stem of the North Fork Crow River. The purpose of this technical memorandum is to describe the methods and assumptions used to create and calibrate the QUAL2K model.

1.0 INTRODUCTION

1.1 Model Selection

The U.S. EPA River and Stream Water Quality Model (QUAL2K) version 7 is a modernized version of the QUAL2E model developed by Dr. Steven Chapra with Tufts University and Greg Pelletier with Washington State. It was selected to analyze County Ditch 31 (CD31) because it is a relatively simple surface water quality model that can be used during steady-state conditions to model nutrient, algal and dissolved oxygen dynamics.

1.2 General Overview of Model

The model was built using late summer synoptic survey data collected on August 26th-27th, 2008. Stream locations and physical features were built in to the model first before proceeding to hydraulic calibration. With the diffuse flow inputs incorporated, the conservative water quality parameters (such as water temperature and conductivity) were adjusted to match monitored observations. Then, chlorophyll-*a* (phytoplankton production), nutrients (phosphorus and nitrogen components), and carbonaceous biochemical oxygen demand (CBOD) were calibrated by adjusting tributary/groundwater contributions and/or kinetic coefficients within the range of published values. In some cases, reach specific kinetic rates and in-stream nutrient fluxes were assigned to model geochemical processes believed to be unique to certain reaches. Finally, bottom algae and sediment oxygen demand were adjusted for each reach to match observed dissolved oxygen data.

2.0 MODEL SETUP AND INPUTS

The River and Stream Water Quality Model (QUAL2K version 7) covers CD31 from where it crosses Meridan Ave S near the outlet of the Woodland wetland system south-east of Montrose, MN. to its confluence with the North Fork Crow River. The stretch of the creek, explicitly modeled, represents approximately 2.58 miles (4.15 km) subdivided in to four reaches. The start of each main stem reach correlates with a monitoring station location or change in stream hydrology/morphometry (Figure 2.1, Table 2.1 and Table 2.2). There are no registered point sources that directly discharge to this stretch of CD31.

Table 2.1 Model reach characteristics.

Reach	Description	US River km	DS River km	Distance (km)	Distance (mile)
1	CD31-01 to CD31-02	4.15	2.13	2.02	1.26
2	CD31-02 to Hwy 25	2.13	1.75	0.38	0.23
3	Hwy 25 to CD31-03	1.75	0.73	1.02	0.64
4	CD31-03 to North Fork Crow	0.73	0.00	0.73	0.45

Table 2.2 Monitoring locations.

Reach	Reach Start Monitoring Location ID	Description	Data Collected
1	CD31-01	Meridan Ave SE	Q, Grab, Field
2	CD31-02	Highway 12	ToT, Q, Field, Sonde
4	CD31-03	Brighton Ave SE	ToT, Q, Grab, Field

Q = Flow gauged.
ToT = Time of Travel determined from dye study.
Grab = Water quality grab sample collected and lab analyzed for typical pollutants (total kjeldahl nitrogen (TKN), ammonia nitrogen (NH_3-N), nitrate nitrogen (NO_2-N), 5-day and ultimate carbonaceous biological oxygen demand ($CBOD_{5\text{-}day}$ & $CBOD_u$), total phosphorus (TP), ortho-phosphorus (soluble reactive phosphorus), total organic carbon (TOC), and chlorophyll-*a*).
Field = In-field measurement of temperature, conductivity, pH, and dissolved oxygen (DO).
Sonde = continuous data sonde deployed to hourly temperature, DO, pH, conductivity data

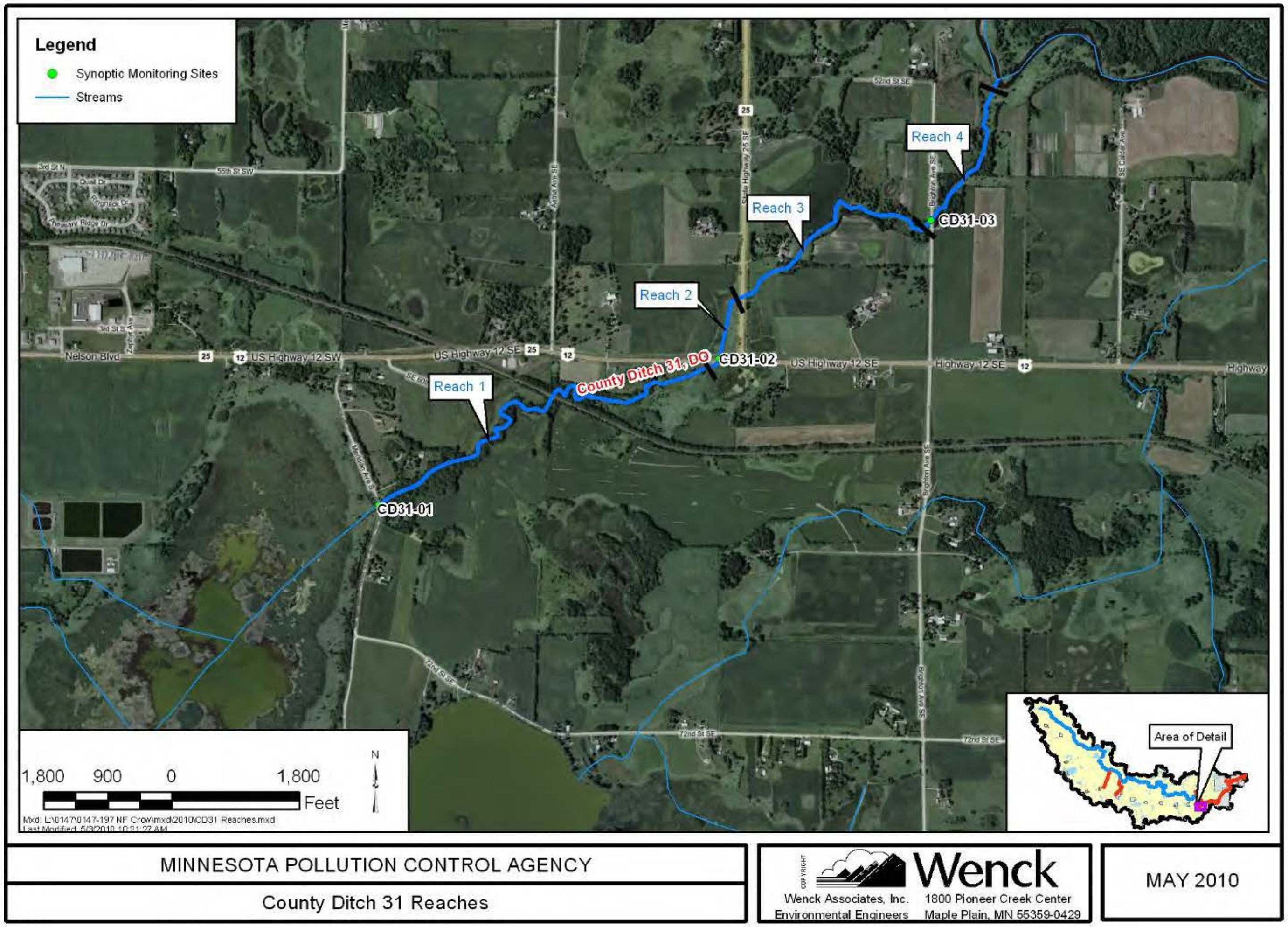

Figure 2.1 Monitoring stations and reaches on CD31.

2.1 Channel Slope

Reaeration may be prescribed by the user or calculated using one of eight hydraulic-based reaeration models built into QUAL2K. The Tsivoglou-Neal reaeration model was selected for CD31 because it is the most appropriate model to predict reaeration for flows less than 10 cfs (Tsivoglou and Neal, 1972; Thomann and Mueller, 1987). This reaeration model formula is shown below:

$K_a = 1.8 \times V \times S$ for $1 < Q < 10$ cfs

Where:
K_a = reaeration rate coefficient at 20°C (base e, day $^{-1}$)
V = average velocity (ft/s)
S = slope of energy gradient (ft/mile)

Channel slope and velocity are the variables used to calculate reaeration in each reach. Average channel slopes are based on data from an elevation survey conducted by Wenck in the fall of 2008 (Figure 2.2 and Table 2.3).

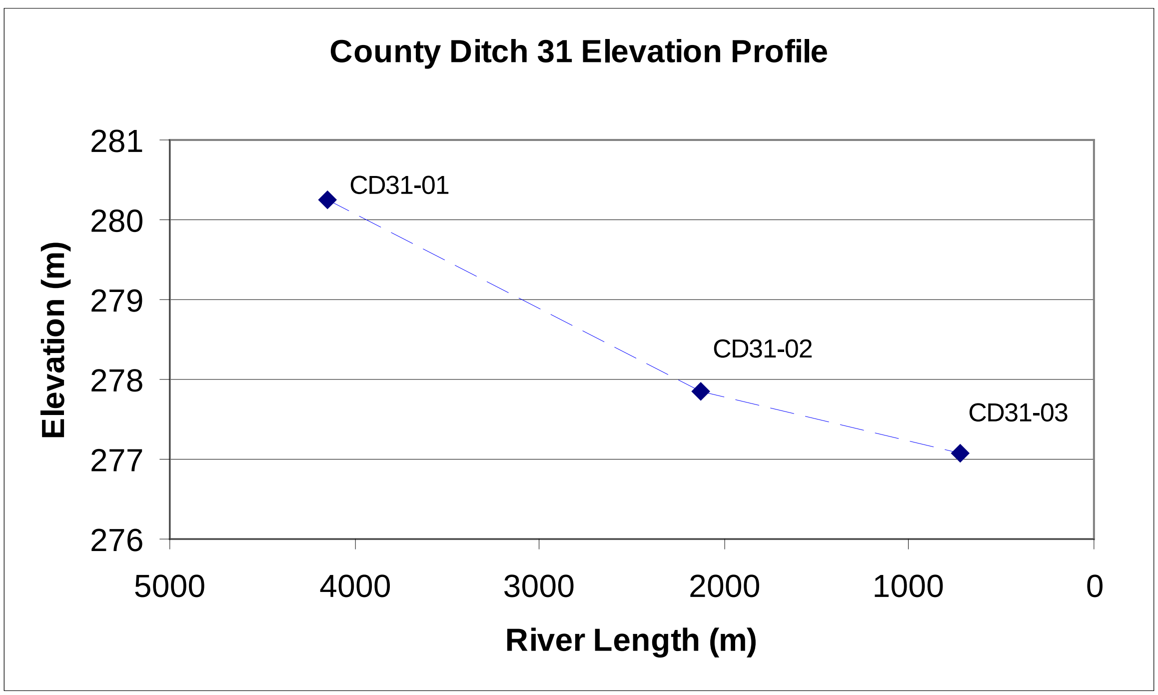

Figure 2.2 Survey elevations used to estimate reach slopes for County Ditch 31.

Table 2.3 County Ditch 31 Longitudinal Elevation Survey Summary.

Monitoring Station	River Kilometer	River Mile	Elevation (meters)	Elevation (feet)	Slope (ft/mile)
CD31-01	4.15	2.58	280.25	919.46	---
CD31-02	2.13	1.32	277.85	911.58	6.25
CD31-03	0.73	0.45	277.07	909.02	2.94
				Total Slope	4.90

2.2 Weather and Physical Processes

Hourly weather measurements of temperature, cloud conditions, relative humidity and wind speed were downloaded from the National Weather Service (NWS) NOAA Minneapolis-St. Paul Airport. Stream canopy coverage was established based on field observations and investigation of air photos in GIS (Table 2.4).

Table 2.4 County Ditch 31 canopy cover.

Reach	Description	Canopy coverage (%)
1	CD31-01 to CD31-02	40
2	CD31-02 to Hwy 25	0
3	Hwy 25 to CD31-03	15
4	CD31-03 to North Fork Crow	25

2.3 Headwaters

The Minnesota Department of Natural Resources (DNR) stream file shows County Ditch 31 headwaters to be the outflow from the Woodland wetland system south-east of Montrose, MN. Historically, the MPCA has monitored one site upstream of the Woodland wetland System (CD31-00) at Armitage Avenue. This site was visited prior to the synoptic survey and observed to be dry. Thus, all water quality and flow data collected at station CD31-01 was used to represent the upstream boundary condition/headwater in the QUAL2K model.

As noted in Table 2.2, no data sonde was deployed at the upstream boundary/headwaters (CD31-01). Field parameter data collected with the hand-held sonde at the beginning of the synoptic survey on August 26th was used to represent headwater temperature, conductivity, dissolved oxygen and pH.

2.4 Carbonaceous Biochemical Oxygen Demand (CBOD)

The old EPA model (QUAL2E) version had one type of CBOD with one decay rate. The modernized version (QUAL2K) now includes two forms of CBOD to represent organic carbon; a slowly oxidizing form (slow CBOD) and a rapidly oxidizing form (fast CBOD). This allows the model to decay CBOD at two decay rates, if deemed necessary. This model enhancement is great for waste streams with organic carbons in the form of sugar, glucose, etc.. Both 5-day CBOD ($CBOD_5$)and ultimate CBOD ($CBOD_u$)were collected at each monitoring station during the synoptic survey. $CBOD_u$ measurements were used to represent the breakdown of organic carbon over $CBOD_5$ in the model since this measurement more accurately represents total potential carbonaceous oxygen demand.

3.0 HYDRAULIC CALIBRATION

Modeled hydraulic inputs were derived from flow gauging data collected during the August 26th-27th synoptic survey. Total discharge was calibrated first before calibrating travel time. All hydraulic inputs and calibration adjustments are described in the following sections.

3.1 Hydraulic Rating Curves

QUAL2K hydraulics may be modeled using power function rating curves, weirs (dam/drop structures) or Manning's equations. Hydraulics for all CD31 reaches were represented using power function rating curves based on flow gauging data collected during the synoptic survey. The power function option relates mean velocity and depth to flow in each reach. QUAL2K uses five coefficients to define reach hydraulics, as follows:

- Velocity (mps) = $a\ Q^b$
- Depth (m) = $c\ Q^d + e$

in which Q is flow in cubic meters per second. Depth and velocity rating curves were constructed using gauged flow data from the time of travel study. Gauging stations with similar channel dimensions and flow characteristics were combined in to one rating curve to provide more robust velocity/depth versus flow relationships (Figures 3.1 - 3.3). Applying the principals of hydraulic geometry (Leopold and Maddock, 1953), there is on additional power function that defines channel width:

- Width (m) = $f\ Q^g$

Because the width, depth and velocity are a function of discharge, the following rules apply to the coefficients and exponents of these power functions. The sum of the exponents equal one ($b + d + g = 1.0$), and the product of the coefficients equal one ($a \times c \times f = 1.0$). The representative hydraulic rating curves for each reach was selected based on proximity to gauging stations and typical channel dimensions throughout the reach. The hydraulic coefficients and exponents for each QUAL2K reach are summarized in Table 3.1.

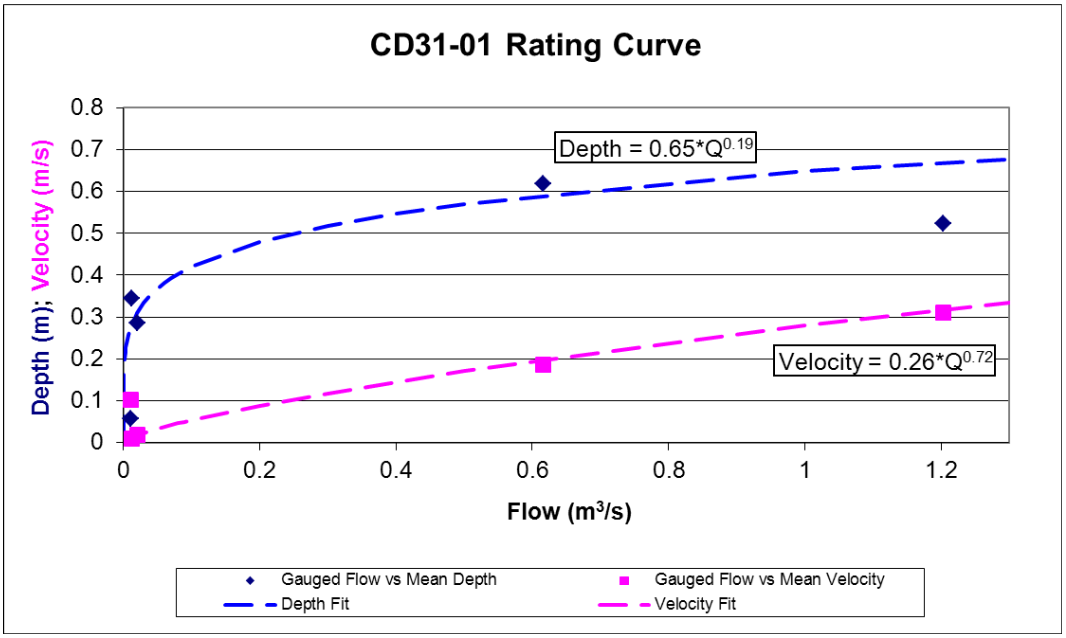

Figure 3.1 Hydraulic rating curve plot for gauging station CD31-01.

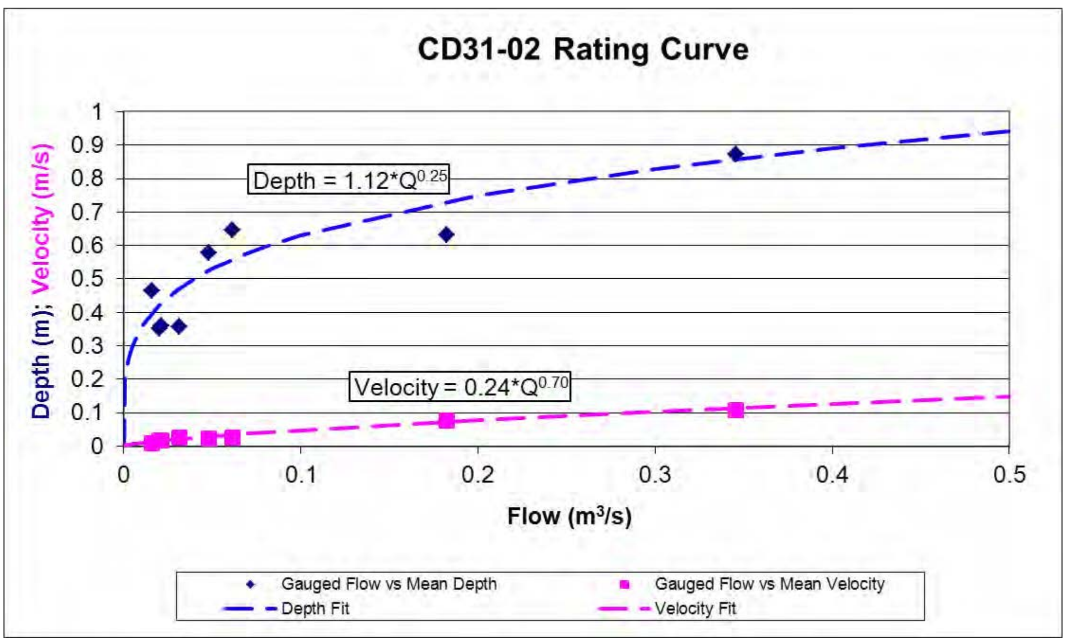

Figure 3.2 Hydraulic rating curve plot for gauging station CD31-02.

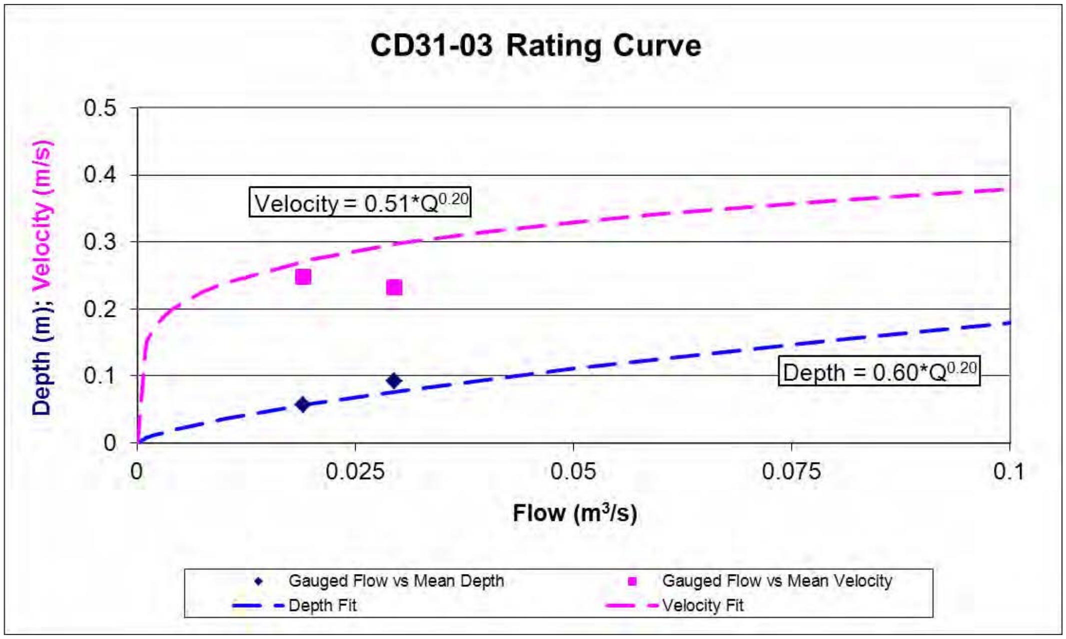

Figure 3.3 Hydraulic rating curve plot for gauging station CD31-03.

Table 3.1 Summary of hydraulic coefficients and exponents assigned to each reach.

		Velocity		Depth		
Reach	**Rating Curve used**	**Coeff.**	**Exp.**	**Coeff.**	**Exp.**	**Adjustments**
1	CD31-01*	0.26	0.72	0.65	0.19	None
2	CD31-02*	0.24	0.70	1.12	0.25	None
3	CD31-03	0.51^{Δ}	0.20	0.60	0.20	Decreased velocity coefficient to match travel time
4	CD31-03*	0.51^{Δ}	0.20	0.60	0.20	Decreased velocity coefficient to match travel time

* denotes that the monitoring station is at the upstream end of the reach.

Δ denotes a change in the hydraulic coefficients or exponent.

3.2 Flow Calibration

CD31 tributaries were not accessible to determine if they were contributing flow during the synoptic survey and dye study. Thus, all observed increases in flow between gauging stations were built in to the model as diffuse sources (Table 3.2). The model was deemed calibrated for total discharge once all point source and diffuse source flows were built in to the model (Figure 3.4.)

Table 3.2 Modeled diffuse source inflow for CD31.

Reach	Total Inflow throughout reach (m^3/s)	Justification
Reach 1 (CD31-01 to CD31-02)	0.004	Calculated based on flow gauging data
Reach 2+3 (CD31-02 to CD31-03)	0.003	Calculated based on flow gauging data
Reach 4 (CD31-03 to Outlet)	0.002	Calculated based on upstream flow gauging data

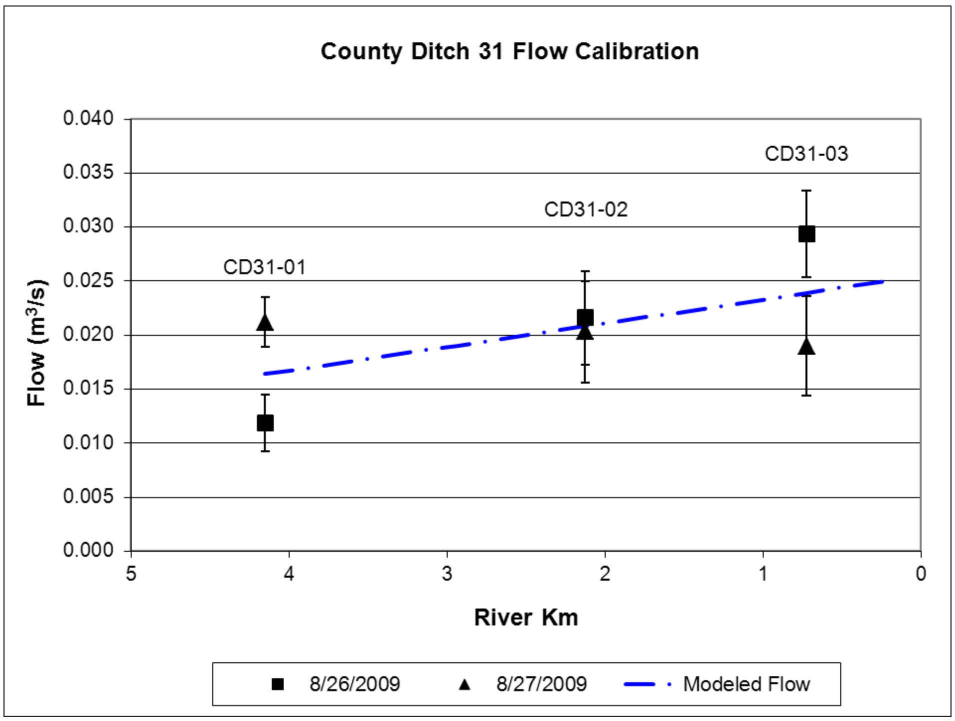

Figure 3.4 Final County Ditch 31 Flow calibration with diffuse and point source inflows.

3.3 Time of Travel Calibration

With total flow calibrated, rating curve coefficients and exponents for reaches 3 and 4 had to be adjusted slightly to lower velocity to meet time of travel measurements (Table 3.1). With total flow calibrated and the necessary hydraulic adjustments made, model predicted travel times for each reach were close to observed travel times (Figure 3.5).

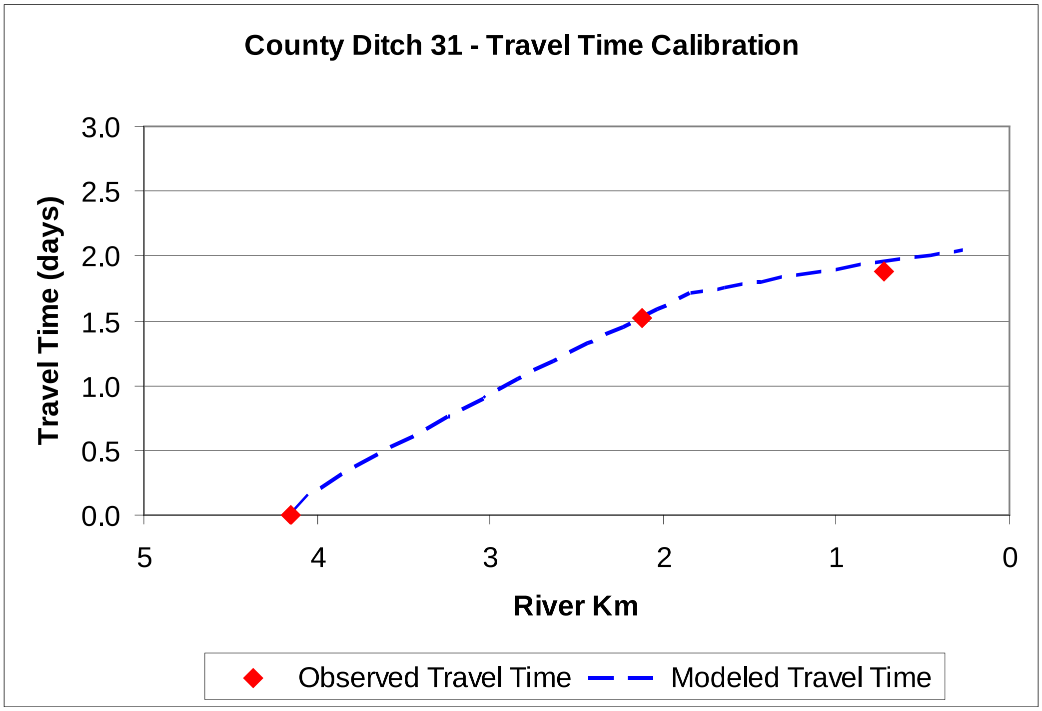

Figure 3.5 CD31 time of travel calibration.

4.0 WATER QUALITY CALIBRATION

All water quality model inputs were derived from data collected during the August 26-27, 2009 synoptic survey. Tributary and/or groundwater parameters were estimated based on literature values and calibration to in-stream water quality data. The QUAL2K model was set up to simulate temperature, flow, velocity, depth, organic nitrogen (ON), ammonia nitrogen (NH_3-N), nitrate/nitrite nitrogen (NO_2/ NO_3-N), $CBOD_u$, dissolved oxygen (DO), sediment oxygen demand (SOD), total phosphorus (TP) and chlorophyll-*a*. All model changes to global and reach specific kinetic rates as well as point source, diffuse and in-stream loadings are discussed in this section.

4.1 General Kinetic Rates

Seven kinetic rates were adjusted from model default values in order to meet longitudinal changes in observed water quality data. All kinetic rates were adjusted within the range of published values (Table 4.1).

Table 4.1 QUAL2K kinetic rates adjusted from model default values.

Rate	Calibrated Rate	Default Rate	Literature Range	Citation/Study Area
Reaeration Model	Tsivoglou and Neal	User Specified	Thomann and Mueller, 1987 cite that Tsivoglou and Neal, 1976; best for small, shallow streams (1-15 cfs)	
$CBOD_u$ oxidation rate (day^{-1})	0.23	0.23	0.02 – 0.60	Bowie et al., 1985 Table 3-17 p152 Kansas (6 rivers) Michigan (3 rivers) reported by Bansal, 1975
Organic-N Hydrolysis (day^{-1}) *The release of ammonia due to decay of organic nitrogen*	0.30	0.20	0.1 – 0.4	Baca et al., 1973
Organic-N Settling Velocity (m/d)	0.05		influenced by a material's size, shape, and density and the speed of water	
Organic-P Hydrolosis (day^{-1}) *The release of phosphate due to decay of organic phosphorus*	0.30	0.20	0.10 – 0.70	Baca et al., 1973 Baca and Arnett, 1976
Organic-P Settling Velocity (m/d)	0.05		influenced by a material's size, shape, and density and the speed of water	
Inorganic-P settling (m/d)	0.01	2.0	influenced by a material's size, shape, and density and the speed of water	
Phytoplankton Settling (m/d)	0.25	0.50	0 – 2	Bowie et al., 1985 Table 6-19 p352 Chen & Orlob, 1975 and Smith, 1978

4.2 Diffuse Source Loadings

Initially, all flow increases were assigned typical groundwater water quality values and then adjusted upward to meet in-stream water quality results (Table 4.2). All nitrogen parameters, chlorophyll *a* and $CBOD_u$ in reaches 1-4 were adjusted furthest from typical groundwater literature values. This suggests either high tributary/draintile or in-stream loading of these parameters that cannot be accounted for by adjusting model kinetic rates.

Table 4.2 Modeled diffuse source parameters for CD31.

Parameter	Reaches 1-4	Justification
Temp (C)	16	Calibrated adjustment to in-stream conditions
Sp. Cond (umhos)	900	Calibrated adjustment to in-stream conditions
DO	5.00	Calibrated adjustment to in-stream conditions
Organic- N (µg/L)	2500	Calibrated adjustment to in-stream conditions
Nitrate (µg/L)	2000	Calibrated adjustment to in-stream conditions.
Organic-P (µg/L)	11.20	Typical MN groundwater literature value (MPCA, 1999)
Inorganic-P (µg/L)	44.80	Typical MN groundwater literature value (MPCA, 1999)
$CBOD_u$ (mg O_2/L)	40 (reach 1) 20 (reach 2-3)	Calibrated adjustment to in-stream conditions.
Phytoplankton (µg/L)	30	Calibrated adjustment to in-stream conditions

4.3 Final Water Quality Calibration

$CBOD_u$, chlorophyll-*a* and all forms of nitrogen and phosphorus were calibrated once diffuse source water quality parameters and kinetic rates were properly incorporated into the model. The model performed well in predicting loads and concentrations of the primary water quality parameters that affect dissolved oxygen.

5.0 DISSOLVED OXYGEN CALIBRATION

5.1 Diurnal Oxygen Calibration

Even though water column algae was accurately depicted during water quality calibration, initial model runs predicted significantly smaller diurnal DO variability than was observed in the field. This suggests there was in-situ primary production that was not accounted for or under-represented in these model runs. QUAL2K has a bottom algae component that can simulate photosynthesis and nutrient uptake of any non-suspended algae. Bottom algae channel coverage was adjusted by reach in order to increase primary production and match the photosynthesis/respiration swings in the observed continuous DO data (Table 5.1). It is assumed that this bottom algae component represents all elements of primary production (attached algae, submerged macrophytes, rooted aquatic vegetation) that could not be measured or quantified in the field.

5.2 Sediment Oxygen Demand

Sediment oxygen demand (SOD) is calculated in QUAL2K based on the delivery and breakdown of particulate organic matter from the water column. Currently, the model does not have a macrophyte or riparian vegetation SOD component, nor does it incorporate any upland sediment transported and deposited during non-steady state storms events. The model does allow the user to assign SOD coverage (% of channel bottom) for each reach and also prescribe SOD that is added to the model predicted rate to account for SOD outside the modeling framework. SOD in streams varies depending on sediment type but is typically between 0.05 (mineral soils) and 2.00 (estuarine mud) g O_2/m^2/day (Thomann and Mueller, 1987). County Ditch 31 is a typical agricultural stream that has been ditched and straightened and, as a result, is relatively deep and slow moving during baseflow conditions. There appeared to be little or no settling/deposition during the low-flow synoptic survey as the channel sediments throughout the system were composed of soft, fine-grained particles.

Dissolved oxygen concentrations should be close to calibration as long as reasonable assumptions were made in allocating nutrient loads and adjusting kinetic rates. Model predicted dissolved oxygen concentrations for the hydraulic/phytoplankton/bottom algae/nutrient calibrated model were slightly lower than observed throughout CD31. Thus, SOD bottom coverage was decreased in each reach to ~~lower~~ increase DO concentrations to match observed values (Table 5.1).

Table 5.1 Reach specific SOD and bottom algae coverage.

Reach	Bottom SOD coverage (%)	Bottom Algae Coverage (%)	Justification
1	20	50	Wide, muddy bottomed channel, moderate rooted riparian vegetation
2	20	50	Typical muddy bottomed channel, moderate aquatic vegetation
3	20	50	Transition to channel bottoms with more sand and rock substrate
4	20	50	Transition to channel bottoms with more sand and rock substrate

5.3 Final Dissolved Oxygen Calibration

Figures 5.1 shows the final calibration results for model-predicted and observed dissolved oxygen concentrations. Field DO grabs were collected on August 26 and August 27 using the hand-held YSI and are labeled with the time of sample collection, if available. Also shown are continuous dissolved oxygen measurements for August 26th-27th (shown in plots as the range of data between minimum and maximum as orange and blue “I”). The average of the continuous DO is marked on the plot with an orange or blue box dependant on the day.

The model performs well in predicting the average daily dissolved oxygen concentration (in plot as black dashed line) at the CD31-02 monitoring station with continuous DO measurements. The model also does a good job predicting diurnal patterns (daily minimum and maximum, shown in plots as blue dashed lines).

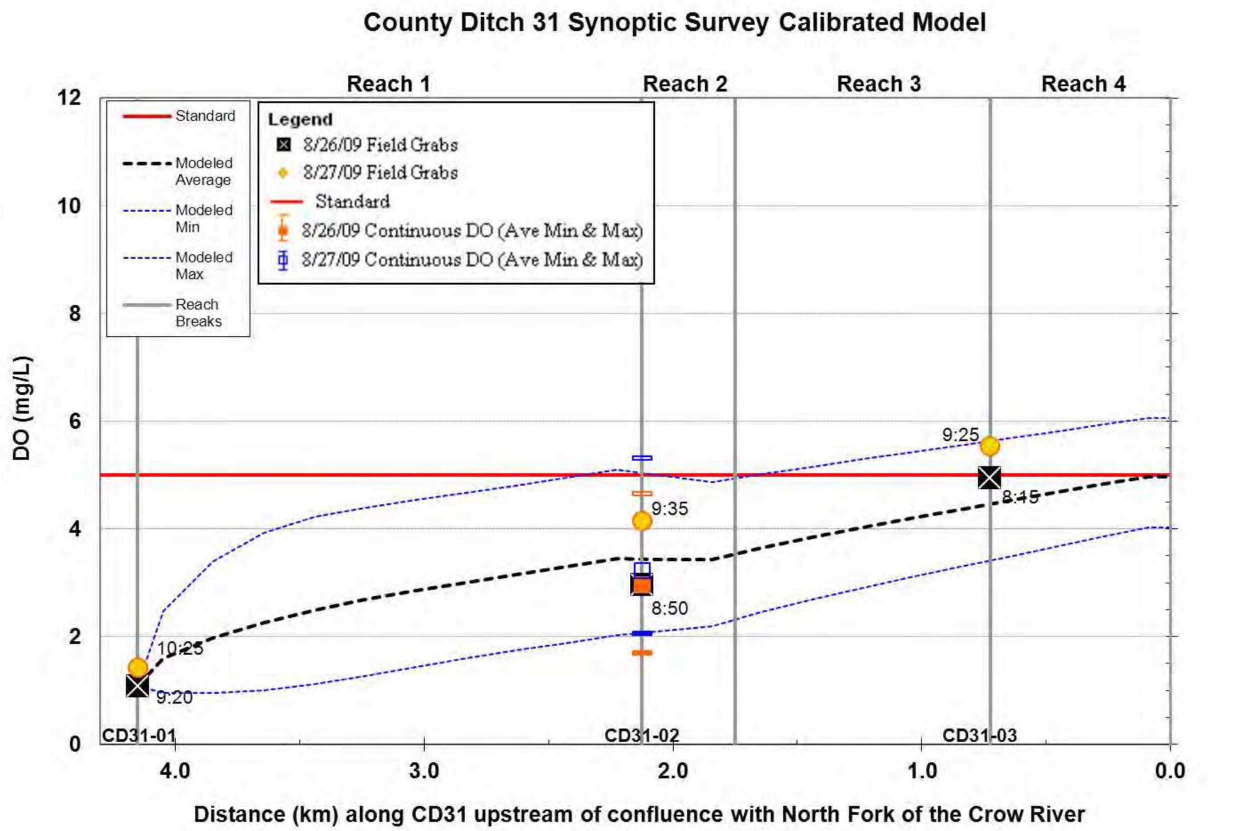

Figure 5.1 CD31 calibrated dissolved oxygen longitudinal profile.

6.0 SENSITIVITY ANALYSIS

To evaluate the sensitivity of model predicted DO to changes in model variables, seven kinetic rates (Table 6.1were adjusted by specific percentages. The following tables summarize the affect these changes have on the average model-predicted dissolved oxygen concentration for the entire modeled stretch of CD31. Results show DO throughout the system is most sensitive to the breakdown of organic carbon and nitrogen (CBOD oxidation and organic-N hydrolosis) and the kinetic rates driving SOD levels (nitrogen and phytoplankton settling). Phosphorus reactions appear to have very little affect on dissolved oxygen throughout CD31. This exercise suggests sediment processes and nitrogen transformations play the biggest role in consuming dissolved oxygen during this particular calibration/sampling event.

Table 6.1 DO sensitivity to kinetic rates.

Kinetic rate	+25%	-25%	Default
$CBOD_u$ oxidation rate (day^{-1})	-0.6%	0.9%	-0.3%
Organic-N Hydrolosis (day^{-1})	-2.8%	3.1%	4.0%
Organic-N Settling (m/d)	-1.9%	1.9%	-6.2%
Organic-P Hydrolosis (day^{-1})	0.0%	0.0%	0.0%
Organic-P Settling (m/d)	0.0%	0.0%	0.0%
Inorganic-P Settling (m/d)	0.0%	0.0%	0.0%
Phytoplankton Settling (m/d)	-0.6%	0.9%	-2.2%

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TECHNICAL MEMORANDUM

TO: Diane Sander, Crow River Organization of Water Watershed Coordinator

CC: Maggie Leach, MPCA Regional Impaired Waters Coordinator

FROM: Joe Bischoff, Project Manager
Pamela Massaro, P.E.
Jeff Strom

DATE: September, 2011

SUBJECT: Grove Creek Dissolved Oxygen TMDL
Description of QUAL2K Modeling Methods and Results

Wenck Associates, Inc. has developed and calibrated a QUAL2K model for Grove Creek from the U.S. Highway 12 crossing to the Creek's confluence with the main-stem of the North Fork Crow River just downstream of Meeker County Road 30 near Manannah, MN. The purpose of this technical memorandum is to describe the methods and assumptions used to create and calibrate the QUAL2K model.

1.0 INTRODUCTION

1.1 Model Selection

The U.S. EPA River and Stream Water Quality Model (QUAL2K) version 7 is a modernized version of the QUAL2E model developed by Dr. Steven Chapra with Tufts University and Greg Pelletier with Washington State. It was selected to analyze Grove Creek because it is a relatively simple surface water quality model that can be used during steady-state conditions to model nutrient, algal and dissolved oxygen dynamics.

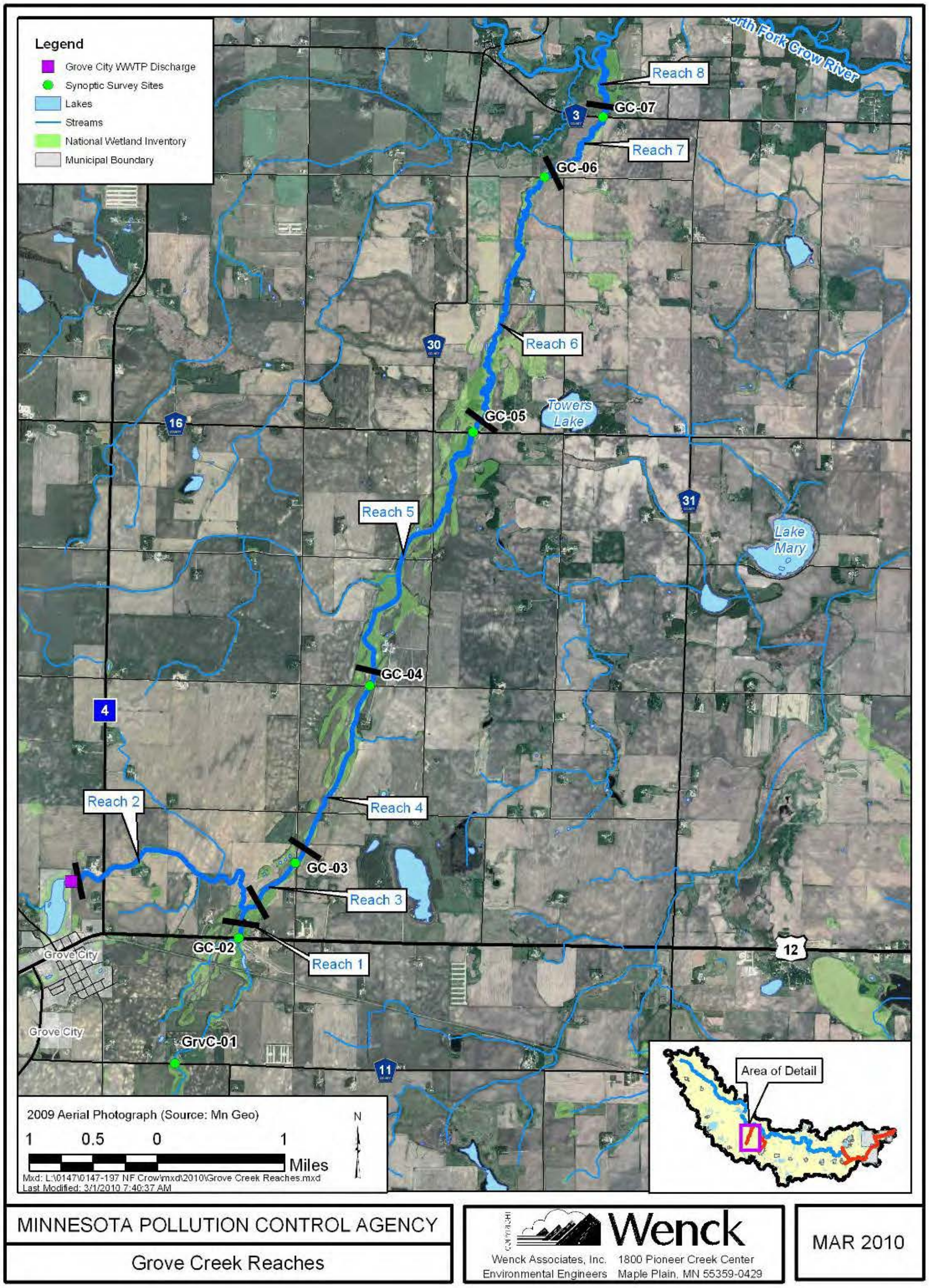

Figure 1.1 Monitoring stations and reaches on Grove Creek.

1.2 General Overview of the Model

The model was built using late summer synoptic survey data collected on September 3-4, 2008. Stream locations and physical features were built in to the model first before proceeding to hydraulic calibration. With the diffuse flow inputs incorporated, the conservative water quality parameters (such as water temperature and conductivity) were adjusted to match monitored observations. Then, chlorophyll-*a* (phytoplankton production), nutrients (phosphorus and nitrogen components), and carbonaceous biological oxygen demand (CBOD) were calibrated by adjusting tributary/groundwater contributions and/or kinetic coefficients within the range of published values. In some cases, reach specific kinetic rates and in-stream nutrient fluxes were assigned to model geochemical processes believed to be unique to certain reaches. Finally, bottom algae and sediment oxygen demand was adjusted for each reach to match observed dissolved oxygen data.

2.0 MODEL SETUP AND INPUTS

The River and Stream Water Quality Model (QUAL2K version 7) covers the main stem of Grove Creek from where it crosses US Highway 12 East of Grove City to its confluence with the North Fork Crow River. The stretch of the creek, explicitly modeled, represents approximately 10.4 main stem miles (16.67 km) subdivided in to seven reaches as well as one 2.0 mile (3.22 km) tributary reach. The start of each main stem reach correlates with a monitoring station location (Figure 1.1, Table 2.1 and Table 2.2). No data was collected for the tributary reach nor did there appear to be a large flow increase between gauging stations where this tributary enters the main-stem. Therefore, it was assumed the only source of flow in this section was the Grove City wastewater treatment facility (WWTF) located at the headwater of this reach.

Table 2.1 Model reach characteristics.

Reach	Description	US River km	DS River km	Distance (km)	Distance (mile)
1	GC-02 to tributary inflow	16.67	16.30	0.37	0.23
2 (tributary reach)	Grove City WWTF discharge to tributary outflow to Grove Creek	3.21	0.00	3.21	1.99
3	Tributary inflow to GC-03	16.30	15.37	0.93	0.58
4	GC-03 to GC-04	15.37	12.91	2.46	1.53
5	GC-04 to GC-05	12.91	8.46	4.45	2.77
6	GC-05 to GC-06	8.46	3.44	5.02	3.12
7	GC-06 to GC-07	3.44	1.61	1.83	1.14
8	GC-07 to outflow to North Fork Crow River	1.61	0.00	1.61	1.00

Table 2.2 Monitoring locations.

Reach	Reach Start Monitoring Location ID	Description	Data Collected
n/a	GC-01	273^{rd} Street	None
1	GC-02	US Highway 12	Q, Grab, Field
4	GC-03	560th Avenue	Q, Field
5	GC-04	300th Street	Q, Grab, Field
6	GC-05	County Road 16	Q, Grab, Field, ToT
7	GC-06	340th Street	Field
8	GC-07	County Road 3	Q, Grab, Field, ToT

Q = Flow gauged.
ToT = Time of Travel determined from dye study.
Grab = Water quality grab sample collected and lab analyzed for typical pollutants (total kjeldahl nitrogen (TKN), ammonia nitrogen (NH_3-N), nitrate nitrogen (NO_2-N), 5-day and ultimate carbonaceous biological oxygen demand ($CBOD_{5\text{-}day}$ & $CBOD_u$), total phosphorus (TP), ortho-phosphorus (soluble reactive phosphorus), total organic carbon (TOC), and chlorophyll-*a*).
Field = In-field measurement of temperature, conductivity, pH, and dissolved oxygen (DO).

2.1 Channel Slope

Reaeration may be prescribed by the user or calculated using one of eight hydraulic-based reaeration models built in to QUAL2K. The Tsivoglou-Neal reaeration model was selected for Grove Creek because it is the most appropriate model to predict reaeration for flows less than 10 cfs (Tsivoglou and Neal, 1972; Thomann and Mueller, 1987). This reaeration model formula is shown below:

$$K_a = 1.8 \times V \times S \qquad \text{for} \qquad 1 < Q < 10 \text{ cfs}$$

Where:
K_a = reaeration rate coefficient at 20°C (base e, day $^{-1}$)
V = average velocity (ft/s)
S = slope of energy gradient (ft/mile)

Channel slope and velocity are the variables used to calculate reaeration in each reach. Average channel slopes are based on data from an elevation survey conducted by Wenck in the fall of 2008 (Figure 2.1 and Table 2.3).

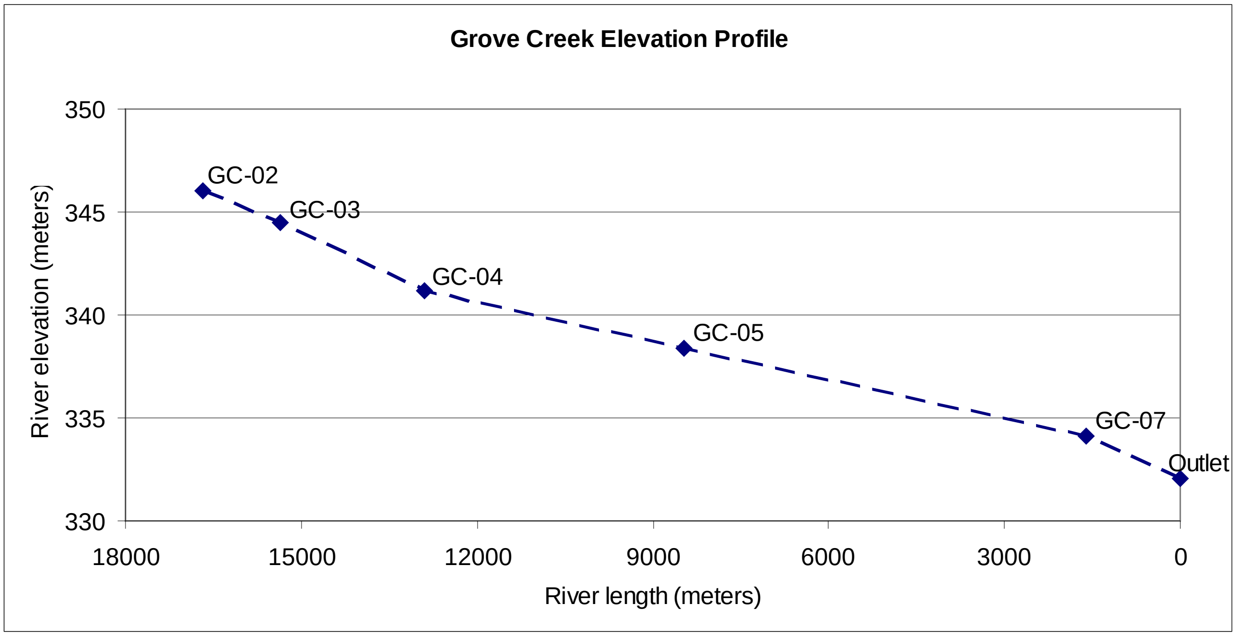

Figure 2.1 Survey elevations used to estimate reach slopes for Grove Creek.

Table 2.3 Grove Creek Longitudinal Elevation Survey Summary.

Monitoring Station	River Kilometer	River Mile	Elevation (meters)	Elevation (feet)	Slope (ft/mile)
GC-02	16.7	10.4	346.0	1135.2	---
GC-03	15.4	9.5	344.5	1130.3	6.00
GC-04	12.9	8.0	341.2	1119.4	7.13
GC-05	8.5	5.3	338.4	1110.3	3.30
GC-07	1.6	1.0	334.1	1096.1	3.33
Outlet	0.0	0.0	332.1	1089.5	6.57
				Total Slope	4.40

2.2 Weather and Physical Processes

Hourly weather measurements of temperature, cloud conditions, relative humidity and wind speed were downloaded from the National Weather Service (NWS) NOAA Litchfield Municipal Airport. Channel coverage and shading was set to 0% for all reaches due to the lack of canopy cover.

2.3 Headwaters

The Minnesota Department of Natural Resources (DNR) stream file shows Grove Creek begins at the tributary inflow downstream of the US Highway 12 crossing (GC-02). Historically, the MPCA has monitored one site upstream of GC-02 (GC-01 at 273rd Street). GC-01 was visited prior to the synoptic survey and had standing water with no observable velocity. Thus, all water quality and flow data collected at station GC-02 was used to represent the upstream boundary condition/headwater in the QUAL2K model.

As noted in Table 2.2, a data sonde was not deployed at the upstream boundary/headwaters (GC-02). Instead, hourly data from GC-03's data sonde monitored on September 3, 2008 was used to simulate temperature, conductivity, dissolved oxygen and pH at GC-02. Continuous dissolved oxygen measured by field staff at GC-02 was 30% less at 8:45 on 9/3/08 than DO recorded at the same time by the continuous data sonde at GC-03. Thus, a diurnal DO curve was simulated for the model's headwaters (GC-02) by lowering continuous DO readings at GC-03 by 30%. Temperature, conductivity and pH showed little difference between the two sampling stations as continuous measurements from GC-03 were applied to the GC-02 headwater station.

2.4 Point Sources

Grove City Waste Water Treatment Facility (WWTF) is the only National Pollutant Discharge Elimination System (NPDES) point source in the Grove Creek watershed (MN0023574). This facility is located at the eastern outflow of Grove Lake north of Grove City and has a continuous discharge (SD002) to an unnamed tributary that flows to Grove Creek downstream of GC-02. The facility also has a bypass (SD001) that has been know to discharge untreated wastewater. The permitted facility includes a collection system, lift station, bar screen, oxidation ditch, final clarifer and chlorine contact tank. The facility is designed to treat an average annual flow of 0.106 million gallons per day. Effluent monitoring data for this facility was not available for the dates of the synoptic survey and dye study. Monthly discharge monitoring reports (DMRs) from 1999-2008 were available through the MPCA. The facility's permitted average annual flow was used to model total facility discharge during the synoptic survey and time of travel study. Modeled effluent water quality parameters were set to concentrations in the September 2008 daily monitoring report. For those parameters not reported in the DMR, effluent concentrations were adjusted to meet monitored water quality data downstream of the facility discharge. All parameters calibrated to meet observed data are supported by literature values of achievable treatment levels for wastewater treatment plants (Tchobanoglous, 1991). Table 2.4 show the final values used in the calibrated model to represent Grove City WWTF.

Table 2.4 Modeled values for Grove City WWTF discharge to tributary of Grove Creek**.**

Paramter	Modeled Value	Source
Flow (m^3/s)	0.005	Permitted annual average
Temp (C)	20	Calibrated to in-stream data
Sp. Cond (umhos)	0.6	Calibrated to in-stream data
DO (mg/L)	4.5	DMR – monthly minimum
Fast CBOD (mg/L)	5.0	DMR – maximum weekly average $CBOD_5$
Ammonia (µg/L)	1000	Literature value
Nitrate (µg/L)	5000	Literature value
Organic-P (µg/L)	1105	DMR – Assumed TP was 50% Organic-P
Inorganic-P (µg/L)	1105	DMR – Assumed TP 50% Inorganic-P
pH	7.3	DMR – midpoint of monthly min/max

2.5 Carbonaceous Oxygen Demand (CBOD)

QUAL2K calculates nitrogenous oxygen demand separate from carbonaceous oxygen demand (CBOD) by requiring separate inputs of $CBOD_{ultimate}$, organic nitrogen and reduced nitrogen. $BOD_{ultimate}$, not $CBOD_{ultimate}$ was analyzed during the Grove Creek synoptic survey. Biochemical oxygen demand (BOD) is a measure of the oxygen consumed by bacteria from the decomposition of organic matter. CBOD measures oxidation of the carbon fraction of the organic matter. A $CBOD_{ultimate}$ fraction was estimated by subtracting the oxygen equivalents (4.57 mg O_2 per mg reduced nitrogen) of the reduced nitrogen in the sample according to the following equation (Thomann et al., 1987; Chapra et al., 2007):

$$CBOD_{ultimate} = BOD_{ultimate} - (4.57*TKN)$$

Resulting $CBOD_{ultimate}$ estimates were extremely low in the most upstream reach and at or below detection in downstream reaches, suggesting only one type/source of CBOD exists throughout the system.

The old EPA model (QUAL2E) version had one type of CBOD with one decay rate. The modernized version (QUAL2K) now includes two forms of CBOD to represent organic carbon; a slowly oxidizing form (slow CBOD) and a rapidly oxidizing form (fast CBOD). This allows the model to decay CBOD at two decay rates, if deemed necessary. This model enhancement is great for waste streams with organic carbons in the form of sugar, glucose, etc. Based on the CBOD data collected, it is reasonable to assume there is only one oxidizing form of CBOD. For this reason, all $CBOD_{ultimate}$ was represented in the model as fast CBOD.

3.0 HYDRAULIC CALIBRATION

Modeled hydraulic inputs were derived from flow gauging data collected during the September 3, 2008 synoptic survey. Total discharge was calibrated first before moving on to time of travel calibration. All hydraulic inputs and calibration adjustments are described in the following sections.

3.1 Hydraulic Rating Curves

QUAL2K hydraulics may be modeled using power function rating curves, weirs (dam/drop structures) or Manning's equations. Hydraulics for all Grove Creek reaches were represented using power function rating curves from flow gauging data collected during the synoptic survey. The power function option relates mean velocity and depth to flow in each reach. QUAL2K uses five coefficients to define reach hydraulics, as follows:

- Velocity (mps) = $a\ Q^b$
- Depth (m) = $c\ Q^d + e$

in which Q is flow in cubic meters per second. Depth and velocity rating curves were constructed using gauged flow data from the time of travel study. Gauging stations with similar channel dimensions and flow characteristics were combined in to one rating curve to provide more robust velocity/depth versus flow relationships (Figures 3.1 through 3.4). Applying the principals of hydraulic geometry (Leopold and Maddock, 1953), there is another power function for width:

- Width (m) = f Q^g

Because the width, depth and velocity are a function of discharge, the following rules apply to the coefficients and exponents of these power functions. The sum of the exponents equal one ($b + d + g = 1.0$), and the product of the coefficients equal one ($a \times c \times f = 1.0$). The representative hydraulic rating curves for each reach was selected based on proximity to gauging stations and typical channel dimensions throughout the reach. The hydraulic coefficients and exponents for each QUAL2K reach are summarized in Table 3.1. Table 3.1 also documents that no calibration adjustments were needed.

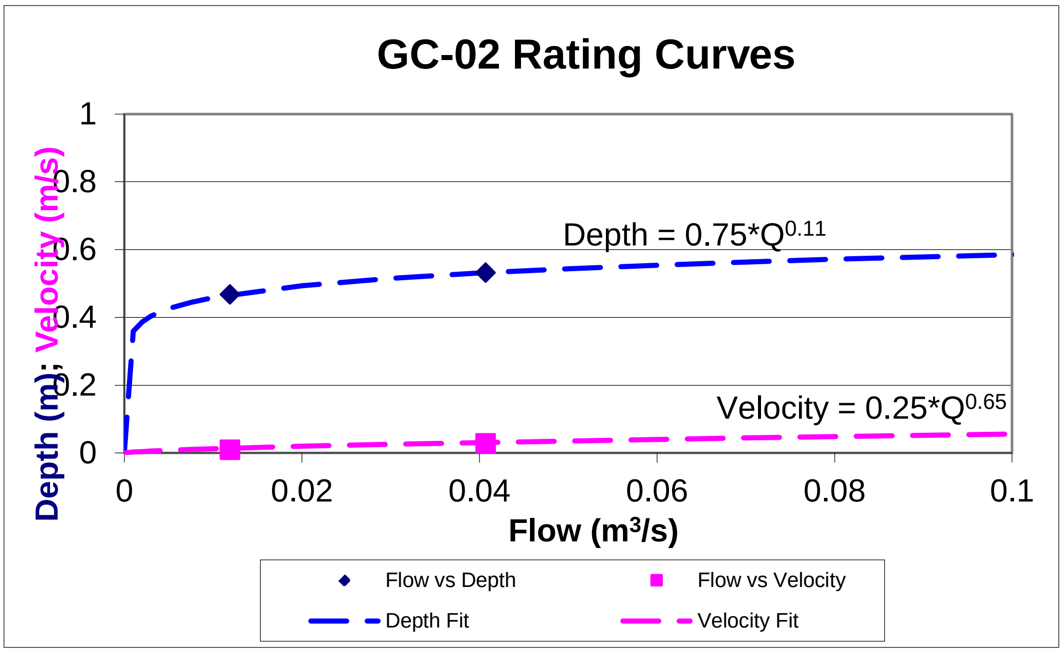

Figure 3.1 Hydraulic rating curve plot for gauging stations GC-02.

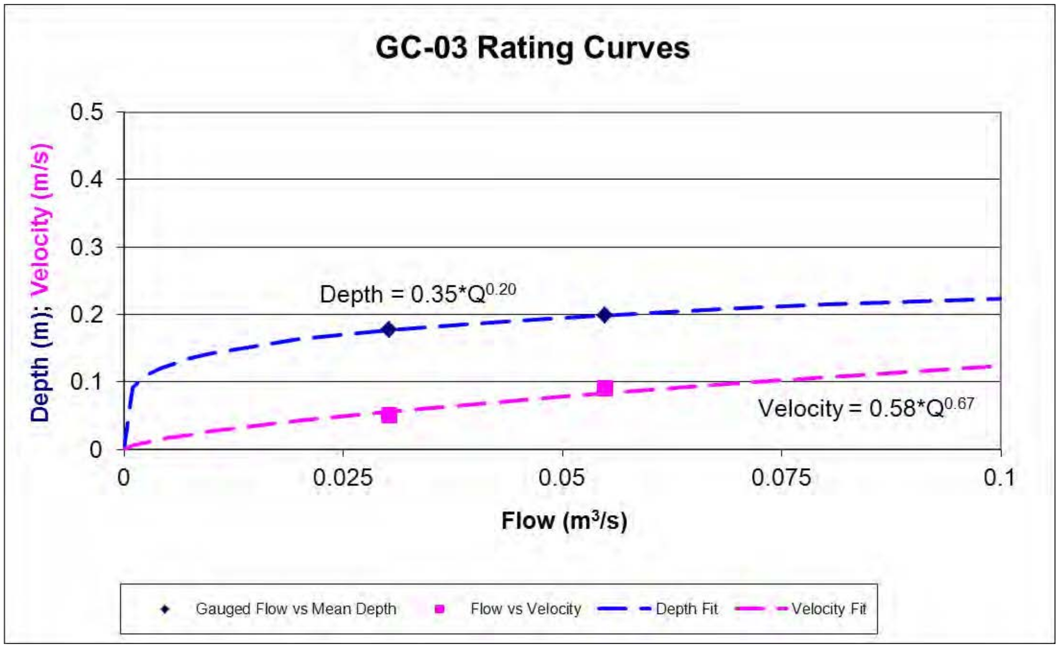

Figure 3.2 Hydraulic rating curve plot for gauging stations GC-03.

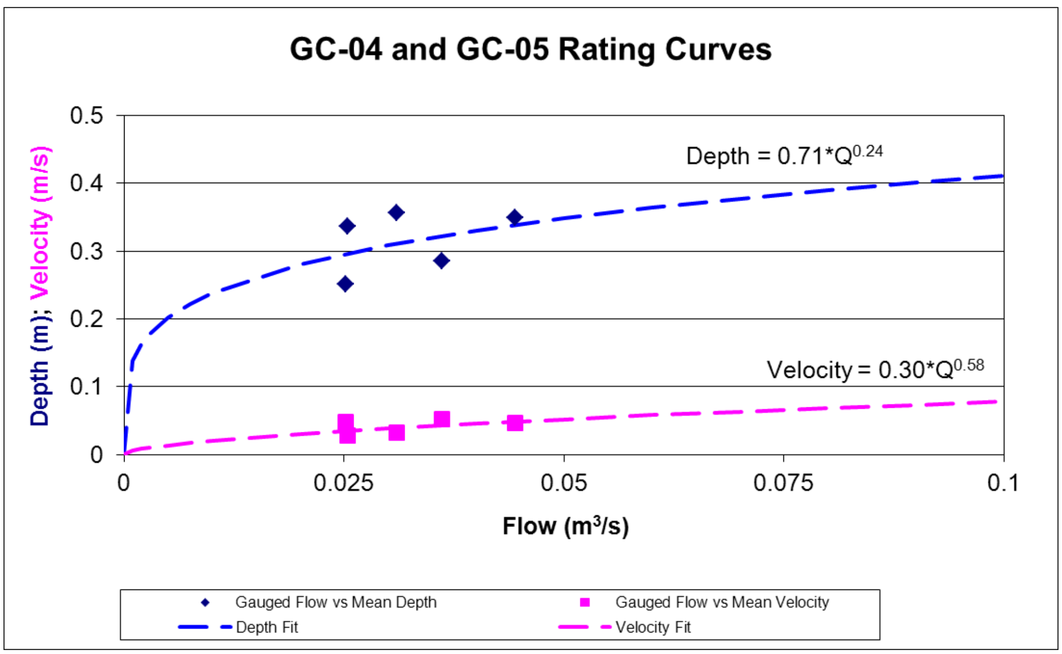

Figure 3.3 Hydraulic rating curve plot for gauging stations GC-04 and GC-05.

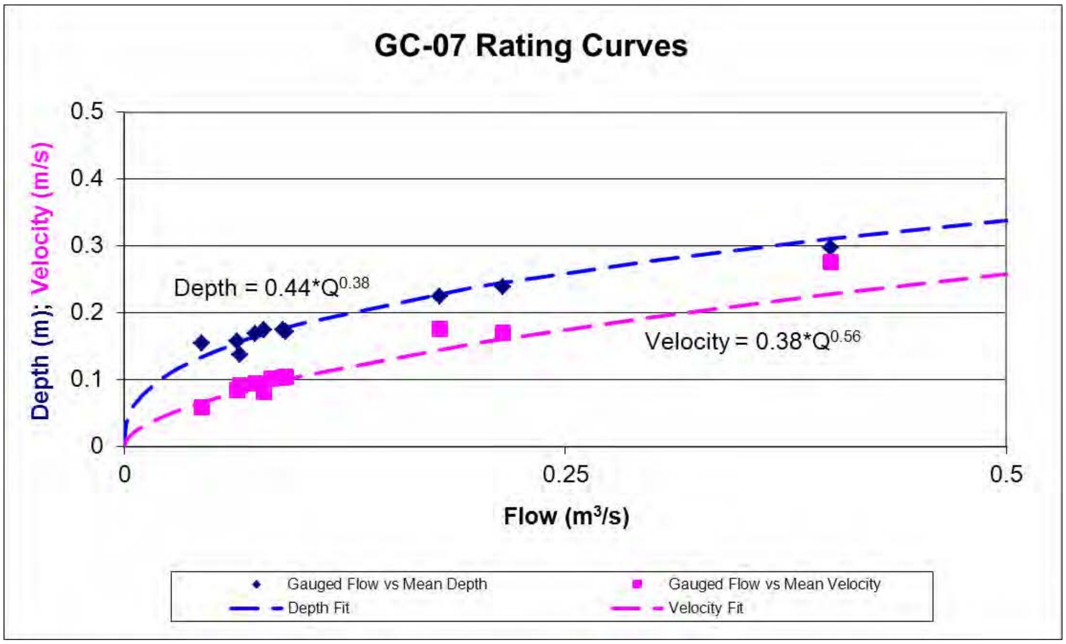

Figure 3.4 Hydraulic rating curve plot for gauging station GC-07.

Table 3.1 Summary of hydraulic coefficients and exponents assigned to each reach.

		Velocity		**Depth**		
Reach	**Rating Curve used**	**Coeff.**	**Exp.**	**Coeff.**	**Exp.**	**Adjustments**
1	GC-03	0.58	0.67	0.35	0.20	None
2 (trib)	GC-03	0.58	0.67	0.35	0.20	None
3	GC-03	0.58	0.67	0.35	0.20	None
4	GC-04 +GC-05	0.30	0.58	0.71	0.24	None
5	*GC-04 +GC-05	0.30	0.58	0.71	0.24	None
6	GC-07	0.38	0.56	0.44	0.38	None
7	GC-07	0.38	0.56	0.44	0.38	None
8	*GC-07	0.38	0.56	0.44	0.38	None

* denotes that the monitoring station is at the upstream end of the reach

3.2 Flow Calibration

Grove Creek tributaries were not accessible to determine if they were contributing flow during the synoptic survey and dye study. Thus, all observed increases in flow between gauging stations were built in to the model as diffuse sources (Table 3.2). The model was deemed calibrated for total discharge once all point source and diffuse source flows were built in to the model (Figure 3.5.)

Table 3.2 Modeled diffuse source inflow for Grove Creek.

Reach	Total Inflow throughout reach (m^3/s)	Justification
Reach 5 (GC-04 to GC-05)	0.008	Calculated based on flow gauging data
Reach 6+7 (GC-05 to GC-07)	0.026	Calculated based on flow gauging data
Reach 8 (GC-07 to Outlet)	0.006	Calculated based on flow gauging data

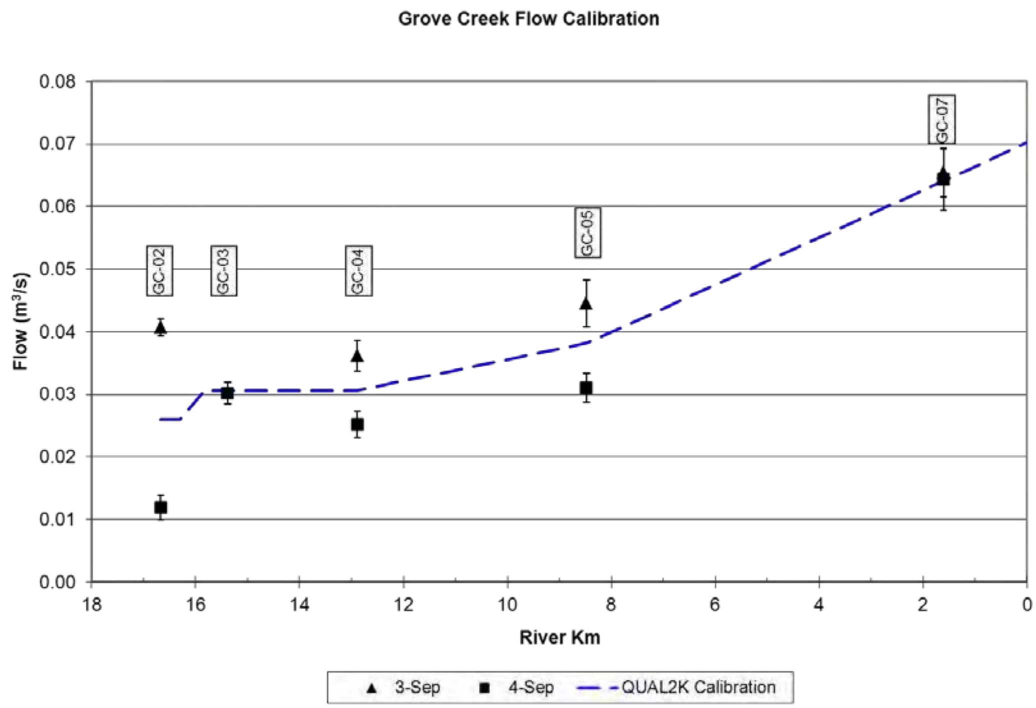

Figure 3.5 Final Grove Creek Flow calibration with diffuse and point source inflows.

3.3 Time of Travel Calibration

With total flow calibrated, the rating curve coefficients and exponents required no adjustments to meet travel times measured for the lower stretch of Grove Creek (GC-05 to GC-07). With total flow calibrated, model predicted travel times fo this reach matched observed times and support using the depth and velocity coefficients and exponents with no changes (Figure 3.6).

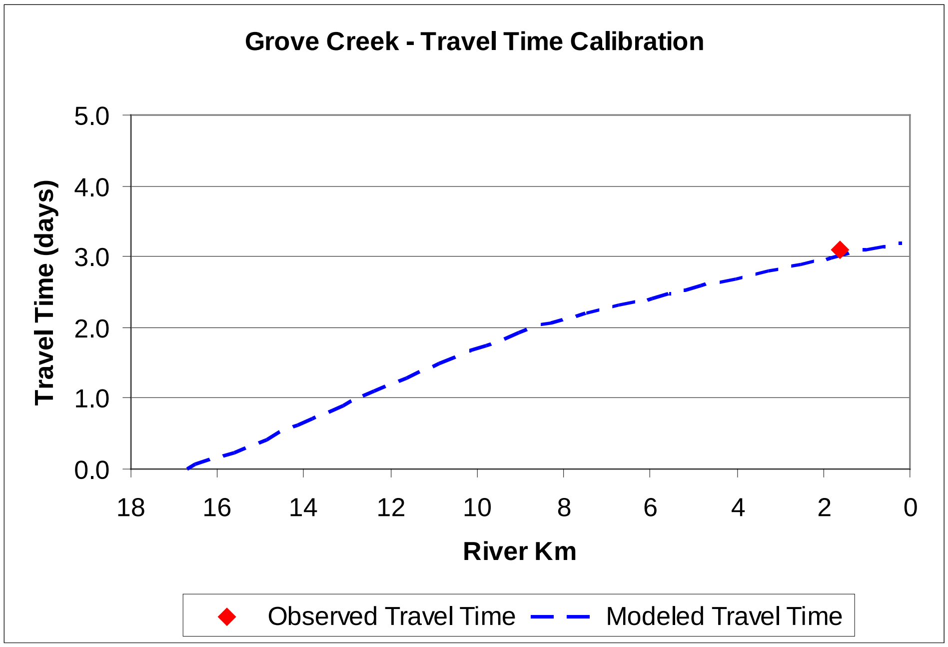

Figure 3.6 Grove Creek time of travel calibration.

4.0 WATER QUALITY CALIBRATION

All water quality model inputs were derived from data collected during the September 3-4, 2008 synoptic survey. Tributary and/or groundwater parameters were estimated based on literature values and calibration to in-stream water quality data. The QUAL2K model was set up to simulate temperature, flow, velocity, depth, chloride, organic nitrogen (ON), ammonia nitrogen (NH_3-N), nitrate/nitrite nitrogen (NO_2/ NO_3-N), ultimate carbonaceous biological oxygen demand ($CBOD_u$), dissolved oxygen (DO), sediment oxygen demand (SOD), total phosphorus (TP), chlorophyll-*a*. All model changes to global and reach specific kinetic rates as well as point source, diffuse and in-stream loadings are discussed in this section.

4.1 General Kinetic Rates

Five kinetic rates were adjusted from default values in order to meet longitudinal changes in observed water quality data. All kinetic rates were adjusted within the range of published values (Table 4.1).

Table 4.1 QUAL2K kinetic rates adjusted from model default values.

Rate	Calibrated Rate	Default Rate	Literature Range	Citation/Study Area
Reaeration Model	Tsivoglou and Neal	User Specified	Thomann and Mueller, 1987 cite that Tsivoglou and Neal, 1976; best for small, shallow streams (1-15 cfs)	
Fast CBOD oxidation rate (day^{-1})	2.0	0.23	0.02 – 0.60 0.56 – 3.37	Bowie et al., 1985 Table 3-17 p152 Kansas (6 rivers) Michigan (3 rivers) reported by Bansal, 1975
Organic-N Hydrolysis (day^{-1}) *The release of ammonia due to decay of organic nitrogen*	0.03	0.20	0.02 – 0.10 0.03 – 0.20	Bowie et al., 1985 Table 5-3 p259 Scavia, 1980 Di Toro & Matystik, 1980
Organic-P Hydrolosis (day^{-1}) *The release of phosphate due to decay of organic phosphorus*	0.80	0.20	0.50 – 0.80 0.02	Bowie et al., 1985 Table 5-5 p266 Jorgenson, 1976 Bowie et al., 1980
Inorganic-P settling (m/d)	0.2	2.0	influenced by a material's size, shape, and density and the speed of water	
Phytoplankton Settling (m/d)	0.10	0.50	0 – 2	Bowie et al., 1985 Table 6-19 p352 Chen & Orlob, 1975 and Smith, 1978

4.2 In-stream Loadings and Reach Specific Rates

In addition to global changes to kinetic rates, individual reaches required specific kinetic rate adjustments to calibrate to in-stream water quality data. Monitored data from reaches 4 and 5 display nutrient loadings and losses not predicted by the default and adjusted kinetic rates. It was noted during the synoptic survey that Grove Creek flows were obstructed creating backwater conditions and a relatively large pond (~75 m in diameter) downstream of GC-03 in reach 4.

Figure 4.1 Reach 4 pond (Source: Google Maps).


Figure 4.2 View of Pond from 560th Avenue.

During the synoptic survey, the Reach 4 pond was approximately 1-2 meters deep and contained a large carp population. Time of travel analysis for Reaches 4-5 suggest the dye did not make it out of this reach or was too mixed and diluted to be detected at the downstream monitoring station. Water quality downstream of this in-channel pond indicates mass load decreases of nitrate and a mass load increase of inorganic phosphorus. The flow increase through this reach was calculated as zero which suggests these changes can be attributed to in-stream denitrification and phosphorus loading. Table 4.2 summarizes the reach specific calibration adjustments made to Reaches 4-5 to represent the in-stream mass loads.

Table 4.2 Summary of reach specific sediment fluxes and kinetic rates.

Reach	Rate	Reach Specific Rate	Default Rate	Literature Range	Justification
4 (GC-03-GC-04)	Sediment Denitrification transfer coefficient (m/d)	1.0	0	0.0-1.0	Ponded reach with high denitrification rates supported by Bowie et al., 1985 Table 5-4 pp 262; Baca & Arnett, 1976
	Sediment Inorganic-P Flux (mg P/m^2/d)	75	Model calculated	9.6 - 95	In-channel pond/reservoir reach with high P-release rates. Carp population and unique hydrologic features justifies elevated P-release (Muddy River, Boston MA total dissolved phosphorus flux aerobic and anaerobic conditions from Fillos and Swanson 1975)
	Sediment NH_4 Flux (mg N/m^2/d)	25	Model Calculated	0-300	In-channel pond/reservoir reach with anoxic conditions and organic-rich sediments (rate supported by Thomann and Mueller, 1987)
	Phytoplankton settling (m/d)	0.50	0.50	0.04 – 0.60	In-channel pond/reservoir settles phytoplankton from inflowing waters supported by Jorgensen et al. 1978
5 (GC-04-GC-05)	Sediment Denitrification transfer coefficient (m/d)	1.0	0	0.0-1.0	Muddy reach with anaerobic conditions and high denitrification rates supported by Bowie et al., 1985 Table 5-4 pp 262; Baca & Arnett, 1976
	Sediment Inorganic-P Flux (mg P/m^2/d)	25	Model Calculated	9.6 - 95	Muddy, slow moving eutrophic reach with anaerobic conditions (Muddy River, Boston MA total dissolved phosphorus flux aerobic and anaerobic conditions from Fillos and Swanson 1975)
	Sediment NH_4 Flux (mg N/m^2/d)	50	Model Calculated	0-300	Muddy, slow moving low-DO reach with anaerobic conditions (rate supported by Thomann and Mueller, 1987).

As documented in Table 4.2 the sediment related parameters are modeled at the upper end (or above) the literature range. This is justified due to the unique geochemical effects the reservoir in Reach 4 has on the water discharged from the pond. Field staff observed carp stirring up the nutrient rich sediments within the pond shown in Figure 4.2. The water leaving the pond was noticeably more turbid than water entering the pond. A pond of this size, without carp activity, might act as a sediment trap.

4.3 Diffuse Source Loadings

Initially, all flow increases were assigned typical groundwater water quality values and then adjusted upward to meet in-stream water quality results (Table 4.3). Nitrate, organic nitrogen and inorganic phosphorus in reaches 5-8 were adjusted furthest from typical groundwater literature values. This suggests either high tributary/draintile or in-stream loading of these parameters that cannot be accounted for by adjusting model kinetic rates.

Table 4.3 Modeled diffuse source parameters for Grove Creek.

Parameter	Reach 5 (GC-04-GC-05)	Justification	Reaches 6-8 (GC-05-Outlet)	Justification
Temp (C)	9.15	Based on USGS groundwater atlas (Lindholm et al., 1974)	9.15	Based on USGS groundwater atlas (Lindholm et al., 1974)
Sp. Cond (umhos)	0.60	Calibrated adjustment to in-stream conditions	0.60	Calibrated adjustment to in-stream conditions
DO	1.6	Mean of published groundwater data	1.6	Mean of published groundwater data
Organic- N (µg/L)	4000	Calibrated adjustment to in-stream conditions	224	Calibrated adjustment to in-stream conditions
Nitrate (µg/L)	5000	Calibrated adjustment to in-stream conditions. Within Range of USGS groundwater atlas (Lindholm et al., 1974)	5000	Calibrated adjustment to in-stream conditions Within Range of USGS groundwater atlas (Lindholm et al., 1974)
Organic-P (µg/L)	300	Calibrated adjustment to in-stream conditions	11.20	Typical MN groundwater literature value (MPCA, 1999)
Inorganic-P (µg/L)	400	Calibrated adjustment to in-stream conditions	400	Calibrated adjustment to in-stream conditions
Phytoplankton (µg/L)	30	Calibrated adjustment to in-stream conditions	---	Typical MN groundwater value

4.4 Final Water Quality Calibration

$CBOD_{fast}$, chlorophyll-*a* and all forms of nitrogen and phosphorus were calibrated once diffuse source water quality parameters and kinetic rates were properly incorporated into the model. The model performed well in predicting loads and concentrations of the primary water quality parameters that affect dissolved oxygen.

5.0 DISSOLVED OXYGEN CALIBRATION

5.1 Diurnal Oxygen Calibration

The Grove model applies the Half Saturation formulations defining the relationship between light penetration and resulting photosynthesis. Though water column algae is accurately predicted in the model, additional modeling adjustments were needed to better predict the daily minimum and maximum DO observations. This suggests there was in-situ primary production not accounted for or under-represented in the initial model runs. In the QUAL2K model, the bottom algae component simulates photosynthesis and nutrient uptake of any non-suspended algae. In the Grove model, the bottom algae channel coverage was adjusted by reach to match the photosynthesis/respiration swings in the observed continuous DO data (Table 5.1). It is assumed that this bottom algae component defined in QUAL2K represents all elements of primary production (attached algae, submerged macrophytes, rooted aquatic vegetation) that could not be measured or quantified in the field.

5.2 Sediment Oxygen Demand

Sediment oxygen demand (SOD) is calculated in QUAL2K based on the delivery and breakdown of particulate organic matter from the water column. Currently, the model does not have a macrophyte or riparian vegetation SOD component, nor does it incorporate any upland sediment transported and deposited during non-steady state storms events. The model does allow the user to prescribe SOD to specific reaches that is added to the model predicted rate to account for SOD outside the modeling framework. SOD in streams varies depending on sediment type but is typically between 0.05 (mineral soils) and 2.00 (estuarine mud) g O_2/m^2/day (Thomann and Mueller, 1987). Grove Creek is a typical agricultural stream that has been ditched and straightened and, as a result, is relatively deep and slow moving during baseflow conditions. While there appeared to be little or no settling/deposition during the low-flow synoptic survey, channel sediments throughout Grove Creek are extremely muddy and composed of soft, fine-grained particles.

Dissolved oxygen concentrations should be close to calibration as long as reasonable assumptions were made in allocating nutrient loads and adjusting kinetic rates. Model predicted dissolved oxygen concentrations for the hydraulic/phytoplankton/bottom algae/nutrient calibrated model were slightly higher than observed throughout Grove Creek. Additional SOD was assigned to each reach to lower mean oxygen concentrations to match observed values (Table 5.1).

Table 5.1 Reach specific SOD and bottom algae coverage.

Reach	**SOD** g O_2/m^2/day	**Bottom Algae Coverage** (%)	**Justification**
1	0.00	25	Typical muddy bottomed channel, moderate aquatic vegetation
2	0.00	25	Typical muddy bottomed channel, moderate aquatic vegetation
3	0.00	25	Typical muddy bottomed channel, moderate aquatic vegetation
4	2.50	60	Typical muddy bottomed channel, in-stream pond/reservoir with more rooted riparian vegetation
5	1.00	60	Wide, muddy bottomed channel, more rooted riparian vegetation
6	0.60	25	Typical muddy bottomed channel, moderate aquatic vegetation
7	0.60	25	Typical muddy bottomed channel, moderate aquatic vegetation
8	0.60	25	Typical muddy bottomed channel, moderate aquatic vegetation

5.3 Final Dissolved Oxygen Calibration

Figures 5.1 shows the final calibration results for model-predicted and observed dissolved oxygen concentrations. Field grabs of dissolved oxygen were taken on September 3 and September 4 using the hand-held YSI. The field grabs are labeled with the time of sample collection, if available. Also shown are continuous dissolved oxygen measurements for September 3rd and September 4th (shown in plots as the range of data between minimum and maximum as orange and blue “I”). The average of the continuous DO is marked on the plot with an orange or blue box dependant on the day. All field grab measurements were taken by Wenck staff between 8:00 am and 10:30 am on 9/3/2008 and between 10:30 am and 4:00 pm on 9/4/2008.

The model performs well in predicting average daily dissolved oxygen concentrations (in plot as black dashed line) at the two monitoring stations with continuous DO measurements (GC-03 and GC-07). The model also does a good job predicting diurnal patterns (daily minimum and maximum, shown in plots as blue dashed lines).

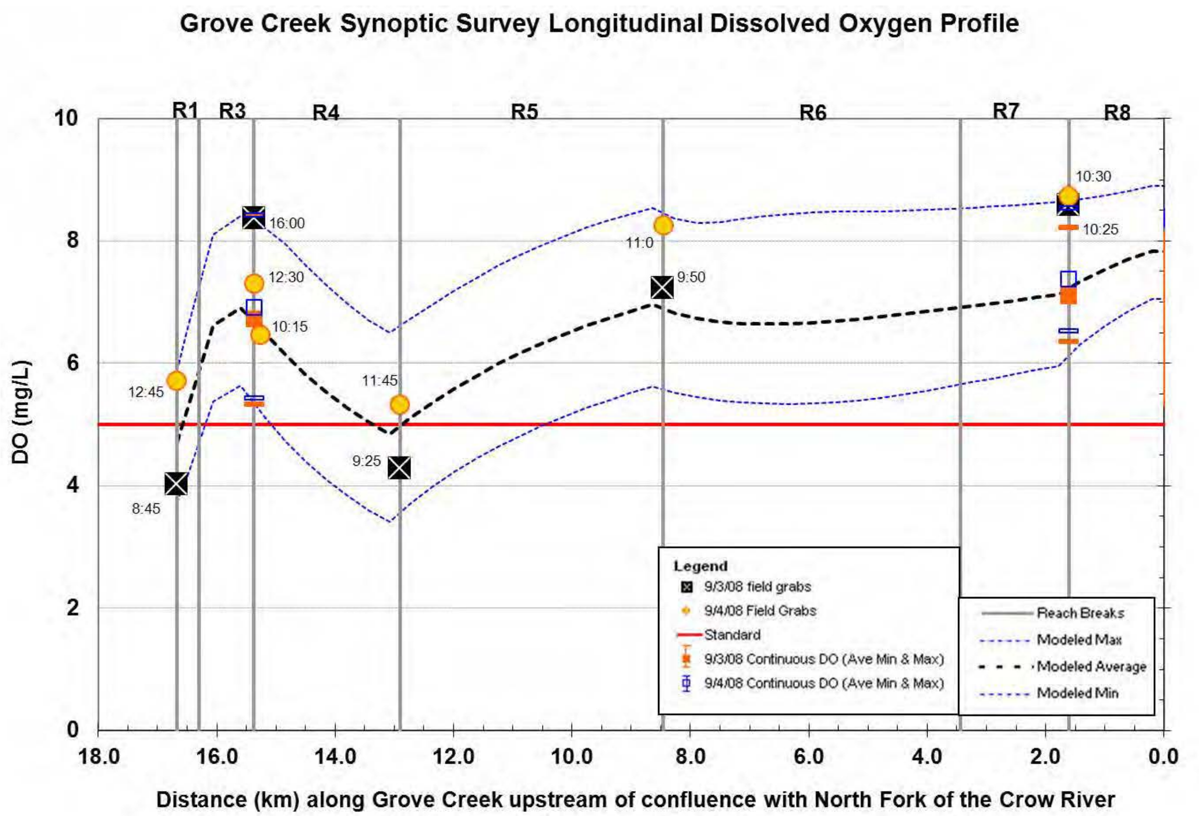

Figure 5.1 Grove Creek calibrated dissolved oxygen longitudinal profile.

6.0 SENSITIVITY ANALYSIS

To evaluate the sensitivity of model predicted dissolved oxygen to changes in model variables, seven kinetic rates (Table 6.1), four reach specific rates (Table 6.2), and channel slopes (Table 6.3) were removed or adjusted by specific percentages. The following tables summarize the affect these changes have on the average model-predicted dissolved oxygen concentration for the entire modeled stretch of Grove Creek. Results show DO throughout the system is most sensitive to the kinetic rates driving SOD levels (nitrogen and phytoplankton settling), as well as the SOD settings themselves. CBOD oxidation and nutrient hydrolysis rates are less sensitive to dissolved oxygen throughout Grove Creek. This exercise suggests sediment processes play a bigger role than water column processes in consuming dissolved oxygen during this particular calibration/sampling event.

Table 6.1 DO sensitivity to kinetic rates.

Kinetic rate	+25%	-25%	Default
$CBOD_u$ oxidation rate (day^{-1})	-0.3%	0.2%	2.6%
Organic-N Hydrolosis (day^{-1})	-0.2%	0.0%	-1.9%
Organic-N Settling (m/d)	-1.7%	2.2%	--
Organic-P Hydrolosis (day^{-1})	0.0%	-0.2%	-0.2%
Organic-P Settling (m/d)	-0.2%	0.0%	--
Inorganic-P Settling (m/d)	-0.3%	0.2%	-6.4%
Phytoplankton Settling (m/d)	-0.5%	0.3%	-2.8%

Table 6.2 DO sensitivity to reach rates.

Action	DO Sensitivity
Remove Sediment Denitrification Transfer Coefficient in reaches 4-5	1.7%
Remove reach specific phytoplankton settling rate in reach 4	2.6%
Remove prescribed NH_4 flux in reaches 4-5	2.2%
Remove prescribed Inorganic-P flux in reaches 4-6	-1.4%
Remove prescribed SOD in all reaches	44.0%
Remove all SOD by setting SOD channel coverage to 0%	74.4%

Table 6.3 DO sensitivity to channel slope.

Channel Slope	DO Sensitivity
Increased by 25%	6.5%
Decreased by 25%	-8.5%

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TECHNICAL MEMORANDUM

TO: Diane Sander, Crow River Organization of Water Watershed Coordinator

CC: Maggie Leach, MPCA Regional Impaired Waters Coordinator

FROM: Joe Bischoff, Project Manager
Pamela Massaro, P.E.
Jeff Strom

DATE: September, 2011

SUBJECT: Jewitts Creek Dissolved Oxygen TMDL
Description of QUAL2K Modeling Methods and Results

Wenck Associates, Inc. has developed and calibrated a QUAL2K model for Jewitts Creek from West 4th Street in Litchfield to the Creek's confluence with the main-stem of the North Fork Crow River upstream of Meeker County Road 34. The purpose of this technical memorandum is to describe the methods and assumptions used to create and calibrate the QUAL2K model.

1.0 INTRODUCTION

1.1 Model Selection

The U.S. EPA River and Stream Water Quality Model (QUAL2K) version 7 is a modernized version of the QUAL2E model developed by Dr. Steven Chapra with Tufts University and Greg Pelletier with Washington State. It was selected to analyze Jewitts Creek because it is a relatively simple surface water quality model that can be used during steady-state conditions to model nutrient, algal and dissolved oxygen dynamics.

1.2 General Overview of the Model

The model was built using late summer synoptic survey data collected on September 3-4, 2008. Stream locations and physical features were built in to the model first before proceeding to hydraulic calibration. With the diffuse flow inputs incorporated, the conservative water quality parameters (such as water temperature and conductivity) were adjusted to match monitored observations. Then, chlorophyll-*a* (phytoplankton production), nutrients (phosphorus and nitrogen components), and carbonaceous biological oxygen demand (CBOD) were calibrated by adjusting tributary/groundwater contributions and/or kinetic coefficients within the range of published values. In some cases, reach specific kinetic rates and in-stream nutrient fluxes were assigned to model geochemical processes believed to be unique to certain reaches. Finally, bottom algae and sediment oxygen demand were adjusted for each reach to match observed dissolved oxygen data.

2.0 MODEL SETUP AND INPUTS

The QUAL2K model covers the main stem of Jewitts Creek from where it crosses West 4th Street in Litchfield, MN to its confluence with North Fork Crow River upstream of Meeker County Road 34. This stretch of Jewitts Creek, explicitly modeled, represents approximately 1.1 miles (1.75 km) as five individual reaches. The start of each reach correlates with a monitoring station location, road crossing, or physical change in stream hydrology (Figure 2.1, Table 2.1 and Table 2.2).

Table 2.1 Model reach characteristics.

Reach	Description	Upstream River km	Downstream River km	Distance (km)	Distance (mile)	Slope (m/m)
1	West 4th Street (JC-03) to MN Hwy 24 (JC-04)	10.53	8.78	1.75	1.1	0.0016
2	MN Hwy 42 (JC-04) to County Hwy 34 (JC-05)	8.78	5.86	2.92	1.8	0.0017
3	County Hwy 34 (JC-05) to 300th Street (JC-06)	5.86	2.30	3.56	2.2	0.0009
4	300th Street (JC-06) to 310th Street (JC-07)	2.30	0.60	1.70	1.1	0.0007
5	310th St. (JC-07) to Outflow to North Fork Crow River	0.60	0	0.60	0.4	0.0008

Table 2.2 Monitoring locations.

Reach	Reach Start Monitoring Location ID	Description	Data Collected
None	JC-00	Jewitts Creek at Lake Ripley outlet	None
None	JC-01	Jewitts Creek at 260th Street crossing	None
None	JC-02	Jewitts Creek at CSAH 1 crossing	Q
1	JC-03	Jewitts Creek at W. 4th Street Crossing in Litchfield	Q, Grab, Field
2	JC-04	Jewitts Creek at MN Highway 42 crossing	Q, BOD, Field, DO
3	JC-05	Jewitts Creek at County Highway 34 crossing	Q, Grab, Field, ToT, DO
4	JC-06	Jewitts Creek at 300th Street crossing	Q, Grab, Field, DO
5	JC-07	Jewitts Creek at 310th Street Crossing	Q, Grab, Field, ToT

Q = Flow gauged.
ToT = Time of Travel determined from dye study.
Grab = Water quality grab sample collected and lab analyzed for typical pollutants (total kjeldahl nitrogen (TKN), ammonia nitrogen (NH_3-N), nitrate nitrogen (NO_2-N), 5-day and ultimate carbonaceous biological oxygen demand ($CBOD_{5\text{-day}}$ & $CBOD_u$), total phosphorus (TP), ortho-phosphorus (soluble reactive phosphorus), total organic carbon (TOC), and chlorophyll-*a*).
BOD = Water quality grab sample collected and lab analyzed for $CBOD_{5\text{-day}}$ & $CBOD_u$.
Field = In-field measurement of temperature, conductivity, pH, and dissolved oxygen (DO).
DO = Data sondes deployed to collect continuous measurements of dissolved oxygen, temperature, pH and conductivity.

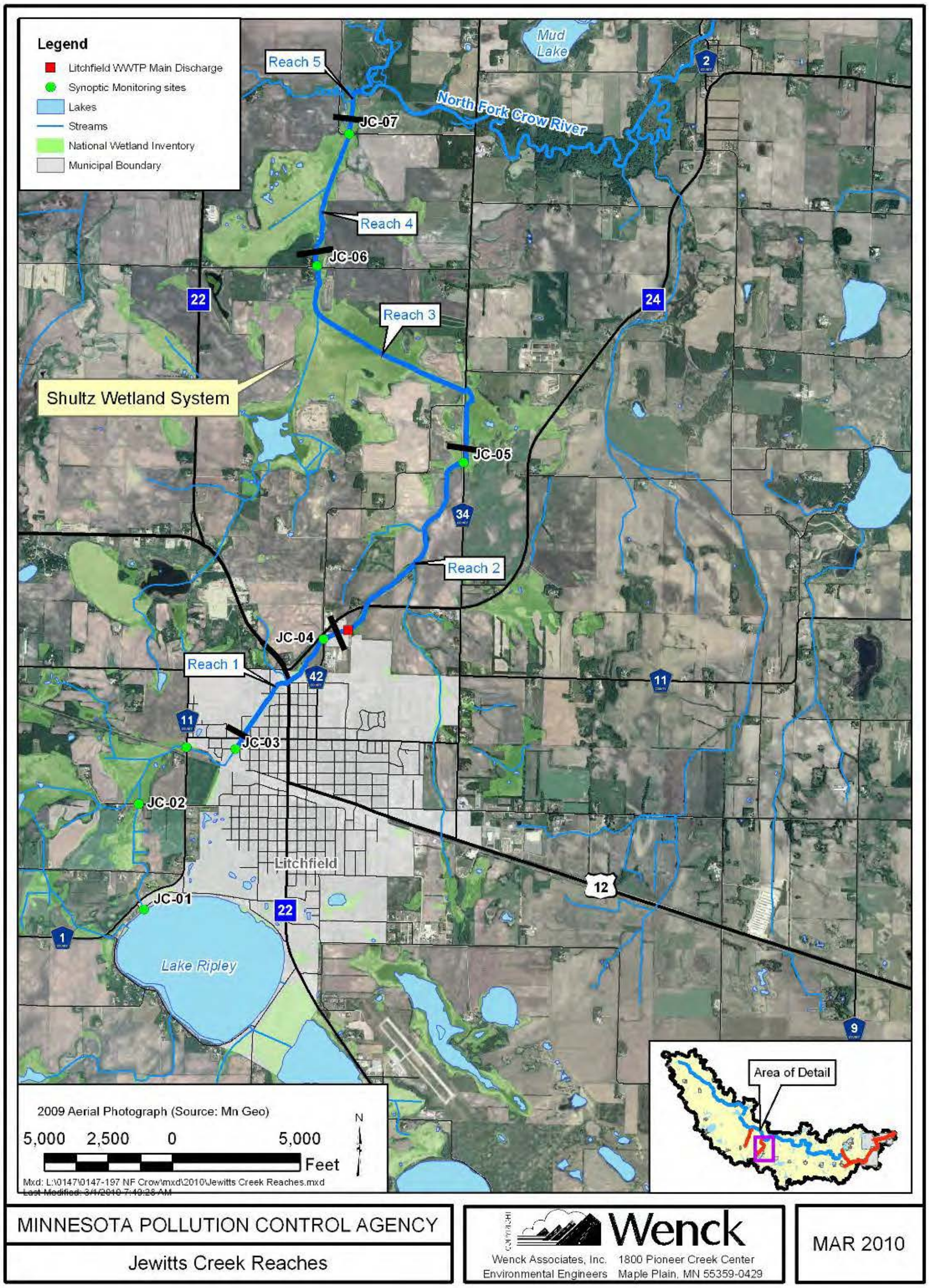

Figure 2.1 Monitoring stations and reaches on Jewitts Creek.

2.1 Channel Slope

Reaeration in QUAL2K may be prescribed by the user or calculated using one of eight hydraulic-based reaeration formulas built into the model. The Tsivoglou-Neal reaeration model was selected for Jewitts Creek because it is the most appropriate to calculate reaeration when flow is below 10 cfs (Tsivoglou and Neal, 1976; Thomann and Mueller, 1987). This reaeration model formula is shown below:

$K_a = 1.8 \times V \times S$ for $1 < Q < 10$ cfs

Where:
K_a = reaeration rate coefficient at 20°C (base e, day $^{-1}$)
V = average velocity (ft/s)
S = slope of energy gradient (ft/mile)

The channel slope and velocity are the variables in calculating reaeration in each reach. Average channel slopes were calculated based on data from an elevation survey conducted by Wenck in the fall of 2008 (Figure 2.2 and Table 2.3).

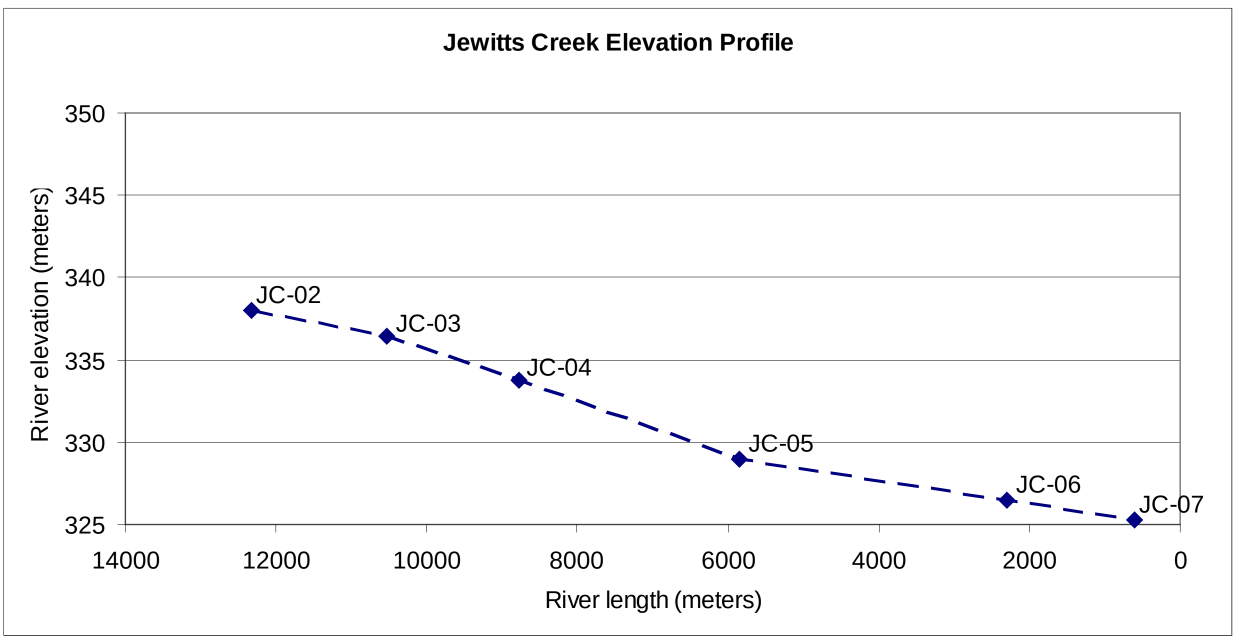

Figure 2.2 Longitudinal elevation survey and modeled reach slopes for Jewitts Creek.

Table 2.3: Jewitts Creek Longitudinal Elevation Survey Summary

Reach Start Monitoring Location ID	River Kilometer	River Mile	Elevation (meters)	Elevation (feet)	Slope (ft/mile)
JC-02	12.3	7.7	338.0	1109.0	---
JC-03	10.5	6.5	336.4	1103.7	4.68
JC-04	8.8	5.5	333.7	1094.9	8.11
JC-05	5.9	3.6	328.9	1079.2	8.63
JC-06	2.3	1.4	326.5	1071.3	3.60
JC-07	0.6	0.4	325.3	1067.3	3.74
				Total Slope	5.71

2.2 Weather and Physical Processes

Hourly weather measurements of temperature, cloud conditions, relative humidity and wind speed were downloaded from the National Weather Service (NWS) NOAA Litchfield Municipal Airport. Channel coverage and shading was set to 0 percent for all reaches due to the lack of canopy cover.

2.3 Headwaters

The Minnesota Department of Natural Resources (DNR) stream file shows Jewitts Creek headwaters to be located at the outlet of Ripley Lake (shown on Figure 1.1 as JC-00). During the synoptic survey, JC-00 contained standing water but no velocity. Flow was gauged downstream at the 260th Street crossing (JC-01) west of Litchfield but there was not enough (less than 0.09 cfs) to initiate a dye study or collect reliable water quality samples. Gauged flow at JC-03 at West 4th Street near the Public Works building in Litchfield was higher (~1.21 cfs) and more suitable for monitoring. Thus, all water quality data collected at this station on September 3-4, 2008 was used to represent the upstream boundary condition/headwater in the model. As noted in Table 2.2, a data sonde was not deployed at the JC-03 headwater station. Hourly data from JC-04's data sonde monitored on September 3, 2008 was used to represent the upstream boundary condition (JC-03). Dissolved oxygen, pH and conductivity data were used as monitored. The hourly temperature data had to be uniformly adjusted by a factor of 0.8, so that the model predicted temperature at JC-04 matched monitored values.

2.4 Point Sources

Litchfield Waste Water Treatment Facility (WWTF) is the only National Pollutant Discharge Elimination System (NPDES) point source located in the Jewitts Creek watershed (MN0023973). This continuously discharging facility is located just north of the Meeker County Fairgrounds and is designed to treat an average wet weather flow of 2.37 million gallons per day. The facility includes processes to removes both nitrogen and phosphorus, the effluent is aerated before the discharge reaches Jewitts Creek through outfall SD001. Effluent monitoring data for this facility was not available for the dates of the synoptic survey and dye study. Daily flow data from 1999-2006 and monthly flow data from 1999-2008 were available through the Minnesota Pollution Control Agency (MPCA) NPDES Discharge Monitoring Reports (DMRs). Modeled facility discharge was estimated by taking the average discharge on September 3 for the last five years in which daily flow data was available (2002-2006). Modeled effluent water quality parameters were set to concentrations in the September 2008 daily monitoring report (Table 2.4).

Table 2.4 Modeled values for Litchfield WWTP discharge to Jewitts Creek.

Paramter	Modeled Value	Source
Flow (m^3/s)	0.064	Mean of monitored daily effluent on 9/3 (2002-2006)
Temp (C)	20.00	Calibrated to in-stream data
Sp. Cond (umhos)	2.00	Calibrated to in-stream data
Dissolved Oxygen	7.00	DMR – monthly minimum
Fast CBOD (mg/L)	2.00	DMR – maximum weekly average
Organic-N (µg/L)	1000	Calibrated to in-stream data
Ammonia (µg/L)	200	DMR – monthly average
Nitrate (µg/L)	5000	Calibrated to in-stream data
Organic-P (µg/L)	300	DMR – Assumed TP was all Organic-P
Inorganic-P (µg/L)	0	DMR – Assumed TP was all Organic-P
pH	7.5	DMR – midpoint of monthly min/max

2.5 Carbonaceous Oxygen Demand (CBOD)

QUAL2K calculates nitrogenous oxygen demand separate from carbonaceous oxygen demand (CBOD) by requiring separate inputs of $CBOD_{ultimate}$, organic nitrogen and reduced nitrogen. $BOD_{ultimate}$, not $CBOD_{ultimate}$ was analyzed during the Jewitts Creek synoptic survey. Biochemical oxygen demand (BOD) is a measure of the oxygen consumed by bacteria from the decomposition of organic matter. CBOD measures oxidation of the carbon fraction of organic mater. This $CBOD_{ultimate}$ fraction was estimated by subtracting the oxygen equivalents (4.57 mg O_2 per mg reduced nitrogen) of the reduced nitrogen in the sample according to the following equation (Thomann et al., 1987; Chapra et al., 2007):

$$CBOD_{ultimate} = BOD_{ultimate} - (4.57*TKN)$$

Resulting $CBOD_{ultimate}$ estimates were extremely low in the most upstream reach and at or below detection in downstream reaches, suggesting only one type/source of CBOD exists throughout the system.

The old EPA model (QUAL2E) version had one type of CBOD with one decay rate. The modernized version (QUAL2K) now includes two forms of CBOD to represent organic carbon; a slowly oxidizing form (slow CBOD) and a rapidly oxidizing form (fast CBOD). This allows the model to decay CBOD at two decay rates, if deemed necessary. This model enhancement is great for waste streams with organic carbons in the form of sugar, glucose, etc. Based on the CBOD data collected, it is reasonable to assume there is only one oxidizing form of CBOD. For this reason, all $CBOD_{ultimate}$ was represented in the model as fast CBOD.

3.0 HYDRAULIC CALIBRATION

Modeled hydraulic inputs were derived from the flow gauging data collected during the September 3, 2008 synoptic survey. Total discharge was calibrated first before moving on to time of travel calibration. All hydraulic inputs and calibration adjustments are described in the following sections.

3.1 Hydraulic Rating Curves

QUAL2K hydraulics may be modeled using power function rating curves, weirs (dam/drop structures) or Manning's equations. Hydraulics for all Jewitts Creek reaches were represented using power function rating curves from flow gauging data collected during the synoptic survey. The power function option relates mean velocity and depth to flow in each reach. QUAL2K uses five coefficients to define reach hydraulics, as follows:

- Velocity (m/sec) = a Q^b
- Depth (m) = c Q^d + e

in which Q is flow in cubic meters per second. Depth and velocity rating curves were constructed using gauged flow data from the time of travel study. Gauging stations with similar channel dimensions and flow characteristics were combined in to one rating curve to provide more robust velocity/depth versus flow relationships (Figures 3.1 through 3.3). Applying the principals of hydraulic geometry (Leopold and Maddock, 1953), there is another power function for width.

- Width (m) = f Q^g

Because the width, depth and velocity are a function of discharge, the following rules apply to the coefficients and exponents of these power functions. The sum of the exponents equal one ($b + d + g = 1.0$), and the product of the coefficients equal one ($a \times c \times f = 1.0$). The representative hydraulic rating curves for each reach was selected based on proximity to gauging stations and typical channel dimensions throughout the reach. The hydraulic coefficients and exponents for each QUAL2K reach are summarized in Table 3.1 Along with adjustments made during calibration.

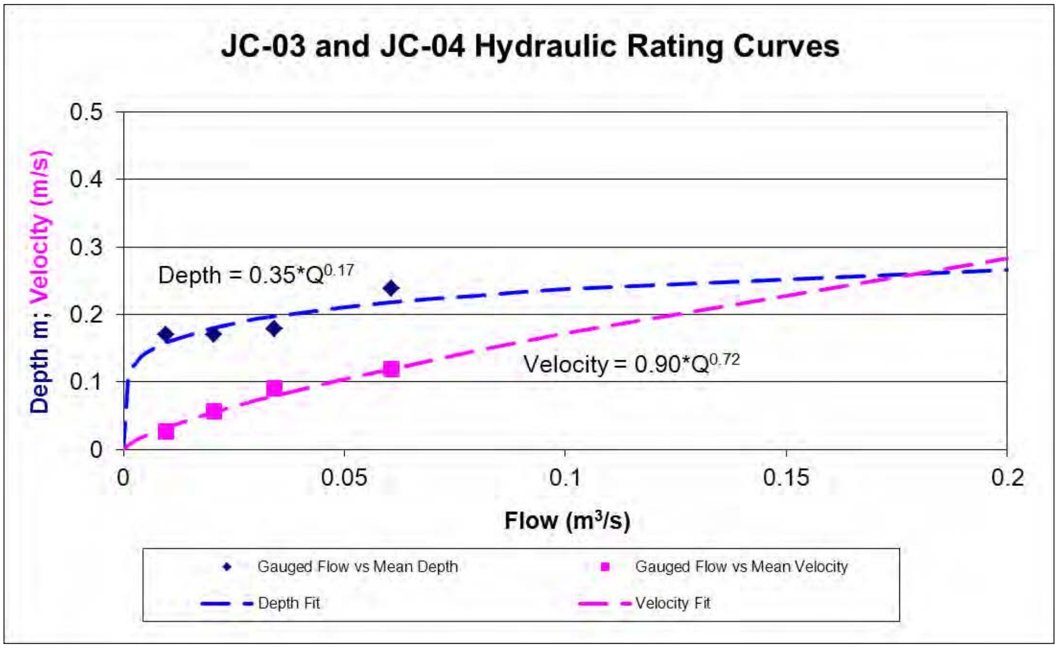

Figure 3.1 Hydraulic rating curve plot for gauging stations JC-03 and JC-04.

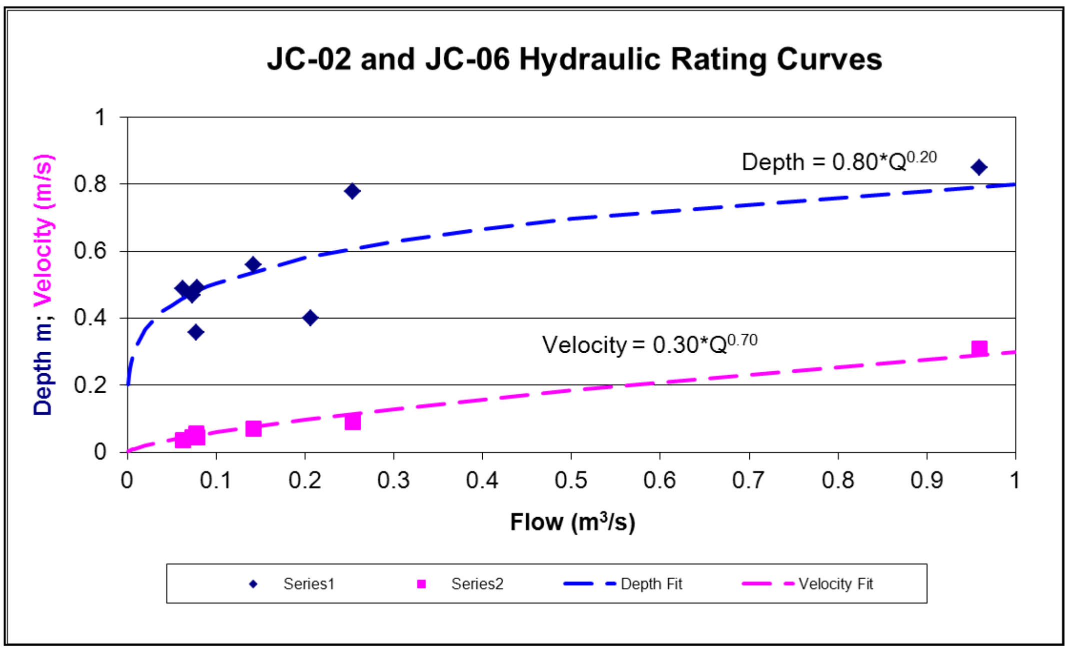

Figure 3.2 Hydraulic rating curve plot for gauging stations JC-02 and JC-06.

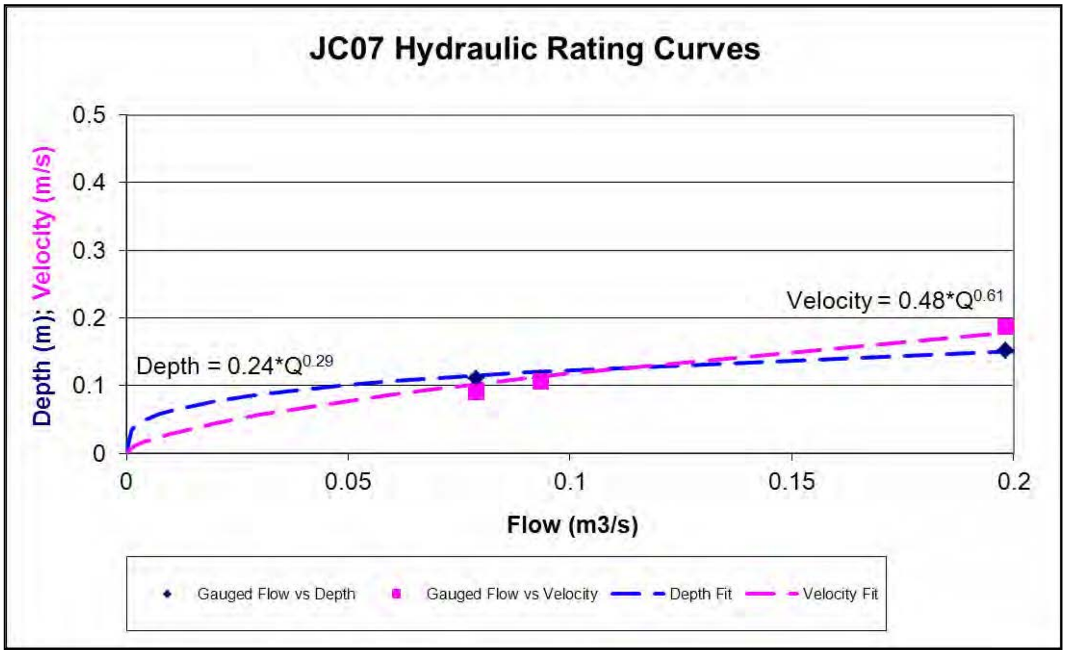

Figure 3.3 Hydraulic rating curve plot for gauging stations JC-07

Table 3.1 Summary of the hydraulic coefficients and exponents assigned to each reach.

Reach	Rating Curve Used	Velocity Coeff.	Velocity Exp.	Depth Coeff.	Depth Exp.	Adjustments
1	JC-03*+JC-04	0.90	0.72	0.35	0.17	None
2	JC-02+JC-06	0.30	0.70	0.80	0.20	None
3	JC-02+JC-06	0.18 Δ	0.70	0.80	0.20	Wetland reach - lowered velocity coefficient
4	JC-07	0.48	0.61	0.24	0.29	None
5	JC-07*	0.48	0.61	0.24	0.29	None

* denotes that the monitoring station is at the upstream end of the reach.

Δ denotes a change in the hydraulic coefficients or exponent.

3.2 Flow Calibration

Jewitts Creek tributaries were not accessible to determine if they were contributing flow during the synoptic survey and dye study. Thus, monitored changes in flow between gauging stations were built in to the model as diffuse sources. All diffuse source flow inputs are described in Table 3.2. Reaches 3-5 were modeled as both flow abstractions and diffuse inflows in order to capture observed nutrient loading through the Shultz Wetland System. It should be noted that the wetland system was modeled as a net flow loss to match observed data. The model was deemed calibrated for total discharge once all point source and diffuse source flows were built in to the model (Figure 3.4.). The model predicted flow is within the error bars of the monitored flows.

Table 3.2 Modeled diffuse source inflow for Jewitts Creek

Reach	Total flow throughout reach (m^3/s)
Reach 1 (JC-03 to JC-05)	-0.01*
Reach 2 (JC-04 to JC-05)	0.02
Reaches 3-5 (JC-05 to Outlet)	0.04
Reaches 3-5 (JC-05 to Outlet)	-0.06*

* denotes that negative flow values are abstractions (outflows), while positive flow values are inflows.

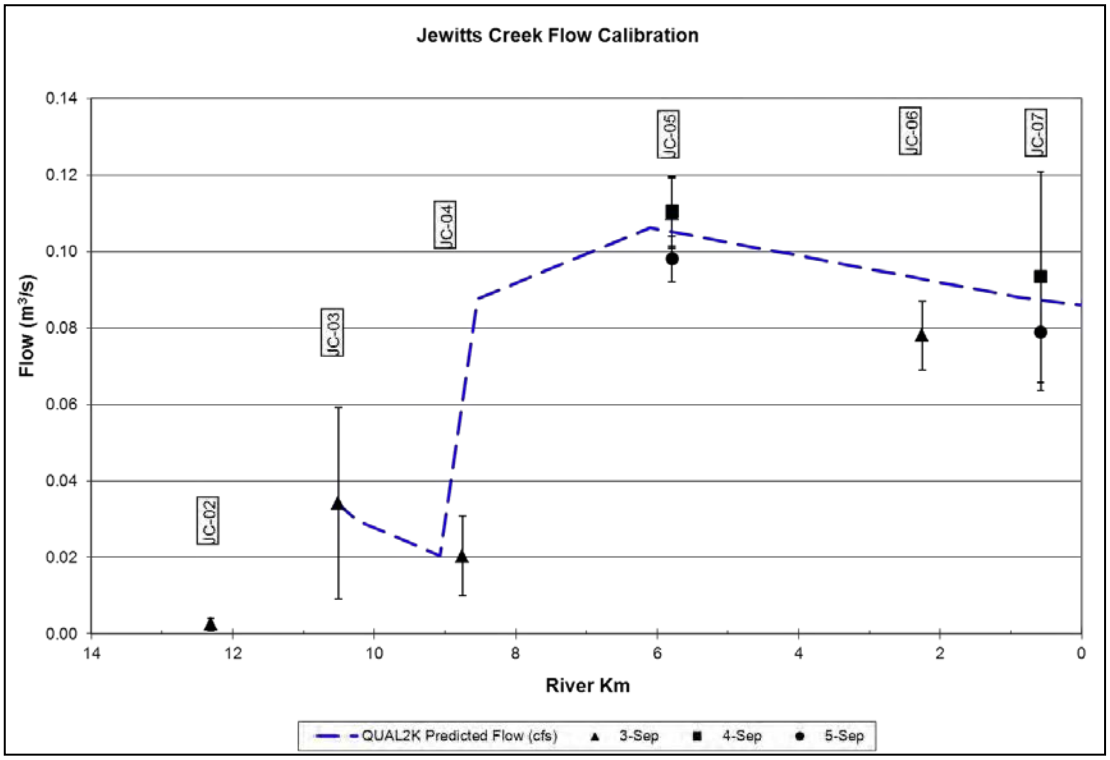

Figure 3.4 Final Jewitts Creek Flow calibration with diffuse and point source inflows.

3.3 Time of Travel Calibration

With total flow calibrated, rating curve coefficients and exponents were adjusted to meet travel times calculated during the dye study portion of the synoptic survey. Reach 3 was the only reach where travel time could not be modeled using gauging station rating curves. Reach 3 represents a large, channelized lake/wetland (Schultz Wetland System), west of MN Highway 24 and south of 300th Street. Dye study results supported adjusting the gauged hydraulic coefficient (velocity) to represent a slower than gauged velocity for the main channel thus increasing the hydraulic residence time. The velocity coefficient for this reach had to be lowered by one-half in order to meet time of travel results (Table 3.1 and Figure 3.5).

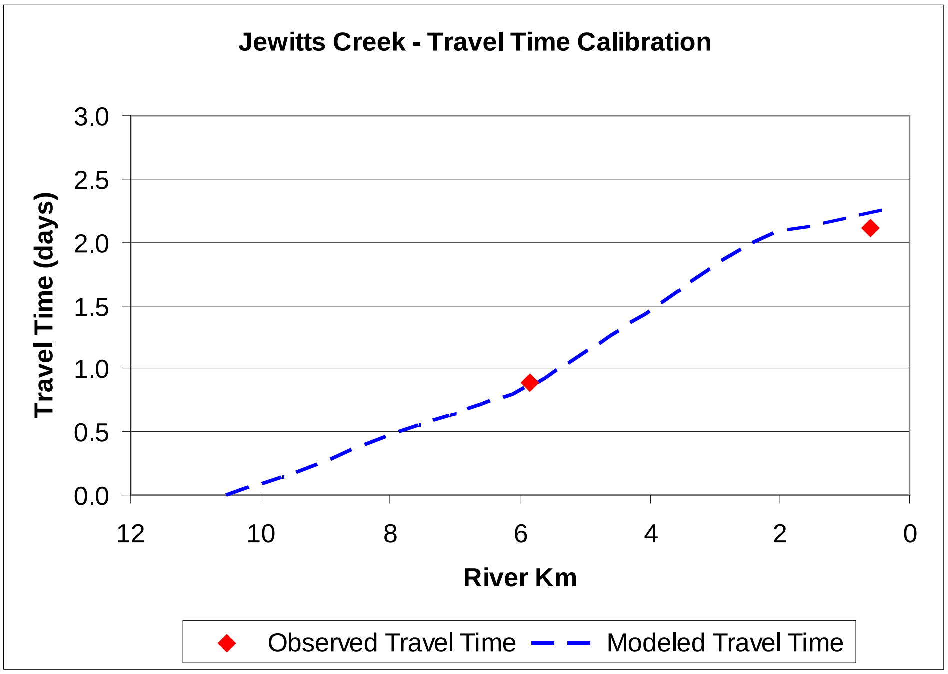

Figure 3.5 Jewitts Creek time of travel calibration.

4.0 WATER QUALITY CALIBRATION

All water quality model inputs were derived from data collected during the September 3, 2008 synoptic survey. Tributary and/or groundwater parameters were estimated based on literature values and calibration to in-stream water quality data. The QUAL2K model was set up to simulate temperature, flow, velocity, depth, chloride, organic nitrogen (ON), ammonia nitrogen (NH_3-N), nitrate/nitrite nitrogen (NO_2/ NO_3-N), ultimate carbonaceous biological oxygen demand ($CBOD_u$), dissolved oxygen (DO), sediment oxygen demand (SOD), total phosphorus (TP), chlorophyll-*a*. All model changes to global and reach specific kinetic rates as well as point source, diffuse and in-stream loadings to calibrate water quality are discussed in this section.

4.1 General Kinetic Rates

Five kinetic rates were adjusted from default values in order to meet longitudinal changes in observed water quality data. All kinetic rates were adjusted within the range of published values (Table 4.1).

Table 4.1 QUAL2K kinetic rates adjusted from model default values.

Rate	Calibrated Rate	Default Rate	Literature Range	Citation/Study Area
Reaeration Model	Tsivoglou and Neal	User Specified	Thomann and Mueller, 1987 cite that Tsivoglou and Neal, 1976; best for small, shallow streams (1-15 cfs)	
Fast CBOD oxidation rate (day^{-1})	2.0	0.23	0.02 – 0.60 0.56 – 3.37	Bowie et al., 1985 Table 3-17 p152 Kansas (6 rivers) Michigan (3 rivers) reported by Bansal, 1975
Organic-N Hydrolysis (day^{-1}) *The release of ammonia due to decay of organic nitrogen*	0.03	0.20	0.02 – 0.10 0.03 – 0.20	Bowie et al., 1985 Table 5-3 p259 Scavia, 1980 Di Toro & Matystik, 1980
Organic-P Hydrolysis (day^{-1}) *The release of phosphate due to decay of organic phosphorus*	0.80	0.20	0.50 – 0.80 0.02	Bowie et al., 1985 Table 5-5 p266 Jorgenson, 1976 Bowie et al., 1980
Inorganic-P settling (m/d)	0.25	2.0	influenced by a material's size, shape, and density and the speed of water	
Phytoplankton Settling (m/d)	0.10	0.50	0 – 2	Bowie et al., 1985 Table 6-19 p352 Chen & Orlob, 1975 and Smith, 1978

4.2 In-stream Loadings and Reach Specific Rates

In addition to global changes to kinetic rates, individual reaches required specific kinetic rate adjustments to calibrate to in-stream water quality data. Water quality data from Reaches 3 and 4-5 display nutrient loadings and losses not predicted by the default and adjusted kinetic rates. Reach 3 flows through a 346 acre lake/wetland complex referred to as the Schultz Wetland System. While flow through this wetland is relatively channelized, air photos suggest the channel widens and interacts with varying fractions of the wetland depending on flow regime. Geochemical samples upstream (JC-05) and downstream (JC-06) of the wetland indicate significant reductions in nitrate and mass loading of inorganic phosphorus. Flow increase through this reach is small which suggests these changes are attributed to stream interactions/exchanges with the larger wetland resulting in denitrification and phosphorus loading.

QUAL2K predicts nutrient release from sediments based on the delivery and breakdown of suspended organic material during steady state conditions. It is not suited to model nutrient release from sediment delivered during non-steady state conditions (storm events or previous conditions) or the breakdown of rooted and floating macrophytes. Previous studies have indicated that significant amounts of total phosphorus have accumulated in the Schultz Wetland System (Magner, 2005). While steps have been taken to reduce water column total phosphorus concentrations upstream of the Schultz Wetland System, the wetland still appears to be a major source of nutrients and eutrophication downstream. Reach specific nutrient fluxes were applied to reaches 3-6 in order to calibrate to the observed nutrient concentrations in the Schultz Wetland System (Table 4.3).

Table 4.3 Summary of reach specific sediment fluxes and kinetic rates.

Reach	Rate	Reach Specific Rate	Default Rate	Literature Range	Justification
3 (JC-05-JC-06)	Sediment denitrification transfer coefficient (m/d)	1.0	0	0.0-1.0	Wide, slow moving Schultz Wetland System reach with muddy bottom and wetland vegetation. Evidence of anaerobic conditions and high denitrification rates supported by Bowie et al., 1985 Table 5-4 pp 262; Baca & Arnett, 1976
	Prescribed Inorganic-P Flux (mg P/m^2/d)	200	Model calculated	9.6 - 95	Eutrophic Schultz Wetland System reach that accumulated TP under previous conditions supported by Magner, 2005. The flux occurs over the entire wetland system and the surface area of the wetland is much larger than the surface area of the modeled reach (Muddy River, Boston, MA total dissolved phosphorus flux aerobic and anaerobic conditions from Fillos and Swanson 1975)
4-5 (JC-06 - Outlet)	Prescribed Inorganic-P Flux (mg P/m^2/d)	60	Model calculated	9.6 – 95	Muddy bottom reach downstream of eutrophic Schultz Wetland System reach (Muddy River, Boston, MA total dissolved phosphorus flux aerobic and anaerobic conditions from Fillos and Swanson 1975)
4-5 (JC-06 – Outlet)	Prescribed NH_4 Flux (mg N/m^2/d)	75	Model calculated	20 - 325	Wide, slow moving reach downstream of wetland system containing sediment with high organic matter content (rate supported by Thormann and Mueller, 1987)

4.3 Point Source Loadings

For water quality parameters not reported in the Litchfield wastewater treatment facility discharge monitoring report, effluent concentrations were adjusted to meet monitored water quality data downstream of the facility discharge (Table 2.4). All parameters calibrated to meet observed data were supported by literature values for achievable treatment levels for wastewater treatment plants (EPA, 1995).

4.4 Diffuse Source Loadings

It is assumed changes in flow across Jewitts Creek (modeled as diffuse sources) are some combination of tributary, draintile and groundwater inflow/outflow. Modeled abstractions (outflows) are removals at the water quality concentrations predicted in the reach. Diffuse source inflows were initially assigned typical groundwater water quality values in QUAL2K and then adjusted upward to meet in-stream water quality results (Table 4.4). Nitrate in Reach 2 and Organic nitrogen in Reaches 2-5 were adjusted furthest from groundwater literature values. This suggests high tributary or in-stream loading of nitrate and organic nitrogen that cannot be accounted for by adjusting model kinetic rates.

Table 4.4 Modeled diffuse source water quality parameters.

Parameter	Reach 2 (JC-04-JC-05)	Justification	Reaches 3-5 (JC-05-Outlet)	Justification
Temp (C)	18.92	Calibrated adjustment to in-stream conditions. Value equal to daily average for 9/3/08 temperature monitored at JC-05.	14.70	Calibrated adjustment to in-stream conditions. Value equal to daily average for 9/3/08 temperature monitored at JC-04.
Sp. Cond (umhos)	0.60	Calibrated adjustment to in-stream conditions	0.60	Calibrated adjustment to in-stream conditions
DO	1.6	Mean of published groundwater data	1.6	Mean of published groundwater data
Organic- N (µg/L)	1000	Calibrated adjustment to in-stream conditions	2700	Calibrated adjustment to in-stream conditions
Nitrate (µg/L)	5000	Calibrated adjustment to in-stream conditions. Within range of USGS groundwater atlas (Lindholm et al., 1974)	1500	Typical MN groundwater literature value and within range of USGS groundwater atlas (MPCA, 1998; Lindholm et al., 1974)
Organic-P (µg/L)	11.20	Typical MN groundwater literature value (MPCA, 1999)	11.20	Typical MN groundwater literature value (MPCA, 1999)
Inorganic-P (µg/L)	44.80	Typical MN groundwater literature value (MPCA, 1999)	44.80	Typical MN groundwater literature value (MPCA, 1999)
Phytoplankton (µg A/L)	75	Calibrated adjustment to in-stream conditions	55	Calibrated adjustment to in-stream conditions

4.5 Final Water Quality Calibration

$CBOD_{fast}$, chlorophyll-*a* and all forms of nitrogen and phosphorus were calibrated once all diffuse source water quality parameters and kinetic rates were properly incorporated into the model. The model performed well in predicting loads and concentrations of the primary water quality parameters that affect dissolved oxygen.

5.0 DISSOLVED OXYGEN CALIBRATION

5.1 Diurnal Oxygen Calibration

The Jewitts Creek model applies the Half Saturation formulations defining the relationship light penetrates the water column and effects algae and the resulting photosynthesis. Though water column algae is accurately predicted in the model (Figure 4.4), additional modeling adjustments were needed to better predict the daily minimum and maximum DO observations. This suggests there was in-situ primary production not accounted for or under-represented in the initial model runs. In the QUAL2K model, the bottom algae component simulates photosynthesis and nutrient uptake of any non-suspended algae. In the Jewitts model, the bottom algae channel coverage was adjusted by reach to match the photosynthesis/respiration swings in the observed continuous DO data (Table 5.1). It is assumed that this bottom algae component defined in QUAL2K represents all elements of primary production (attached algae, submerged macrophytes, rooted aquatic vegetation) that could not be measured or quantified in the field.

5.2 Sediment Oxygen Demand

Sediment oxygen demand (SOD) is calculated in QUAL2K based on the delivery and breakdown of particulate organic matter from the water column. Currently, the model does not have a macrophyte or riparian vegetation SOD component, nor does it incorporate any sediment re-suspended or delivered to the stream channel during non-steady state storms events. The model does allow the user to prescribe SOD to each reach that is added to the model predicted rate to account for SOD outside the modeling framework. SOD in streams varies depending on sediment type but is typically between 0.05 (mineral soils) and 2.00 (estuarine mud) g O_2/m^2/day (Thomann and Mueller, 1987).

Dissolved oxygen concentrations should be close to calibration once diurnal variability is calibrated and reasonable assumptions have been made in allocating nutrient loads and adjusting kinetic rates. Model predicted dissolved oxygen concentrations for the hydraulic/phytoplankton/nutrient calibrated model were slightly higher than the average continuous DO monitored values. Additional SOD was assigned to each reach to lower mean oxygen concentrations to match observed values (Table 5.1).

Table 5.1 SOD prescribed to each reach that is added to the model-predicted SOD under steady state conditions.

Reach	SOD $g\ O_2/m^2/day$	Bottom Algae Coverage (%)	Justification
1	2.5	50	Necessary to lower the upstream boundary condition/headwater DO (as described in Section 2.3) to match JC-04 DO monitored DO data. This could be the result of slow water upstream, or a calibration artifact because of lack of continuous DO data at JC-03.
2	1.0	75	Typical muddy bottomed channel
3	3.1	65	Schultz Wetland System influenced reach
4	2.0	35	Typical muddy bottomed channel
5	1.5	35	Typical muddy bottomed channel

5.3 Final Dissolved Oxygen Calibration

Figure 5.1 shows the final calibration results for model-predicted and observed dissolved oxygen concentrations. Field grabs of dissolved oxygen were taken on September 3 and September 4 using the hand-held YSI. The field grabs are labeled with the time of sample collection, if available. Also shown is the continuous dissolved oxygen data recorded during the September 3rd and September 4th survey (shown in plot as the range of data between minimum and maximum as orange and blue "I"). The average of the continuous DO is marked on the plot with an orange or blue box dependant on the day. All field grab measurements taken by Wenck staff on September 3-4, 2008 were collected between 12:00 pm and 4:00 pm and were closer to representing daily maximums.

The model performs well in predicting average daily dissolved oxygen concentrations (in plot as black dashed line) and diurnal patterns (daily minimum and maximum, shown in plots as blue dashed lines) at the three monitoring stations with continuous DO measurements.

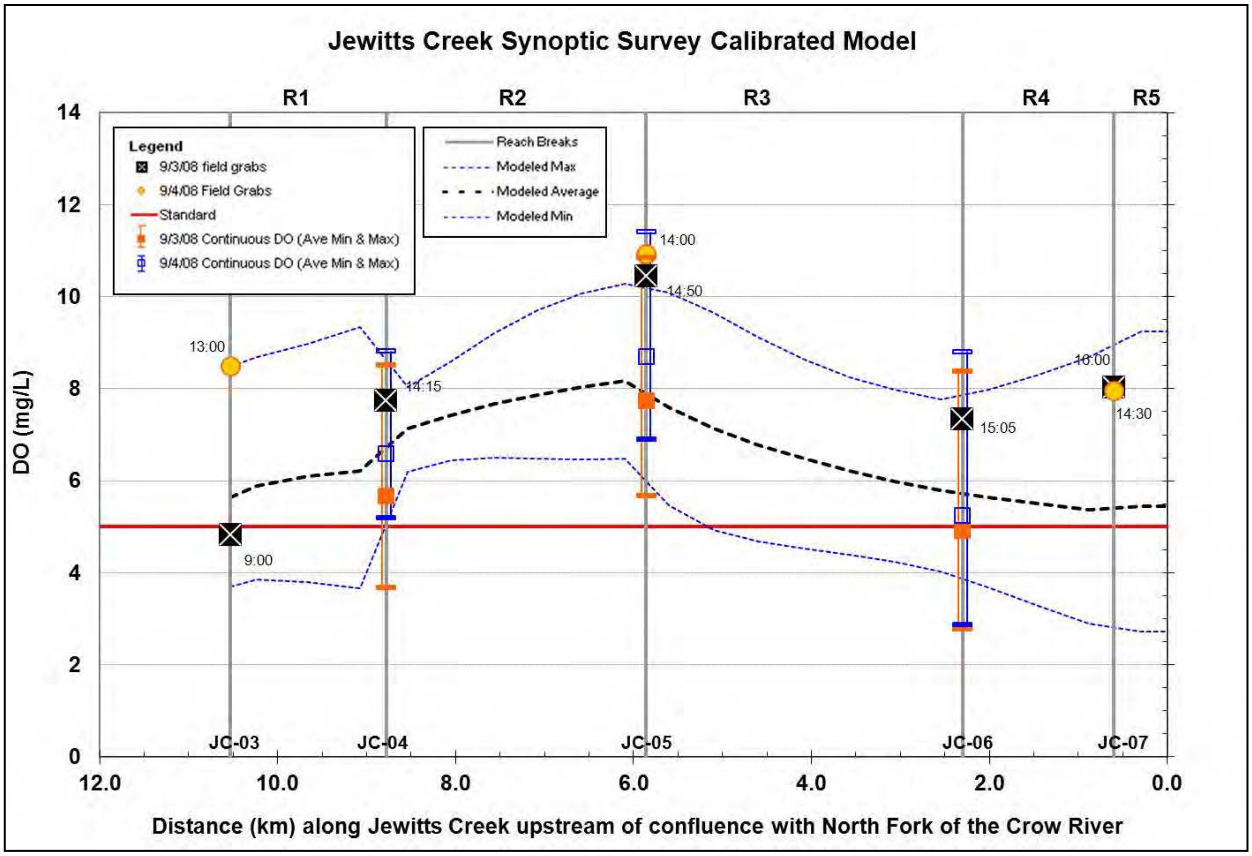

Figure 5.1 Jewitts Creek calibrated dissolved oxygen longitudinal profile.

6.0 SENSITIVITY ANALYSIS

To evaluate the sensitivity of model predicted dissolved oxygen to changes in model variables, seven kinetic rates (Table 6.1), four reach specific rates (Table 6.2), and channel slopes (Table 6.3) were removed or adjusted by specific percentages. The following tables summarize the affect these changes have on the average model-predicted dissolved oxygen concentration for the entire modeled stretch of Jewitts Creek. Results show DO throughout the system is most sensitive to the kinetic rates driving SOD levels (nitrogen and phytoplankton settling) as well as the SOD settings themselves. CBOD oxidation and nutrient hydrolysis rates are less sensitive to dissolved oxygen throughout Jewitts Creek. This exercise suggests sediment processes play a bigger role than water column processes in consuming dissolved oxygen during this particular calibration/sampling event.

Table 6.1 DO sensitivity to kinetic rates.

Kinetic rate	+25%	-25%	Default
$CBOD_u$ oxidation rate (day^{-1})	-0.3%	0.3%	2.8%
Organic-N Hydrolysis (day^{-1})	-0.2%	0.0%	-1.4%
Organic-N Settling (m/d)	-0.9%	1.1%	--
Organic-P Hydrolysis (day^{-1})	0.0%	-0.2%	-0.3%
Organic-P Settling (m/d)	0.0%	0.0%	--
Inorganic-P Settling (m/d)	-0.2%	0.0%	-1.1%
Phytoplankton Settling (m/d)	0.0%	-0.2%	0.9%

Table 6.2 DO sensitivity to reach rates.

Action	DO Sensitivity
Remove sediment denitrification transfer coefficient in reach 3	0.5%
Remove prescribed sediment inorganic-P flux in reaches 3-5	-2.0%
Remove prescribed SOD in all reaches	41.7%
Remove all SOD from model by setting SOD channel coverage to 0%	48.2%

Table 6.3 DO sensitivity to channel slope.

Channel Slope	DO Sensitivity
Increased by 25 percent	5.1%
Decreased by 25 percent	-6.7%

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TECHNICAL MEMORANDUM

TO: Diane Sander, Crow River Organization of Water Watershed Coordinator

CC: Maggie Leach, MPCA Regional Impaired Waters Coordinator

FROM: Joe Bischoff, Project Manager
Pamela Massaro, P.E.
Jeff Strom

DATE: September, 2011

SUBJECT: Mill Creek Dissolved Oxygen TMDL
Description of QUAL2K Modeling Methods and Results

Wenck Associates, Inc. has developed and calibrated a QUAL2K model for Mill Creek from the outlet of Deer Lake to the creek's confluence with the main-stem of the North Fork Crow River. The purpose of this technical memorandum is to describe the methods and assumptions used to create and calibrate the QUAL2K model.

1.0 INTRODUCTION

1.1 Model Selection

The U.S. EPA River and Stream Water Quality Model (QUAL2K) version 7 is a modernized version of the QUAL2E model developed by Dr. Steven Chapra with Tufts University and Greg Pelletier with Washington State. It was selected to analyze Mill Creek because it is a relatively simple surface water quality model that can be used during steady-state conditions to model nutrient, algal and dissolved oxygen dynamics.

1.2 General Overview of Model

First, a QUAL2K model was built and calibrated for Mill Creek using late summer synoptic survey data collected on September 1^{st}-2^{nd}, 2009. Then, using the synoptic survey calibrated model, a scenario was setup to model Mill Creek oxygen dynamics on August 3^{rd}, 2009 when DO violations were recorded and stream flow was close to 7Q10 conditions. Stream locations and physical features were built in to the late summer synoptic survey model first before proceeding to hydraulic calibration. With the diffuse flow inputs incorporated, the conservative water quality parameters (such as water temperature and conductivity) were adjusted to match monitored observations. Then, chlorophyll-*a* (phytoplankton production), nutrients (phosphorus and nitrogen components), and carbonaceous biochemical oxygen demand (CBOD) were calibrated by adjusting tributary/groundwater contributions and/or kinetic coefficients within the range of published values. Finally, bottom algae and sediment oxygen demand were adjusted for each reach to match observed dissolved oxygen data.

2.0 MODEL SETUP AND INPUTS

The River and Stream Water Quality Model (QUAL2K version 7) covers Mill Creek from its outlet of Deer Lake at 10th Street SW to its confluence with the North Fork Crow River. This stretch of Mill Creek, explicitly modeled, represents approximately 4.23 kilometers (2.63 miles) subdivided in to four reaches. The start of each reach coincides with a monitoring station location or change in stream hydrology/morphometry (Figure 2.1, Table 2.1 and Table 2.2). There are no registered point sources that directly discharge to this stretch of Mill Creek.

Table 2.1 Model reach characteristics.

Reach	Description	US River km	DS River km	Distance (km)
1	MilC-02 to River km 3.85	4.23	3.85	0.38
2	River km 3.85 to Unnamed Trib	3.85	3.10	0.75
3	Unnamed Trib to MilCr-03	3.10	1.78	1.32
4	MilC-03 to Outflow to NFC	1.78	0.00	1.78

Table 2.2 Synoptic survey monitoring station data collection.

Reach	Monitoring Location ID	Description	Data Collected
1	MilCr-02	10th Street SW Crossing	ToT, Q, Grab, Field, Sonde
4	MilCr-03	Co Rd 12 Crossing	ToT, Q, Grab, Field

Q = Flow gauged.
ToT = Time of Travel determined from dye study.
Grab = Water quality grab sample collected and lab analyzed for typical pollutants (total kjeldahl nitrogen (TKN), ammonia nitrogen (NH_3-N), nitrate nitrogen (NO_2-N), 5-day and ultimate carbonaceous biological oxygen demand ($CBOD_{5\text{-}day}$ & $CBOD_u$), total phosphorus (TP), ortho-phosphorus (soluble reactive phosphorus), total organic carbon (TOC), and chlorophyll-*a*).
Field = In-field measurement of temperature, conductivity, pH, and dissolved oxygen (DO).
Sonde = continuous data sonde deployed to hourly temperature, DO, pH, conductivity data

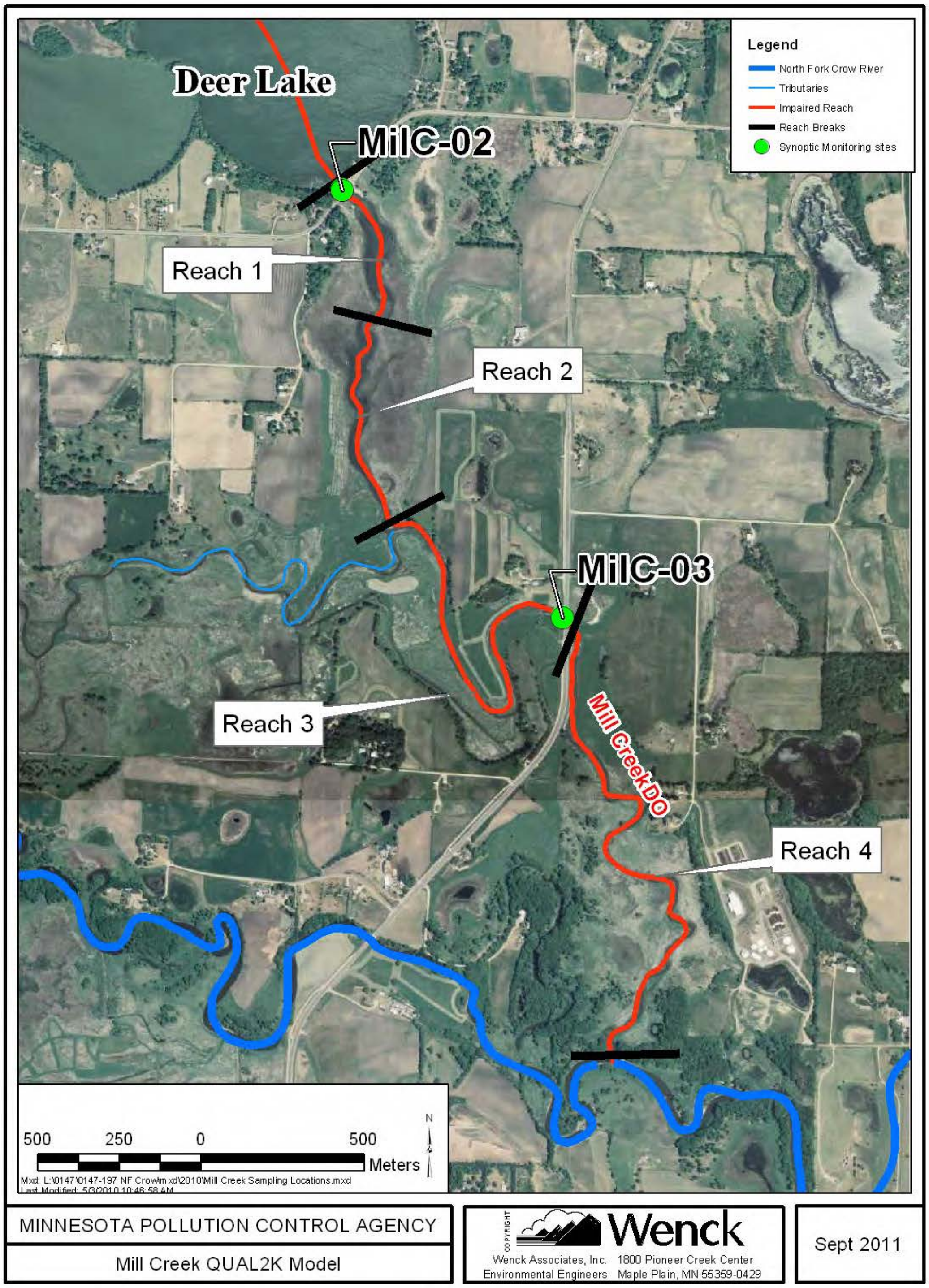

Figure 2.1 Monitoring stations and reaches on Mill Creek.

2.1 Channel Slope

Reaeration may be prescribed by the user or calculated using one of eight hydraulic-based reaeration models built into QUAL2K. The Tsivoglou-Neal reaeration model was selected for Mill Creek because it is the most appropriate model to predict reaeration for flows less than 20 cfs (Tsivoglou and Neal, 1972; Thomann and Mueller, 1987). This reaeration model formula is shown below:

$$K_a = 1.8 \times V \times S \qquad \text{for} \qquad 1 < Q < 10 \text{ cfs}$$

Where:
K_a = reaeration rate coefficient at 20°C (base e, day $^{-1}$)
V = average velocity (ft/s)
S = slope of energy gradient (ft/mile)

Channel slope and velocity are the variables used to calculate reaeration in each reach. Average channel slopes are based on data from an elevation survey conducted by Wenck in the fall of 2008 (Table 2.3).

Table 2.3 Mill Creek Longitudinal Elevation Survey Summary.

Monitoring Station	River Kilometer	Elevation (meters)	Slope
MilC-02	4.23	277.31	0.00035
MilC-03	1.78	276.44	
NFC Outflow	0	275.81	

2.2 Weather and Physical Processes

Hourly weather measurements of temperature, cloud conditions, relative humidity and wind speed were downloaded from the National Weather Service (NWS) NOAA Minneapolis-St. Paul Airport. Stream canopy coverage was set to zero percent based on field observations and investigation of air photos in GIS.

2.3 Headwaters

The Minnesota Department of Natural Resources (DNR) stream file shows Mill Creek headwaters to be the outflow from Deer Lake south-west of Buffalo, MN. Thus, all water quality and flow data collected at station MilC-02 was used to represent the upstream boundary condition/headwater in the QUAL2K model. As noted in Table 2.2, no data sonde was deployed at MilC-02 to record continuous DO during the September 1st-2nd synoptic survey. Instead, only individual field DO measurements were made in the middle of the afternoon on both days using a hand-held data sonde. However, continuous data sondes were deployed at MilC-02, MilC-03 and in the Unnamed Tributary from August 24th-30th, 2010 as part of the North Fork Crow River Watershed Phase II monitoring plan. Results from this sampling event indicate average daily dissolved oxygen leaving Deer Lake (MilC-02) was approximately 25% higher than the average daily dissolved oxygen recorded at MilC-03. Thus, headwater dissolved oxygen in the QUAL2K model was set 25% higher than the average daily DO recorded on September 1st at MilC-03.

2.4 Carbonaceous Biochemical Oxygen Demand (CBOD)

The old EPA model (QUAL2E) version had one type of CBOD with one decay rate. The modernized version (QUAL2K) now includes two forms of CBOD to represent organic carbon; a slowly oxidizing form (slow CBOD) and a rapidly oxidizing form (fast CBOD). This allows the model to decay CBOD at two decay rates, if deemed necessary. This model enhancement is great for waste streams with organic carbons in the form of sugar, glucose, etc.. Both 5-day CBOD ($CBOD_5$) and ultimate CBOD ($CBOD_u$) were collected at each monitoring station during the synoptic survey. $CBOD_u$ measurements were used to represent the breakdown of organic carbon over $CBOD_5$ in the model since this measurement more accurately represents total potential carbonaceous oxygen demand.

3.0 HYDRAULIC CALIBRATION

Modeled hydraulic inputs were derived from flow gauging data collected during the September 1st-2nd 2009 synoptic survey. Total discharge was calibrated first before calibrating travel time. All hydraulic inputs and calibration adjustments are described in the following sections.

3.1 Hydraulic Rating Curves

QUAL2K hydraulics may be modeled using power function rating curves, weirs (dam/drop structures) or Manning's equations. Hydraulics for all Mill Creek reaches were represented using power function rating curves based on flow gauging data collected during the synoptic survey. The power function option relates mean velocity and depth to flow in each reach. QUAL2K uses five coefficients to define reach hydraulics, as follows:

- Velocity (mps) = $a\,Q^b$
- Depth (m) = $c\,Q^d + e$

in which Q is flow in cubic meters per second. Depth and velocity rating curves were constructed using gauged flow data from the time of travel study. Gauging stations with similar channel dimensions and flow characteristics were combined in to one rating curve to provide more robust velocity/depth versus flow relationships (Figures 3.1 - 3.2). Applying the principals of hydraulic geometry (Leopold and Maddock, 1953), there is one additional power function that defines channel width:

- Width (m) = $f\,Q^g$

Because the width, depth and velocity are a function of discharge, the following rules apply to the coefficients and exponents of these power functions. The sum of the exponents equal one ($b + d + g = 1.0$), and the product of the coefficients equal one ($a \times c \times f = 1.0$). The representative hydraulic rating curves for each reach was selected based on proximity to gauging stations and typical channel dimensions throughout the reach. The hydraulic coefficients and exponents for each QUAL2K reach are summarized in Table 3.1.

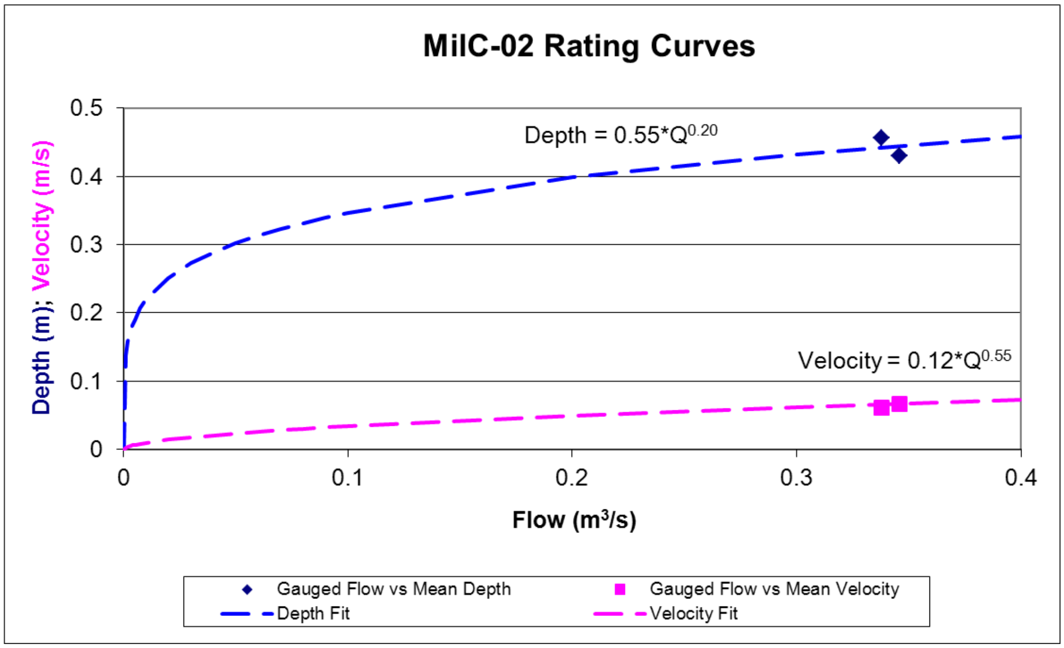

Figure 3.1 Hydraulic rating curve plot for gauging station MilC-02.

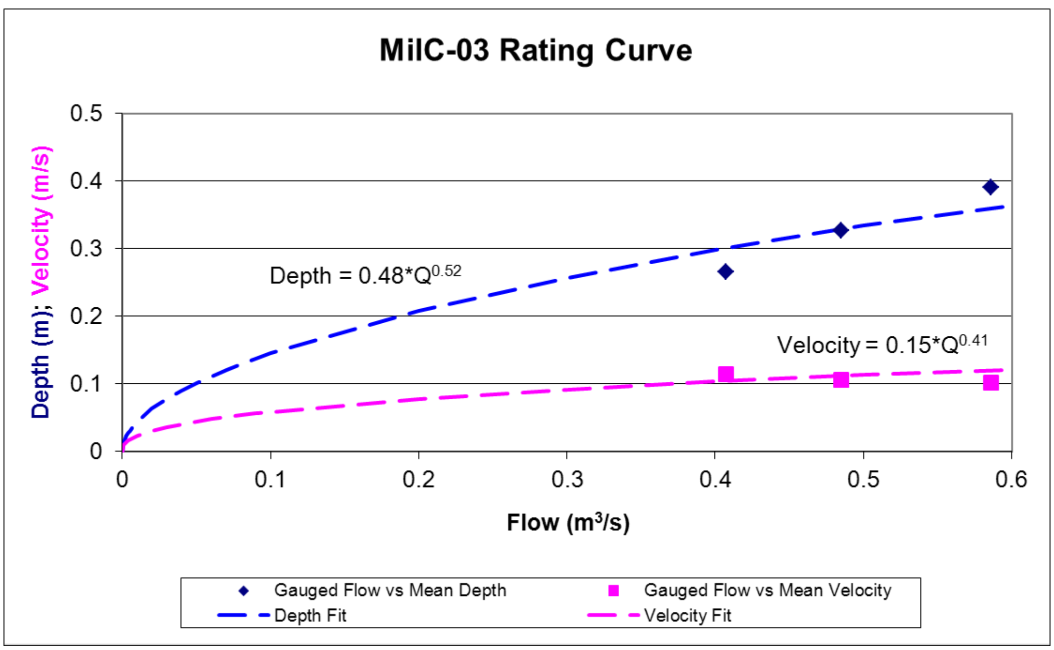

Figure 3.2 Hydraulic rating curve plot for gauging station MilC-03.

Table 3.1 Summary of hydraulic coefficients and exponents assigned to each reach.

Reach	Rating Curve used	Velocity		Depth		Adjustments
		Coeff.	Exp.	Coeff.	Exp.	
1	MilC-03	0.07	0.41	0.48	0.52	Decreased velocity coefficient to match travel time
2	MilC-03	0.15	0.41	0.48	0.52	None
3	MilC-03	0.15	0.41	0.48	0.52	None
4	MilC-03	0.15	0.41	0.48	0.52	None

3.2 Flow Calibration

Mill Creek tributaries were not accessible to measure flow and water quality during the synoptic survey and dye study. It was assumed all flow increases between the MilC-02 and MilC-03 monitoring stations were from the Unnamed Tributary that drains the western portion of the Mill Creek watershed and dischargers to Mill Creek at river kilometer 3.10. This tributary was built in to the model as a tributary point source inflow. Tributary flow was set to 0.10 m^3/s (3.67 cfs) to match modeled flow and observed flow during the September 1st-2nd synoptic survey (Figure 3.3).

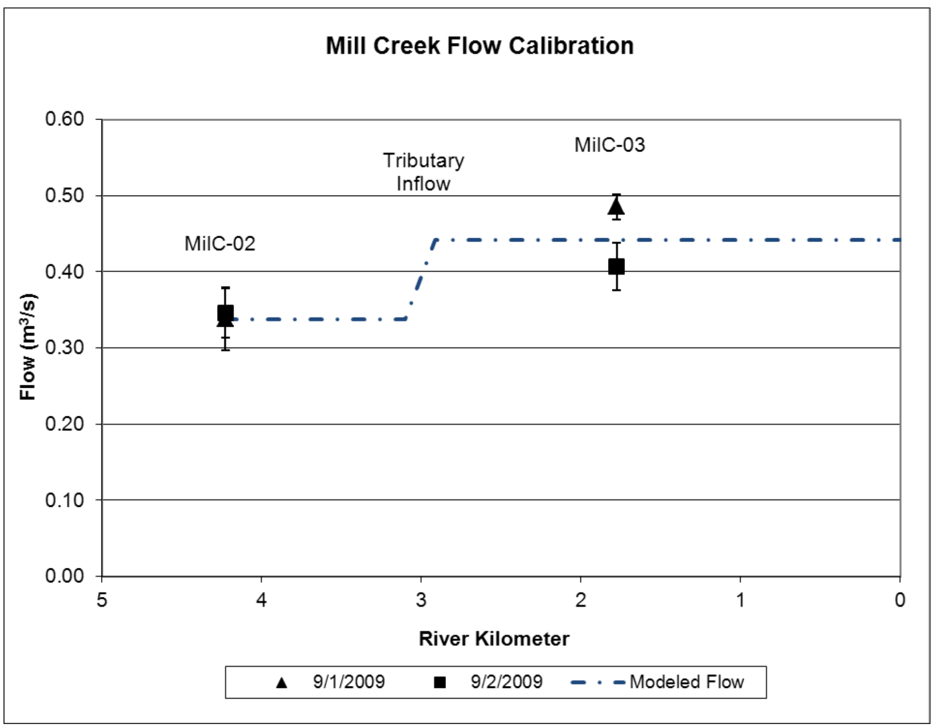

Figure 3.3 Final Mill Creek flow calibration with tributary inflow.

3.3 Time of Travel Calibration

With total flow calibrated, the rating curve coefficient reach 1 had to be adjusted slightly to lower velocity to meet time of travel measurements (Table 3.1). With total flow calibrated and the necessary hydraulic adjustments made, model predicted travel times for each reach were close to observed travel times (Figure 3.4).

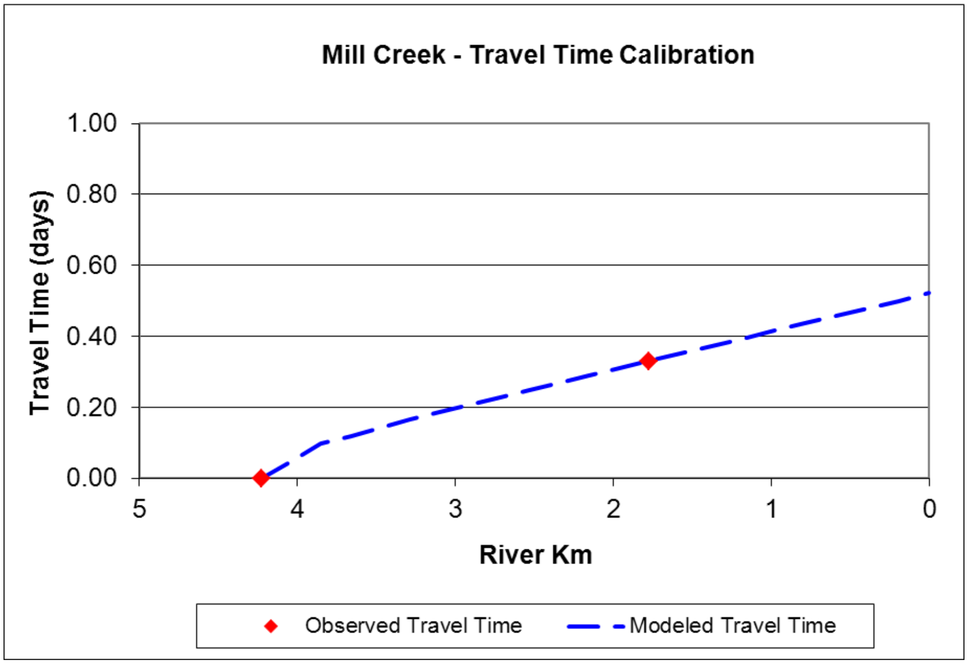

Figure 3.4 Mill Creek travel time calibration.

4.0 WATER QUALITY CALIBRATION

All water quality model inputs were derived from data collected during the September 1-2, 2009 synoptic survey. Tributary parameters were estimated based on literature values and calibration to in-stream water quality data. The QUAL2K model was set up to simulate temperature, flow, velocity, depth, organic nitrogen (ON), ammonia nitrogen (NH_3-N), nitrate/nitrite nitrogen (NO_2/ NO_3-N), $CBOD_u$, dissolved oxygen (DO), sediment oxygen demand (SOD), total phosphorus (TP) and chlorophyll-*a*. All model changes to global and reach specific kinetic rates as well as point source, diffuse and in-stream loadings are discussed in this section.

4.1 General Kinetic Rates

Eight model settings and kinetic rates were adjusted from model default values in order to meet longitudinal changes in observed water quality data. All kinetic rates were adjusted within the range of published values (Table 4.1).

Table 4.1 QUAL2K kinetic rates adjusted from model default values.

Rate	Calibrated Rate	Default Rate	Literature Range	Citation/Study Area
Reaeration Model	Tsivoglou and Neal	User Specified	Thomann and Mueller, 1987 cite that Tsivoglou and Neal, 1976; best for small, shallow streams (1-15 cfs)	
$CBOD_u$ oxidation rate (day^{-1})	0.30	0.23	0.02 – 0.60	Bowie et al., 1985 Table 3-17 p152 Kansas (6 rivers) Michigan (3 rivers) reported by Bansal, 1975
Organic-N Hydrolysis (day^{-1}) *The release of ammonia due to decay of organic nitrogen*	<0.01	0.20	0.1 – 0.4	Baca et al., 1973 Ammonia levels do not indicate significant Organic-N hydrolysis
Organic-N Settling Velocity (m/d)	0.01		influenced by a material's size, shape, and density and the speed of water	
Organic-P Hydrolosis (day^{-1}) *The release of phosphate due to decay of organic phosphorus*	0.05	0.20	0.10 – 0.70	Baca et al., 1973 Baca and Arnett, 1976
Organic-P Settling Velocity (m/d)	0.2		influenced by a material's size, shape, and density and the speed of water	
Inorganic-P settling (m/d)	0.25	2.0	influenced by a material's size, shape, and density and the speed of water	
Phytoplankton Settling (m/d)	0.1	0.50	0 – 2	Bowie et al., 1985 Table 6-19 p352 Chen & Orlob, 1975 and Smith, 1978

4.2 Tributary Inflow Water Quality

Initially, all flow increases were set to headwater water quality conditions and then adjusted upward or downward to meet in-stream water quality at MilC-03 (Table 4.2). Nitrogen and phytoplankton parameters were set lower than the Deer Lake headwater conditions while organic and inorganic phosphorus were higher. This suggests the Unnamed Tributary flowing to Mill Creek is not heavily influenced by lake discharge and displays similar water quality conditions to other small streams in the North Fork Crow River watershed.

Table 4.2 Modeled diffuse source parameters for Mill Creek.

Parameter	Reaches 1-4	Justification
Temp (C)	23	Calibrated adjustment to in-stream conditions
Sp. Cond (umhos)	516	Calibrated adjustment to in-stream conditions
DO	9.24	Calibrated adjustment to in-stream conditions
Organic- N (µg/L)	1000	Calibrated adjustment to in-stream conditions
Nitrate (µg/L)	<5	Calibrated adjustment to in-stream conditions
Organic-P (µg/L)	120	Calibrated adjustment to in-stream conditions
Inorganic-P (µg/L)	50	Calibrated adjustment to in-stream conditions
$CBOD_u$ (mg O_2/L)	5	Calibrated adjustment to in-stream conditions
Phytoplankton (µg-A/L)	5	Calibrated adjustment to in-stream conditions

4.3 Final Water Quality Calibration

$CBOD_u$, chlorophyll-*a* and all forms of nitrogen and phosphorus were calibrated once diffuse source water quality parameters and kinetic rates were properly incorporated into the model. The model performed well in predicting loads and concentrations of the primary water quality parameters that affect dissolved oxygen.

5.0 DISSOLVED OXYGEN CALIBRATION

5.1 Diurnal Oxygen Calibration

Even though water column algae was accurately depicted during water quality calibration, initial model runs predicted significantly smaller diurnal DO variability than was observed in the field. This suggests there was in-situ primary production that was not accounted for or under-represented in these model runs. QUAL2K has a bottom algae component that can simulate photosynthesis and nutrient uptake of any non-suspended algae. Bottom algae channel coverage was adjusted by reach in order to increase primary production and match the photosynthesis/respiration swings in the observed continuous DO data (Table 5.1). It is assumed that this bottom algae component represents all elements of primary production (attached algae, submerged macrophytes, rooted aquatic vegetation) that could not be measured or quantified in the field.

5.2 Sediment Oxygen Demand

Sediment oxygen demand (SOD) is calculated in QUAL2K based on the delivery and breakdown of particulate organic matter from the water column. Currently, the model does not have a macrophyte or riparian vegetation SOD component, nor does it incorporate any upland sediment transported and deposited during non-steady state storms events. The model does allow the user to assign SOD coverage (% of channel bottom) for each reach and also prescribe SOD that is added to the model predicted rate to account for SOD outside the modeling framework. SOD in streams varies depending on sediment type but is typically between 0.05 (mineral soils) and 2.00 (estuarine mud) g O_2/m^2/day (Thomann and Mueller, 1987). Mill Creek is a typical agricultural stream that has been ditched, straightened and/or widened in some areas. As a result, the stream is relatively deep and slow moving during baseflow conditions. There appeared to be minimal settling/deposition during the low-flow synoptic survey as the channel sediments throughout the system were composed of a mixture of larger rocks and soft, fine-grained particles.

Dissolved oxygen concentrations should be close to calibration as long as reasonable assumptions were made in allocating nutrient loads and adjusting kinetic rates. Model predicted dissolved oxygen concentrations for the hydraulic/phytoplankton/bottom algae/nutrient calibrated model were slightly lower than observed throughout Mill Creek. Thus, SOD bottom coverage was decreased in each reach to increase DO concentrations to match observed values (Table 5.1).

Table 5.1 Reach specific SOD and bottom algae coverage.

Reach	Bottom SOD coverage (%)	Bottom Algae Coverage (%)	Description
1	10	100	Over-widened channel, mixture of mud and hard bottom substrate, moderate rooted riparian vegetation
2	10	100	Over-widened channel, mixture of mud and hard bottom substrate, moderate rooted riparian vegetation
3	10	100	Over-widened channel, mixture of mud and hard bottom substrate, moderate rooted riparian vegetation
4	10	100	Over-widened channel, mixture of mud and hard bottom substrate, moderate rooted riparian vegetation

5.3 Final Dissolved Oxygen Calibration

Figure 5.1 shows the final calibration results for model-predicted and observed dissolved oxygen concentrations. Field DO grabs were collected on September 1st and 2nd using the hand-held YSI and are labeled with the time of sample collection, if available. Also shown are continuous dissolved oxygen measurements during the synoptic survey (shown in plots as the range of data between minimum and maximum as orange and blue “I”). The average of the continuous DO is marked on the plot with an orange or blue box dependant on the day.

The model performs well in predicting the average daily dissolved oxygen concentration (in plot as black dashed line) at the MilC-03 monitoring station with continuous DO measurements. The model also performs relatively well in predicting diurnal DO (daily minimum and maximum, shown in plots as blue dashed lines).

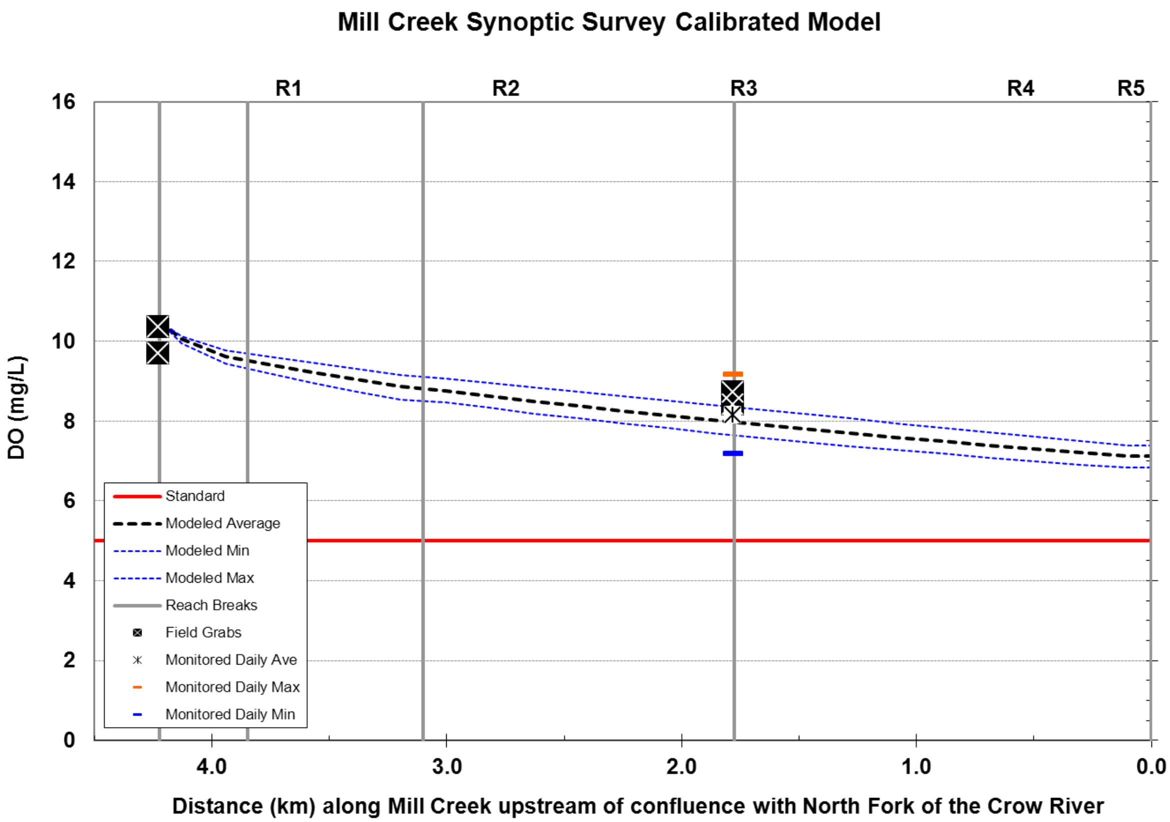

Figure 5.1 Mill Creek calibrated dissolved oxygen longitudinal profile.

6.0 AUGUST 3RD 2009 LOW-FLOW MODEL SIMULATION

There were no dissolved oxygen violations recorded throughout Mill Creek during the September 1st-2nd 2009 synoptic survey. In order to analyze low-flow DO violations in the system, the synoptic survey calibrated model was used to simulate a different summer low-flow event when DO violations were recorded. Continuous DO monitoring in 2009 indicated minimum DO at the MilC-03 monitoring station dropped well below the 5.0 mg/L DO standard during low-flow conditions on August 3rd (Figure 2.4 in the Mill Creek Historic Data and Synoptic Survey Methods and Results Memo). Average daily flow at MilC-03 on August 3rd, 2009 was 0.03 m^3/s (1.02 cfs) or approximately 93% less than the flow (15.00 cfs) recorded during the September 1-2, 2009 synoptic survey. Thus, August 3rd model simulation headwater (MilC-02) and Unnamed Tributary inflow were set 93% less than synoptic survey flow conditions. Besides one chlorophyll-a grab sample on 8/11/2009, there was no other summer water quality monitoring in Mill Creek in 2009. As a result, headwater and tributary water quality conditions for the August 3rd simulation were initially set equal to September 1st-2nd synoptic survey measurements and then adjusted upward or downward during DO model calibration.

Table 6.1 September 1-2nd synoptic survey and August 3rd low-flow simulation QUAL2K headwater and tributary water quality inputs/adjustments.

Parameter	Date	Headwater	Justification	Unnamed Tributary	Justification
DO	9/1/2009	10.50 (ave)	[1] Simulated	9.24 (ave)	[1] Simulated
(mg/L)	8/3/2009	24.66 (ave)	[2] Simulated	23.95 (ave)	[2] Simulated
CBODu	9/1/2009	17.90	Measured	5.00	[3] Adjustment
(mg/L)	8/3/2009	11.00	[4] Adjustment	5.00	[3] Adjustement
Organic Nitrogen	9/1/2009	1570	Measured	1000	[3] Adjustment
(µg/L)	8/3/2009	1570	No change	1000	[3] Adjustement
Ammonia	9/1/2009	0	Measured	0	[3] Adjustrment
(µg/L)	8/3/2009	5	[4] Adjustment	5	[4] Adjustment
Organic-P	9/1/2009	15	Measured	120	[3] Adjustment
(µg/L)	8/3/2009	58	[5] Estimated	120	[3] Adjustment
Inorganic-P	9/1/2009	14	Measured	50	[3] Adjustment
(µg/L)	8/3/2009	14	No change	50	[3] Adjustment
Phytoplankton	9/1/2009	43	Measured	5	[3] Adjustment
(µg-A/L)	8/3/2009	60	[5] Estimated	30	[4] Adjustement

[1] Simulated using continuous YSI measurements at MilC-03 on 9/1/2009. Value was estimated using relationships from continuous YSI data collected at MilC-03, MilC-02 on August 24th-30th, 2010.
[2] Simulated using continuous YSI measurements at MilC-03 on 8/3/2009. Value was estimated using relationships from continuous YSI data collected at MilC-03, MilC-02 on August 24th-30th, 2010.
[3] Calibration adjustment to meet in-stream water quality conditions on 9/1/2009.
[4] Calibration adjustment to meet in-stream continuous DO measurements at MilC-03 on 8/3/2009.
[5] Estimated value based on Mill Creek water quality sampling on 8/11/2009.

Figure 6.1 compares model predicted DO for the August 3rd low-flow QUAL2K model simulation to observed conditions at the MilC-03 monitoring station. The model performs reasonably well in predicting the average daily dissolved oxygen concentration and diurnal DO patterns

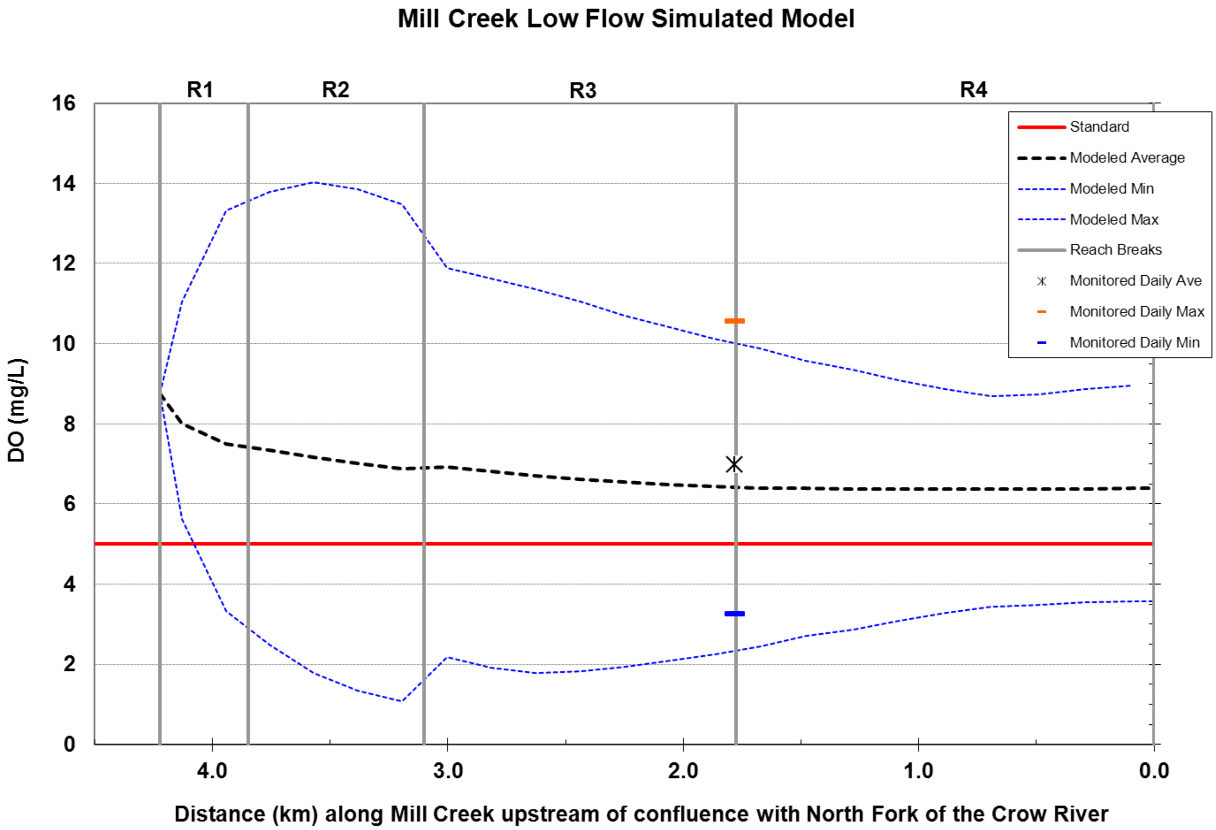

Figure 6.1 Mill Creek August 3rd low-flow model simulation dissolved oxygen longitudinal profile.

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TECHNICAL MEMORANDUM

TO: Diane Sander, Crow River Organization of Water Watershed Coordinator

CC: Maggie Leach, MPCA Regional Impaired Waters Coordinator

FROM: Joe Bischoff, Project Manager
Pamela Massaro, P.E.
Jeff Strom

DATE: September, 2011

SUBJECT: Regal Creek Dissolved Oxygen TMDL
Description of QUAL2K Modeling Methods and Results

Wenck Associates, Inc. has developed and calibrated a QUAL2K model for Regal Creek from County State Aide Highway 35 in St. Michael, MN to the Creek's confluence with the main-stem of the North Fork Crow River. The purpose of this technical memorandum is to describe the methods and assumptions used to create and calibrate the QUAL2K model.

1.0 INTRODUCTION

1.1 Model Selection

The U.S. EPA River and Stream Water Quality Model (QUAL2K) version 7 is a modernized version of the QUAL2E model developed by Dr. Steven Chapra with Tufts University and Greg Pelletier with Washington State. It was selected to analyze Regal Creek because it is a relatively simple surface water quality model that can be used during steady-state conditions to model nutrient, algal and dissolved oxygen dynamics.

1.2 General Overview of the Model

The model was built using late summer synoptic survey data collected on August 26-27, 2009. Stream locations and physical features were built in to the model first before proceeding to hydraulic calibration. With the diffuse flow inputs incorporated, the conservative water quality parameters (such as water temperature and conductivity) were adjusted to match monitored observations. Then, chlorophyll-*a* (phytoplankton production), nutrients (phosphorus and nitrogen components), and 5-day carbonaceous biological oxygen demand ($CBOD_5$) were calibrated by adjusting tributary/groundwater contributions and/or kinetic coefficients within the range of published values. In some cases, reach specific kinetic rates and in-stream nutrient fluxes were assigned to model geochemical processes believed to be unique to certain reaches. Finally, bottom algae and sediment oxygen demand were adjusted for each reach to match observed dissolved oxygen data.

2.0 MODEL SETUP AND INPUTS

The QUAL2K model covers the main stem of Regal Creek from where it crosses CSAH-35 in St. Michael, MN to its confluence with North Fork Crow River. This stretch of Regal Creek, explicitly modeled, represents approximately 2.14 miles (3.45 km) as three individual reaches. The start of each reach correlates with a monitoring station location (Figure 2.1, Table 2.1 and Table 2.2).

Table 2.1 Model reach characteristics.

Reach	Description	Upstream River km	Downstream River km	Distance (km)	Distance (miles)	Slope (m/m)
1	CSAH 35 (RC-01) to CSAH 19 (RC-02)	3.45	2.15	1.30	0.81	0.004
2	CSAH 19 (RC-02) to Meadowlark Rd (RC-03)	2.15	1.15	1.00	0.62	0.005
3	Meadowlark Rd (RC-03) to North Fork Crow	1.15	0.00	1.15	0.71	0.007

Table 2.2 Monitoring locations.

Reach	Reach Start Monitoring Location ID	Description	Data Collected
1	RC-01	Regal Creek at CSAH 35 Crossing	Q, Grab, BOD, Field
2	RC-02	Regal Creek at CSAH 19 Crossing	Q, BOD, Field, ToT, DO
3	RC-03	Regal Creek at Meadowlark Rd	Q, Grab, BOD, Field, ToT

Q = Flow gauged.
ToT = Time of Travel determined from dye study.
Grab = Water quality grab sample collected and lab analyzed for typical pollutants (total kjeldahl nitrogen (TKN), ammonia nitrogen (NH_3-N), nitrate nitrogen (NO_2-N), 5-day and ultimate carbonaceous biological oxygen demand ($CBOD_{5\text{-}day}$ & $CBOD_u$), total phosphorus (TP), ortho-phosphorus (soluble reactive phosphorus), total organic carbon (TOC), and chlorophyll-*a*).
BOD = Water quality grab sample collected and lab analyzed for $CBOD_{5\text{-}day}$ & $CBOD_u$.
Field = In-field measurement of temperature, conductivity, pH, and dissolved oxygen (DO).
DO = Data sondes deployed to collect continuous measurements of dissolved oxygen, temperature, pH and conductivity.

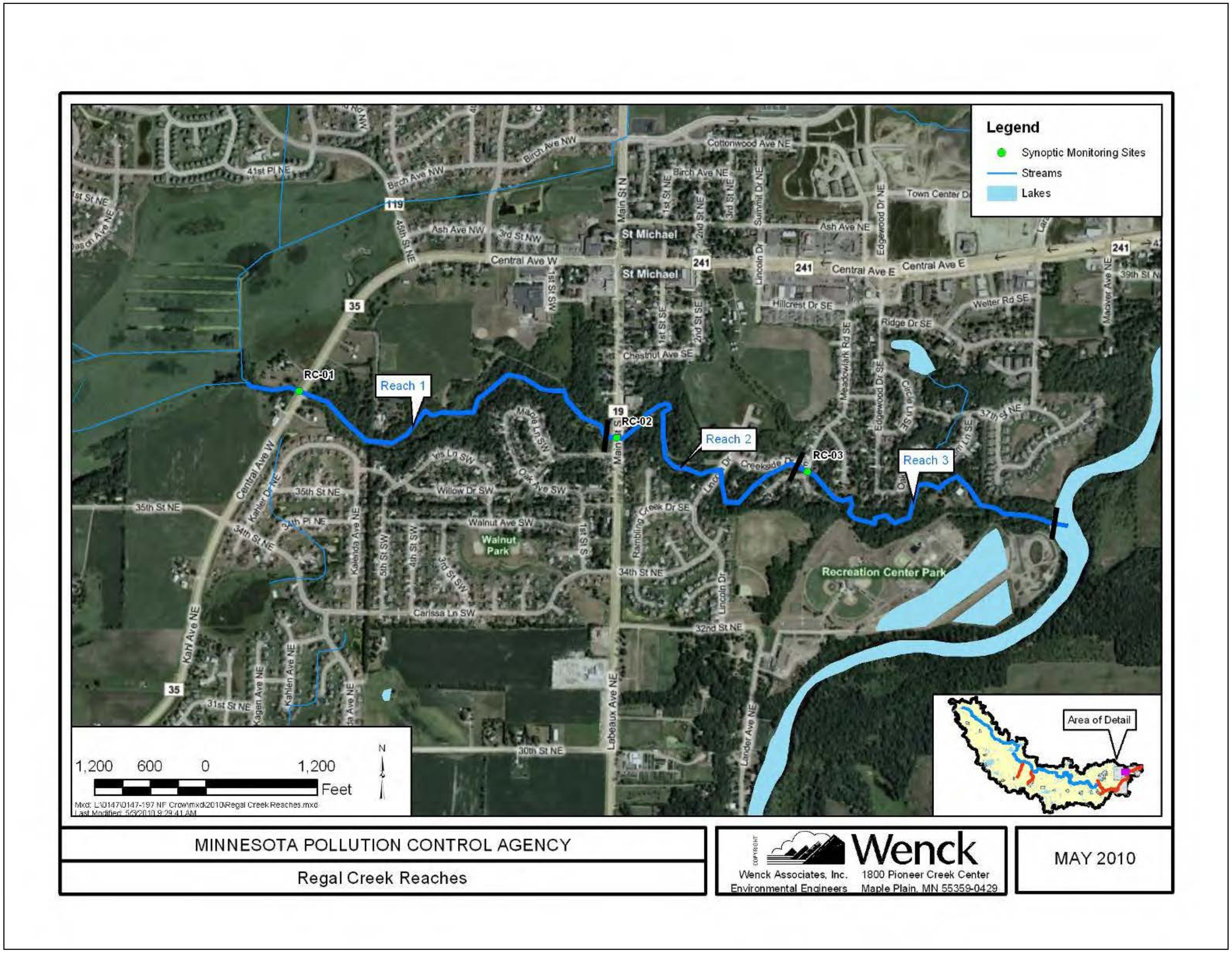

Figure 2.1 Monitoring stations and reaches on Regal Creek

2.1 Weather and Physical Processes

Hourly weather measurements of temperature, cloud conditions, relative humidity and wind speed were downloaded from the National Weather Service (NWS) NOAA Minneapolis-St. Paul Airport. Stream canopy coverage and shading was set to 75 percent for all reaches based on field observations and GIS air photos.

2.2 Headwaters

The Minnesota Department of Natural Resources (DNR) stream file shows Regal Creek headwaters to be located at the wetland upstream of CSAH-35 in St. Michael, MN. During the synoptic survey, flow was gauged downstream of the CSAH-35 (RC-01) culvert and deemed suitable to initiate the dye study and collect water quality samples. All flow and water quality data collected at the RC-01 station on August 26-27 was used to represent the upstream boundary condition/headwater for the Regal Creek QUAL2K model. As noted in Table 2.2, a data sonde was not deployed at the RC-01 station. Field dissolved oxygen measurements collected at this station in the late-morning/early-afternoon were extremely low (<1.0 mg/L). It is assumed there was virtually no diurnal DO swing at this site since these measurements were collected when photosynthesis is highest and DO should be closer to daily maximums. Thus, the DO, temperature, pH and conductivity measured in the field on 8/26/09 were used to represent model headwater conditions.

2.3 Carbonaceous Biochemical Oxygen Demand (CBOD)

The old EPA model (QUAL2E) version had one type of CBOD with one decay rate. The modernized version (QUAL2K) now includes two forms of CBOD to represent organic carbon; a slowly oxidizing form (slow CBOD) and a rapidly oxidizing form (fast CBOD). This allows the model to decay CBOD at two decay rates, if deemed necessary. This model enhancement is great for waste streams with organic carbons in the form of sugar, glucose, etc.. Both 5-day CBOD ($CBOD_5$) and ultimate CBOD ($CBOD_u$)were collected at each monitoring station during the synoptic survey. $CBOD_u$ measurements were used so that all potential carbonaceous oxygen consumption is represented in the model.

3.0 HYDRAULIC CALIBRATION

Modeled hydraulic inputs were derived from the flow gauging data collected during the August 26th and 27th synoptic survey. Total discharge was calibrated prior to calibrating travel time. All hydraulic inputs and calibration adjustments are described in the following sections.

3.1 Hydraulic Rating Curves

QUAL2K hydraulics may be modeled using power function rating curves, weirs (dam/drop structures) or Manning's equations. Hydraulics for all Regal Creek reaches were represented using power function rating curves based on flow gauging data collected during the synoptic survey. The rating curve option relates mean velocity and depth to flow in each reach. QUAL2K uses five coefficients to define reach hydraulics, as follows:

- Velocity (m/sec) = a Q^b
- Depth (m) = c Q^d + e

in which Q is flow in cubic meters per second. Depth and velocity rating curves were constructed using gauged flow data from the time of travel study. Gauging stations with similar channel dimensions and flow characteristics were combined in to one rating curve to provide more robust velocity/depth versus flow relationships (Figures 3.1 - 3.3). Applying the principals of hydraulic geometry (Leopold and Maddock, 1953), there is one additional power function that defines width:

- Width (m) = f Q^g

Because the width, depth and velocity are a function of discharge, the following rules apply to the coefficients and exponents of these power functions. The sum of the exponents equal one ($b + d + g = 1.0$), and the product of the coefficients equal one ($a \times c \times f = 1.0$). The representative hydraulic rating curves for each reach were selected based on proximity to gauging stations and typical channel dimensions throughout the reach. The hydraulic coefficients and exponents for each QUAL2K reach are summarized in Table 3.1 along with adjustments made during calibration.

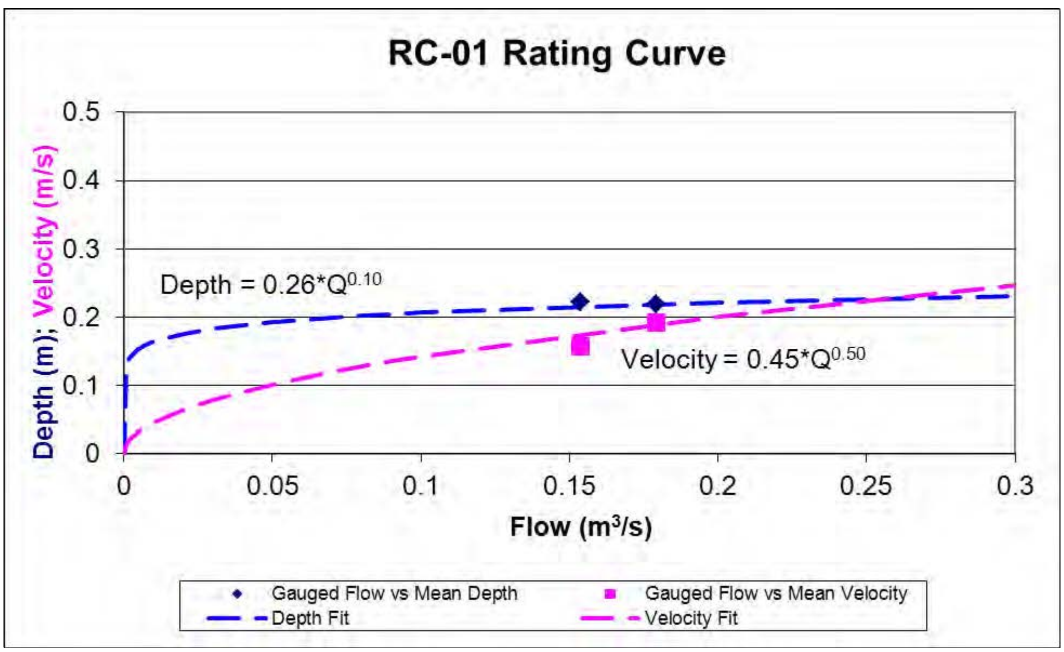

Figure 3.1 Hydraulic rating curve plot for gauging station RC-01.

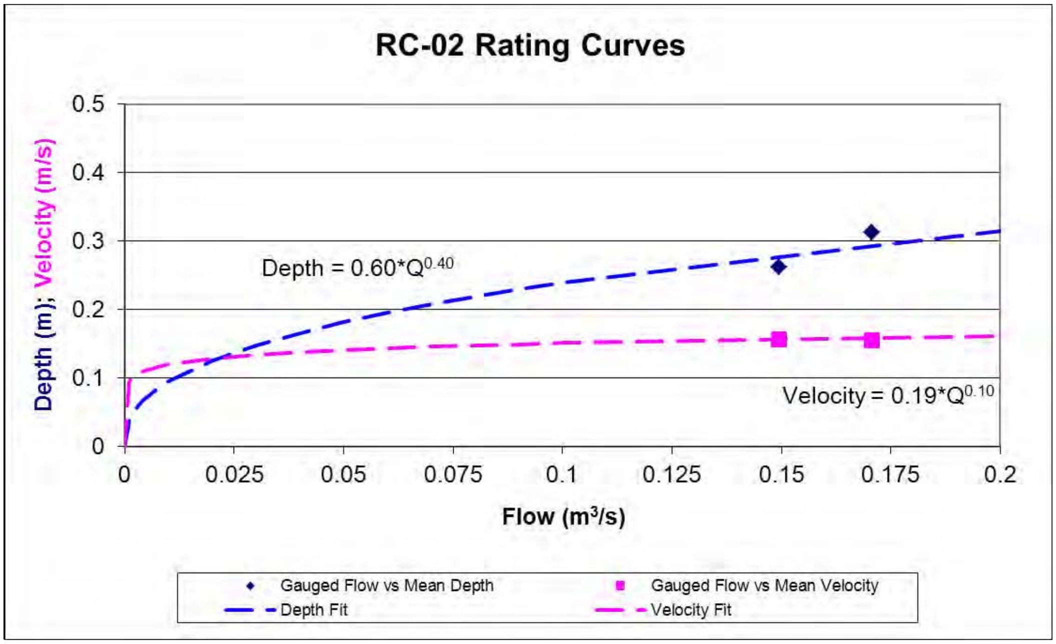

Figure 3.2 Hydraulic rating curve plot for gauging station RC-02.

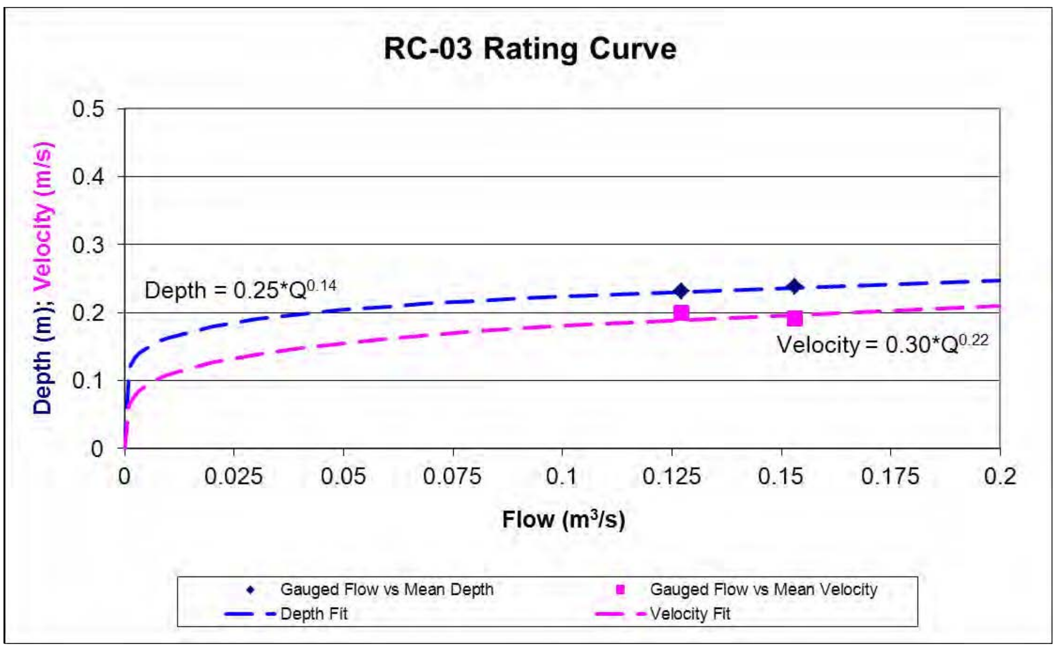

Figure 3.3 Hydraulic rating curve plot for gauging station RC-03.

Table 3.1 Summary of the hydraulic coefficients and exponents assigned to each reach.

Reach	Rating Curve Used	Velocity		Depth		Adjustments
		Coeff.	Exp.	Coeff.	Exp.	
1	RC-02	0.19	0.10	0.60	0.40	
2	RC-03	0.40$^{\Delta}$	0.22	0.25	0.14	Velocity coefficient increased to match travel time measurements
3	RC-03	0.40$^{\Delta}$	0.22	0.25	0.14	Velocity coefficient increased to match travel time measurements

* denotes that the monitoring station is at the upstream end of the reach.

$^{\Delta}$ denotes a change in the hydraulic coefficients or exponent.

3.2 Flow Calibration

Regal Creek tributaries and inflows were not accessible to determine if they were contributing flow during the synoptic survey and dye study. Thus, monitored changes in flow between gauging stations were built in to the model as diffuse inflows or abstractions. All diffuse sources are described in Table 3.2. Flow gauging data suggests Regal Creek was a losing stream between RC-01 and RC-03 during the August synoptic survey (Figure 3.4).

Table 3.2 Modeled diffuse source inflow/abstractions for Regal Creek

Reach	Total flow throughout reach (m^3/s)*	Flow Rate (m^3 per River kilometer)*
Reach 1 (RC-01 to RC-02)	-0.008*	-0.006*
Reach 2 (RC-02 to RC-03)	-0.023*	-0.023*

* denotes that negative flow values are abstractions (outflows), while positive flow values are inflows.

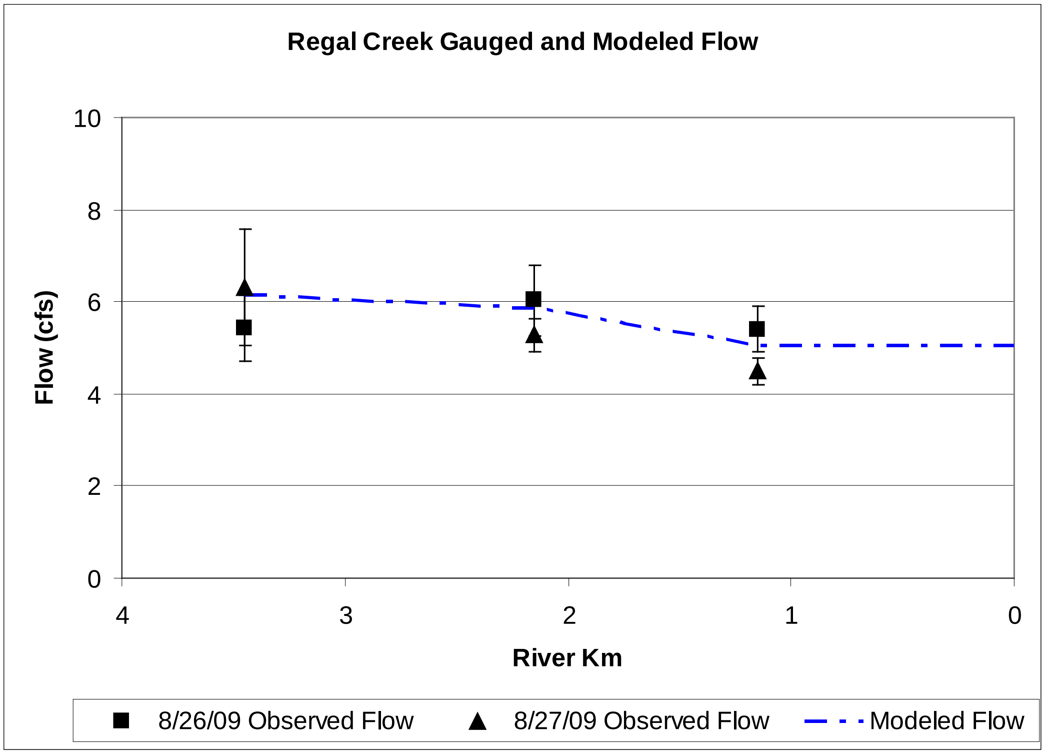

Figure 3.4 Final Regal Creek Flow calibration with diffuse inflows/abstractions. Error bars on observed measurements represent estimated uncertainty of the Flow-Tracker field measurement.

3.3 Time of Travel Calibration

With total flow calibrated, rating curve coefficients and exponents were adjusted to meet travel times calculated during the dye study portion of the synoptic survey. Reaches 2 and 3 (RC-03 rating curve) were the only reaches where travel time did not match observed using the assigned gauging station rating curves. Observed travel times support adjusting RC-03's hydraulic velocity coefficient to represent faster velocities for reaches 2 and 3 than were measured at the downstream station. This adjustment effectively matched model and observed travel time (Figure 3.5).

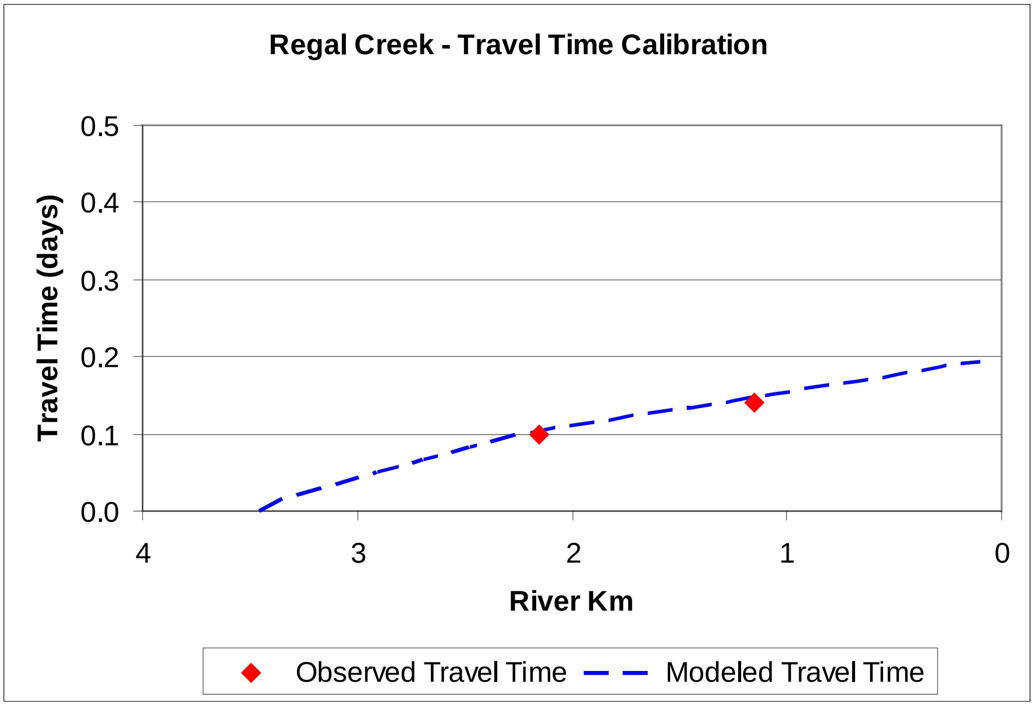

Figure 3.5 Regal Creek time of travel calibration.

4.0 WATER QUALITY CALIBRATION

All water quality model inputs were derived from data collected during the August 26-27, 2009 synoptic survey. The QUAL2K model was set up to simulate temperature, flow, velocity, depth, organic nitrogen (ON), ammonia nitrogen (NH_3-N), nitrate/nitrite nitrogen (NO_2/ NO_3-N), $CBOD_u$, DO, sediment oxygen demand (SOD), total phosphorus (TP), chlorophyll-*a*. All model changes to global and reach specific kinetic rates to calibrate water quality are discussed in this section.

4.1 Reaeration Formula

Reaeration in QUAL2K may be prescribed by the user or calculated using one of eight hydraulic-based reaeration formulas built into the model. The O'Connor-Dobbins reaeration model was selected for Regal Creek because it is the most appropriate to calculate reaeration when stream velocity is 0.5 - 1.6 feet per second (O'Connor and Dobbins, 1958). Regal Creek velocities were 0.5 – 0.6 feet per second during the August 26-27 synoptic survey. The O'Connor-Dobbins reaeration model formula is shown below:

$K_{ah}(20) = 3.93(U^{0.5}/H^{1.5})$

Where:
K_a = reaeration rate coefficient at 20°C (base e, day $^{-1}$)

U = mean water velocity (m/s)
H = mean water depth (m)

Flow velocity and water depth are the variables used to calculate reaeration in each reach. These variables were measured in the field at each monitoring station during flow gauging and represented in the model using hydraulic rating curves (Section 3.1).

4.2 General Kinetic Rates

Seven kinetic rates were adjusted from model default values in order to meet longitudinal changes in observed water quality data. All kinetic rates were adjusted within the range of published values (Table 4.1).

Table 4.1 QUAL2K kinetic rates adjusted from model default values.

Rate	Calibrated Rate	Default Rate	Literature Range	Citation/Study Area
Reaeration Model	O'Connor-Dobbins	User Specified	Most appropriate for stream velocities 0.5 to 1.5 feet per second (O'Connor and Dobbins, 1958)	
$CBOD_u$ oxidation rate (day^{-1})	0.3	0.23	0.02 – 0.60 0.56 – 3.37	Bowie et al., 1985 Table 3-17 p152 Kansas (6 rivers) Michigan (3 rivers) reported by Bansal, 1975
Organic-N Settling Velocity (m/d)	1.0	0.10	influenced by a material's size, shape, and density and the speed of water	
Ammonium Nitrification (day^{-1})	4	1	0.5 – 9.0 3.1 – 6.2	Koltz, 1982 Wezernak et al., 1968
Organic-P Settling Velocity (m/d)	1.0	0.10	influenced by a material's size, shape, and density and the speed of water	
Inorganic-P settling (m/d)	1.0	2.0	influenced by a material's size, shape, and density and the speed of water	

4.3 Final Water Quality Calibration

$CBOD_{ultimate}$, chlorophyll-*a* and all forms of nitrogen and phosphorus were calibrated once global and reach specific kinetic rates were properly adjusted. The model performed well in predicting loads and concentrations of the primary water quality parameters that affect dissolved oxygen.

5.0 DISSOLVED OXYGEN CALIBRATION

5.1 Diurnal Oxygen Calibration

Continuous DO data recorded at RC-02 suggest DO varied no more than 0.3 mg/L between daily minimum and maximum during the August 26 and 27 synoptic survey. Once water column algae was accurately predicted in the model (Figure 4.4), no additional model adjustments were needed to calibrate diurnal DO (Figure 5.1). This implies non-suspended photosynthesis (attached algae, submerged macrophytes, rooted aquatic vegetation) does not play a significant role in the DO dynamics of Regal Creek under these flow conditions.

5.2 Sediment Oxygen Demand

Sediment oxygen demand (SOD) is calculated in QUAL2K based on the delivery and breakdown of particulate organic matter from the water column. Currently, the model does not have a macrophyte or riparian vegetation SOD component, nor does it incorporate any upland sediment transported and deposited during non-steady state storms events. The model does allow the user to assign SOD coverage (% of channel bottom) for each reach and also prescribe SOD that is added to the model predicted rate to account for SOD outside the modeling framework. SOD in streams varies depending on sediment type but is typically between 0.05 (mineral soils) and 2.00 (estuarine mud) g O^2/m^2/day (Thomann and Mueller, 1987). For the most part, Regal Creek sediments appeared to contain very little organic matter as the channel bottom was comprised of large rocks and fine sand.

Dissolved oxygen concentrations should be close to calibration as long as reasonable assumptions were made in allocating nutrient loads and adjusting kinetic rates. Model predicted dissolved oxygen concentrations for the hydraulic/phytoplankton/bottom algae/nutrient calibrated model were slightly lower than observed throughout CD31. Thus, SOD bottom coverage was decreased in each reach to increase DO concentrations to match observed values (Table 5.1).

Table 5.1 SOD prescribed to each reach that is added to model-predicted SOD under steady state conditions.

Reach	Bottom SOD Coverage (%)	Bottom Algae Coverage (%)	Description
1	0	100	Reach displays muddier sediments near wetland headwaters (RC-01) and larger sediment particles moving downstream
2	0	100	Rock and sandy bottom reach with very little organic matter
3	0	100	Rock and sandy bottom reach with very little organic matter

5.3 Final Dissolved Oxygen Calibration

Figure 5.1 shows the final calibration results for model-predicted and observed DO concentrations. Field grabs of dissolved oxygen were taken on August 26 and August 27 using the hand-held YSI. The field grabs are labeled with the sample collection time, if available. Also shown is the continuous dissolved oxygen data recorded during the synoptic survey (shown in plot as the range of data between minimum and maximum as orange and blue "I"). The average of the continuous DO is marked on the plot with an orange or blue box dependant on the day. The model performs well in predicting average daily DO concentrations (in plot as black dashed line) and the diurnal pattern (daily minimum and maximum, shown in plots as blue dashed lines) at the RC-02 monitoring stations with continuous DO measurements.

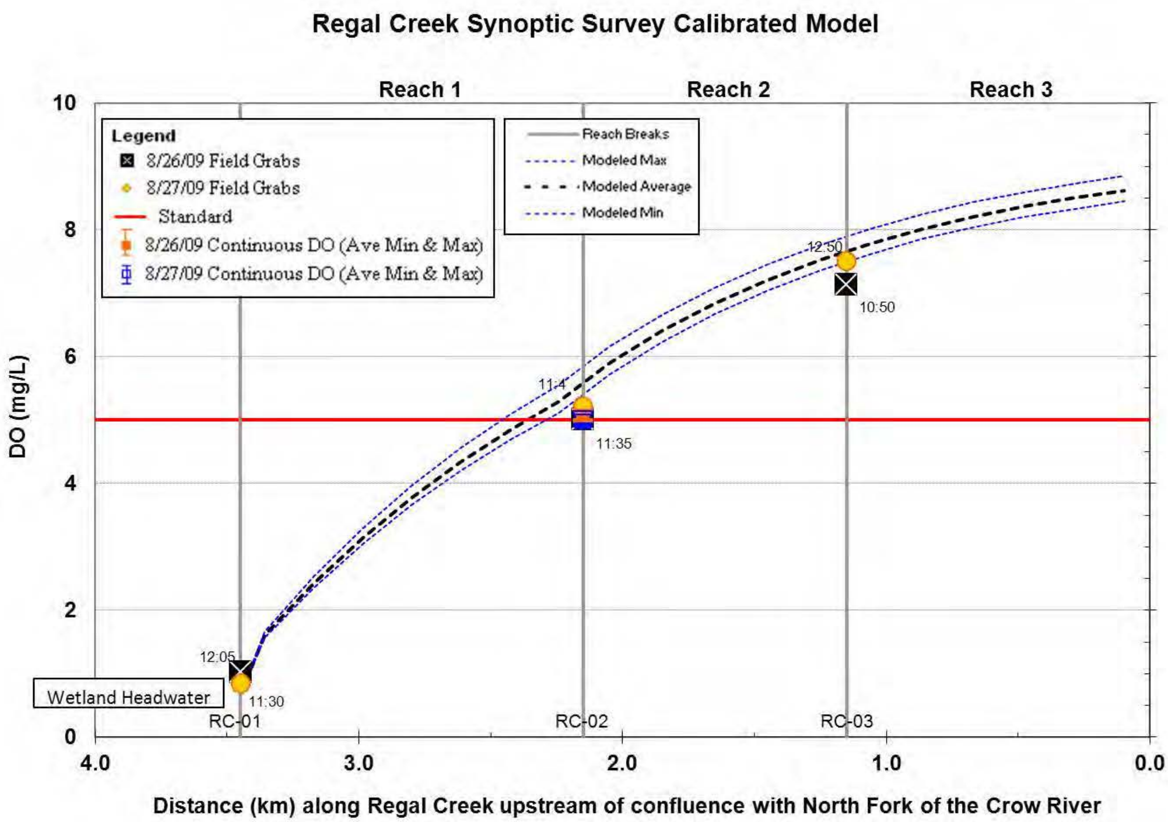

Figure 5.1 Regal Creek calibrated dissolved oxygen longitudinal profile.

6.0 SENSITIVITY ANALYSIS

To evaluate the sensitivity of model predicted DO to changes in model variables, eight kinetic rates (Table 6.1) were removed or adjusted by specific percentages. Table 6.1 summarizes the affect these changes have on the average model-predicted DO concentration for the entire modeled stretch of Regal Creek. Results show DO throughout the system is only slightly sensitive to CBOD oxidation and ammonium nitrification rates. This exercise suggests headwater conditions and stream hydrology play a bigger role than water column processes in dissolved oxygen dynamics under these flow conditions.

Table 6.1 DO sensitivity to kinetic rates.

Kinetic rate	**+25%**	**-25%**	**Default**
$CBOD_u$ oxidation rate (day^{-1})	-0.7%	0.7%	2.5%
Organic-N Hydrolysis (day^{-1})	0.0%	0.2%	---
Organic-N Settling (m/d)	0.0%	0.0%	0.0%
Ammonium Nitrification (day^{-1})	-0.2%	0.3%	0.8%
Organic-P Hydrolysis (day^{-1})	0.0%	0.0%	0.0%
Organic-P Settling (m/d)	0.0%	0.0%	0.0%
Inorganic-P Settling (m/d)	0.0%	0.0%	0.0%
Phytoplankton Settling (m/d)	0.0%	0.0%	---

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