Shingle Creek and Bass Creek Biota and Dissolved Oxygen TMDL

Wenck File #1240-81

Prepared for:

SHINGLE CREEK WATERSHED MANAGEMENT COMMISSION

Prepared by:

WENCK ASSOCIATES, INC.
1800 Pioneer Creek Center
P.O. Box 249
Maple Plain, Minnesota 55359-0249
(763) 479-4200

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Wenck
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Location	Shingle and Bass Creeks are located in the cities of Plymouth, New Hope, Brooklyn Park, Brooklyn Center, and Minneapolis in Hennepin County, Minnesota, in the Upper Mississippi River Basin.	2-1
303(d) Listing Information	Shingle Creek (HUC 07010206-506) was placed on the Minnesota 303(d) list in 2004 for low levels of dissolved oxygen impairing aquatic life. In 2006 it was placed on the 303(d) list for impaired biotic integrity as measured by bioassessment of macro-invertebrates. Bass Creek (HUC 07010206-784) was placed on the 303(d) list in 2002 for impaired biotic integrity as measured by fish bioassessment.	1-1 - 1-3
Applicable Water Quality Standards/ Numeric Targets	Criteria set forth in Minn. R. 7050.0150 (3) and (6) (biotic integrity) and 7050.0222 (4) (dissolved oxygen). For Shingle Creek the dissolved oxygen standard is not less than 5.0 mg/L as a daily minimum. For Shingle and Bass Creeks the biotic integrity standards are the Index of Biotic Integrity thresholds for fish and macroinvertebrates for small, low-gradient streams in the Upper Mississippi River Basin.	1-2 – 1-3
Loading Capacity (expressed as daily load)	The loading capacity is the Total Maximum Daily Load of total oxygen demand. The load capacity is 75.2 kg/day total oxygen demand for the Upper Shingle Creek Watershed and 374.9 kg/day for the Lower Shingle Creek Watershed.	4-1 - 4-4
Wasteload Allocation	The wasteload is that part of the loading capacity allocated to existing and future point sources. The wasteload is 35.8 kg/day nitrogenous biochemical oxygen demand (NBOD) from diffuse sources for the Upper Shingle Creek Watershed and 11.8 kg/day for the Lower Shingle Creek Watershed. The City of Minneapolis has an individual NPDES permit for Stormwater – NPDES Permit # MN 0061018. Other permit holders are covered under the Phase II General NPDES Stormwater Permit – MNR040000. The wasteload is allocated to these permit holders as a categorical allocation.	4-3 – 4-4

Permit Holder	**MS4 ID or Permit Number**	**Permit Holder**	**MS4 ID or Permit Number**
Brooklyn Center	MS400006	Osseo	MS400043
Brooklyn Park	MS400007	Plymouth	MS400112
Crystal	MS400012	Robbinsdale	MS400046
Maple Grove	MS400102	Hennepin Cty	MS400138

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<tr><td rowspan="7">Load Allocation</td><td colspan="4">The portion of the loading capacity allocated to existing and future nonpoint sources. It is expressed in kg/day of carbonaceous biochemical oxygen demand (CBOD), nitrogenous biochemical oxygen demand (NBOD), and sediment oxygen demand (SOD).

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<tr><td>Seasonal Variation</td><td colspan="4">Seasonal variation is accounted for by establishing the TMDL for the critical condition, which is low flow.</td><td>4-6</td></tr>
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<tr><td>Implementation</td><td colspan="4">This TMDL sets forth an implementation framework and general load reduction strategies that will be explained and refined through development of an Implementation Plan.</td><td>Section 5</td></tr>
<tr><td>Public Participation</td><td colspan="4">Public Comment Period: June 20, 2011 – August 15, 2011
Comments received: None</td><td>7-1</td></tr>
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Executive Summary

This Total Maximum Daily Load (TMDL) study addresses the dissolved oxygen impairment in Shingle Creek and biotic integrity impairments in Shingle and Bass Creeks, in Hennepin County, Minnesota. The goal of this TMDL is to quantify the pollutant reductions needed to meet State water quality standards for dissolved oxygen in Shingle Creek and State Index of Biotic Integrity standards in Shingle and Bass Creeks. This Shingle and Bass Creeks Biota and Dissolved Oxygen TMDL is being established in accordance with Section 303(d) of the Clean Water Act.

The Shingle Creek watershed covers 44.7 square miles in east-central Hennepin County, Minnesota. Shingle Creek begins at the junction of Bass Creek and Eagle Creek in the City of Brooklyn Park, flows easterly, then southerly for a total of 11.3 miles before discharging into the Mississippi River in Minneapolis. Bass Creek is the outlet of Bass Lake, and is about 2.4 miles long. Bass Creek is formed at the weir that controls the level of Boulder Ridge Pond, the last in a series of wetlands downstream of Bass Lake.

The watershed is fully developed with dense urban and suburban land uses. Shingle Creek has been substantially altered from conditions documented in the 1855 Public Land Survey. A portion was straightened and dredged in 1910 to serve as County Ditch #13. Over time most of the rest of the stream has been channelized, widened and dredged to better convey stormwater discharged to the stream. Bass Creek appears to be an historically intermittent channel too small to be recorded on the Public Land Survey and then later ditched to drain wetlands and/or provide agricultural drainage, or it was created to provide those functions.

A Stressor Identification study evaluated the potential causes of the impaired biotic integrity of both streams. Potential candidate causes of the impairments that were ruled out include: temperature, pH, nutrients, turbidity/TSS, and toxic chemicals. Five stressors that are potential candidate causes were examined in more detail: low dissolved oxygen; altered habitat; loss of connectedness; altered hydrology; and ionic strength, specifically chloride. The evidence for altered hydrology is strongest followed closely by low dissolved oxygen and lack of habitat. While the loss of connectedness and ionic strength are plausible stressors and are likely contributing to the impairment, there is less direct evidence of their role.

Hydraulic models for Shingle Creek were developed to assess the conditions resulting in persistent low dissolved oxygen. A scenario assessment determined that the likely causes were low-oxygen discharge from headwaters wetlands and excessive sediment oxygen demand resulting from the overwide channel. Stream restoration on both Shingle Creek and Bass Creek to create a low-flow channel, add reaeration structures, and enhance habitat and improvements to headwaters wetlands would have the most impact in increasing dissolved oxygen and improving biotic integrity.

1.0 Introduction

1.1 PURPOSE

This Total Maximum Daily Load (TMDL) study addresses the dissolved oxygen impairment in Shingle Creek and biotic integrity impairments in Shingle and Bass Creeks. The goal of this TMDL is to quantify the pollutant reductions needed to meet State water quality standards for dissolved oxygen in Shingle Creek and State Index of Biotic Integrity standards in Shingle and Bass Creeks. This Shingle and Bass Creeks Biota and Dissolved Oxygen TMDL is established in accordance with Section 303(d) of the Clean Water Act.

This TMDL provides wasteload allocations (WLAs) and load allocations (LAs) for the Upper Shingle Creek Watershed, which includes Bass Creek, and the Lower Shingle Creek Watershed. Based on the current State standard for dissolved oxygen, the TMDL establishes a numeric target of a daily minimum of 5.0 mg/L dissolved oxygen.

1.2 PROBLEM IDENTIFICATION

Shingle Creek (HUC 07010206-506) was first placed on the State of Minnesota's 303(d) list of impaired waters in 2004 for low levels of dissolved oxygen impairing aquatic life. In 2006 it was placed on the 303(d) list for impaired biotic integrity as measured by bioassessment of macroinvertebrates. Bass Creek (HUC 07010206-784 formerly 07010206-527) was placed on the 303(d) list in 2002 for impaired biotic integrity as measured by fish bioassessment. Bass Creek is a tributary of Shingle Creek, which is formed at the confluence of Bass Creek and Eagle Creek, another tributary.

1.3 IMPAIRED WATERS AND MINNESOTA WATER QUALITY STANDARDS

1.3.1 State of Minnesota Standards and Designated Uses

Shingle and Bass Creeks are urban streams classified as class 2B waters for which aquatic life and recreation are the protected beneficial uses. The Minnesota Pollution Control Agency's (MPCA) projected schedule for TMDL completions, as indicated on the 303(d) impaired waters list, implicitly reflects Minnesota's priority ranking of this TMDL. The TMDL was scheduled to be initiated in 2007 and completed by 2011. 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.

Dissolved Oxygen. 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 standard applies at the 7-day, 10-year low flow (Table 1.1.) The monitoring stations are located in Brooklyn Park between Brooklyn Boulevard and Zane Avenues North (SC-2 and SC-3); SC-1 is the USGS (United States Geological Survey) monitoring site in Minneapolis at Queen Avenue North; and SC-0 is in Minneapolis in Webber Park.

Table 1.1. Seven-day, ten-year low flow (7Q10) for Shingle Creek.

Monitoring Station	River Kilometer	7Q10 Flow (cfs)
Upper Shingle Creek at Stations SC-2 and SC-3	5.47	0.00
Lower Shingle Creek at Station SC-1 (USGS Station)	3.20	0.11
Lower Shingle Creek at Station SC-0	1.13	0.05

Biotic Integrity. Minnesota's standard for biotic integrity is set forth in Minn. R. 7050.0150 (3) and (6). The standard uses an Index of Biotic Integrity (IBI) which evaluates and integrates multiple attributes of the aquatic community, or "metrics," to evaluate a complex biological system. Each metric is based upon a structural (e.g., species composition) or functional (e.g., feeding habits) aspect of the aquatic community that changes in a predictable way in response to human disturbance. Fish and macroinvertebrate IBIs are expressed as a score that ranges from 0-100, with 100 being the best score possible. The MPCA has evaluated fish and macroinvertebrate communities at numerous reference sites across Minnesota that have been minimally impacted by human activity, and has established IBI impairment thresholds based on stream drainage area, ecoregion, and major basin. A stream's biota is considered to be impaired when the IBI for fish or macroinvertebrates falls below the threshold established for that category of stream.

1.3.2 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 7050.0407 lists water body classifications and Chapter 7050.2222 (5) lists applicable water quality standards for the impaired reaches.

Shingle Creek was 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.

To be listed as biologically impaired, a fish or macroinvertebrate IBI must fall below a threshold established by stream category and major basin. Both Shingle and Bass Creeks are considered small, low gradient streams (5 to 35 mi^2 drainage area) in the Upper Mississippi River Basin. The fish IBI threshold is a score of 46, and the macroinvertebrate threshold is a score of 54.

1.4 ANALYSIS OF IMPAIRMENT

Table 1.2 shows the 2010 revised dissolved oxygen (DO) criteria and the relevant Shingle Creek data. Shingle Creek exceeds the revised DO impairment listing criteria.

Table 1.2. 2010 revised DO impairment listing criteria and relevant Shingle Creek data 2001-2009.

Criterion	Requirement	Shingle Creek Data
Number of independent observations	20 observations (over at least 2 years)	317 total observations, 65 (21%) less than 5.0 mg/L
May-September observations	Must be taken prior to 9:00 a.m. over at least two years	29 confirmed May-September pre-9:00 a.m. observations
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)	29 observations, 13 (45%) less than 5.0 mg/L
DO standard must be met during October-April	90% of the time (no more than 10% below standard)	105 observations, 6 (6%) less than 5.0 mg/L
Number of violations	Must be at least 3	At least 21 violations

Table 1.3 shows the Index of Biotic Integrity scores used to evaluate Shingle and Bass Creeks for biotic impairment.

Table 1.3. Index of Biotic Integrity listing criteria and relevant Shingle and Bass Creek data.

Stream and IBI	Impairment Threshold	Shingle/Bass Creek IBI
Shingle Creek – fish	46	49
Shingle Creek – macroinvertebrates	54	20
Bass Creek –fish	46	12
Bass Creek - macroinvertebrates	54	67

Note: IBI data are from 2000 MPCA and DNR collections.

1.5 DATA USED IN THE TMDL

This TMDL incorporates monitoring conducted for this report as well as previous studies and TMDLs prepared by the Shingle Creek Watershed Management Commission (Commission) and others. This includes:

- A longitudinal DO survey conducted on Bass and Shingle Creeks for this study in August 2007.
- Two dye studies and synoptic surveys conducted on Shingle Creek for this study in June and September 2008.
- A Stressor Identification (ID) report completed in 2010 for this study for Shingle Creek and Bass Creek fish and macroinvertebrates.
- The Shingle Creek Chloride TMDL approved by the MPCA and EPA in 2007 and Implementation Plan approved by the MPCA in 2007.

- The Shingle Creek Corridor Study and Corridor Study Phase II completed by the Commission in 2005 and 2007 respectively.
- Chemical, physical, and biological monitoring conducted by the Commission, MPCA, Minnesota Department of Natural Resources (DNR), and USGS.

2.0 Watershed and Stream Characterization

2.1 SHINGLE CREEK WATERSHED DESCRIPTION

The Shingle Creek watershed covers 44.7 square miles in east-central Hennepin County including nine municipalities (Figure 2.1). Shingle Creek begins at the junction of Bass Creek and Eagle Creek in Brooklyn Park, flows easterly, then southerly for a total of 11.3 miles before discharging into the Mississippi River in Minneapolis. Bass Creek is the outlet of Bass Lake, and is approximately 2.4 miles long. Bass Creek is formed at the weir that controls the level of Boulder Ridge Pond, the last in a series of wetlands downstream of Bass Lake.

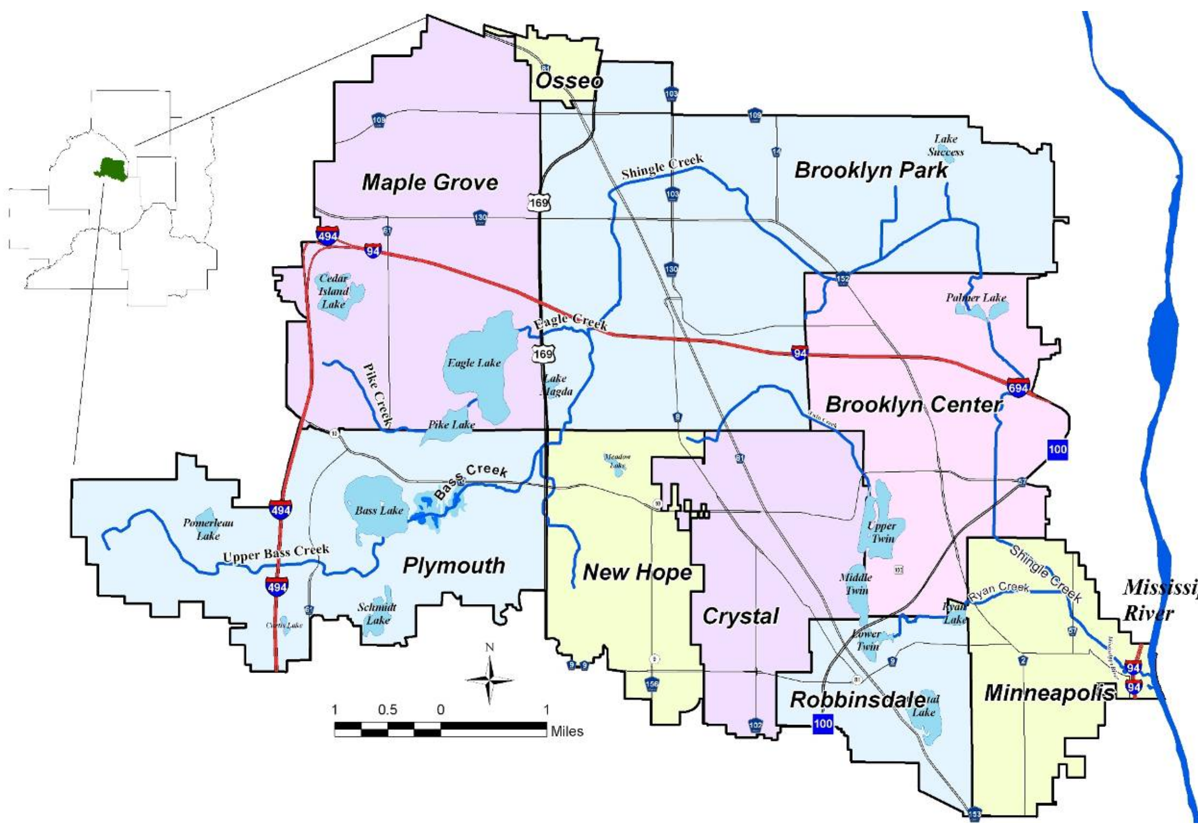

Figure 2.1. The Shingle Creek watershed in Hennepin County, Minnesota.

2.2 LAND USE

The Shingle Creek watershed is almost entirely developed. Table 2.1 details 2005 land use, which is illustrated on Figure 2.2. Single family residential is the largest land use classification at 44 percent of the total watershed area. Park, Recreation, and Open Space uses constitute about 10 percent of the watershed area, and about 15.5 percent of the watershed area is used for commercial or industrial purposes. A large gravel mining area in the upper watershed is being redeveloped in phases with mixed commercial and residential uses ("Arbor Lakes"). About seven percent of the watershed is undeveloped, and those lands are mainly wetland in the upper watershed (Plymouth and Maple Grove). Only a few agricultural parcels remain in the upper watershed, and those are primarily grazing lands. The entire watershed is on average 30-35 percent impervious. The lower watershed is more densely developed and is more impervious than the upper watershed.

A network of storm sewers and channels drains the entire watershed. There are at least 60 mapped storm sewer outfalls into Shingle and Bass Creeks, and there are almost certainly additional unmapped discharges. About 20 open channels, some natural small streams and some man-made ditches, also discharge to the creek, mostly in Brooklyn Park. Much of the upper watershed developed after the Shingle Creek Watershed Management Commission enacted stormwater detention and treatment regulations so there is significant treatment and stormwater rate control in place. However, most of the lower watershed is lacking treatment and rate control. Cities in the lower watershed are incorporating volume management, rate control, and water quality treatment into street reconstruction and redevelopment projects but it will be decades before the retrofit of the lower watershed is complete.

Table 2.1. 2005 land use in the Shingle Creek watershed.

LAND USE	Area (acres)	Percent
Single Family Residential	12,530	43.8%
Park, Recreation or Preserve	2,837	9.9%
Industrial and Utility	2,476	8.7%
Undeveloped	2,054	7.2%
Commercial	1,933	6.8%
Institutional	1,464	5.1%
Water	1,301	4.5%
Major Highways	1,180	4.1%
Extractive	1,108	3.9%
Multi-Family Residential	944	3.3%
Airport	382	1.3%
Mixed Use	162	0.6%
Agriculture	160	0.6%
Railway	68	0.2%
Farmsteads	14	0.0%
TOTAL	28,612	

Source: Metropolitan Council, derived from city Comprehensive Plans.

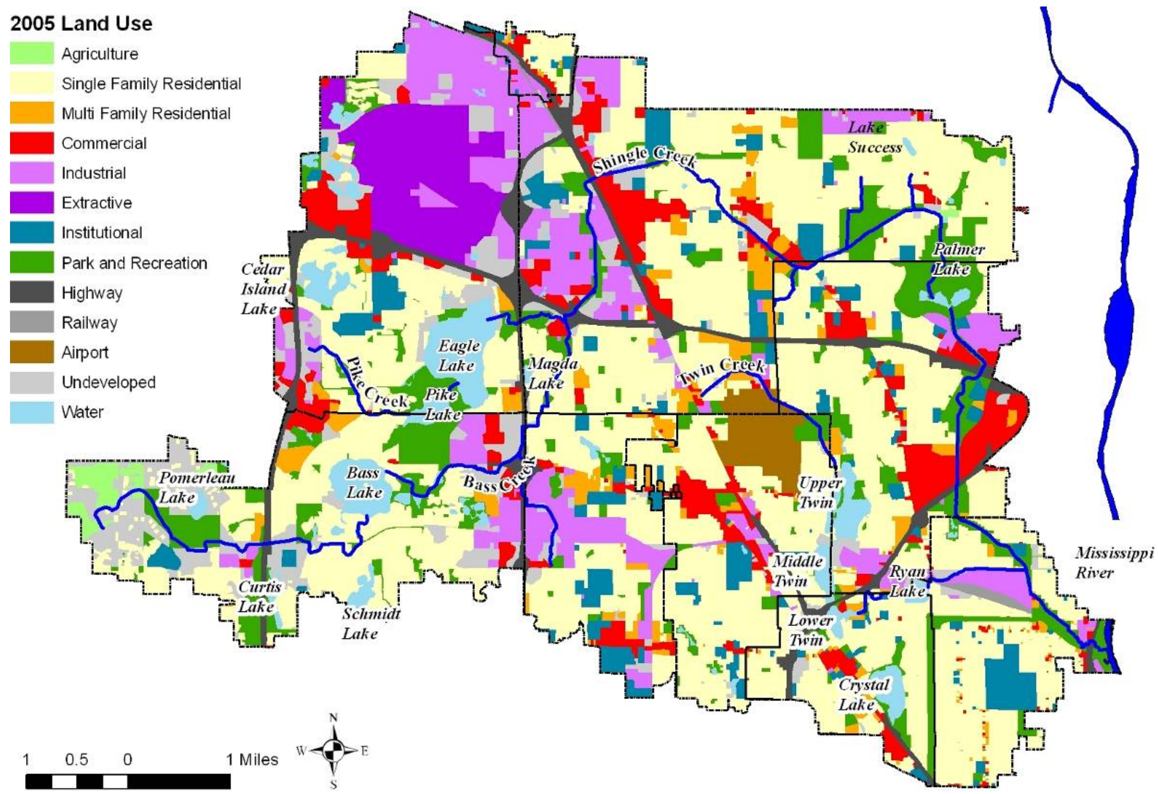

Figure 2.2. 2005 land use in the Shingle Creek watershed.

2.3 DISSOLVED OXYGEN IN SHINGLE CREEK

This TMDL focuses on data collected from 2000 through 2009 because time of day data is lacking for samples prior to 1996 and the time of day data recorded prior to 2000 appears unreliable. Since 2000, there have been 201 discrete DO observations collected between May 1 and October 1 at the three long-term monitoring stations on Shingle Creek (Table 2.2). Approximately 29% of these observations (58 total) were less than the 5.0 mg/L DO standard. Twenty-nine of the 201 DO measurements were collected prior to 9:00 am, and 13 of the 29 (45%) were less than the DO standard, which exceeds the 10% needed for a stream to be considered impaired. Appendix A contains a more detailed discussion of Shingle Creek historic DO data.

Table 2.2. Shingle Creek May through September DO observations from 2000-2009.

Site	Observations	Violations	Percent Violations	Observations (pre-9AM)	Violations (pre-9AM)	% Violations (pre-9AM)
SC-00	78	22	28%	11	5	45%
SC-Queen	55	29	53%	10	7	70%
SC-03	68	7	10%	8	1	13%
Total	201	58	29%	29	13	45%

2.4 FACTORS INFLUENCING DISSOLVED OXYGEN IN SHINGLE CREEK

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 water temperatures are high and stream flows are low.

2.4.1 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; there are none in the Shingle Creek watershed. However, there are several nonpoint source factors within the listed reach that may be causing 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 usually 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 at the three long-term Shingle Creek monitoring stations are generally low and consistently below National Urban Runoff Program (NURP) standards and other literature values for urban watersheds as well as typical summer effluent limits for registered point source dischargers (USEPA, 1983; Marsalek, 1990). Five-day CBOD ($CBOD_5$) monitoring in Shingle Creek indicates concentrations are usually below average NURP BOD_5 concentrations and at or around typical North Central Hardwood Forest (NCHF) ecoregion BOD_5 stream values (Figure 2.3). It should be pointed out that the typical literature values are presented in total BOD, not CBOD or NBOD. However, since Shingle Creek ammonia concentrations are low, short-term NBOD ($NBOD_5$) is assumed to comprise a very small fraction of total BOD_5 in the system. Thus water column BOD, while still a factor, does not appear to be the driving force of oxygen depletion in Shingle Creek. More detail regarding BOD is presented in Appendix A.

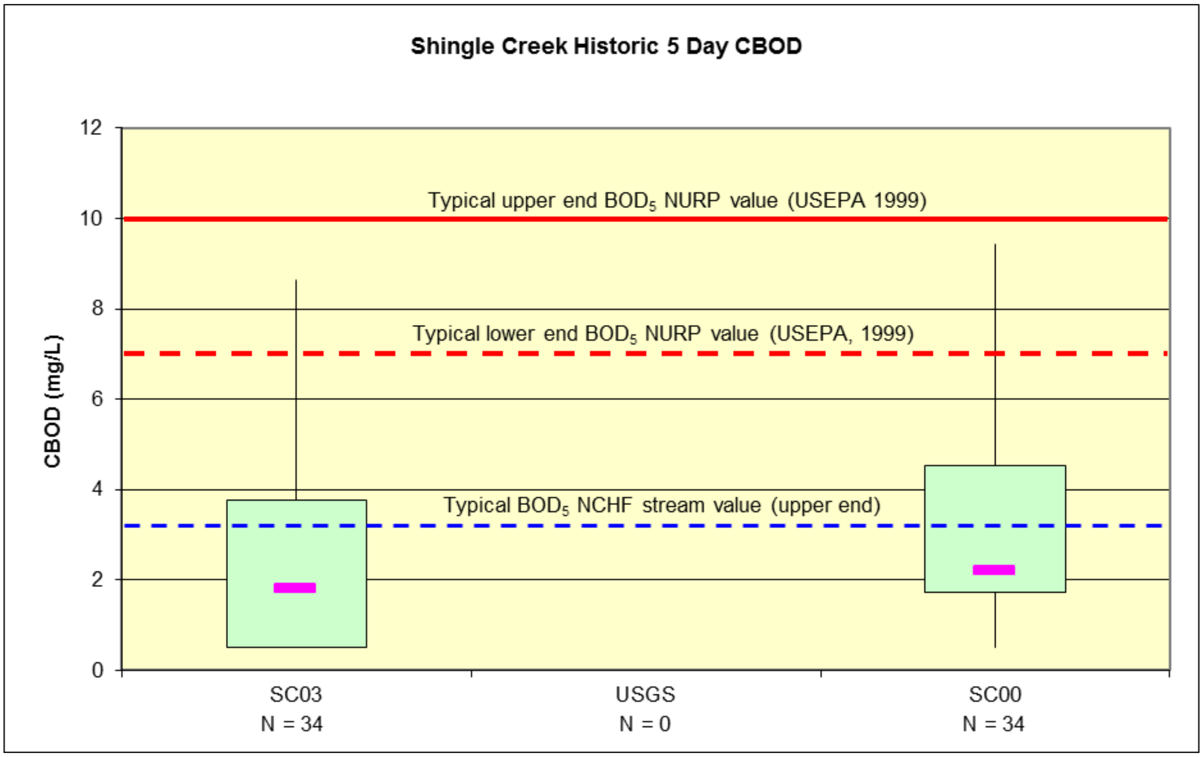

Figure 2.3. Box plots of historic $CBOD_5$ sampling in Shingle Creek from May through September, 2005-2008. Note: The upper and lower edge of each box represent the 75th and 25th percentile of the data range for each site. Error bars above and below each box represent the 95th and 5th percentile of the dataset. The pink dash is the median CBOD concentration of all data collected.

2.4.2 Sediment Oxygen Demand

Another factor that influences 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, Shingle Creek has been ditched, straightened and over-widened in certain reaches, and runs through two major flow-through wetlands (I-94 Wetland and Palmer Lake). The stream modifications have lowered average velocity throughout these reaches resulting in accumulation of organic matter and fine sediment particles. Field observations confirm these reaches 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 prescribed in a QUAL2K model for each of the reaches to represent monitored field DO 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.

2.4.3 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 release nutrients into the water column. Median Shingle Creek historic total and ortho-phosphorus concentrations are close to the upper end of typical north central hardwood forest ecoregion streams. However, the upper limits of the monitored data are within the NURP literature range for urban and residential runoff (Figure 2.4). While chlorophyll-a concentrations have not been routinely monitored in Shingle Creek, longitudinal data was collected as part of the June and September synoptic survey performed for this TMDL in 2008 (Appendix B). This data shows that concentrations were highest in or leaving the two wetland systems (I-94 wetland and Palmer Lake) and decreased at stations downstream of these features. While there is currently no chlorophyll-a standard for streams, concentrations were typically below the 20 µg/L standard for North Central Hardwood Forest shallow lakes. The only exception was a 42 µg/L concentration measured at the outlet of Palmer Lake during the September synoptic survey. These data suggest that water column primary production likely plays a role in dissolved oxygen dynamics in Shingle Creek, however there is no water quality evidence indicating the systems are experiencing severe eutrophication.

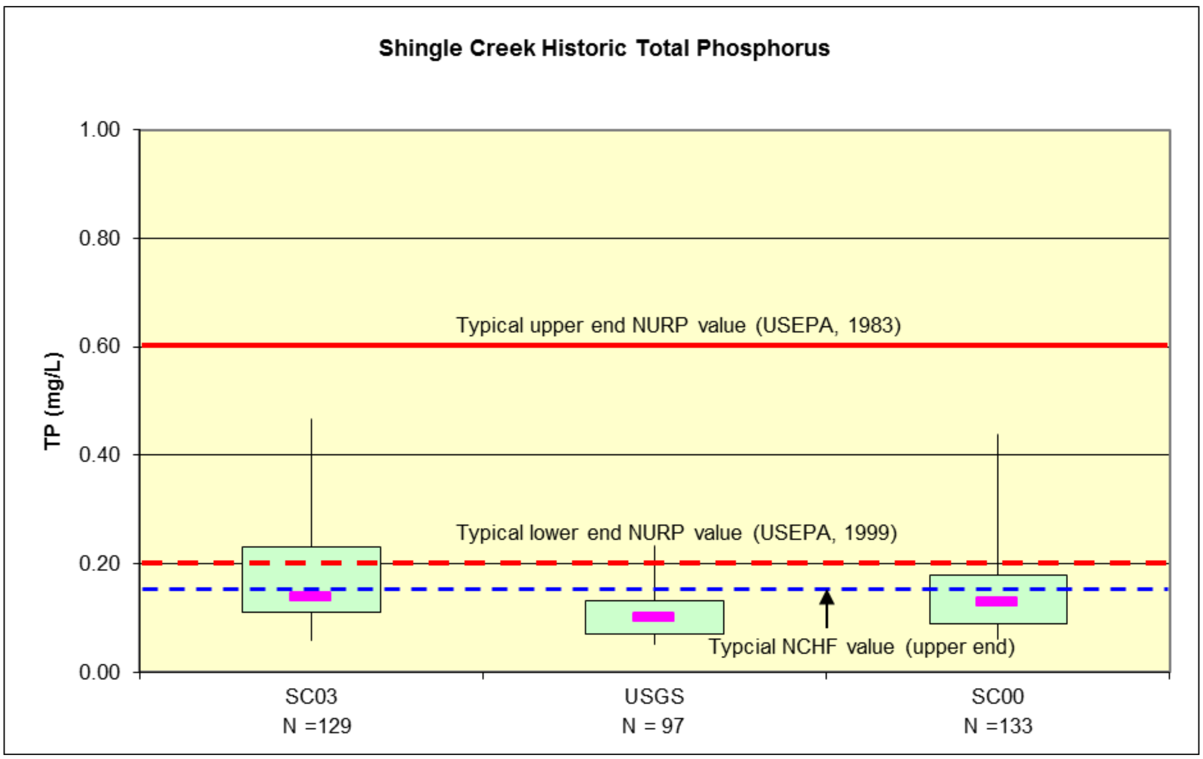

Figure 2.4. Box plots showing historic total phosphorus sampling in Shingle Creek from May through September, 1996-2009.
Note: The upper and lower edge of each box represent the 75^{th} and 25^{th} percentile of the data range for each site. Error bars above and below each box represent the 95^{th} and 5^{th} percentile of the dataset. The pink dash is the median total phosphorus concentration of all data collected

2.4.4 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 on Shingle Creek is quite variable. Typically, where Shingle Creek flows through park land there is dense canopy cover; through developed areas there is moderate to little canopy coverage. Notable areas with little to no canopy coverage include the large, flow through wetlands; the wide, slow moving reach in Brooklyn Center between I-94 and Bass Lake Road; and the commercial areas of Brooklyn Park. Shingle Creek's average daily temperature from May through September is at the upper end of typical North Central Hardwood Forest streams (2-21°C).

Maximum daily temperatures fall slightly outside this range (typically in the 20-25°C range, with some days at 25-30°C). Diel temperature fluctuations from May through September ranged from 1°C to nearly 9°C (Appendix A). Vannote and Sweeney (1980) analyzed data collected by the USGS on various streams and found that diel temperature fluctuation in natural streams varied by stream order. Temperature in third order streams such as Shingle Creek was found on average to vary by a maximum of 8-9°C per day. This suggests that Shingle Creek temperatures for the most part fall within the typical range for warm water, third order streams in its ecoregion. Water temperatures and canopy coverage likely play a significant role in the oxygen concentrations and biogeochemical cycling in Shingle Creek and all aquatic systems.

2.4.5 Stream Geomorphology

Oxygen diffusion rates are highest in rocky bottomed streams with swift moving, agitated waters. Thus, changes to stream morphology such as channelization, deepening/widening, weirs/dams and flow-through wetlands can greatly affect reaeration and DO concentrations. Shingle Creek has been significantly altered by urbanization. The segment between Xerxes Avenue North in Brooklyn Park and Webber Park in Minneapolis was dredged and straightened in 1910 by Hennepin County as Ditch #13.

A project in 1960 dredged and straightened the reach between Brooklyn Boulevard west of Zane Avenue North and Brooklyn Boulevard west of Noble Avenue North (Figure 2.5). That and other reaches have been periodically dredged to widen and deepen the stream into a trapezoidal channel with a flat bottom to better convey high streamflows. Periods of very low flow have also been increased through a reduction in infiltration in the watershed. During these periods flow in the overwide channel may be only a few inches deep, or may be limited to a low-flow channel meandering across the streambed. Figure 2.6 illustrates a typical late summer condition with exposed sediments; shallow, stagnant pools; and excessive algae growth, all of which deplete dissolved oxygen. In addition, reaeration structures such as riffles have been removed to reduce channel roughness and improve channel flow capacity. This can lead to extended periods of low dissolved oxygen.

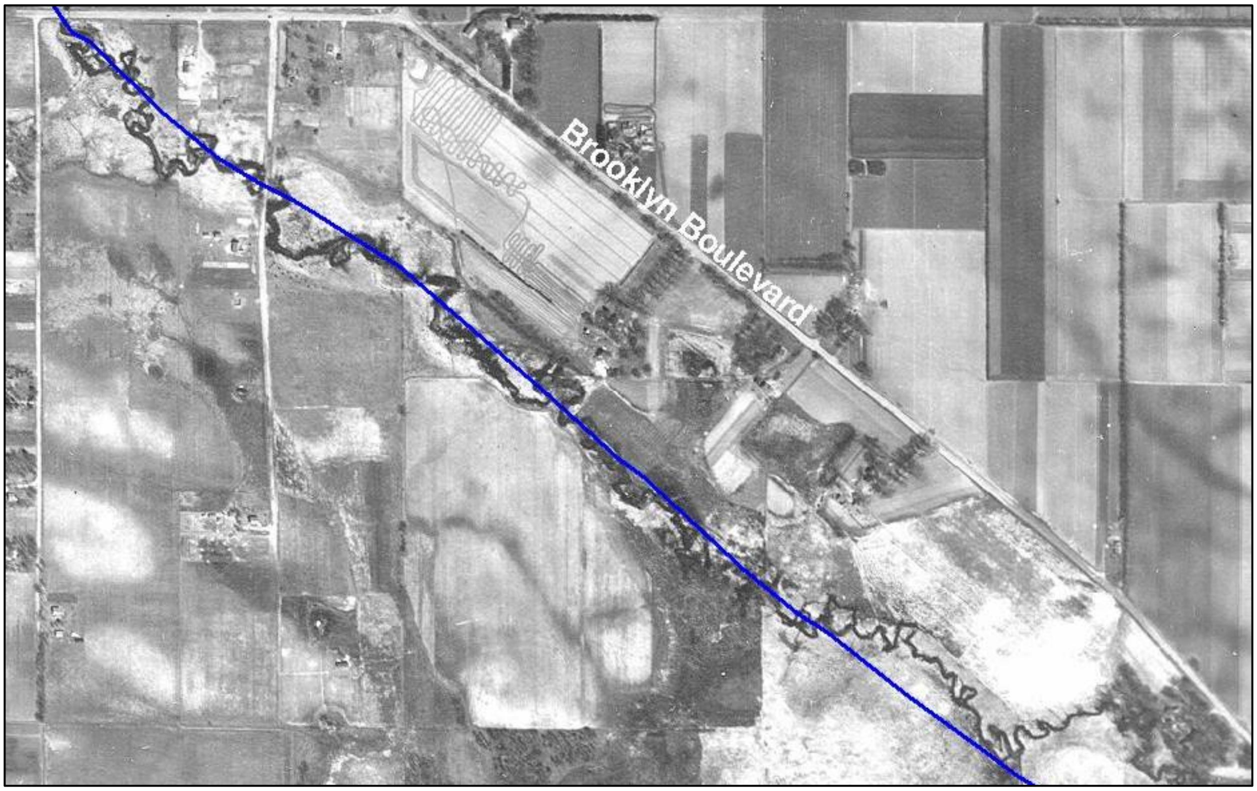

Figure 2.5. 1947 aerial photo of Shingle Creek at Zane Avenue in Brooklyn Park.
Note: The blue line is the current stream alignment, constructed in 1960


Figure 2.6. Shingle Creek upstream of Brooklyn Boulevard in late summer.

2.5 BIOTIC INTEGRITY IN SHINGLE AND BASS CREEKS

The MPCA has developed an Index of Biotic Integrity (IBI) to evaluate the biological health of streams in the State. Currently, an IBI has been developed for two biological communities, fish and macroinvertebrates. Shingle Creek is impaired based on the macroinvertebrate IBI (M-IBI) while Bass Creek is impaired based on the fish IBI (F-IBI).

Limited data are available to evaluate the integrity of the fish and macroinvertebrate communities and the effects of potential stressors. Fish data are over ten years old and available at only two locations, and droughts in 2008 and 2009 prevented an update of the fish surveys for the streams. Existing data suggests an unexpected fish species richness in Shingle Creek, with a more limited and pollution-tolerant community in Bass Creek. There are more recent and more spatially distributed macroinvertebrate data, but there are only a few data points for each location. The macroinvertebrate community is dominated by pollution-tolerant taxa, although sites with slightly better habitat appear to support some more moderately-tolerant organisms.

2.6 FACTORS INFLUENCING BIOTIC INTEGRITY IN SHINGLE AND BASS CREEKS

A Stressor Identification analysis was prepared for this TMDL using the United States Environmental Protection Agency's (US EPA) and MPCA's Stressor Identification guidance (Jasperson 2009) and the US EPA's Causal Analysis/Diagnosis Decision Information System (CADDIS). CADDIS (USEPA 2007), a methodology for conducting a stepwise analysis of candidate causes of impairment, characterizes the potential relationships between candidate causes and stressors, and identifies the probable stressors based on the strength of evidence from available data.

Potential candidate causes of the impairments that were ruled out based on a review of available data include: temperature, pH, nutrients, turbidity/TSS, and toxic chemicals. Five stressors that are potential candidate causes were examined in more detail: low dissolved oxygen; altered habitat; loss of connectedness; altered hydrology; and ionic strength, specifically chloride. The Shingle Creek and Bass Creek Stressor Identification Report (Wenck 2010) is incorporated into this report by reference and available on the MPCA's website at http://www.pca.state.mn.us/index.php/water/water-types-and-programs/surface-water/basins-and-watersheds/upper-mississippi-river-basin/project-shingle-bass-creeks-biota-oxygen.html.

2.6.1 Dissolved Oxygen

Living aquatic organisms such as fish and macroinvertebrates require oxygen to sustain life. Decreases in DO levels can cause changes in the types and numbers of fish and aquatic macroinvertebrates in surface waters, and shift the community composition to species that are tolerant of lower levels or wider diel swings in DO. As noted above, data collected on Shingle Creek since 1990 and on Bass Creek for this DO TMDL indicate that both streams experience significant fluctuations in dissolved oxygen, and frequently fall below the 5.0 mg/L standard necessary to sustain aquatic life.

2.6.2 Altered Habitat

Habitat describes the place where organisms feed, reproduce, shelter and escape predation. In streams, habitat for macroinvertebrates and fish includes the rocks and sediments of the stream bottom and banks; the plants growing in the stream or attached to rocks or debris in the stream; grasses and leaf litter and other organic material that falls into the stream; and logs, sticks, twigs, and other woody debris. Habitat also includes elements of stream structure: streambed depressions that provide deeper pools of water; side channels, backwaters or other stream formations that are places outside the primary flow channel; and the vegetation on and adjacent to the streambank.

Each species has a specific set of habitat requirements, but can often tolerate conditions that are not ideal. Habitat complexity is necessary to provide an environment with a variety of attributes that can support a robust assemblage of organisms.

As detailed in the Shingle Creek Corridor Study and the Stressor ID, the biological integrity of both streams is compromised by the lack of complex habitat for macroinvertebrates and fish. The streams exhibit minimal sinuosity and very few of the riffle and pool sequences that often characterize natural streams. The pools present tend to be shallow, although some new riffle and pool habitat has been constructed in Minneapolis and in Brooklyn Park. Woody debris, vital for habitat and substrate diversity, is generally absent. Both streams are characterized by lack of habitat diversity, shallow pool depth, absence of riffles, and poor quality riparian vegetation. There are few backwaters or offline areas available to provide refuge to fish and invertebrates during times of high flow. The shallow pools and flat channel bottom provide minimal refuge during low flows.

2.6.3 Loss of Connectedness

Connectedness and connectivity are important concepts in ecology, referring to the contiguousness of landscapes and features. Contiguous landscapes such as stream corridors provide continuous, connected habitat that allow organisms to move freely between locations for different life cycle needs or to take refuge from unusual conditions.

Especially in altered and impacted urban streams, conditions may periodically reduce or eliminate a population of an organism or assemblage. Drought, excessive flow, and physical alteration are some stressors that occur infrequently but which may result in impacts to the local biota. When those conditions stabilize, populations may be reestablished through colonization from other locations. Most commonly, recolonization occurs from upstream or downstream reaches or from connected lakes, streams or wetlands.

Altered hydrology also can impact connectedness. Increased flow rates and volumes can cause the stream to incise in its channel, eliminating access to its natural floodplain and riparian wetlands. Organisms that require both aquatic and upland habitat may not be able to escape a deeply incised channel.

As areas develop, humans may introduce barriers that disconnect landscapes. Stream structures may prohibit movement between reaches. Removal of habitat such as replacement of wooded cover with a residential land use may eliminate the protected habitat corridor for recolonization between unconnected water resources. These barriers isolate stream reaches and organisms may not have access to life cycle habitats.

Physical barriers on Shingle and Bass Creeks likely significantly inhibit connectivity and limit recolonization. One of the most significant barriers is the seven-foot drop structure in Webber Park that disconnects Shingle Creek from the Mississippi River. However, that structure has the beneficial impact of protecting Shingle Creek and other upstream resources from invasion by unwelcome exotic and invasive species in the Mississippi River. River species are unable to swim upstream to colonize Shingle Creek, thus most fish in Shingle and Bass Creeks are lake species that have been swept over the Bass and Eagle Lakes outlet structures. A detailed discussion and map of physical barriers is presented in the Stressor ID.

Land cover change has also fragmented habitat and limits connectivity. Except for the Palmer Lake basin, the Shingle and Bass Creek riparian areas contain relatively small patches of natural land cover interspersed with areas of dense urban and suburban development, with developed land cover often extended to the banks of the two streams. This limits the ability of terrestrial and aquatic species to move between reaches or to recolonize from other lakes and streams.

2.6.4 Altered Hydrology

Loss of flow, low flows, or prolonged duration of low flow conditions can reduce overall habitat availability by decreasing water volume and wetted channel area. Prolonged duration of low flows tends to favor macroinvertebrate and fish species that prefer standing-water habitats.

High-flow events can physically remove species from the channel to a downstream location. High flows also mobilize pebbles, sediment, woody debris, and plant material that can dislodge organisms. Frequent high-flow events can decrease species richness by eliminating or reducing populations that have not developed coping mechanisms, such as an ability to cling to substrate or burrow into sediments. Macroinvertebrate assemblages may shift to include more species with relatively short life cycles.

As detailed in the Shingle Creek Corridor Study and the Stressor ID, flow in Shingle and Bass Creeks has been fundamentally altered from pre-development conditions. A network of storm sewers and channels efficiently deliver runoff to the streams, which rise rapidly and fall almost as rapidly. The increased imperviousness of the watershed and decreased infiltration to groundwater has significantly reduced base-flow, and the streams are often dry by midsummer. The hydrology of the streams is thus extremely variable.

2.6.5 Chloride

Shingle Creek is an Impaired Water due to chloride concentrations in excess of state water quality standards. A TMDL for that impairment was completed and approved in 2007 (SCWMC 2007). That TMDL linked the excessive chloride concentrations to the application of road salt for winter de-icing in the 44.7 square mile watershed, which is crisscrossed with a dense network of local, county, and state roads, highways, and interstate highways. Bass Creek was added to the Impaired Waters list in 2010 for excess chloride.

Chronic exposure to chloride at higher concentrations (1,000 mg/L+) can be lethal to fish and macroinvertebrates as well as other aquatic organisms (Environment Canada 2001). At lower concentrations, species that are intolerant of chloride may not survive, and the biotic community will select to only salt-tolerant species. There are other potential impacts from chloride use that may impact the biota. Additives and impurities in road salt may introduce toxic metals and nutrients into the stream. Salt spray from a stream road crossing may kill streambank vegetation, destabilizing banks and increasing erosion and sedimentation in the stream.

Shingle Creek and Bass Creek experience periods of high chloride concentration, typically during spring snowmelt and during short winter snowmelt events. During these winter and early spring events, short-term chloride concentrations in excess of 1,000 mg/L have been recorded. By about May of each year chloride concentrations fall below the 230 mg/L chronic exposure standard and stay well below that standard until the snow season begins around November.

3.0 Modeling Approach

3.1 SHINGLE CREEK MODEL SETUP AND DEVELOPMENT

The computational framework, or model, chosen for determining the DO TMDL for Shingle Creek was the River and Stream Water Quality Model (QUAL2K). QUAL2K (USEPA 2009) is a public domain model and 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 throughout Shingle Creek making this an appropriate model for analyzing DO violations in this system.

Two summer synoptic surveys were conducted to collect the data necessary to build and calibrate two separate QUAL2K models for Shingle Creek. The intent was to capture one higher summer base-flow event (June 9, 2008 survey) and one late summer base-flow (September 17, 2008 survey). Figure 3.1 shows the location of each synoptic survey sampling event on the long-term flow duration curve.

Early in the model development stage, it was apparent QUAL2K had difficulties modeling the hydrologic and geochemical interactions occurring at Palmer Lake, a large wetland basin through which Shingle Creek flows. Thus, it was decided that both the June and September models would be further subdivided into two separate model runs: one above Palmer Lake from the I-94 Wetland to where Shingle Creek enters the lake (referred to as the Upper Shingle Creek model, Figure 3.2) and another below Palmer Lake from the lake's outlet to its junction with the Mississippi River (Lower Shingle Creek model, Figure 3.3). Thus, a total of four models were developed and calibrated for this TMDL. It should be noted that even though only Shingle Creek was modeled for the TMDL, the conditions in Upper Shingle Creek are also representative of Bass Creek. Data collected in Bass Creek for this project verify this assumption.

3.2 OVERVIEW OF THE MODELS

The models were built using both summer high-flow and fall low-flow synoptic survey data. Stream locations 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 adjusted for each reach to match observed dissolved oxygen data.

Figures 3.4 through 3.7 show final calibration results for model-predicted and observed dissolved oxygen concentrations. All observed measurements (squares) were collected during the June and September synoptic surveys. Daily minimums and maximums are based on continuous DO data from YSI sensor data loggers. Field measurements were collected using a hand-held YSI sensor between 12:00 pm and 3:00 pm during each synoptic survey. The models were validated using dissolved oxygen data from the longitudinal dissolved oxygen profile conducted on August 16, 2007. For a complete discussion of the methods and assumptions used to build, calibrate and validate these models refer to Appendix C.

As detailed in Appendix C, the models performed well in predicting loads and concentrations of the primary water quality parameters that affect DO. With the addition of prescribed SOD, the models performed well at predicting high flow DO and reasonably well at predicting low flow DO.
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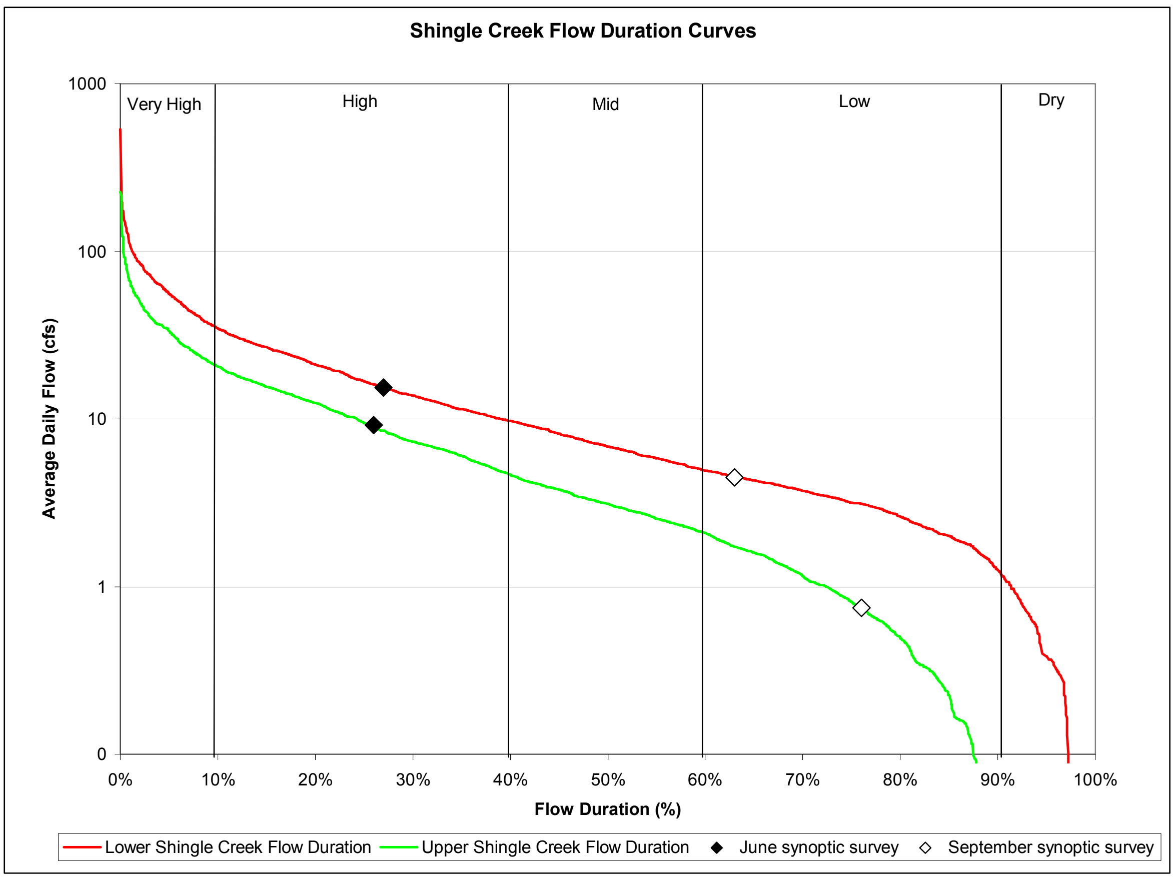

Figure 3.1. Location of each synoptic survey on the long-term Shingle Creek flow duration curves.
Note: Flow durations were developed from the long-term average daily flow record for each station from 2003-2009.

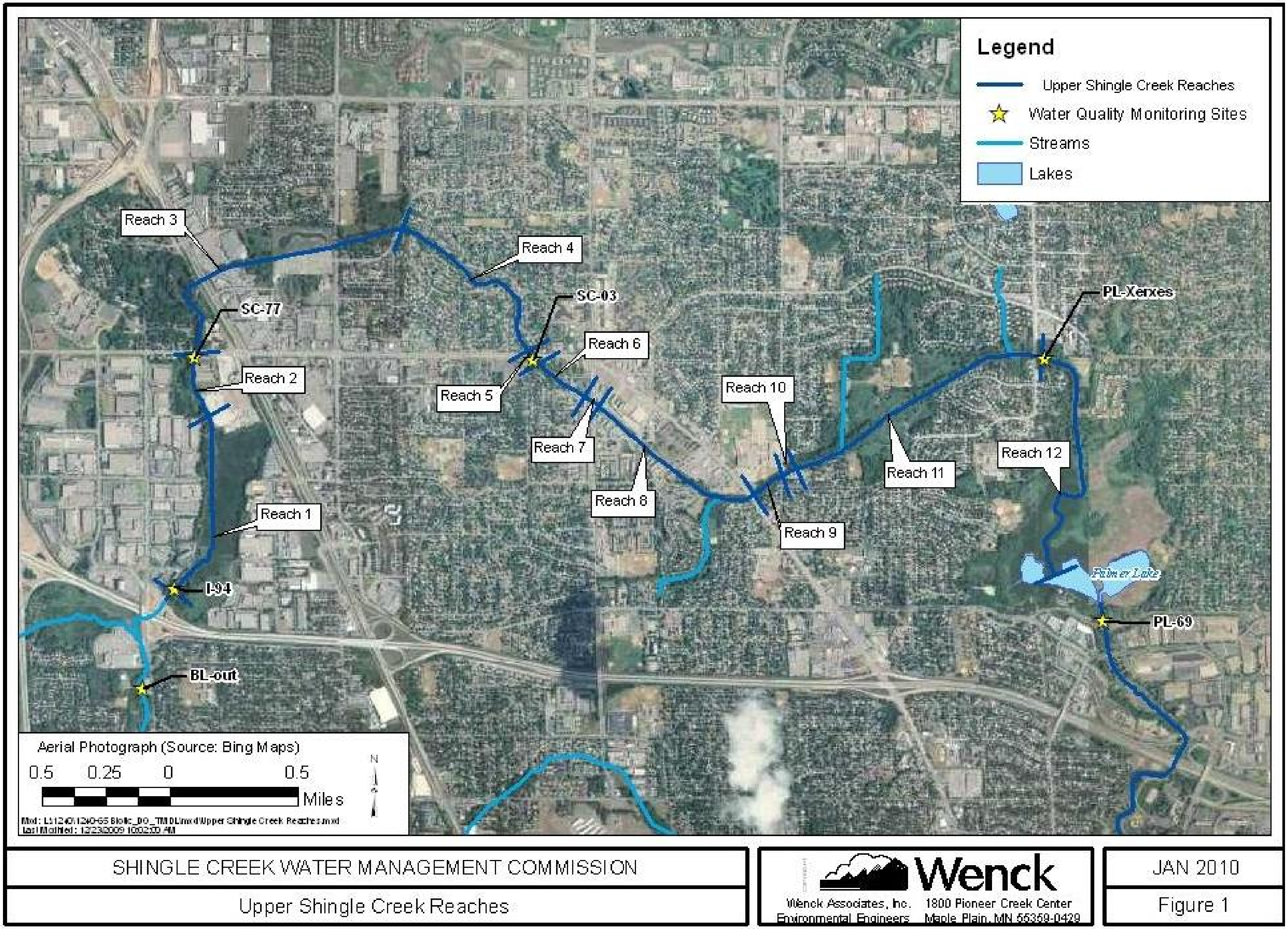

Figure 3.2. Upper Shingle Creek modeled reaches

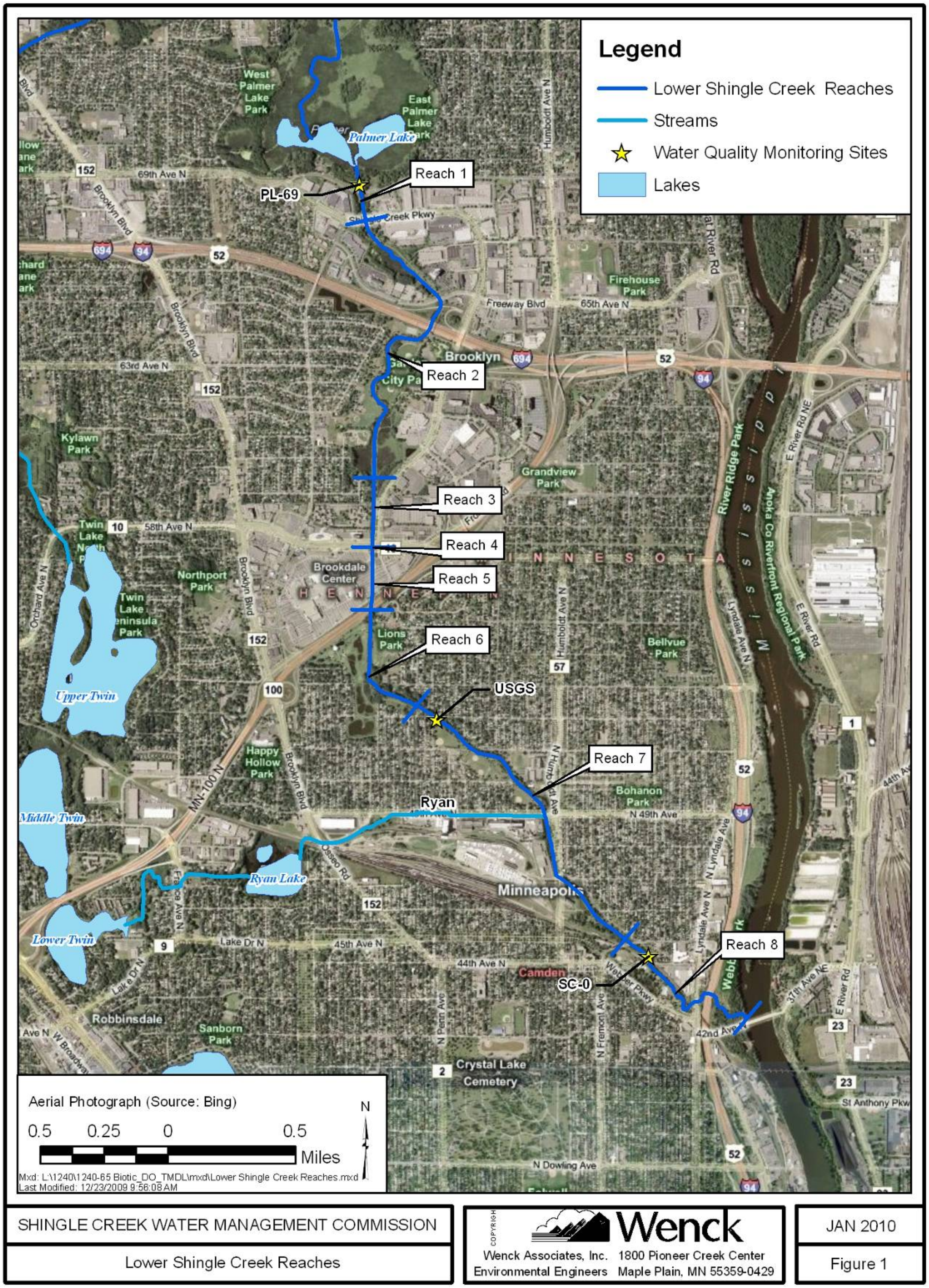

Figure 3.3. Lower Shingle Creek modeled reaches.

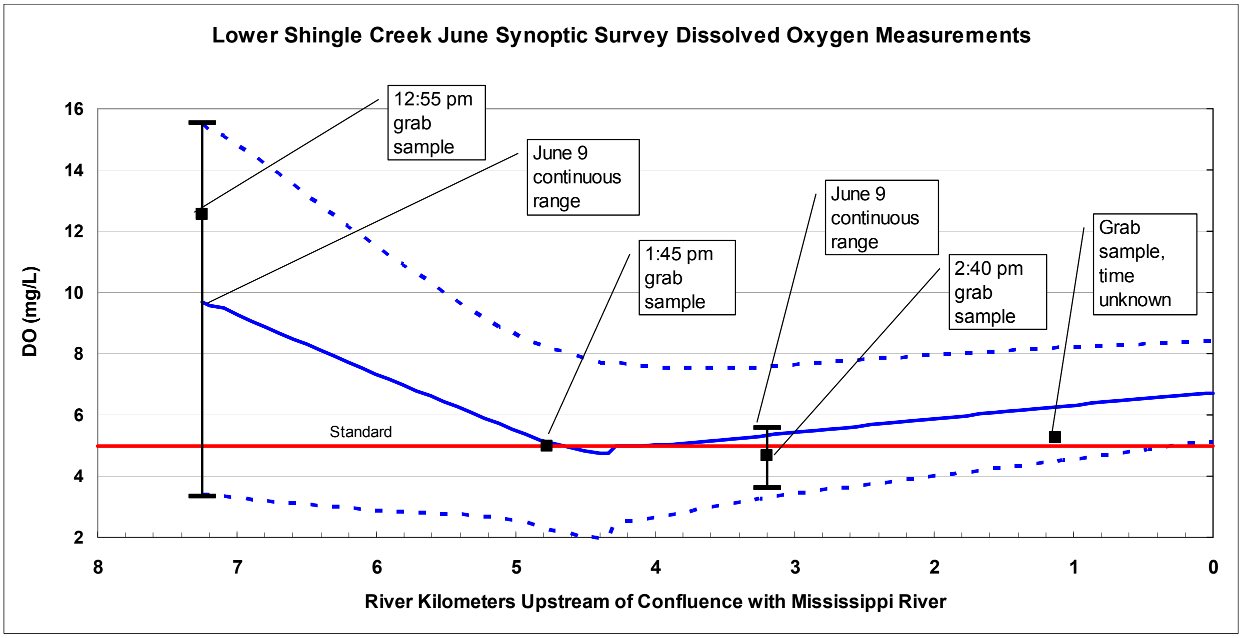

Figure 3.4. June calibrated dissolved oxygen longitudinal profile.
Note: black bars show the range of continuous data recorded at two sites; solid squares are data recorded at four grab sample sites; the dashed lines are the modeled maximums and minimums and the solid line the modeled average DO concentration.

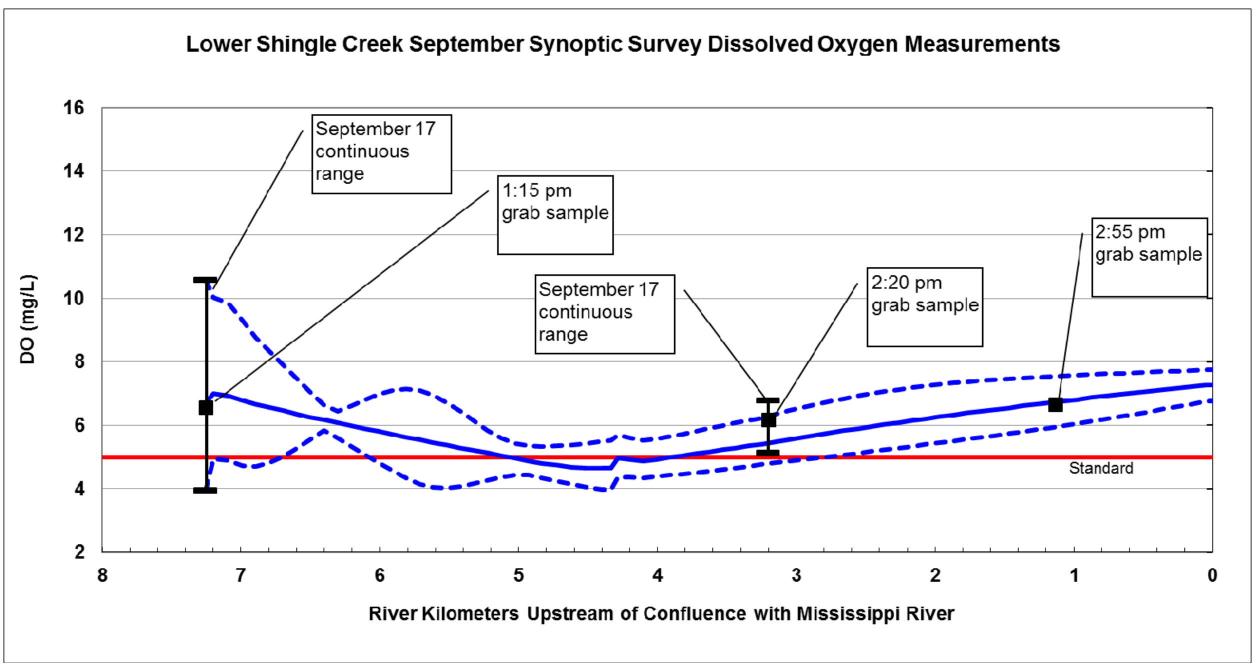

Figure 3.5. September calibrated dissolved oxygen longitudinal profile.
Note: black bars show the range of continuous data recorded at two sites; solid squares are data recorded at four grab sample sites; the dashed lines are the modeled maximums and minimums and the solid line the modeled average DO concentration.

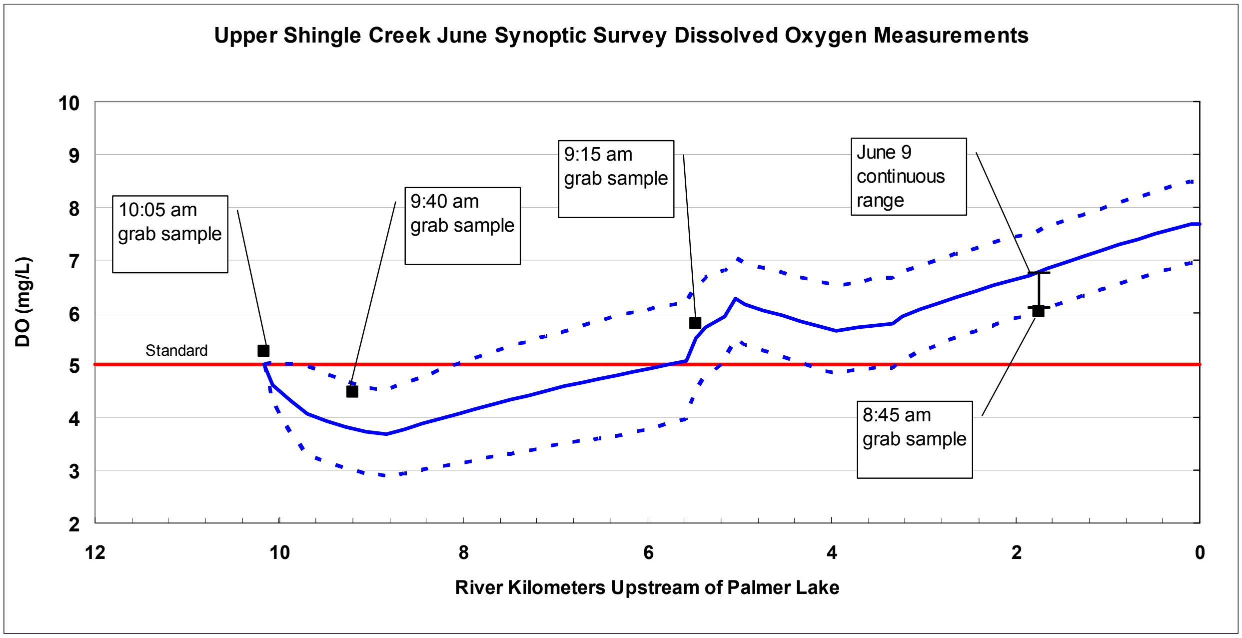

Figure 3.6. June calibrated dissolved oxygen longitudinal profile.
Note: black bars show the range of continuous data recorded at one site; solid squares are data recorded at four grab sample sites; the dashed lines are the modeled maximums and minimums and the solid line the modeled average DO concentration.

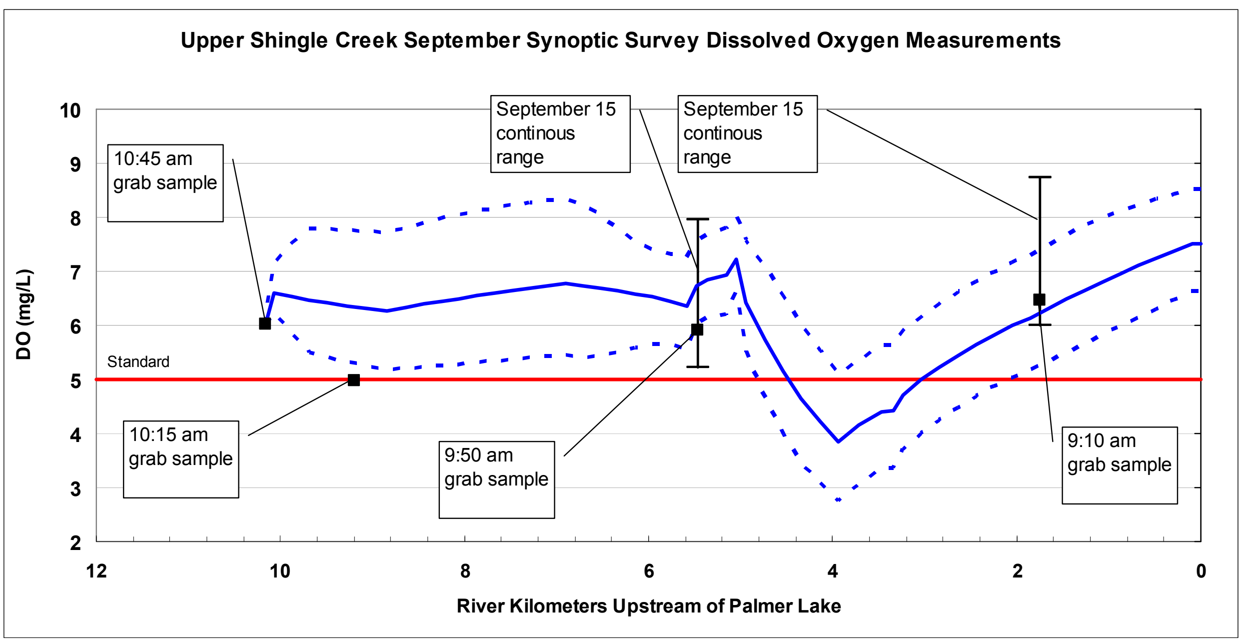

Figure 3.7. September calibrated dissolved oxygen longitudinal profile.
Note: black bars show the range of continuous data recorded at two sites; solid squares are data recorded at four grab sample sites; the dashed lines are the modeled maximums and minimums and the solid line the modeled average DO concentration.

3.3 EVALUATING BIOTIC INTEGRITY

The CADDIS Stressor Identification analysis uses a "strength of evidence" approach to evaluate candidate causes affecting biotic integrity. The five candidate causes identified in the Stressor ID - low dissolved oxygen, lack of habitat, altered hydrology, loss of connectedness, and ionic strength – were evaluated and the results summarized in Table 3.1.

Data are analyzed in terms of associations that might support, weaken or refute the case for a candidate cause. This strength of evidence analysis is a systematic approach that sorts through the available data to determine the most probable cause or causes based on weight of evidence. Each of the types of evidence is scored based on the degree to which it supports or weakens the case using pluses (++) or minuses (--). The number of pluses or minuses depends on the likelihood that an association might be observed by chance rather than because of the true cause. A score of O indicates that the evidence neither supports nor weakens the case for the cause, a D is diagnostic of the cause and an R refutes the case for the cause.

The evidence for altered hydrology is strongest followed closely by dissolved oxygen and lack of habitat. While the loss of connectedness and ionic strength are plausible stressors and are likely contributing to the impairment, there is less direct evidence of their role. Altered hydrology, dissolved oxygen, and habitat are interrelated.

Table 3.1. Stressor identification strength of evidence table.

	Low Dissolved Oxygen	**Altered Habitat**	**Altered Hydrology**	**Loss of Connected-ness**	**Ionic Strength**
Types of Evidence	**Score**	**Score**	**Score**	**Score**	**Score**
Evidence using data from Shingle and Bass Creeks					
Spatial/temporal co-occurrence	O	+	+	O	---
Evidence of exposure, biological mechanism	++	++	++	++	++
Causal pathway	-	+	++	+	-
Field evidence of stressor-response	+	+	++	O	+
Field experiments /manipulation of exposure	O	O	O	O	O
Laboratory analysis of site media	O	O	O	O	O
Temporal sequence	O	O	O	O	O
Verified or tested predictions	+	+	+	O	-
Symptoms	+	+	D	+	+
Evidence using data from other systems					
Mechanistically plausible cause	+	++	+	+	+
Stressor-response in other field studies	O	++	++	++	+
Stressor-response in other lab studies	+	O	O	O	+

	Low Dissolved Oxygen	Altered Habitat	Altered Hydrology	Loss of Connected-ness	Ionic Strength
Types of Evidence	**Score**	**Score**	**Score**	**Score**	**Score**
Stressor-response in ecological models	O	+	+	O	O
Manipulation experiments at other sites	O	O	+	+	O
Analogous stressors	O	O	O	O	++
Multiple lines of evidence					
Consistency of evidence	O	+	+	O	O
Explanatory power of evidence	++	++	++	O	O

4.0 TMDL Allocations

4.1 IDENTIFYING THE APPROPRIATE TMDL PARAMETER

Sensitivity analysis of all four model runs, as discussed in Appendix C, shows the DO level in Shingle Creek is most sensitive to the kinetic rates driving SOD levels such as algae (represented in the model as chlorophyll-a) and particulate nitrogen and phosphorus settling as well as the SOD settings themselves. Water column CBOD oxidation and nutrient hydrolysis rates appear less sensitive, indicating that while there may be diffuse sources of CBOD these processes are not the primary cause of oxygen depletion during the calibration events. This TMDL addresses the Shingle Creek DO impairment. In addition, oxygen demand (as CBOD, NBOD, and SOD) acts as a surrogate for biotic integrity impairment in Shingle Creek as determined by macroinvertebrate bioassessment and Bass Creek as determined by fish bioassessment. Note that even when Shingle and Bass Creeks meet dissolved oxygen requirements in this TMDL, additional restoration strategies will likely need to be implemented in order to meet biotic integrity standards.

Current and historic water column nutrient and chlorophyll-a concentrations in Shingle Creek and Bass Creek are at times high but usually fall within the range of typical North Central Hardwood Forest ecoregion conditions (Appendix A). Moreover, sensitivity analysis suggests dissolved oxygen concentrations are not sensitive to nutrient and chlorophyll-a concentrations and reducing these parameters would not achieve the 5.0 mg/L DO standard. Based on monitoring data and modeling it is apparent sediment oxygen demand is the most appropriate parameter for this TMDL as this process plays the biggest role in consuming dissolved oxygen during critical base-flow conditions.

Most of the explicitly modeled reaches in Shingle Creek required the prescription of additional SOD beyond the model calculated SOD to reach calibration. This additional SOD is the result of overwidened stream channels where velocities are decreased and sedimentation and sediment-water interaction time is increased, a condition which also exists in Bass Creek. These channels have shallow water depths and large areas interacting with organic stream sediments increasing the SOD influence on in-stream dissolved oxygen concentrations. The settled organic material is likely from connected wetland systems and watershed sources; however it is difficult to measure these sources as it is typically a function of bed load.

4.2 TOTAL MAXIMUM DAILY LOAD CALCULATIONS

The numerical TMDL, which is the Total Load Capacity, is the sum of the wasteload allocation (WLA), load allocation (LA), and the margin of safety (MOS). This TMDL is written to solve the TMDL equation for a numeric dissolved oxygen target of a daily minimum of 5.0 mg/L dissolved oxygen across all reaches for the critical, low-flow condition. The TMDL is expressed as a Lower Watershed TMDL, which includes Lower Shingle Creek and the watershed below Palmer Lake, and an Upper Watershed TMDL, which includes Upper Shingle and Bass Creeks and the watershed above Palmer Lake.

4.2.1 Oxygen Deficit Terms

Dissolved oxygen is consumed both in the water column and at the sediment interface. This consumption is expressed in terms of the 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. The only sediment flux NBOD loads presented in this TMDL are those attributed to prescribed NH_3 fluxes, which were supported by model calibration to in-stream water quality samples. For this TMDL, NBOD was calculated by multiplying the sum of organic 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-TX 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). While the wetlands on Shingle and Bass Creeks and in the watershed may be sources of SOD for this TMDL, SOD loads were only determined for explicitly modeled stream reaches.

4.2.2 Load Capacity

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 C, prescribed SOD was necessary in many reaches to adequately calibrate the model for both Upper and Lower Shingle Creek to the observed data. This prescribed SOD represents a load that is either unknown or which QUAL2K has difficulty modeling, for example, the additional SOD generated by stagnant pools when flushing rates are low.

To determine the Load Capacity, SOD rate targets for each reach were established by reducing prescribed SOD globally (by percentage of initial conditions) until it was clear model-predicted minimum daily dissolved oxygen never dropped below the 5.0 mg/L standard. For all four model runs (Upper and Lower Shingle Creek, high flow and low flow), a 100% reduction in prescribed

SOD was required in order to achieve the DO standard. Thus, the average SOD rate in each reach after this reduction, which is the model-predicted SOD only, is the TMDL SOD target rate for each reach. Each SOD target reach rate, represented in g-O_2/m^2/day, was multiplied within the QUAL2K model by the wetted area of the reach to calculate the SOD TMDL in kg/O_2/day for the reach. These loads represent Shingle Creek's loading capacity (Tables 4.1 and 4.2).

4.2.3 Load Allocations

The Load Allocation is oxygen demand from wetland outlet sources and from sediment flux. Upper Shingle Creek flows out of the I-94 Wetland and Lower Shingle Creek from Palmer Lake, a 400+ acre wetland complex. Water quality and flow data from the low-flow samples taken in September 2008 were used to calculate the CBOD and NBOD loads for each site for the current condition. Since the appropriate TMDL parameter is SOD (Section 4.1), the load allocation for wetland sources in the TMDL assumes no change from current conditions.

The load from sediment flux includes both SOD and ammonia release. The current loads are calculated within the QUAL2K model by integrating model-predicted and prescribed release rates across the wetted area of each reach. The TMDL loads are calculated assuming a smaller wetted surface area resulting from stream modifications creating a low-flow channel and eliminating the prescribed SOD. 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 C.

4.2.4 Wasteload Allocations

Oxygen-consuming loads are also contributed to the stream from diffuse sources, including stormwater runoff from the watershed and groundwater. These diffuse sources are calculated using flow and water quality data collected during the synoptic surveys. Modeled diffuse inflow volumes of water are multiplied within the QUAL2K model by model-calibrated diffuse inflow concentrations of CBOD, organic-N, and ammonia to obtain diffuse loads. The very low 7Q10 flow rates (see Table 1.1 on page 1-2), observed conditions and the results of the hydraulic modeling suggest that groundwater inputs are small compared to stormwater inputs. Therefore, it is assumed that the calculated diffuse loads are regulated wasteloads.

Stormwater discharges are regulated under the National Pollution Discharge Elimination System (NPDES) State of Minnesota General Stormwater Permit. Because there is not enough information available to assign diffuse loads to individual permit holders, the wasteload allocations are combined in this TMDL as categorical wasteload allocations assigned to all permitted dischargers in the contributing watershed as listed below with either the MS4 permit identification number or permit number (Minneapolis).

- Brooklyn Center – MS400006
- Brooklyn Park – MS400007
- Crystal – MS400012
- Maple Grove – MS400102
- New Hope – MS400039

- Osseo – MS400043
- Plymouth – MS400112
- Robbinsdale – MS400046
- Hennepin County – MS400138
- MnDOT Metro District – MS400170
- Minneapolis – MN0061018
- North Hennepin Technical College – MS400295
- Hennepin Technical College-Brooklyn Park – MS400198

There are no municipal wastewater dischargers in the watershed. There are three active industrial dischargers in the watershed, but none of their permits include limits or monitoring requirements for oxygen demanding characteristics (NH_3, BOD, COD, CBOD) indicating that oxygen demand is not a concern with these types of effluents. Consequently, they do not require wasteload allocations because their activities do not contribute to the impairment. Stormwater activities from individually permitted, non-MS4 NPDES/SDS stormwater discharges have not been given an individual WLA and will be considered in compliance with provisions of this TMDL if they follow the conditions of the individual permit and implement the appropriate Best Management Practices.

4.2.5 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% was used for the TMDL equation. For this TMDL only reductions in SOD are required, and the MOS applies only to the oxygen deficit terms that require a reduction to achieve the standard. Loads for this TMDL study were calculated using two models which are based on data collected during two synoptic survey sample events. Thus, a 10% MOS accounts for model uncertainty in predicting SOD loads, the uncertainty and assumptions in determining channel dimensions and SOD coverage throughout the system, and the uncertainty in how the stream may respond to changes in SOD loading.

4.3 TOTAL MAXIMUM DAILY LOAD

The Total Maximum Daily Load is the sum of the wasteload and load allocations and the margin of safety. Tables 4.1 and 4.2 show the current loads and the Total Maximum Daily Load allocations by source for the Upper and Lower Watershed for the critical, low-flow condition.

Table 4.1. Current loads and Total Maximum Daily Loads for the Upper Shingle Creek Watershed.

Source	Oxygen Demand (kg/day) from:						Total Oxygen Demand (kg/day)	
	CBOD		NBOD		SOD			
	Current	TMDL	Current	TMDL	Current	TMDL	Current	TMDL
Load: I-94 Wetland	7.8	7.8	18.3	18.3	--	--	26.1	26.1
Load: Sources of Sediment Flux	--	--	--	--	491.9	12.0	491.9	12.0
Wasteload: Diffuse Sources	--[1]	--[1]	35.8	35.8	--	--	35.8	35.8
Margin of Safety	--	--	--	--	--	1.3	--	1.3
Total	7.8	7.8	54.1	54.1	491.9	13.3	553.8	75.2

Table 4.2. Current loads and Total Maximum Daily Loads for the Lower Shingle Creek Watershed.

Source	Oxygen Demand (kg/day) from:						Total Oxygen Demand (kg/day)	
	CBOD		NBOD		SOD			
	Current	TMDL	Current	TMDL	Current	TMDL	Current	TMDL
Load: Palmer Lake	67.3	67.3	50.2	50.2	--	--	117.5	117.5
Load: Sources of Sediment Flux	--	--	117.2	38.4	703.0	186.5	820.2	224.9
Wasteload: Diffuse Sources	--[1]	--[1]	11.8	11.8	--	--	11.8	11.8
Margin of Safety	--	--	--	--	--	20.7	--	20.7
Total	67.3	67.3	179.2	100.4	703.0	207.2	949.5	374.9

4.4 SCENARIOS TO ACHIEVE SOD REDUCTIONS AND THE DO STANDARD

The final step in the TMDL modeling is to identify the specific steps necessary to reduce SOD sufficient to meet the DO standard. Various management scenarios were tested separately and in combination using the four calibrated QUAL2K models to determine how effective each would likely be in meeting the necessary SOD reductions. A complete description of these scenarios and the others that were considered is provided in Appendix D.

4.4.1 Wetland Sources

Continuous dissolved oxygen measurements recorded at the outlet of Palmer Lake indicate the system experiences large diurnal swings in DO, with minimum daily values falling well below the standard during both synoptic surveys (Appendix B). While continuous DO was not recorded at the I-94 Wetland site (Upper Shingle Creek), observations show concentrations were very close to the standard during mid/late morning field visits. Moreover, DO concentrations were well below the standard during an early morning longitudinal survey conducted on August 17, 2007 (Appendix B). Thus each calibrated model was assigned wetland outlet DO that was very close to, and at times below the 5.0 mg/L standard. These low DO conditions makes it extremely difficult, if not impossible for the reaches immediately downstream to achieve the DO standard as a daily minimum. Therefore, either wetland restoration or some other type of alteration to

[1] It is noted that there may be diffuse sources of CBOD, but for practical purposes the absence of loading is supported by model calibration to in-stream water quality samples.

each wetland is needed ensure the water discharged from these systems does not fall below 5.0 mg/L DO as a daily minimum.

4.4.2 Low-Flow Channel Form

Removing prescribed SOD and adjusting diurnal wetland outlet DO so that daily minimums do not fall below 5.0 mg/L were not enough to reduce SOD and increase minimum DO during the September low-flow model runs. Thus, creating a low-flow channel was considered as an additional action for the September low-flow model. Introduction of a low-flow channel is expected to decrease wetted surface area contributing to sediment flux, which in turn decreases SOD while also increasing flow velocities and reaeration.

Applying the principles of hydraulic geometry (Leopold and Maddock, 1953) and selecting a non-erodible design velocity based on the channel sediments (using pebble count data collected), the low-flow channel width and depth were determined using the permissible velocity design method. Generally speaking the width of the dry weather channel was assumed to be roughly one-third of the width of the existing channel while depth was approximately doubled.

4.4.3 Combined Scenario

As further discussed in sections 4.5 and 4.6 below, the critical condition for dissolved oxygen in Shingle Creek and Bass Creek occurs in the late summer, when flows typically are at their lowest. Therefore, the scenarios were tested separately and in various combinations to find a management scenario that was most successful in increasing minimum daily DO to at least 5.0 mg/L during the summer low flow condition. The combination of removing prescribed SOD, increasing wetland outlet DO, and altering the low-flow channel was sufficient to meet the required SOD reductions and increase minimum daily DO for both Upper and Lower Shingle Creek. The model results are shown in Figures 4.1 and 4.2 below.

4.5 SEASONAL AND ANNUAL VARIATION

Seasonal variation is accounted for by establishing the TMDL for the critical low flow condition. By selecting the most sensitive conditions for the stream, dissolved oxygen concentrations in all seasons will be protected.

4.6 CRITICAL CONDITION

The critical condition for this TMDL is the summer low flow season. During summer low flow, stream temperatures are at their maximum resulting in minimal holding capacity for stream dissolved oxygen. Stream velocities are typically low, reducing reaeration of the stream. As a result, summer low flow represents the most sensitive conditions for stream dissolved oxygen.

4.7 RESERVE CAPACITY/FUTURE GROWTH

The Shingle Creek watershed is entirely built out except for some infill lots and a few undeveloped parcels in the far western watershed. No new point sources are anticipated in this watershed. However in the event some are considered in the future then permits for any new sources of oxygen demanding characteristics should include effluent limits designed to ensure that the discharges do not contribute to violations of the dissolved oxygen impairment.

No new growth is anticipated. The Shingle Creek Watershed Management Commission has rules in place for development and redevelopment that require treatment of runoff to remove nutrients and sediment and require runoff rate control and volume management by infiltration or some other type of abstraction. These standards will limit any new sources of diffuse load.

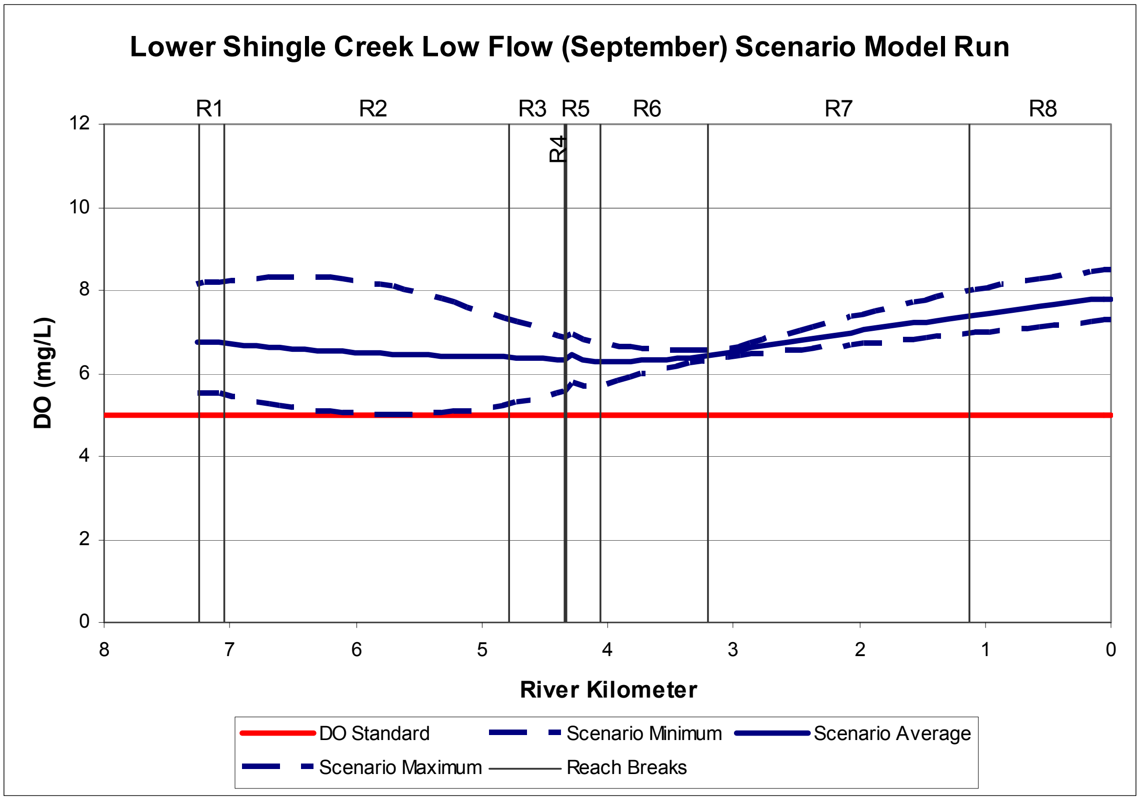

Figure 4.1. Lower Upper Shingle Creek lower flows model run.
Combined scenario removing prescribed SOD, adjusting wetland outlet DO, and adding a low-flow channel.

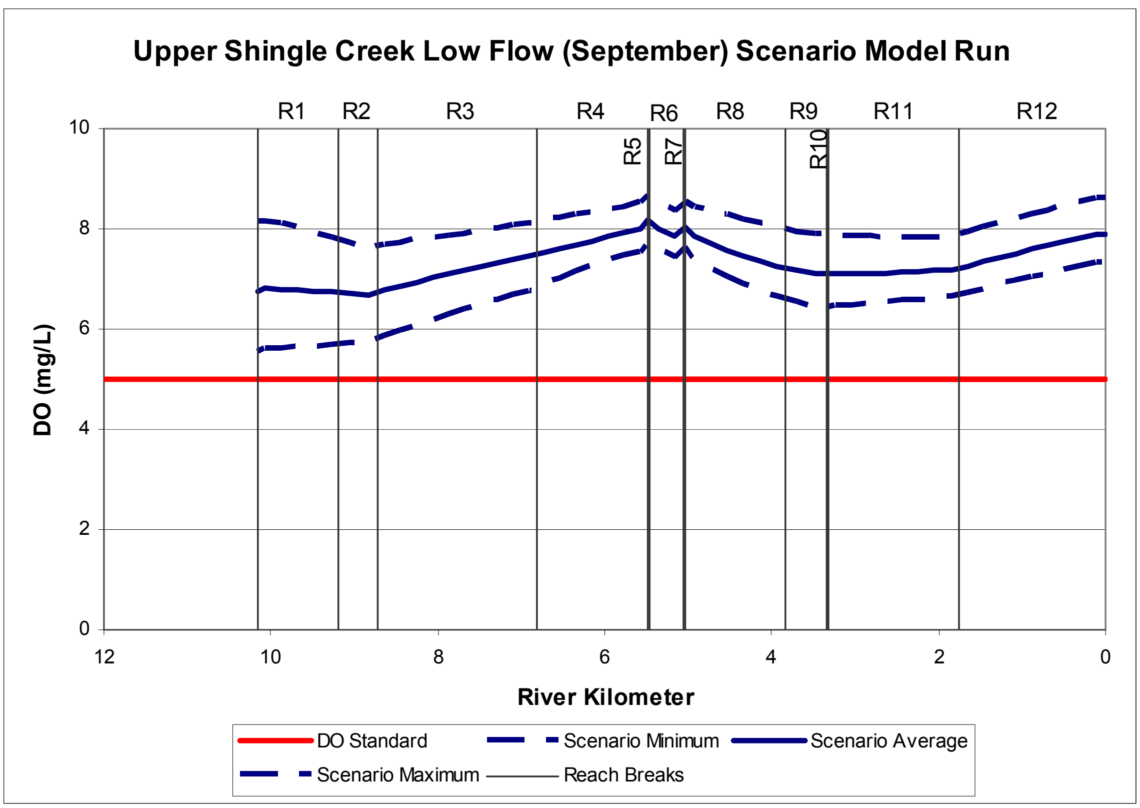

Figure 4.2. Upper Shingle Creek lower flows model run.
Combined scenario removing prescribed SOD, adjusting wetland outlet DO, and adding a low-flow channel.

4.8 NON-TMDL PARAMETERS

The Stressor ID identified five primary stressors affecting biotic integrity in Shingle Creek and Bass Creek. Two of those stressors – low dissolved oxygen and excess chloride - would be addressed by achieving TMDL wasteload and load reductions, either through this TMDL or the previously completed chloride TMDL now in implementation.

Three of the stressors – habitat alteration, altered hydrology, and loss of connectedness – are not associated with a specific pollutant for which a TMDL can be developed. However, based on the Stressor ID and Shingle Creek Corridor Study findings, the goals for those stressors are established below.

4.8.1 Habitat Alteration

While each segment and reach of Shingle and Bass Creeks is unique in the types and extent of habitat present or absent, some general habitat goals can be established for these streams.

- Channel bottom sediments are fairly uniform fine to coarse sand. Increase the diversity of channel bottom substrate and increase average D_{50} particle size.
- Both Shingle and Bass Creeks are very flat, but riffles and pools can be constructed where there is enough grade to enhance rocky substrate and deepen pools.
- The overwidened channel often results in very shallow stream depths. Add a low-flow channel to increase depth where possible.
- In some locations the streams are heavily shaded, and in others there is no canopy coverage at all. Manage riparian trees and vegetation so that at least 25 percent but no more than 90 percent of the stream surface is shaded.
- Remove or minimize barriers to fish and other aquatic and terrestrial organisms, both in the stream and those that inhibit access to and from floodplain, riparian wetlands, and lakes.
- Create or enhance refugia through the addition of woody debris, root wads, deeper pools, backwaters and side pools.
- Restore native vegetation on the streambanks and riparian zone to stabilize streambanks, filter runoff, and provide overhanging vegetation, providing a buffer at least 20 feet wide on both sides of the two streams.

4.8.2 Altered Hydrology

Urbanization in the Shingle Creek watershed has both increased peak flows and reduced base flows. This is most dramatically seen in Upper Shingle Creek where stream flow is 1 cfs or less more than 25 percent of the time. Figure 4.3 presents a generalized desirable flow duration curve for Upper Shingle Creek. A desirable flow regime would reduce peak flows from the current peaks, maintain a stable flow, and sustain a base-flow that would never fall below a desired "ecological base-flow." Generally, the stable flow that would characterize most of the regime would be defined as a flow rate and velocity that would 1) provide sufficient reaeration to keep DO levels above 5.0 mg/L; 2) adequately mobilize and flush sediment; and 3) be tolerated by desirable fish and macroinvertebrate organisms.

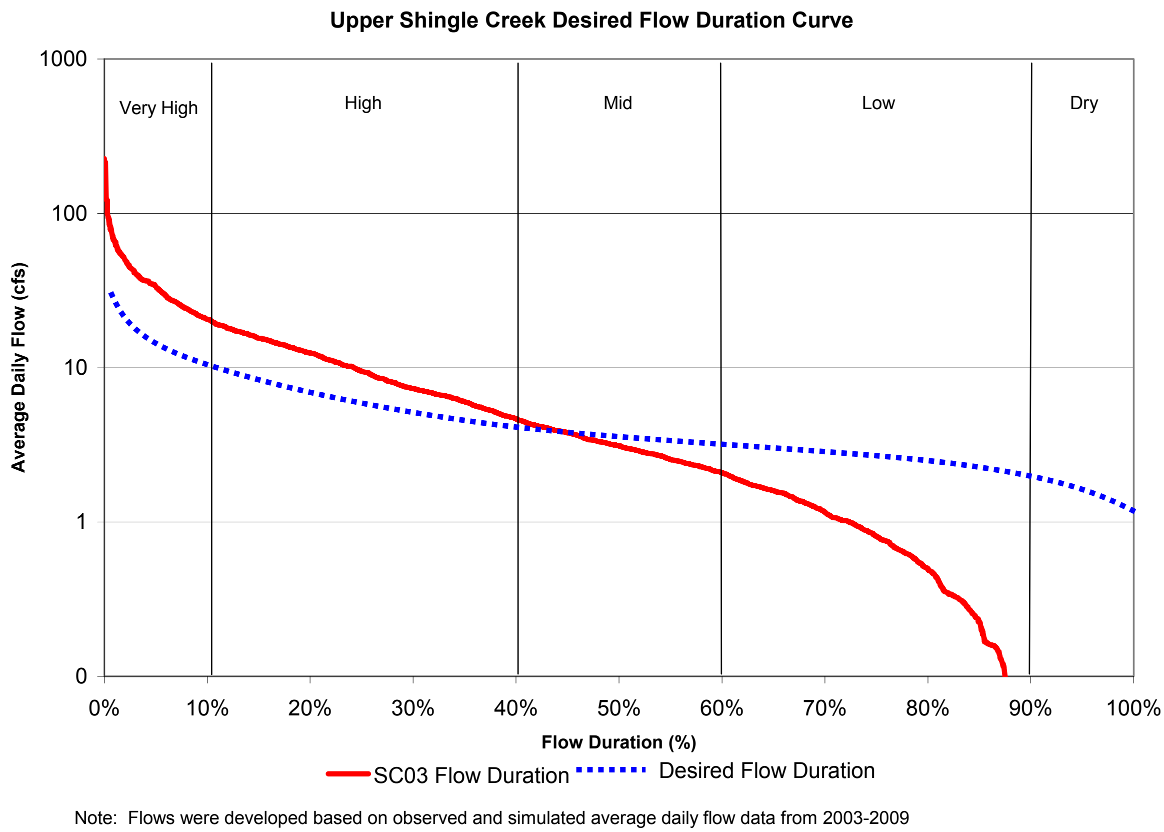

Figure 4.3. Generalized desirable flow duration curve for Upper Shingle Creek.

4.8.3 Loss of Connectedness

The loss of connectedness on Shingle and Bass Creeks relates both to the addition of physical barriers limiting movement as well as loss of contiguousness of landscape that has fragmented habitat. The physical barriers are both human-made, such as drop structures in the stream and lake outlet structures, and natural but human-induced, such as channel incision reducing access to floodplain. Many of the connectedness goals are similar to the habitat goals set forth above.

- Remove or minimize barriers to fish and other aquatic and terrestrial organisms, both in the stream and those that inhibit access to and from floodplain, riparian wetlands, and lakes.
- Create or enhance refugia through the addition of woody debris, root wads, deeper pools, backwaters and side pools.
- Restore native vegetation on the streambanks and riparian zone to stabilize streambanks, filter runoff, provide overhanging vegetation, and provide a buffer at least 20 feet wide on both sides of the two streams.

- Create low-flow channels to carry low flow events and base-flow, and maintain a vegetated floodplain within the channel to carry flows from larger events (Figure 4.4). Regrade streambanks to provide better access to the floodplain.

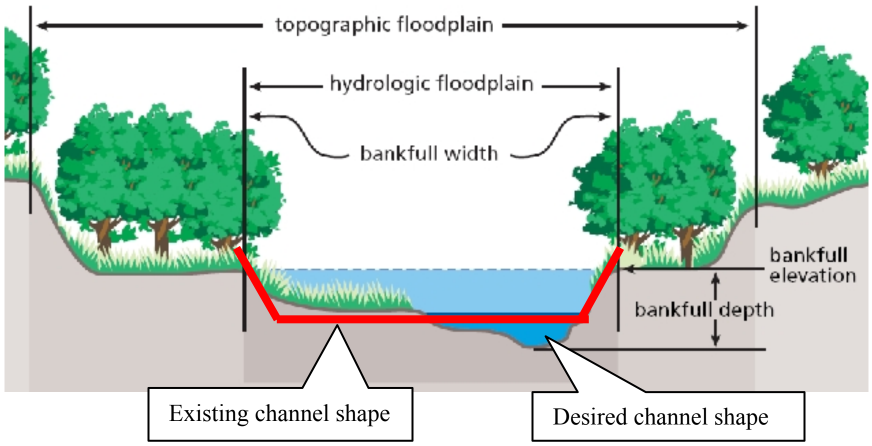

Figure 4.4. Desired Shingle and Bass Creeks channel shape.
(Underlying graphic from the Federal Interagency Stream Restoration Working Group 1998).

5.0 Implementation

5.1 IMPLEMENTATION FRAMEWORK

5.1.1 Shingle Creek Watershed Management Commission

The Commission will coordinate with its member cities on TMDL implementation. The Commission is committed to improving water quality in the Shingle Creek watershed. To this end, it completed a Water Quality Plan and adopted it as a Major Plan Amendment to its Second Generation Watershed Management Plan.

The Water Quality Plan (WQP) is composed of four parts:

- A monitoring plan to track water quality changes over time;
- Detailed management plans for each resource to lay out a specific plan of action for meeting water quality goals;
- A capital improvement plan; and
- An education and public outreach plan.

This WQP charts the course the Commission will take to meet its Watershed Management Plan goals to protect and improve water quality and meet Commission and State water quality standards. While the Plan lays out a series of desired activities and projects, implementation occurs as the Commission's and cities' budgets permit. The Commission as part of the Major Plan Amendment process also developed a cost share formula to provide for Commission participation in the cost of TMDL implementation projects. The Water Quality Plan will be updated and it and the 13 lake and 3 stream TMDL Implementation Plans in the watershed will be integrated into the Third Generation Watershed Management Plan. The Third Generation Plan will be developed in 2011-2012.

The Commission has received significant grant funding from the Minnesota Pollution Control Agency, the Board of Water and Soil Resources, the Metropolitan Council, and the Department of Natural Resources to undertake planning and TMDL implementation projects. The Commission intends to continue to solicit funds and partnerships from these and other sources to supplement the funds provided by the nine cities having land in the Shingle Creek watershed.

5.1.2 Member Cities

Because the Commission is a Joint Powers Organization, it relies on its nine member cities to implement most programs and construct capital improvements. Under the Joint Powers Agreement, cities agree to use their best efforts to carry out directives of the Commission in its exercise of the powers and duties set forth in statute and administrative rule for the protection of water resources. Each city has in place a Local Water Management Plan to address watershed and city goals and objectives; those local plans are periodically updated to reflect resource management plans and adopt or revise strategies for water resource management.

5.2 SEDIMENT OXYGEN DEMAND LOAD REDUCTION STRATEGIES

The following is a description of potential actions for controlling SOD in Shingle and Bass Creeks. These actions will be further developed in the TMDL Implementation Plan. The estimated total cost of implementing these and other potential BMPs ranges from $4 million to $6 million.

5.2.1 Wetland Outlet Reaeration

Both Shingle Creek and Bass Creek are influenced by flow-through wetlands. 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 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. This restoration would also include making habitat improvements as identified in this report. Approximately 12,000 linear feet of Shingle Creek has already been restored or is in process. An additional approximately 26,800 feet could benefit from revised channel morphology at an estimated total cost of $5.1 million. Approximately 4,000 feet on Bass Creek could benefit from restoration, at an estimated cost of $750,000.

5.3 ADDITIONAL BIOTIC INTEGRITY RESTORATION STRATEGIES

Load reduction strategies to decrease sediment oxygen demand will likely not be sufficient to improve biotic integrity in either Bass or Shingle Creeks to meet the biota water quality standards due to the other identified stressors. Additional implementation activities to address these stressors are listed below.

5.3.1 Habitat Restoration

Stream restoration projects that include habitat enhancement and restoration components could lead to improved biotic integrity. Recent projects completed on Shingle Creek in Brooklyn Park include such habitat elements as: rock vanes to provide aeration and varied substrate and to encourage the formation of deeper pools; root wads to introduce woody substrate, provide cover and refuge, and provide lurking areas for aquatic organisms; native streambank vegetation and installation of live stakes to stabilize streambanks and provide opportunities for overhanging vegetation; low-flow channels meandering through a planted point bar; native buffers to reduce runoff and provide upland habitat; and introduction of cobble and boulders to provide additional varied substrate (Figure 5.1). In some reaches additional habitat improvements might include replacement of drop structures with riffle-pools.

These types of improvements are often incorporated into channel morphology restoration projects as described above. However, if completed as a stand-alone project, the estimated cost of stream restoration for habitat is $500,000 per mile. Approximately 12,000 linear feet of Shingle Creek has already been restored or is in process. An additional approximately 26,800 feet could benefit from restoration at an estimated total cost of $2.5 million if completed as stand-alone projects. Approximately 4,000 feet on Bass Creek could benefit from restoration, at an estimated cost of $400,000 if completed as stand-alone projects.

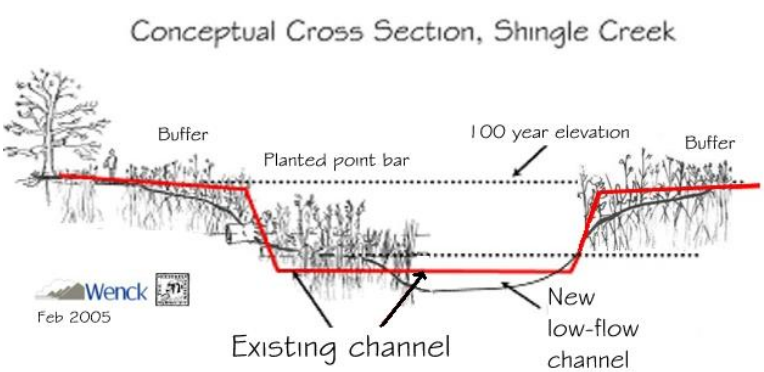

Figure 5.1. Desirable stream cross section with enhanced habitat and a low-flow channel.
Source: SCWMC 2006.

5.3.2 Connectedness Restoration

Remove or Bypass Fish Barriers. While two fish barriers have been removed through stream restoration projects, several barriers to fish migration on Shingle and Bass Creek remain in place. Most of the small drop structures can be replaced with riffle-pool steps with future projects, but two major barriers remain: the seven-foot drop structure in Minneapolis' Webber Park, and the weir and 700' long box culverts conveying Shingle Creek under the parking lot at Brookdale Shopping Center. It is infeasible to remove the Webber Park drop structure due to its proximity to Lyndale Avenue North and I-94 as well as space constraints in Webber Park and an adjacent active railroad track. It may be possible to install a rock-lined fish passage adjacent to the structure at an estimated cost of $50,000 to provide for upstream migration of aquatic organisms.

The Brookdale culverts have been discussed a number of times in the past 10 years for potential daylighting. The culverts pass under parking lots previously owned by one of the anchors, Marshall Fields. That parking lot area was required to meet parking space requirements for the store, which is now closed. As of 2011 the Brookdale Shopping Center is being redeveloped. The City of Brooklyn Center and Hennepin County have expressed interest in a daylighting project should redevelopment provide an opportunity. Daylighting would remove the stream from the culverts and create a natural stream that would no longer be a barrier to movement upstream and downstream. No cost estimate is possible because daylighting would be dependent on potential future redevelopment, in whatever form that would take.

Restore Access to Floodplain and Riparian Wetlands. In less-impacted systems, streams have ready access to floodplain and adjacent riparian wetlands. These areas serve several functions, including refuge from high-flows and breeding or brooding habitat. The current trapezoidal channel form limits access to floodplain. The stream restoration projects described above would include regrading the streambank to provide more ready access to floodplain. In addition, there are several riparian wetlands that could serve as refugia by excavating side channels and pools. The estimated cost of these improvements is $50,000.

5.3.3 Volume Management and Peak Runoff Rate Reduction

Increase infiltration and filtration in the watershed. Encourage the use of infiltration basins, rain gardens, native plantings, and reforestation as a means to reduce runoff volume and peak runoff rates and increase infiltration and evapotranspiration, both on private property and as part of highway, park, and other public projects. This strategy will help to restore surficial groundwater that provides baseflow to the streams. It will also over time help mitigate flashiness by reducing peak flows in the streams. The cost of this strategy varies depending on the Best Management Practice (BMP) and may range from less than $100 for a single property owner installing an individual rain garden to retrofitting parks and open space with native vegetation rather than mowed turf at a cost of $3,000 per acre.

Conduct education and outreach awareness programs. The Education and Outreach Committee of the Commission regularly provides education and outreach information to member cities on these topics for publication in city newsletters, neighborhood and block club fliers, and the city's website. This strategy would encourage the adoption of good individual property management practices for both property owners adjacent to the streams and property owners throughout the watershed. The Commission's current education and outreach budget is $30,000.

5.3.4 Reduce Chloride Loading

In 2007 the MPCA approved an Implementation Plan for the Shingle Creek Chloride TMDL (SCWMC 2007). This Plan identified a number of strategies to help achieve the required watershed-wide chloride reduction of 71 percent. The TMDL established that road salt applied for winter ice control was the primary source of chloride to Shingle Creek and its tributaries including Bass Creek. As identified in the Shingle Creek Stressor ID report, chloride can reduce biotic integrity both directly through impaired water quality and indirectly by stressing streambank stabilizing riparian vegetation near road crossings.

The Shingle Creek Chloride TMDL is now in implementation, and actions are being taken to reduce road salt application through the use of technologies such as pre-wetting salt with brine before it is applied. Hennepin County and Mn/DOT and some of the cities have installed pre-wetting and temperature sensing equipment on all snowplows used in the watershed, while other cities are adopting this technology with routine truck replacements. Pre-wetting requires installation of brine making and storage facilities at a cost of $20,000 – 40,000 per setup. Pre-wetting and temperature sensors add about $10,000 to the cost of plow truck accessories. Other actions underway include the use of chloride-alternative products; applying anti-icing agents to high-priority pavements prior to a snow or ice event; and the experimental use of porous asphalt pavement in strategic intersection locations to prevent the buildup of ice and thus reduce the need to apply road salt.

The Shingle Creek Chloride TMDL Implementation Plan provides for a review every five years to assess progress made toward the required load reductions. The first five year assessment will occur in 2012. That assessment will include an evaluation of the impact of implemented practices as well as an update of strategies to reduce chloride loading.

5.4 ADAPTIVE MANAGEMENT

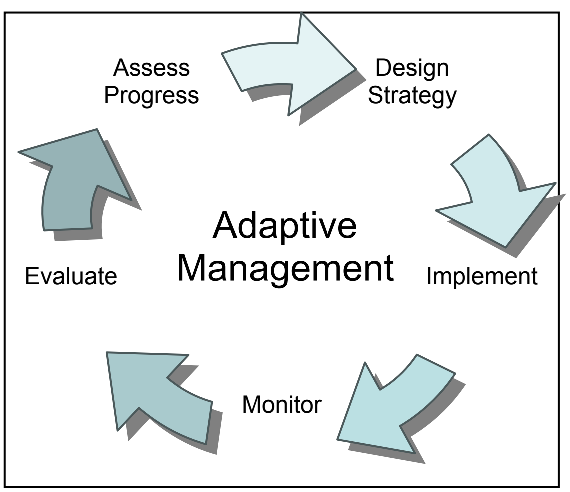

Figure 5.2. Adaptive management.

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 and other stressors within the stream are better understood, management activities both to reduce oxygen demand and to address the other biotic stressors will be changed or refined to efficiently meet the TMDL and lay the groundwork for de-listing the impaired reaches.

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. TMDL implementation will be carried out on an iterative basis so that implementation course corrections based on periodic monitoring and reevaluation can adjust the strategy to meet the standard. Reevaluation every five years will identify those activities that need to be strengthened or other activities that need to be implemented to reach the standards.

6.2 THE SHINGLE CREEK WATERSHED MANAGEMENT COMMISSION

The Shingle Creek Watershed Management Commission was formed in 1984 using a Joint Powers Agreement developed under authority conferred to the member communities by Minnesota Statutes 471.59 and 103B.201 through 103B.251. The Metropolitan Surface Water Management Act (Chapter 509, Laws of 1982, Minnesota Statute Section 473.875 to 473.883 as amended) establishes requirements for preparing watershed management plans within the Twin Cities Metropolitan Area.

Minnesota Rules Chapter 8410 requires watershed management plans to address eight management areas and to include specific goals and policies for each. Strategies and policies for each goal were developed to serve as a management framework in the Commission's Second Generation Watershed Management Plan covering the years 2003-2012. That Plan includes a continuously updated Capital Improvement Program and a Cost Sharing Policy to assist member cities in progressing toward meeting water quality goals. The philosophy of the Commission's Joint Powers Agreement is that the Management Plan establishes certain common goals and standards for water resources management in the watersheds, agreed to by the nine cities having land in the watershed, and implemented by those cities at both the Commission and local levels.

In 2011 the Commission will begin work on its Third Generation Plan covering the years 2013-2022. That plan will update the Second Generation Plan as well as incorporate policies, programs, and activities identified in the 13 lake nutrient TMDLs that have been completed, the Shingle Creek Chloride TMDL, and this Biota and DO TMDL.

6.3 NPDES MS4 STORMWATER PERMITS

NPDES permits for small municipal separate storm sewer systems (MS4) have been issued to the member cities in the watershed as well as Hennepin County, Mn/DOT, and two colleges within the Minnesota State Colleges and Universities system. The City of Minneapolis has an individual NPDES permit for Stormwater – NPDES Permit # MN 0061018. The other cities, Hennepin County, the colleges, and MnDOT Metro District, are covered under the Phase II General NPDES Stormwater Permit – MNR040000. Under the stormwater program, permit holders are required to develop and implement a Stormwater Pollution Prevention Program (SWPPP; MPCA, 2004) that identifies Best Management Practices (BMPs) and measurable goals associated with each of six specified minimum control measures. The unique MS4 identification numbers assigned to these cities, Hennepin County, the colleges and MnDOT Metro District are as follows:

- Brooklyn Center – MS400006
- Brooklyn Park – MS400007
- Crystal – MS400012
- Maple Grove – MS400102
- New Hope – MS400039
- Osseo – MS400043
- Plymouth – MS400112
- Robbinsdale – MS400046
- Hennepin County – MS400138
- MnDOT Metro District – MS400170
- North Hennepin Community College – MS400205
- Hennepin Technical College-Brooklyn Park – MS400198

There are no municipal wastewater discharges in the watershed and three known industrial wastewater dischargers in the watershed. None of the active permits include limits for oxygen demanding characteristics.

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 Program** is not meeting the applicable requirements, schedules and objectives of the **TMDL**, you must modify your **Storm Water Pollution Prevention Program**, as appropriate, within 18 months after the TMDL is approved."

The TMDL Implementation Plan will identify specific BMP opportunities sufficient to achieve a wasteload reduction and the City's SWPPP will be modified accordingly as a product of this plan. Construction stormwater activities are considered in compliance with provisions of the TMDL if they obtain a Construction General Permit under the NPDES program and properly select, install, and maintain all BMPs required under the permit, or 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 Sand and Gravel general permit (MNG49) under the NPDES program and properly select, install and maintain all BMPs required under the permit.

6.4 MONITORING

6.4.1 Monitoring Implementation of Policies and BMPs

The Commission will evaluate progress toward achieving the TMDL in its Annual Water Quality Report. Success will be measured by water quality and biotic improvements and by the completion of or progress toward completion of policies and strategies. The findings of the Annual Water Quality Report and the comments received from the member cities and the public will then be used to formulate the next year's work plan, budget, Capital Improvement Program (CIP) and specific measurable goals and objectives as well as to propose modifications or additions to the management goals, policies, and strategies. At the end of each five year period the Commission will evaluate the success of BMP implementation in progressing towards meeting the water quality goals in this TMDL, and will reconvene the Technical Advisory Committee to determine if adjustments to the Implementation Plan are necessary.

6.4.2 Follow-up Monitoring

The Commission routinely monitors flow and water quality in Shingle Creek at two locations, and partners with the USGS at a third location. Macroinvertebrates are sampled twice a year at four locations on Shingle Creek by student volunteers through the Hennepin County RiverWatch program, which is financially sponsored by the Commission. The Commission has periodically conducted more rigorous invertebrate sampling as a part of special studies and has recently conducted fish sampling on two locations on Bass Creek and two locations on Shingle Creek.

The Commission will continue to routinely monitor Shingle Creek flow and water quality, and will continue to partner with the USGS for as long as the USGS operates its National Water Quality Assessment (NAWQA) Program site on Shingle Creek. The Commission annually updates its Watershed Monitoring Plan and will incorporate periodic routine fish sampling and additional macroinvertebrate sampling on both Shingle and Bass Creeks to supplement the volunteer work.

7.0 Public Participation

7.1 INTRODUCTION

As a part of the strategy to achieve implementation of the necessary reductions, the Shingle Creek Watershed Management Commission (SCWMC) seeks stakeholder and public engagement and participation regarding their concerns, interests, and questions regarding the development of the TMDL.

7.2 TECHNICAL ADVISORY COMMITTEE

A Technical Advisory Committee was established so that interested stakeholders could be involved in key decisions during development of the TMDL. Stakeholders represented on the Technical Advisory Committee or asked to comment on drafts of the TMDL and/or Stressor Identification included local cities, Minnesota Department of Natural Resources (DNR), the Metropolitan Council, the Minnesota Department of Transportation (Mn/DOT) and the Minnesota Pollution Control Agency. All meetings were open to interested individuals and organizations. Technical Advisory Committee meetings where this TMDL was discussed were held on August 14, 2008; February 25, 2010; April 22, 2010; and May 13, 2010.

7.3 PUBLIC MEETINGS

An overview of the TMDL and the proposed methods were presented to the Shingle Creek Watershed Management Commission at a public meeting on August 14, 2008. The results of the TMDL and Stressor Identification were presented to the Commission at public meetings on January 14, 2010 and May 13, 2010. Meeting notes from Shingle Creek Watershed Management Commission meetings can be found at www.shinglecreek.org/.

The official TMDL public comment period was held from June 20, 2011 through August 15, 2011. No comments were received during this public comment period.

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Appendix A
Summary of Historic Dissolved Oxygen Data

1.0 SHINGLE CREEK DISSOLVED OXYGEN DATA

The Shingle Creek Watershed Management Commission collected dissolved oxygen data at different sites along Shingle Creek in 1990-1993 and 2002-2009 (Table 1.1). Seven sites were sampled for dissolved oxygen from 1990-1993 while two sites have been sampled since 2002. Sites SC-00 and SC-03 are currently the primary sampling stations for the Commission's stream monitoring program. Site SC-Queen is located at the Queen Avenue crossing near the border between Minneapolis and Brooklyn Center and is the United States Geological Survey's (USGS) long-term monitoring station for the National Water Quality Assessment (NAWQA) Program. The USGS has monitored instantaneous flow and certain water quality parameters at this site since 1996 and reports results real-time through its web site.

Table 1.1. Shingle Creek water quality monitoring stations and available DO data.

Study Station Name	STORET ID	Location	River Km	# DO Measurements	Violations	Years
SC-Outlet	---	Shingle Creek near drop structure DS of I-94 crossing	0.21	45	0	90-92
SC-00	S001-946	Shingle Creek in Webber Park US of 45th Ave N crossing	1.13	117	25	02-09
SC-Queen (USGS)	USGS-05288705	Shingle Creek at Queen Ave crossing – long-term USGS station	3.20	231	50	90-92, 96-09
SC-BLR	---	Shingle Creek at Bass Lake Rd crossing US of Brookdale Mall culvert	4.78	47	6	90-92
SC-PLO	---	Shingle Creek at 69th Ave crossing DS of Palmer Lake outlet	7.25	47	3	90-92
SC-Noble	---	Shingle Creek at Noble Ave N crossing	11.28	47	2	90-92
SC-02	S003-644	Shingle Creek at Zane Ave N crossing	12.77	63	4	02-07
SC-03	---	Shingle Creek at Brooklyn Blvd crossing US of Zane Ave	13.20	86	6	90-92, 07-09
SC-I94	S003-646	Shingle Creek downstream of I-94 crossing	17.89	42	28	90-92

Note: US = upstream, DS = downstream.

1.1 DISSOLVED OXYGEN GRABS/FIELD MEASUREMENTS

Figures 1.1 through 1.4 graph the dissolved oxygen data available for Shingle Creek by year, river kilometer, month, and time of day.

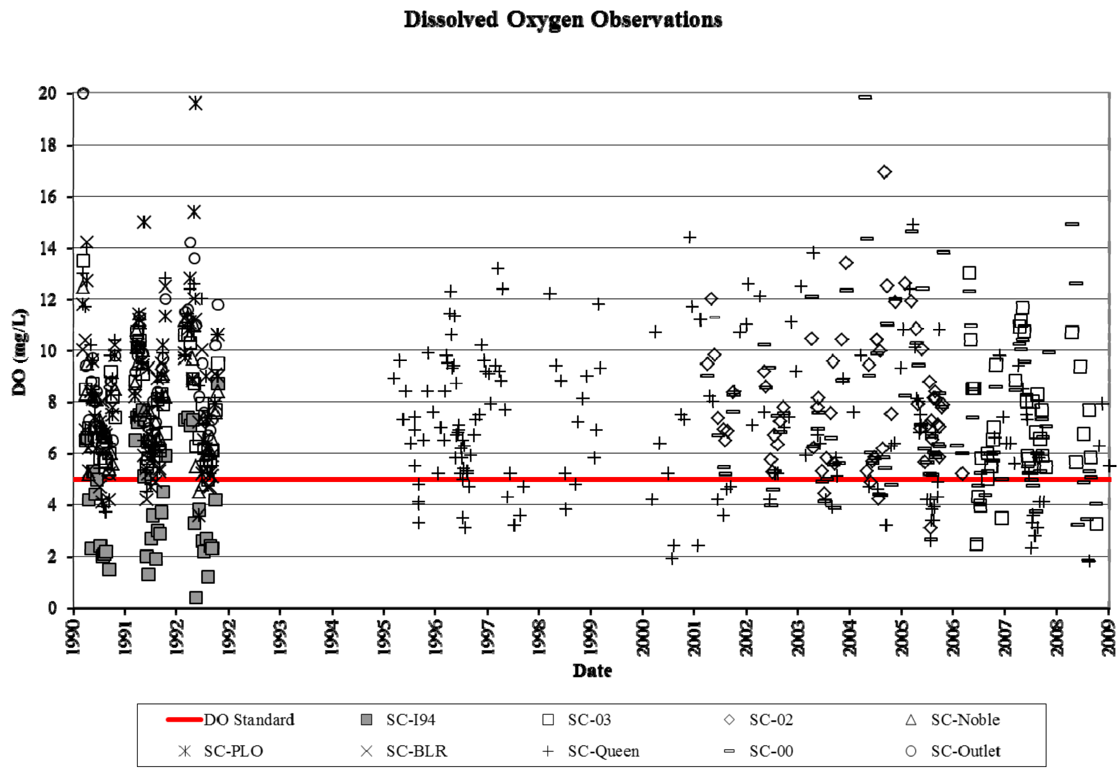


Figure 1.1. Dissolved oxygen data for all Shingle Creek stations by year.

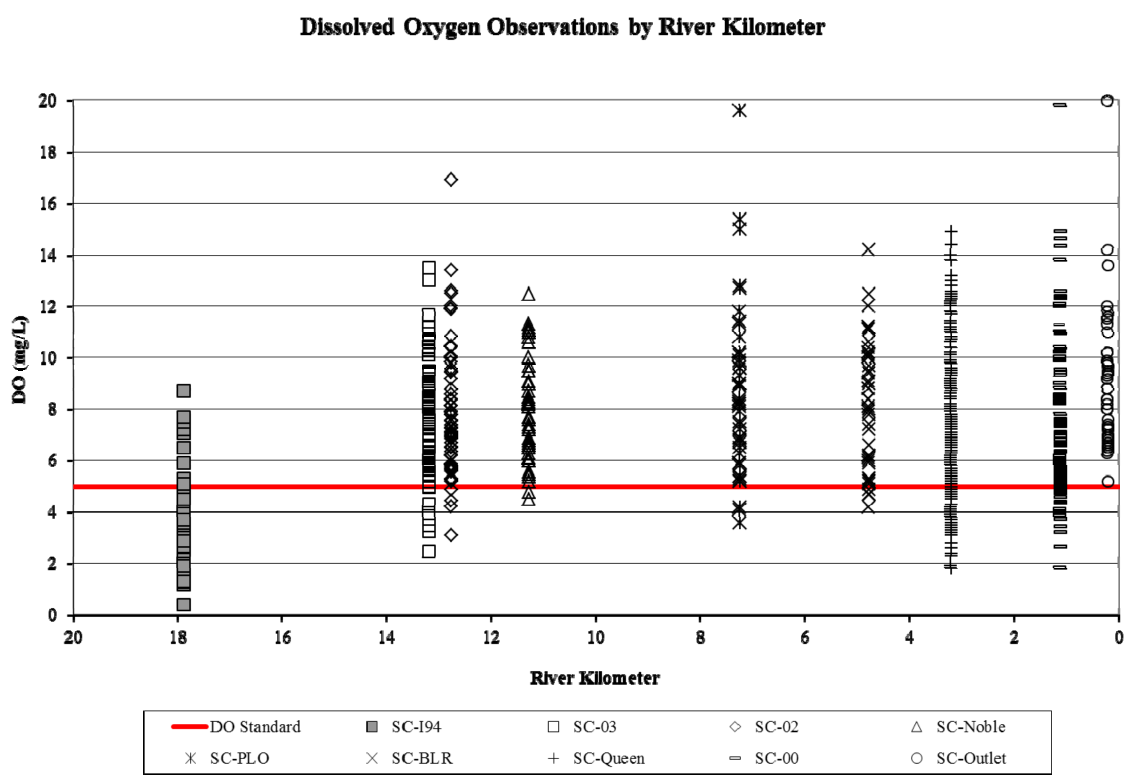


Figure 1.2. Dissolved oxygen data for all Shingle Creek stations by river kilometer.

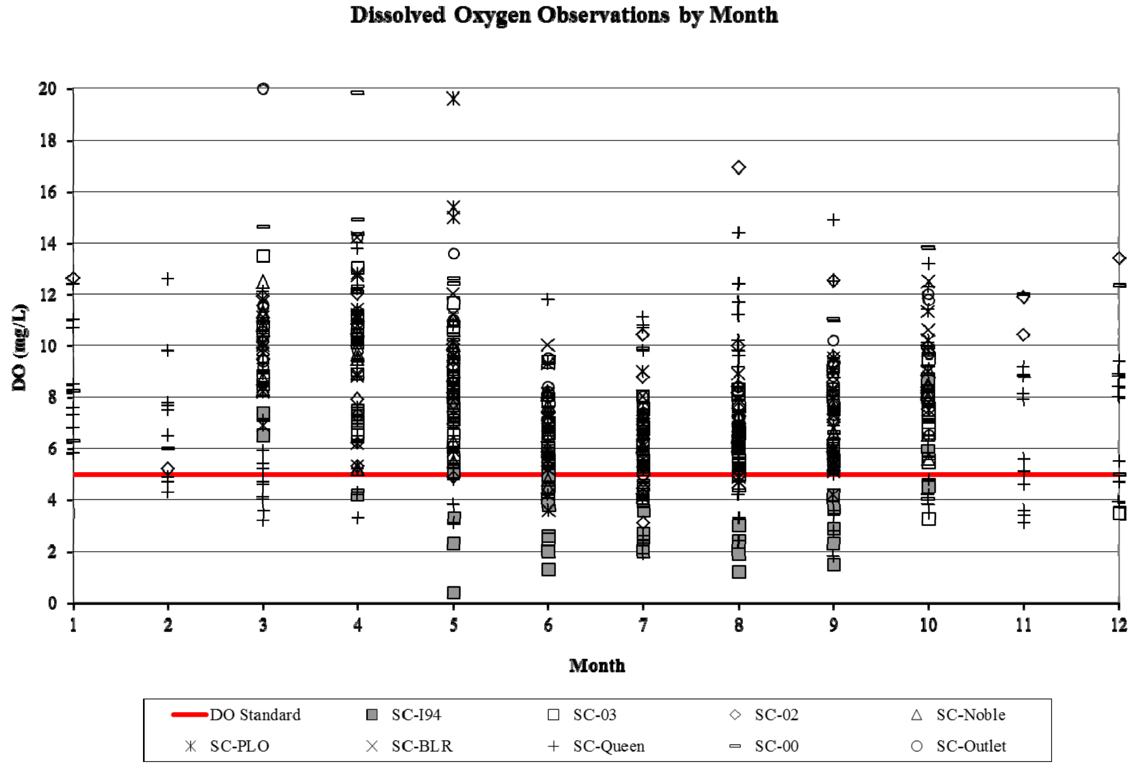


Figure 1.3. Dissolved oxygen data for all Shingle Creek stations by month, regardless of year.

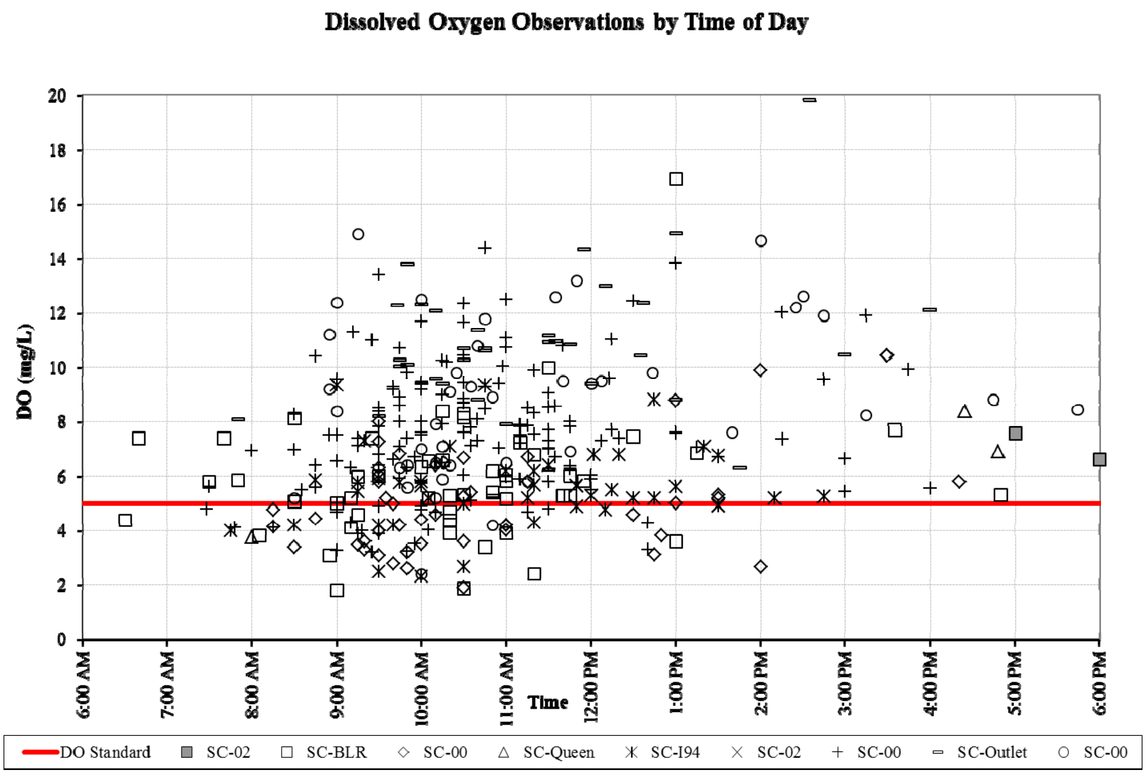


Figure 1.4. Dissolved oxygen data for all Shingle Creek stations by hour, regardless of year and month.

1.2 DISSOLVED OXYGEN RELATION TO FLOW

There is one long-term USGS monitoring station located on Shingle Creek at the Queen Avenue crossing. Average daily flows have been monitored at this station since 1996 (3.2 kilometers or 2 miles upstream from confluence with the Mississippi River). The mean annual flow for water years 1997 through 2009 is 15.2 cubic feet per second (cfs). The maximum average daily flow, 230 cfs, was recorded June 25, 2003. The minimum average daily flow, 0.12 cfs, was recorded August 15, 2005. These statistics are based on flows observed through September 2009. Table 1.2 summarizes annual flow statistics for the USGS station and characterizes the year as a wet, dry or average year based on comparison to the long term average.

Table 1.2. Water year summary for the Shingle Creek USGS station at Queen Avenue.

Water Year	Average Annual Flow at USGS Station (SC-Queen) (cfs)	Percent Variation from Average	Wet / Dry / Average
1997	19.7	29%	Wet
1998	12.1	-21%	Dry
2002	27.9	83%	Wet
2003	20.7	36%	Wet
2004	11.1	-27%	Dry
2005	14.5	-5%	Average
2006	19.4	27%	Wet
2007	10.6	-30%	Dry
2008	12.5	-18%	Dry
2009	3.78	-75%	Dry

Average daily flow can be compared to all dissolved oxygen measurements recorded after the USGS station was established in 1996 (391 of the 725 measurements). Seventy-eight of the 391 DO measurements with paired USGS flow data were below the 5 mg/L standard. Dissolved oxygen and flow exhibit no clear relationship when plotted against one another (Figure 1.5). Representing dissolved oxygen measurements on flow duration plots show the low-flow categories have slightly higher incidence of DO violations compared to the high-flow regimes (Figure 1.6).

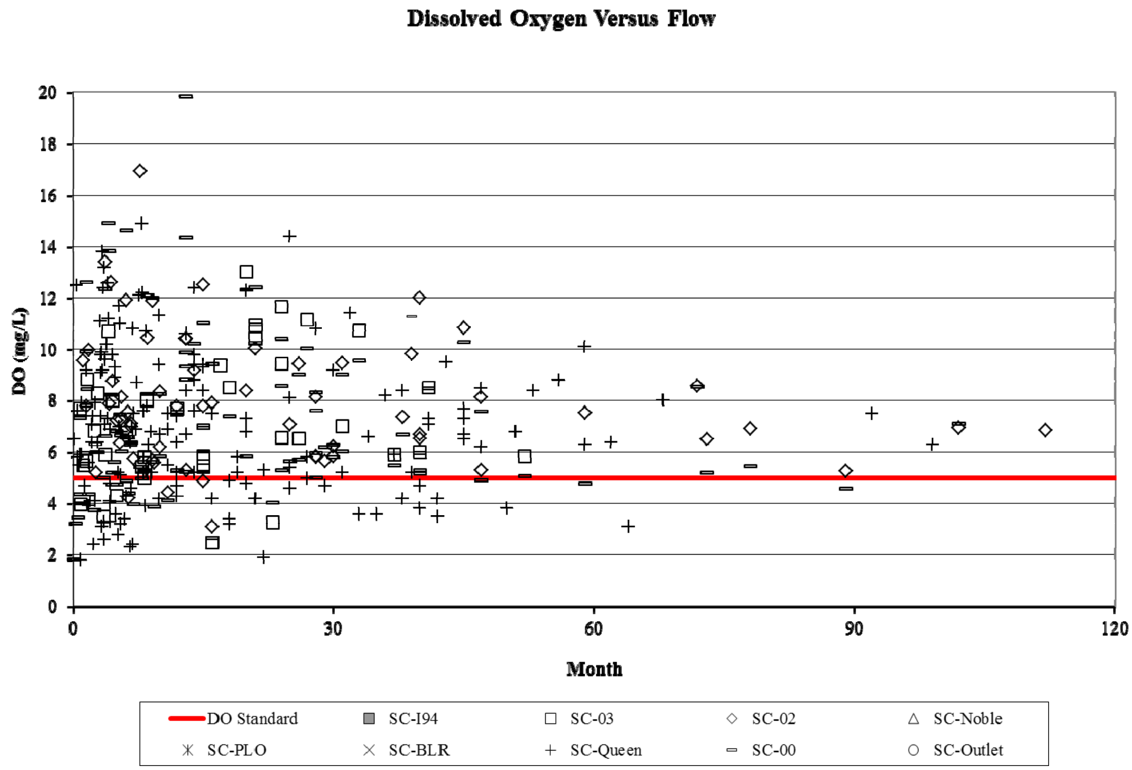


Figure 1.5. Dissolved oxygen compared to average daily flow for all Shingle Creek stations.

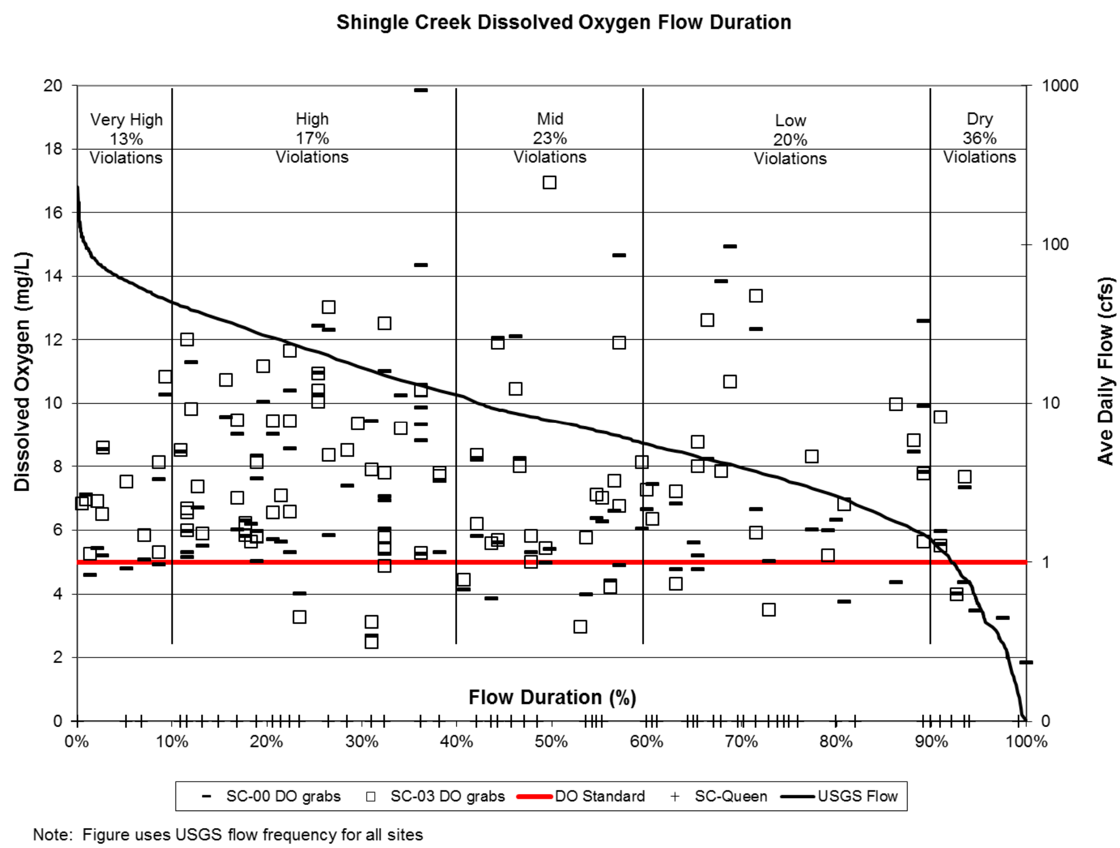


Figure 1.6. Dissolved oxygen flow duration plot using average daily flow data from the USGS (SC-Queen) station.

1.3 WATER QUALITY MONITORING PARAMETERS AFFECTING DO

1.3.1 TEMPERATURE

Temperature has been monitored at stations SC-00 and SC-03 since 2004 and by the USGS at the SC-Queen station since 1996. Average daily temperatures from May through September suggest Shingle Creek is a warm-water stream and at the upper end of the typical range (2-21˚C) for North Central Hardwood Forest ecoregion streams (Table 1.3).

Table 1.3. Average daily temperatures (°C) in Shingle Creek: May-September, 2004-2009.

Parameter	Site	Month				
		May	June	July	August	September
Measurements 2004-2009 (Days)	SC-03	179	180	180	159	141
	SC-Queen	186	179	166	159	179
	SC-00	181	176	184	145	132
Minimum Average Daily Temperature	SC-03	6.8	11.8	15.6	15.3	10.1
	SC-Queen	7.0	13.5	14.0	16.0	10.9
	SC-00	6.7	11.5	14.7	15.2	9.5
Maximum Average Temperature	SC-03	25.3	25.8	28.4	30.0	25.5
	SC-Queen	26.5	27.0	27.0	27.5	24.5
	SC-00	25.6	26.7	26.7	26.0	24.6
Average Daily Temperature	SC-03	14.8	20.0	22.1	19.8	17.1
	SC-Queen	15.8	21.2	21.9	21.5	18.7
	SC-00	15.3	20.8	22.1	21.0	17.7

1.3.2 AMMONIA

Ammonia is produced through excretion by aquatic organisms and the breakdown of organic matter. In aquatic systems, ammonia is rapidly converted to nitrate by nitrifying bacteria, a process which consumes oxygen. Ammonia has been sampled in Shingle Creek at SC-03 (2005-2008), SC-Queen (1996-2009) and at SC-00 (2005-2008). Results indicate ammonia values throughout the system are low and well below typical urban runoff values (Figure 1.7).

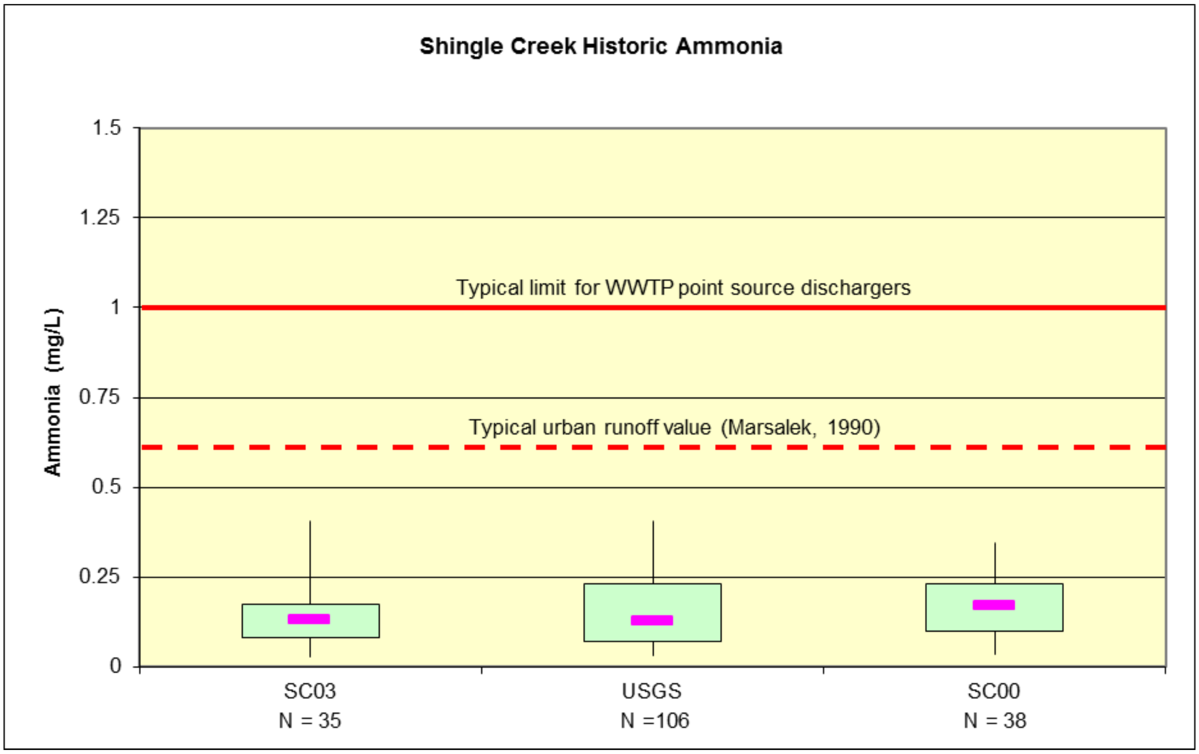


Figure 1.7. Box plots of historic ammonia sampling in Shingle Creek from May through September, 2004-2009 (USGS 1996-2009).

Note. The upper and lower edge of each box represents the 75^{th} and 25^{th} percentile of the data range for each site. Error bars above and below each box represent the 95^{th} and 5^{th} percentile of the dataset. The pink dash is the median concentration of all data collected.

1.3.3 BIOCHEMICAL OXYGEN DEMAND

Biochemical oxygen demand (BOD) is a measure of the oxygen consumed during the breakdown of organic matter. There are two components of BOD: nitrogenous biochemical oxygen demand (NBOD) and carbonaceous biochemical oxygen demand (CBOD). 5-day CBOD was measured by the Shingle Creek WMC from 2005-2008 at the SC-00 and SC-03 monitoring stations. The results show a wide range of $CBOD_5$ concentrations (Figure 1.8). For the most part, measurements were within the range of typical North Central Hardwood Forest ecoregion BOD_5 ($NBOD_5$+$CBOD_5$) values. It is assumed $NBOD_5$ concentrations are low due to low ammonia concentrations throughout the system.

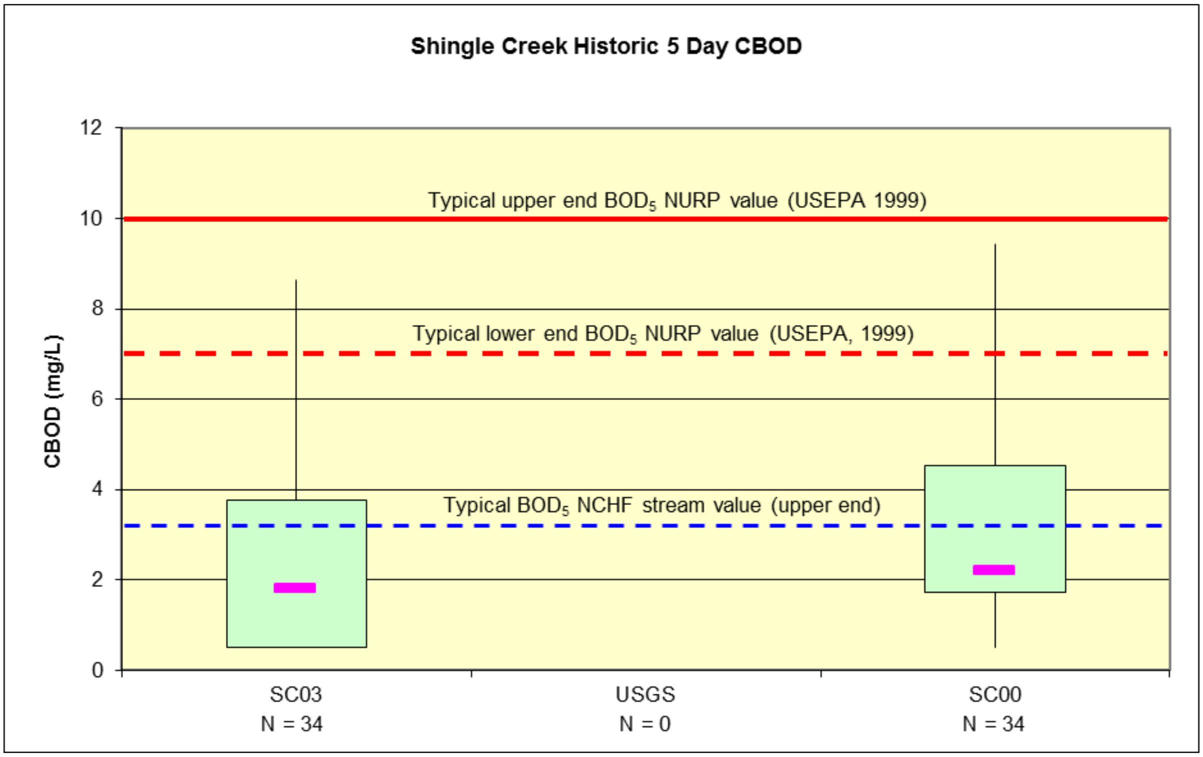


Figure 1.8. Box plots of historic CBOD5 sampling in Shingle Creek from May through September, 2005-2008. Note: The upper and lower edge of each box represent the 75th and 25th percentile of the data range for each site. Error bars above and below each box represent the 95th and 5th percentile of the dataset. The pink dash is the median concentration of all data collected.

1.3.4 PHOSPHORUS

High nutrient concentrations can accelerate primary production, thus increasing diurnal dissolved oxygen concentrations and BOD after the organic matter dies off. Both the Shingle Creek WMC (1997-2009) and the USGS (1996-2009) have monitored phosphorus in Shingle Creek over the past 10 years. Both total phosphorus (TP) and ortho-phosphorus (OP) concentrations are near the upper end of typical north central hardwood forest streams and are usually below average urban runoff values (Figures 1.9 and 1.10).

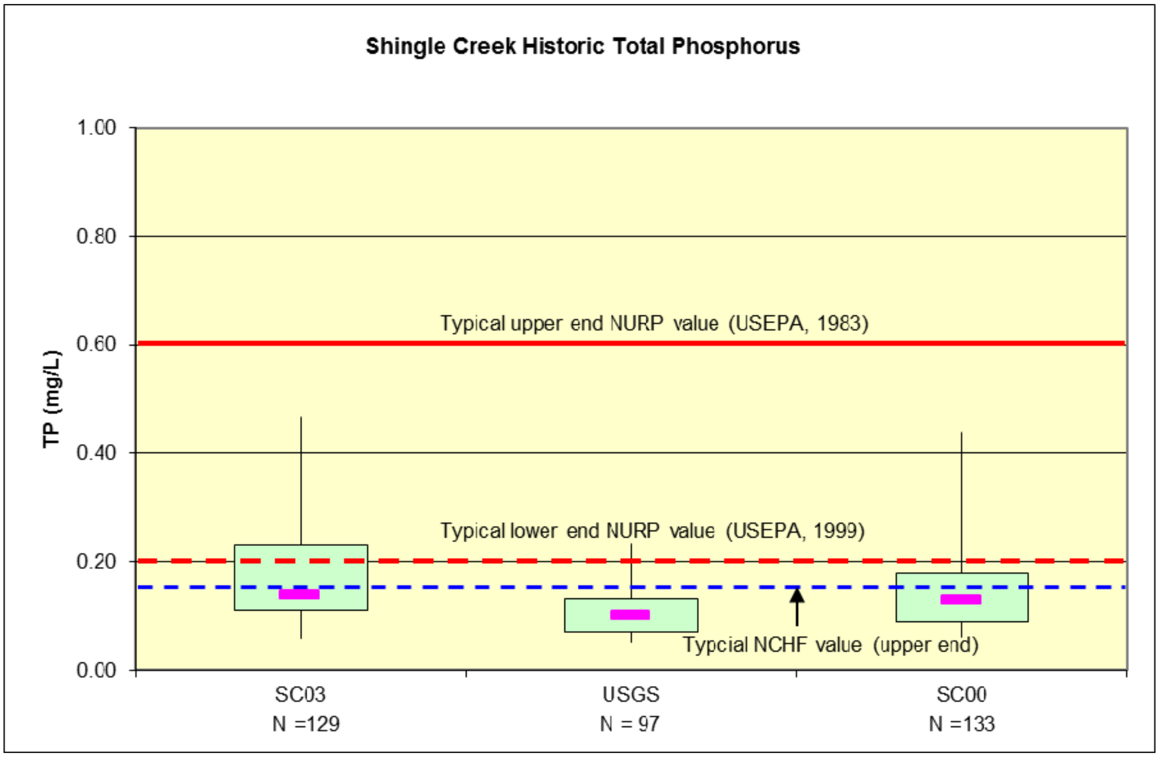


Figure 1.9. Box plots showing historic total phosphorus sampling in Shingle Creek from May through September, 1996-2009.

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 pink dash is the median concentration of all data collected.

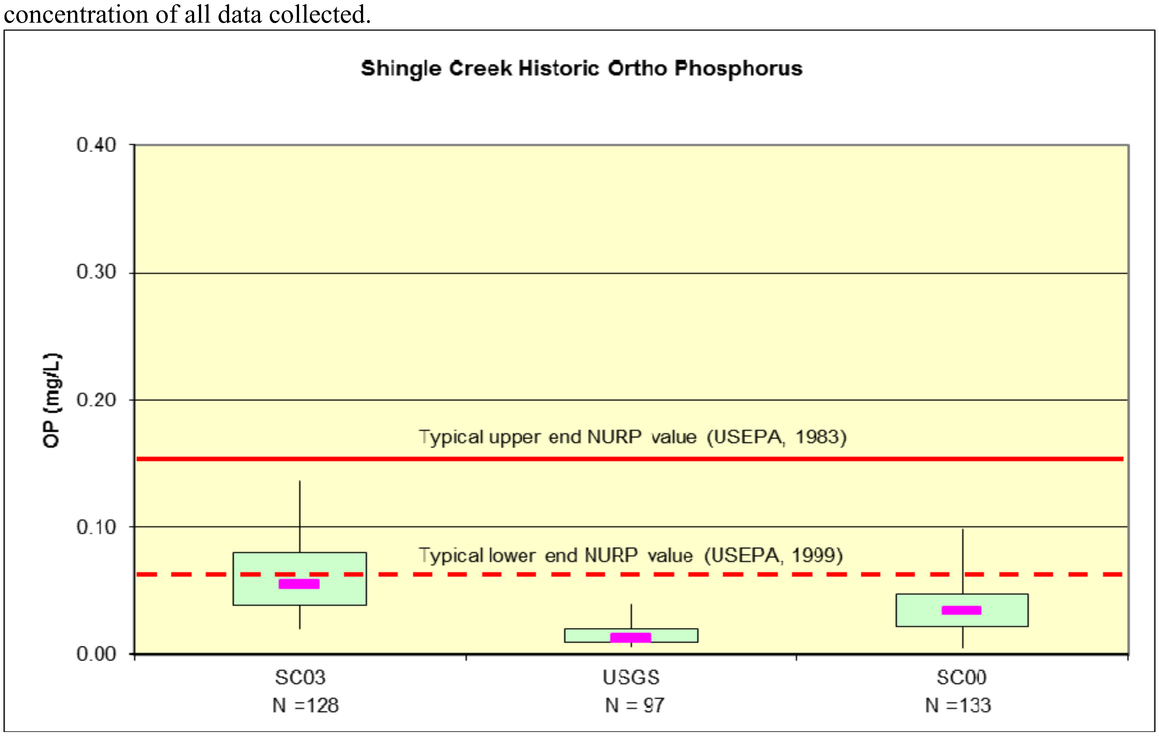


Figure 1.10. Box plots showing historic ortho-phosphorus sampling in Shingle Creek from May through September, 1996-2009.

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 pink dash is the median concentration of all data collected.

Appendix B
Synoptic Survey Methods and Results

1.0 SHINGLE CREEK SYNOPTIC SURVEYS

Synoptic surveys and dye studies were conducted in 2008 to obtain the data needed to construct and calibrate River and Stream Water Quality Models (QUAL2K) for two separate flow events to address Shingle Creek's dissolved oxygen impairment. Also discussed are results from a longitudinal dissolved oxygen survey of Shingle Creek conducted in 2007.

1.1 STUDY AREA AND LOCATIONS

For the purpose of this study Shingle Creek was divided into two segments. The Upper Shingle Creek segment spans from the channelized wetland area located just north of I-94 and east of Boone Avenue in Brooklyn Park to where Shingle Creek flows into Palmer Lake in Brooklyn Park. The Lower Shingle Creek segment spans from the outflow of Palmer Lake in Brooklyn Center to the creek's confluence with the Mississippi River in Minneapolis. All Upper and Lower Shingle Creek sampling stations referred to in this report are defined in Table 1.1.

Table 1.1. Shingle Creek synoptic survey monitoring locations.

Site	Description	Upper/ Lower	Location (River km)	Lab WQ Station	Field Parameter WQ Station	Flow Station	Dye Station
SC-I94	Shingle Creek at wetland just north of I-94	Upper	10.16	X	X	X	X
SC-77	Shingle Creek at 1st Brooklyn Boulevard Crossing	Upper	9.20	X	X	X	X
SC-Candlewood	Shingle Creek at Candlewood Drive Crossing	Upper	6.81	---	---	X	X
SC-03	Shingle Creek at 2nd Brooklyn Boulevard Crossing	Upper	5.47	X	X	X	X
SC-Xerxes	Shingle Creek at Xerxes Avenue Crossing	Upper	1.75	X	X	X	X
SC-PLO	Shingle Creek at 69th Avenue near Palmer Lake Outlet	Lower	7.25	X	X	X	X
SC-BLR	Shingle Creek north of Bass Lake Road Crossing	Lower	4.78	---	X	X	X
SC-Queen (USGS)	Shingle Creek at Queen Avenue Crossing	Lower	3.20	X	X	X	---
SC-00	Shingle Creek in Weber Park north of 45th Avenue North Crossing	Lower	1.13	X	X	X	X

1.2 DYE STUDY

To measure hydraulic time of travel a slug of a tracer (Rhodamine WT dye) was injected at three separate points in Shingle Creek during the June 2008 synoptic survey. Since gauged flows for the September 2008 synoptic survey were lower (1/2 or less than June flows), dye was injected at four separate points (2 Upper and 2 Lower). Dye injection points and monitoring locations for the June and September studies are shown in Figures 1.1 and 1.2. 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 ("Measurement and Computation of Streamflow: Volume 1. Measurement of Stage and Discharge," p. 214).

1.3 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 (cfs). 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.

1.4 WATER QUALITY SAMPLING

Water quality data was collected at seven locations throughout the main stem of Shingle Creek (Figure 1.1). One water sample (grab) was collected and preserved for lab analysis. The lab analyzed each sample 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*. A data sonde (YSI Model 6920 V2) was used in the field to collect the following additional water quality parameters: temperature, conductivity, pH, and dissolved oxygen (DO).

1.5 CONTINUOUS DISSOLVED OXYGEN MEASUREMENTS

Instruments were deployed to monitor continuous DO levels during the dye study and synoptic survey water quality sampling. A data sonde (YSI Model 600 XLM mini-sonde) with internal logging capability was deployed at three locations throughout Shingle Creek during the June survey and four locations during the September survey. These instruments were deployed to monitor continuous DO concentrations at 15-minute intervals for a minimum of 72 hours before, during, and after the synoptic surveys. The instruments also measured and recorded other in-situ parameters such as DO saturation, temperature, conductivity, and pH.

1.6 2007 LONGITUDINAL DISSOLVED OXYGEN SURVEY

A longitudinal survey was completed to measure dissolved oxygen from the headwaters to the outlet of Shingle Creek during early morning on August 17, 2007. Dissolved oxygen and other field parameters for this survey were measured using the same data sonde (YSI Model 6920 V2) to collect field DO readings for the June and September 2008 synoptic surveys.

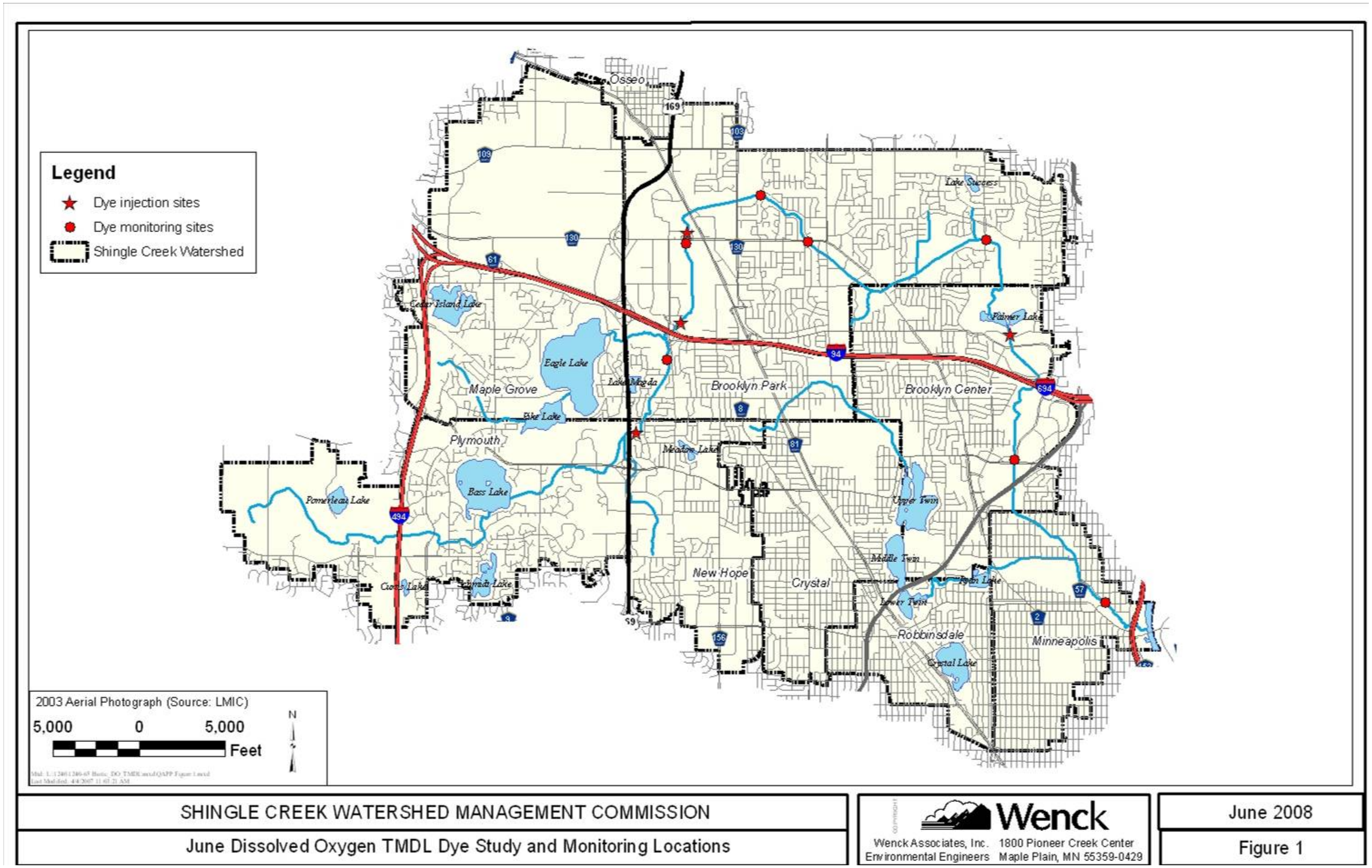


Figure 1.1. Shingle Creek June synoptic survey dye injection and monitoring locations.

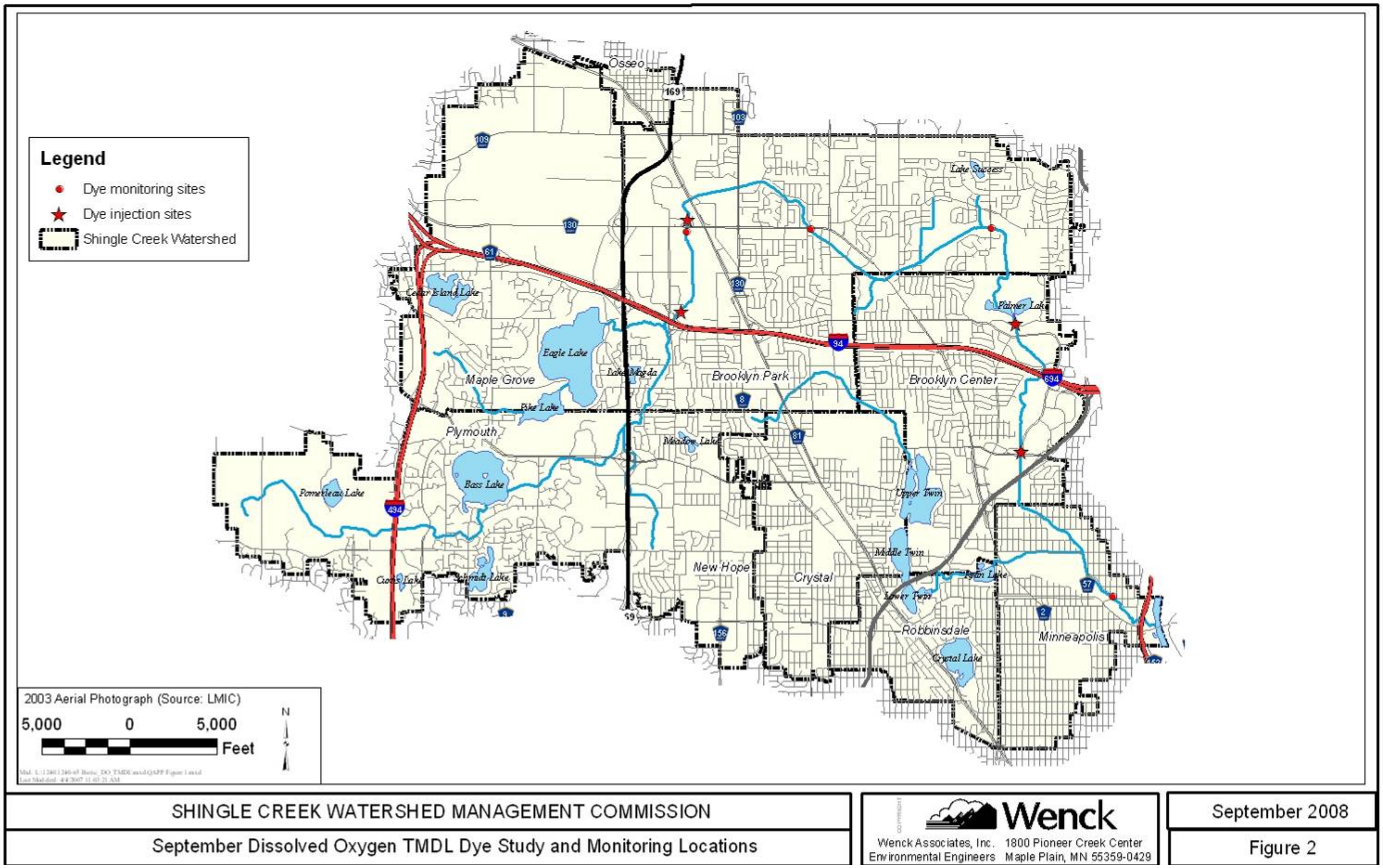


Figure 1.2. Shingle Creek September synoptic survey dye injection and monitoring sites.

2.0 SYNOPTIC SURVEY RESULTS

2.1 DYE STUDY

Results from each dye study are shown in figures 2.1-2.7 and travel times summarized in Tables 2.1 and 2.2. Travel times for Shingle Creek from Candlewood Drive to Palmer Lake (Upper Shingle Creek) could not be estimated during the September low-flow study due to flow loss and/or backwater features “stopping” the dye upstream of Brooklyn Boulevard (SC-03). Grab samples near the Shingle Creek Drive pedestrian bridge upstream of SC-03 show the dye reached this point but was trapped in a series of in-channel pools throughout this reach.

Travel times for most reaches were greater during the September low-flow study compared to the June high-flow study. However, peak travel time for the reach in Lower Shingle Creek between Palmer Lake Outlet (PLO) and Bass Lake Road (BLR) was slightly lower during the low-flow study despite lower flows. It should be pointed out that a majority of this reach flows through channelized wetlands with gradually sloped banks and floodplain access during higher flow regimes.

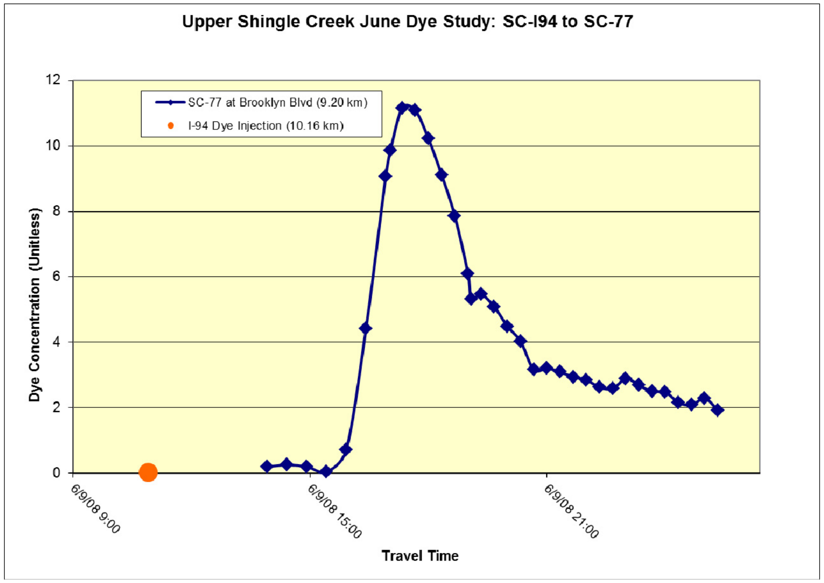
Table 2.1. Estimated travel times from the June 2008 dye study.
Travel times estimated by calculating the time between upstream injection and peak concentration measured downstream.

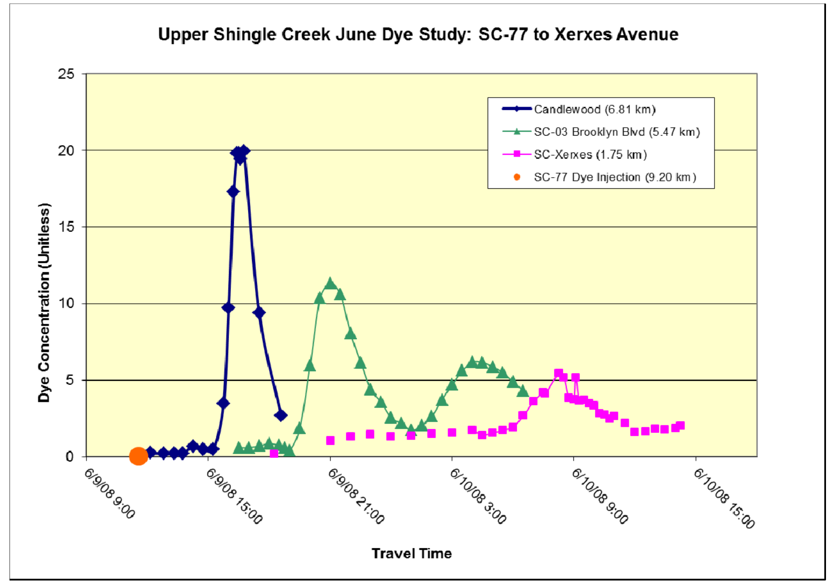
Upper/ Lower	Reach Description	Reach Length (km)	Estimated Travel Time (hrs)	Velocity (ft/sec)
Upper	Wetland North of I-94 to Brooklyn Boulevard (SC-77)	1.43	6.42	0.13
Upper	Brooklyn Boulevard (SC-77) to Candlewood	1.77	4.92	0.33
Upper	Candlewood to Brooklyn Boulevard (SC-03)	1.34	4.50	0.27
Upper	Brooklyn Boulevard (SC-03) to Xerxes Avenue	3.72	11.25	0.30
Lower	Just below Palmer Lake to Bass Lake Road	2.78	16.50	0.16
Lower	Bass Lake Road to SC-00 in Webber Park	3.35	4.00	0.76

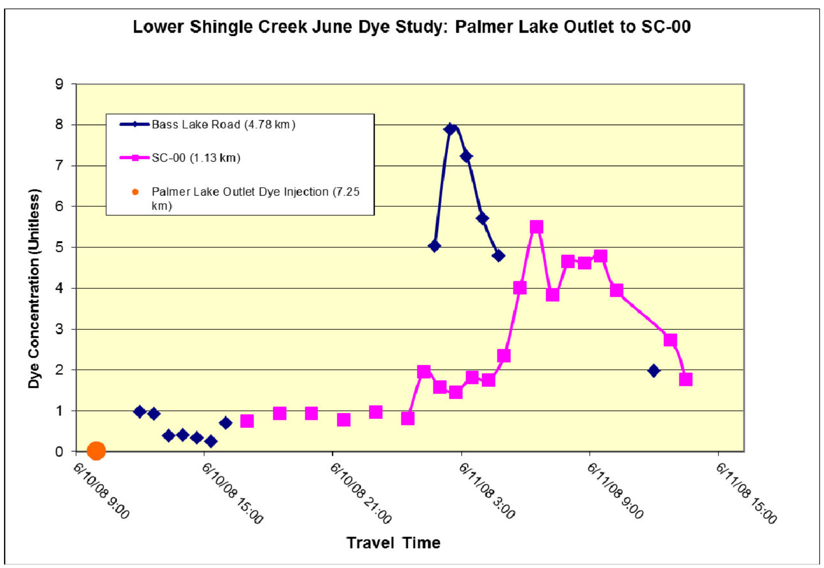
Table 2.2. Estimated travel times from the September 2008 dye study.
Travel times estimated by calculating the time between upstream injection and peak concentration measured downstream.

Upper/ Lower	Reach Description	Reach Length (km)	Estimated Travel Time (hrs)	Velocity (ft/sec)
Upper	Wetland North of I-94 to Brooklyn Boulevard (SC-77)	1.43	18.50	0.07
Upper	Brooklyn Boulevard (SC-77) to Candlewood	1.77	not monitored	--
Upper	Candlewood to Brooklyn Boulevard (SC-03)	1.34	N/A (>4 days)	--
Upper	Brooklyn Boulevard (SC-03) to Xerxes Avenue	3.72	N/A (>4 days)	--
Lower	Just below Palmer Lake to Bass Lake Road	2.78	20.33	0.12
Lower	Bass Lake Road to SC-00 in Webber Park	3.35	15.67	0.19

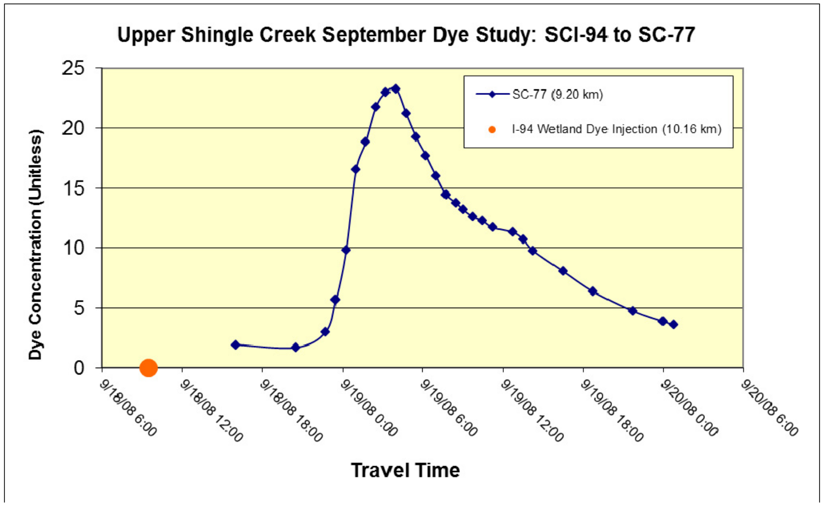
Figures 2.1 to 2.3. June dye study dye concentration time series by reach.

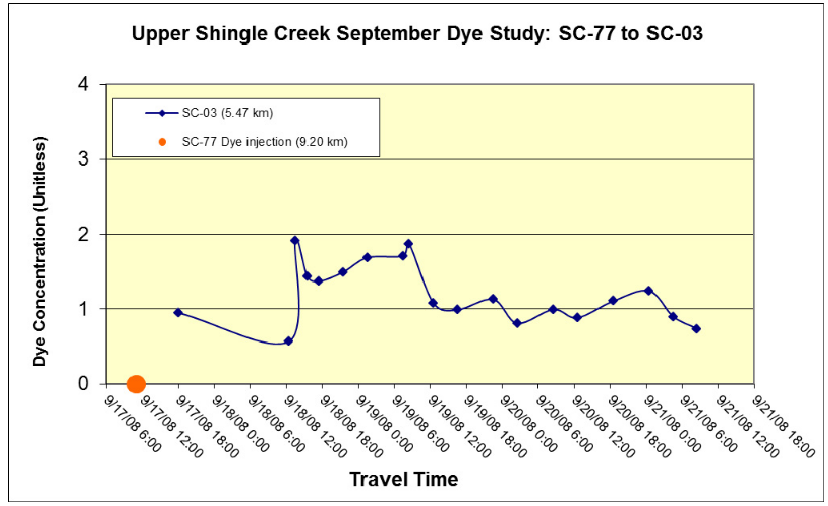


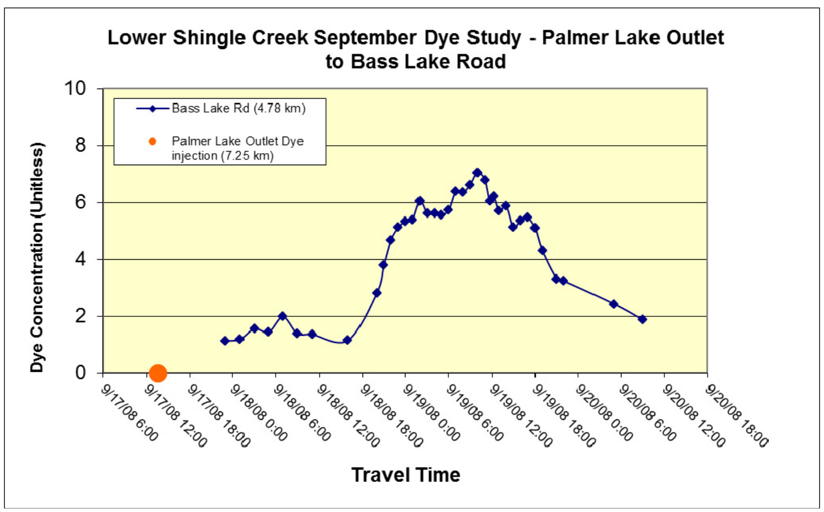


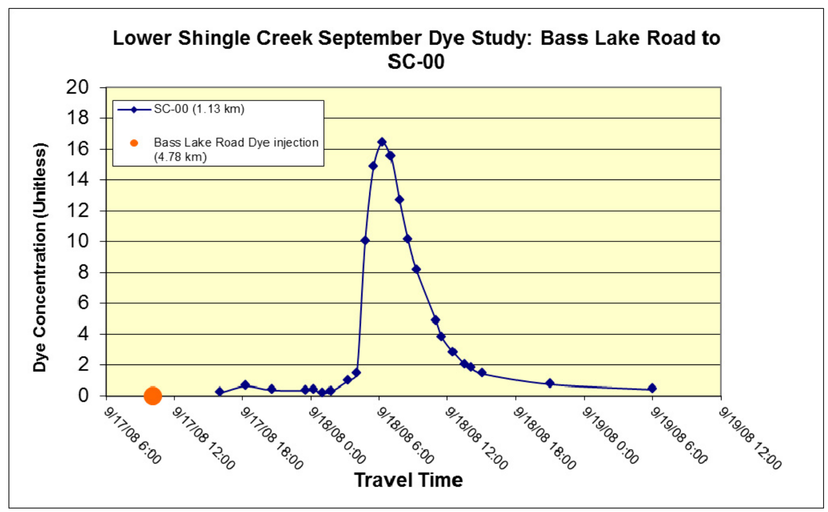


Figures 2.4 to 2.7. September low-flow dye study concentration time series by reach.









2.2 FLOW GAUGING

Results from all stream flow measurements taken during both the high-flow and low-flow studies are shown in Figures 2.8-2.11 and summarized in Tables 2.3 and 2.4. The flow data shows both the Upper and Lower Shingle Creek segments to be gaining streams during the June synoptic survey. During the September synoptic survey, gauged flows varied from one reach to the next as the slower flowing wetland reaches near the I-94 and Palmer Lake headwaters appeared to be losing reaches while the more channelized reaches downstream were gaining.

Shingle Creek is driven almost exclusively by urban runoff and discharge from ponds and wetlands. As a result, flows at individual stations are highly variable from one day to the next throughout the system. While no rain fell on the day of either survey, approximately 1.5 inch of rainfall was recorded in the week leading up to the June synoptic survey and 0.6 inch for the September survey. As a result, total discharge in Upper Shingle Creek decreased by approximately 25 percent and 50 percent per day during the high and low-flow survey, respectively.

Table 2.3. Gauged flow measurements taken during the June 2008 synoptic survey.

Station	Lower/Upper	River km	Q - 6/9 (cfs)	Q - 6/10 (cfs)	Q - 6/11 (cfs)
SC-I94	Upper	10.16	5.20	---	---
SC-77	Upper	9.20	8.50	---	---
SC-Candlewood	Upper	6.81	6.63	---	---
SC-03	Upper	5.47	9.18	---	11.02
SC-Xerxes	Upper	1.75	11.16	8.37	10.96
SC-PLO	Lower	7.25	13.55	10.71	13.88
SC-BLR	Lower	4.78	---	10.50	25.51
SC-Queen	Lower	3.20	15.14	---	---
SC-00	Lower	1.13	14.61	12.07	---

Table 2.4. Gauged flow measurements taken during the September 2008 synoptic survey.

Station	Upper/Lower	River km	Q 9/15 (cfs)	Q 9/16 (cfs)	Q 9/17 (cfs)	Q 9/18 (cfs)	Q 9/19 (cfs)	Q 9/22 (cfs)
SC-I94	Upper	10.16		---	2.12	---	---	---
SC-77	Upper	9.20	5.93	---	2.39	0.87	0.23	0.01
SC-Candlewood	Upper	6.81	4.91	---	---	---	---	---
SC-03	Upper	5.47	3.67	1.58	0.75	0.46	0.67	0
SC-Xerxes	Upper	1.75	7.86	2.87	2.15	---	1.25	0.96
SC-PLO	Lower	7.25	---	6.41	4.74	---	---	1.39
SC-BLR	Lower	4.78	---	---	3.12	1.61	1.93	0
SC-Queen	Lower	3.20	---	6.50	4.56	2.87	---	1.11
SC-00	Lower	1.13	---	---	4.48	2.87	2.91	---

Figures 2.8. Gauged flows by river kilometer for the Upper Shingle Creek June 2008 survey.

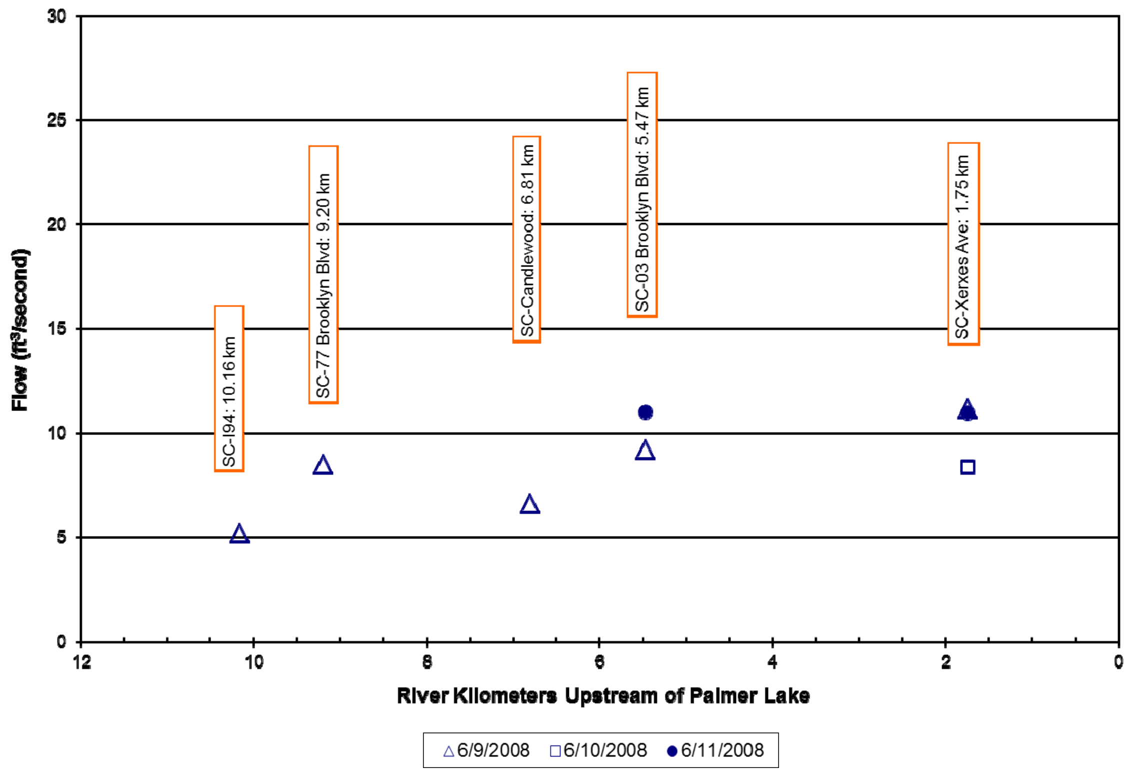


Figure 2.9. Gauged flows by river kilometer for the Upper Shingle Creek September 2008 survey.

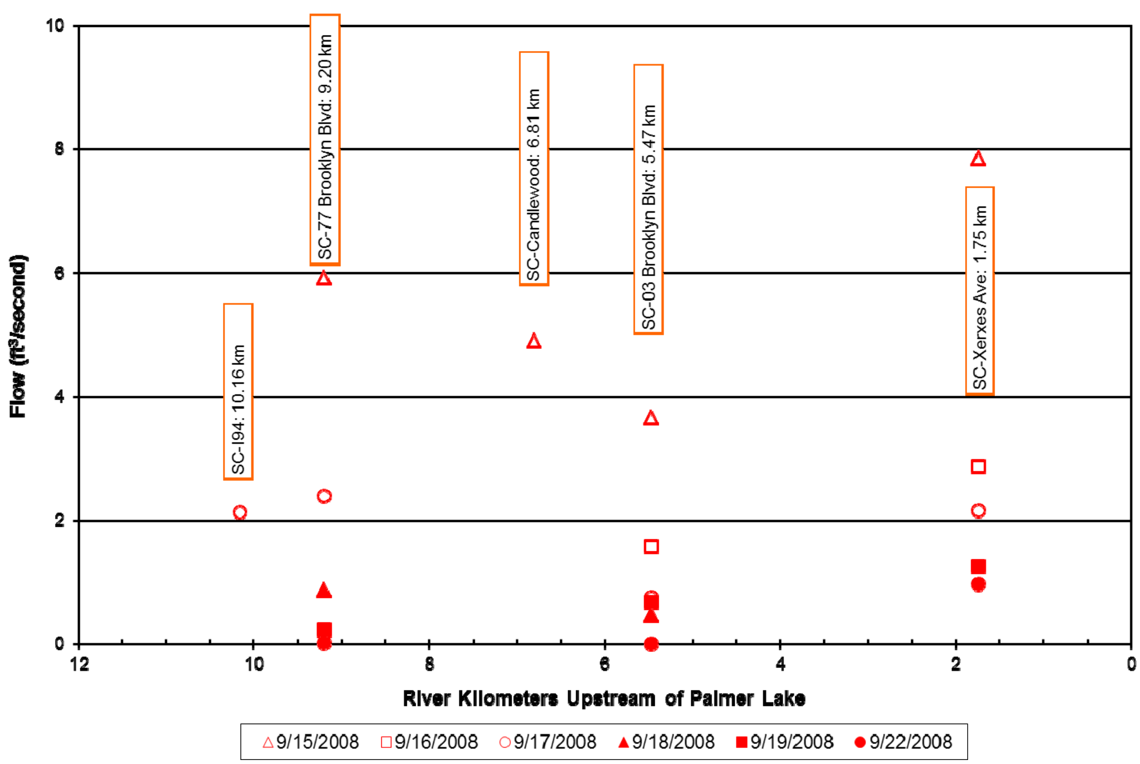


Figure 2.10. Gauged flows by river kilometer for the Lower Shingle Creek June 2008 survey.

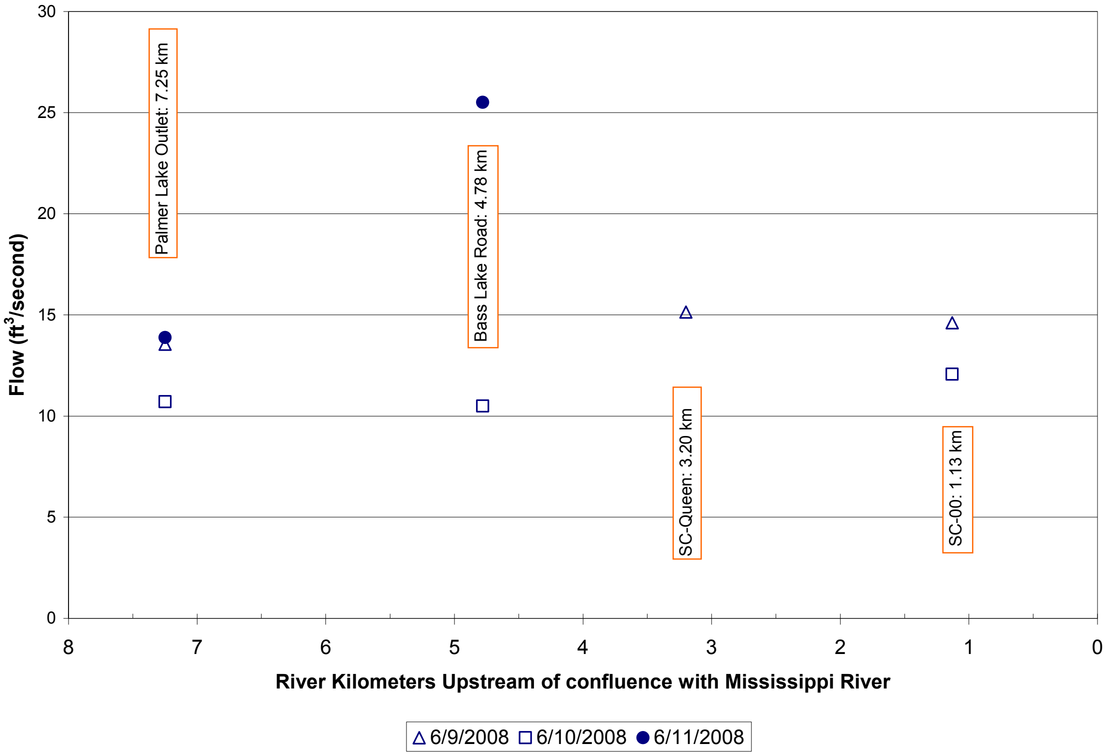
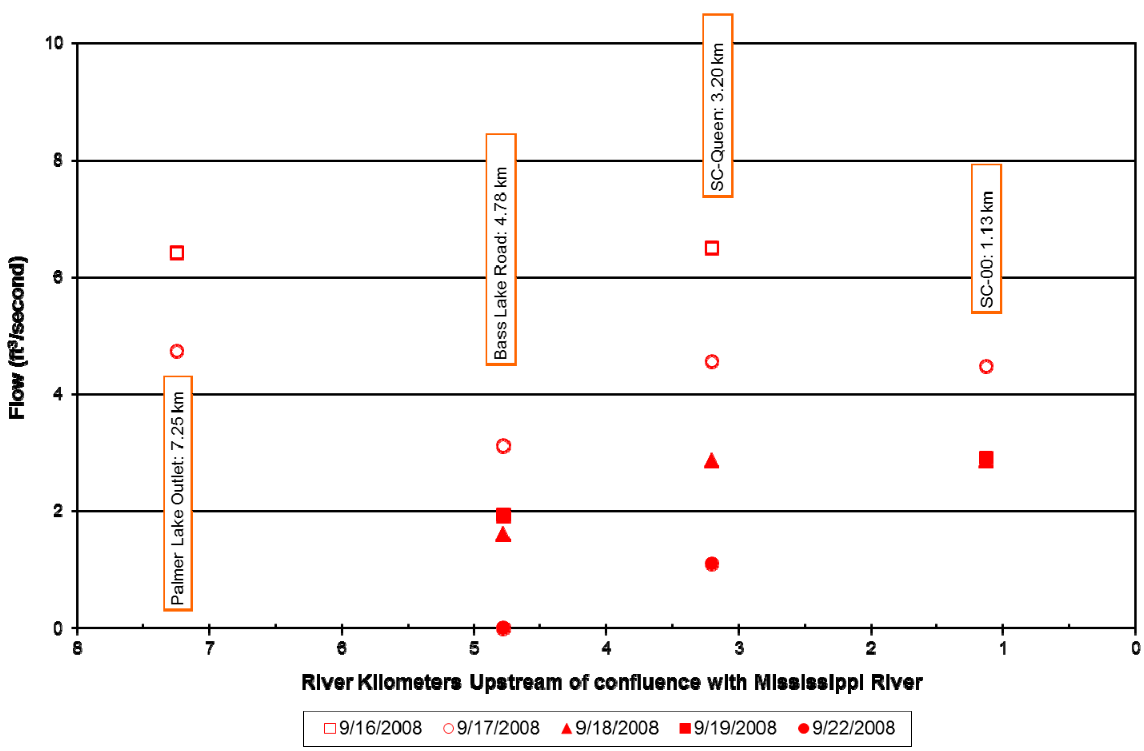


Figure 2.11. Gauged flows by river kilometer for the Lower Shingle Creek September synoptic survey.



2.3 WATER QUALITY

Lab and field water quality results from the June and September surveys are presented in Figures 2.12-2.31 and Tables 2.5 and 2.6. In general, longitudinal changes in water quality from upstream to downstream in Upper and Lower Shingle Creek were consistent between the June and September Surveys. Both stretches displayed higher concentrations of organic-bound nutrients, organic carbon, chlorophyll-*a* and BOD near their wetland headwater reaches. For the most part, these parameters decreased at the downstream monitoring sites as the organic material was broken down, settled out of the water column or was diluted by incoming water.

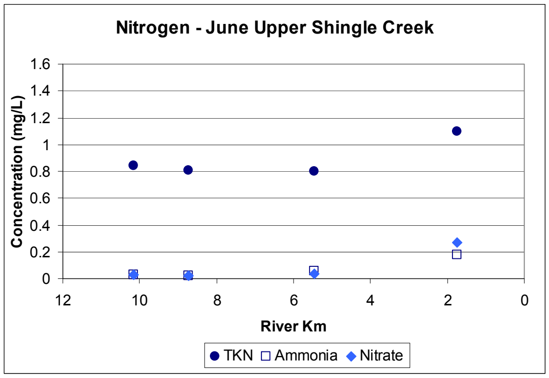
Table 2.5. June 2008 synoptic survey sample results.

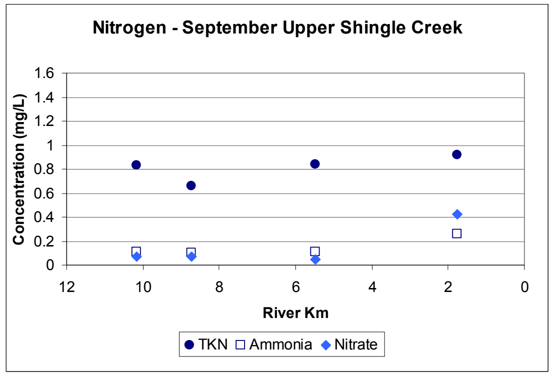
Parameter	Upper Shingle Creek				Lower Shingle Creek		
	SC – I94 (10.16 km)	SC-77 (9.20 km)	SC-03 (5.47 km)	SC-Xerxes (1.75 km)	SC-PLO (7.25 km)	SC-Queen (3.20 km)	SC-00 (1.13 km)
Temperature (Celsius)	19.7	17.93	17.93	16.46	22.25	20.87	21
DO (mg/L)	5.25	4.49	5.78	6.01	12.55	4.65	5.25
pH	7.48	7.5	7.54	7.71	7.95	7.61	7.48
Total Phosphorus (µg/L)	130	130	120	120	160	110	99
Ortho-P (µg/L)	42	55	47	25	19	20	20
TKN (µg/L)	840	810	800	1100	1200	1100	1000
NH_3 (µg/L)	29	22	55	18	150	220	170
Nitrate (µg/L)	25	22	32	270	120	140	200
5-day BOD (mg/L)	<1.0	<1.0	<1.0	<1.0	3.4	2.4	2.1
Ultimate BOD (mg/L)	8.3	7.8	7.8	7.5	12	10	9.6
TOC (mg/L)	12	13	12	10	12	12	11
Chlorophyll-*a* (µg/L)	8	2.8	1.7	4	10	4	4.1

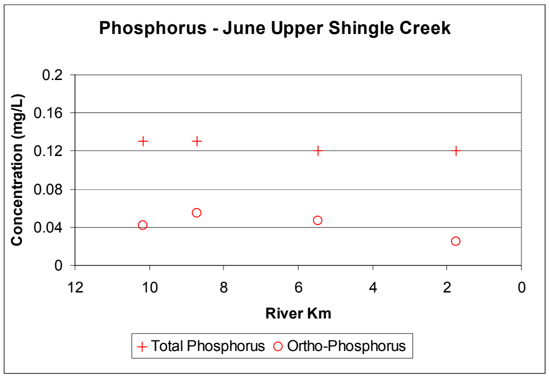
Table 2.6. September 2008 synoptic survey sample results.

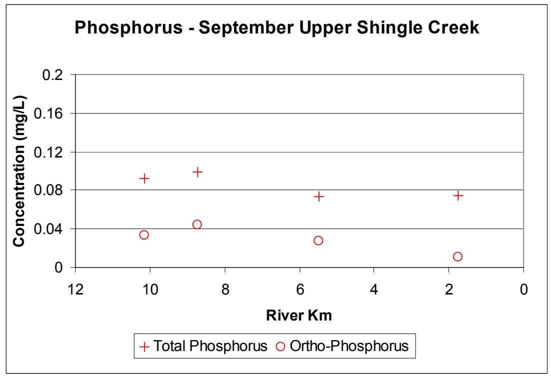
Parameter	Upper Shingle Creek				Lower Shingle Creek		
	SC – I94 (10.16 km)	**SC-77 (9.20 km)**	**SC-03 (5.47 km)**	**SC-Xerxes (1.75 km)**	**SC-PLO (7.25 km)**	**SC-Queen (3.20 km)**	**SC-00 (1.13 km)**
Temperature (Celsius)	16.52	15.32	15.01	13.98	18.65	19.18	19.05
DO (mg/L)	6.02	4.98	5.92	6.47	6.55	6.17	6.65
pH	7.82	8.17	8.71	7.92	7.79	7.83	7.74
Total Phosphorus (µg/L)	92	99	74	75	180	92	71
Ortho-P (µg/L)	33	44	27	11	22	14	11
TKN (µg/L)	830	660	840	920	1500	1000	670
NH_3 (µg/L)	110	100	110	260	240	190	160
Nitrate (µg/L)	68	71	48	420	120	230	320
5-day BOD (mg/L)	<1.00	<1.00	<1.00	<1.00	4.99	3.4	2.37
Ultimate BOD (mg/L)	4.35	4.32	4.12	4.06	13.8	6.55	5.06
TOC (mg/L)	10	9.9	9.3	6.9	8.3	7.5	6.8
Chlorophyll a (µg/L)	1.9	2.5	1.9	3.6	42	15	14

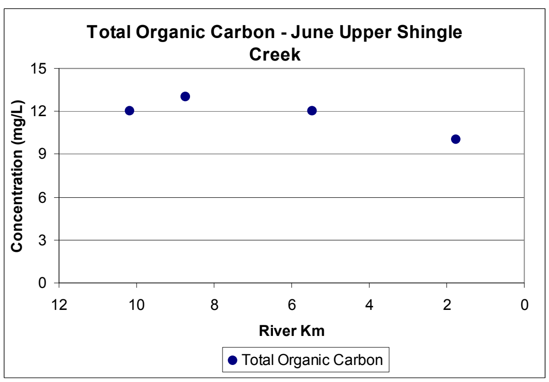
Figures 2.12 to 2.21. June 2008 and September 2008 synoptic survey lab results for Upper Shingle Creek.

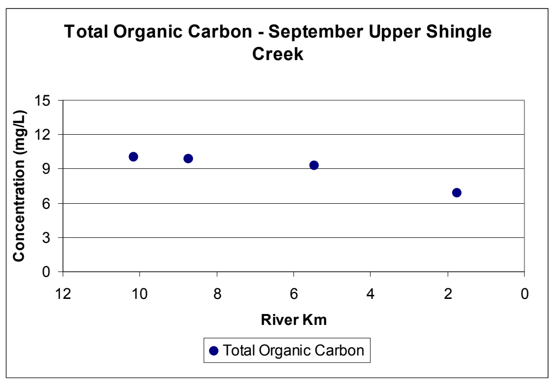


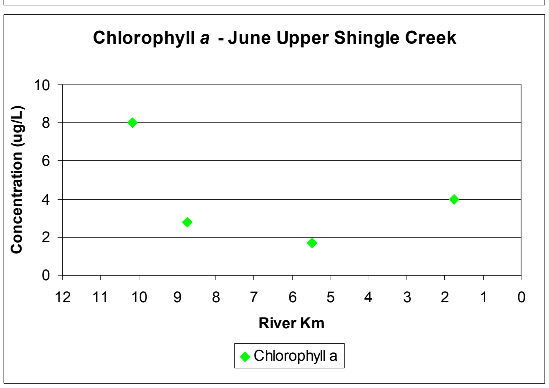


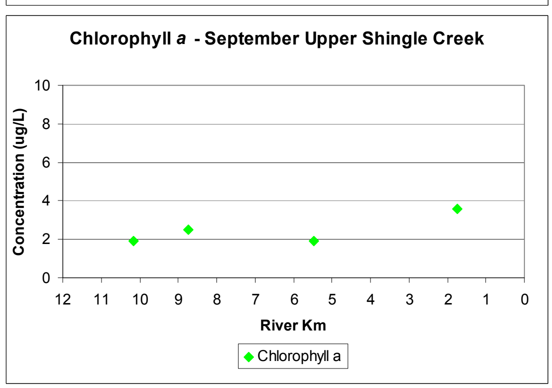


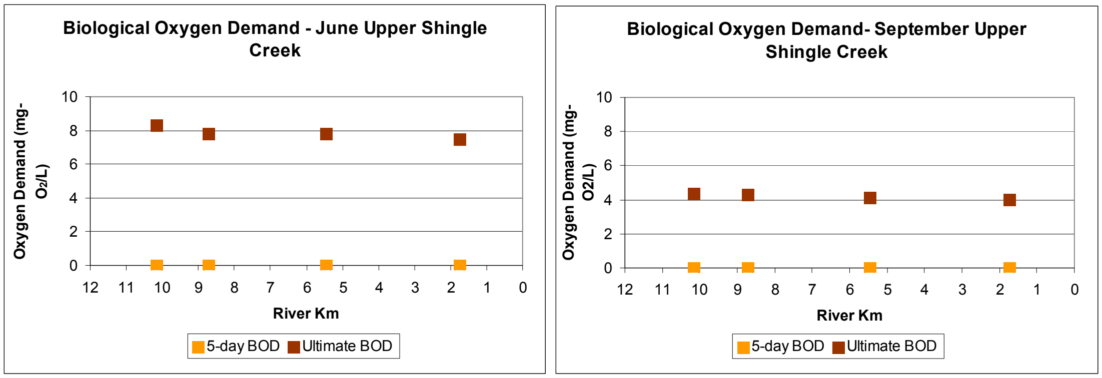




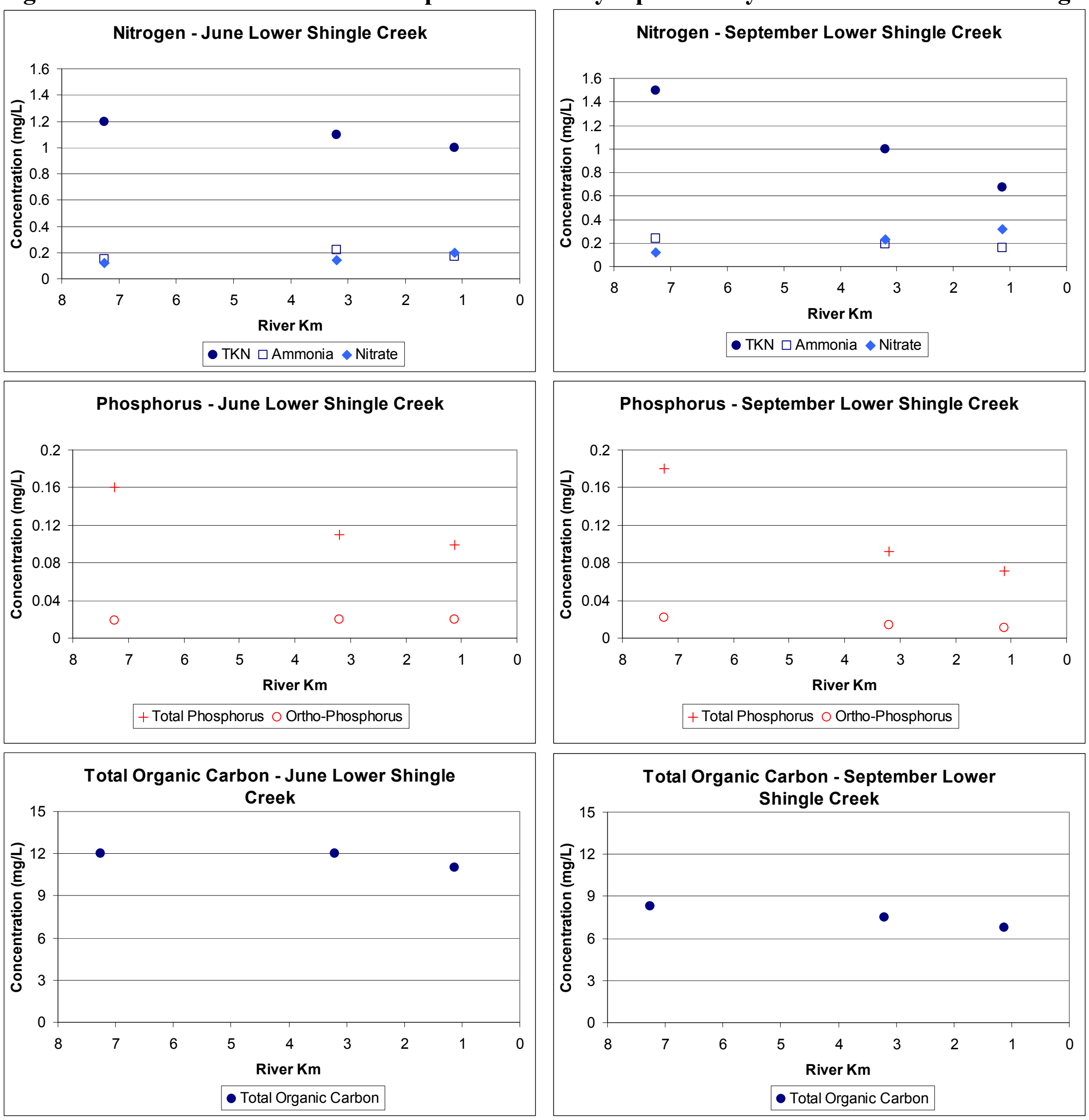


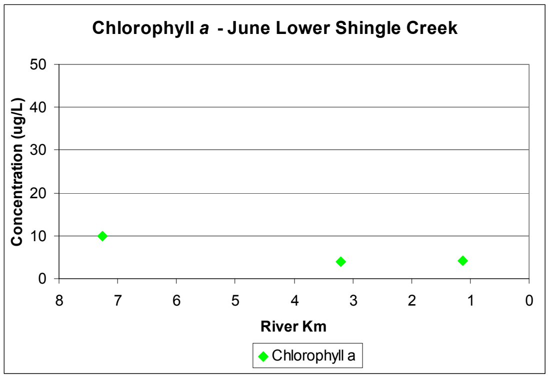


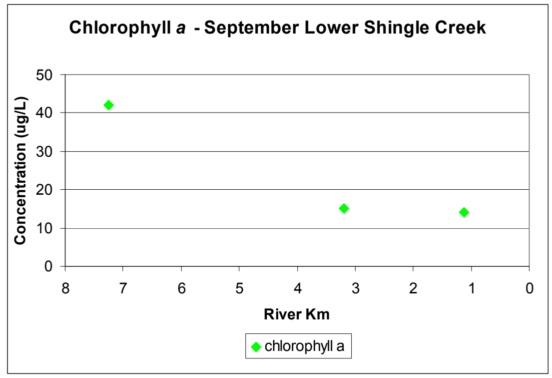


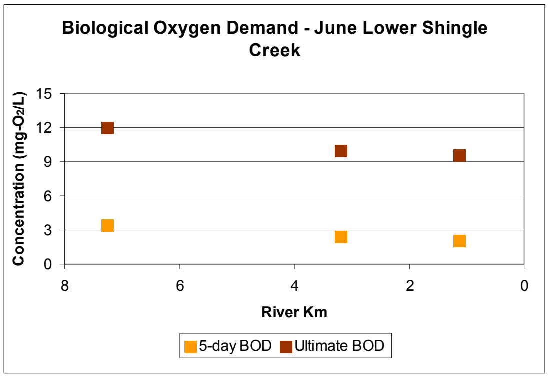


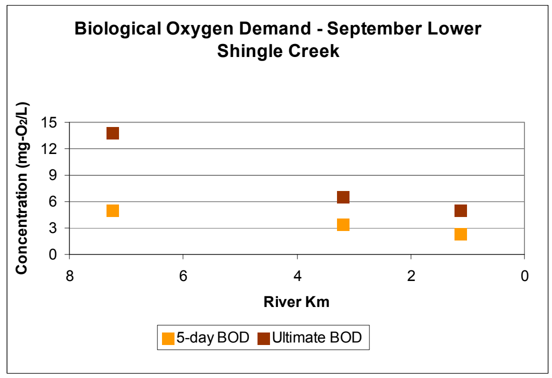
Figures 2.22 to 2.31. June 2008 and September 2008 synoptic survey lab results for Lower Shingle Creek.











2.4 DISSOLVED OXYGEN

2.4.1 Continuous Measurements

Continuous dissolved oxygen data from the sensors deployed during the June 2008 and September 2008 synoptic surveys are presented in Figures 2.32 and 2.33. Dissolved oxygen at the Palmer Lake Outlet Station displayed the largest diurnal DO swing during both synoptic surveys due to high algal and macrophyte productivity in Palmer Lake. Mean DO concentrations at the Palmer Lake Outlet and Queen Avenue stations during the June deployment were 8.6 mg/L and 3.9 mg/L, respectively. Conversely, mean DO concentrations during the September survey were 6.5 mg/L at Palmer Lake site and 6.1 mg/L at Queen Avenue. This suggests there is significantly more dissolved oxygen consumed between the Palmer Lake outlet and Queen Avenue during the June survey than the September survey.

Figure 2.32. June 2008 survey continuous dissolved oxygen concentrations.

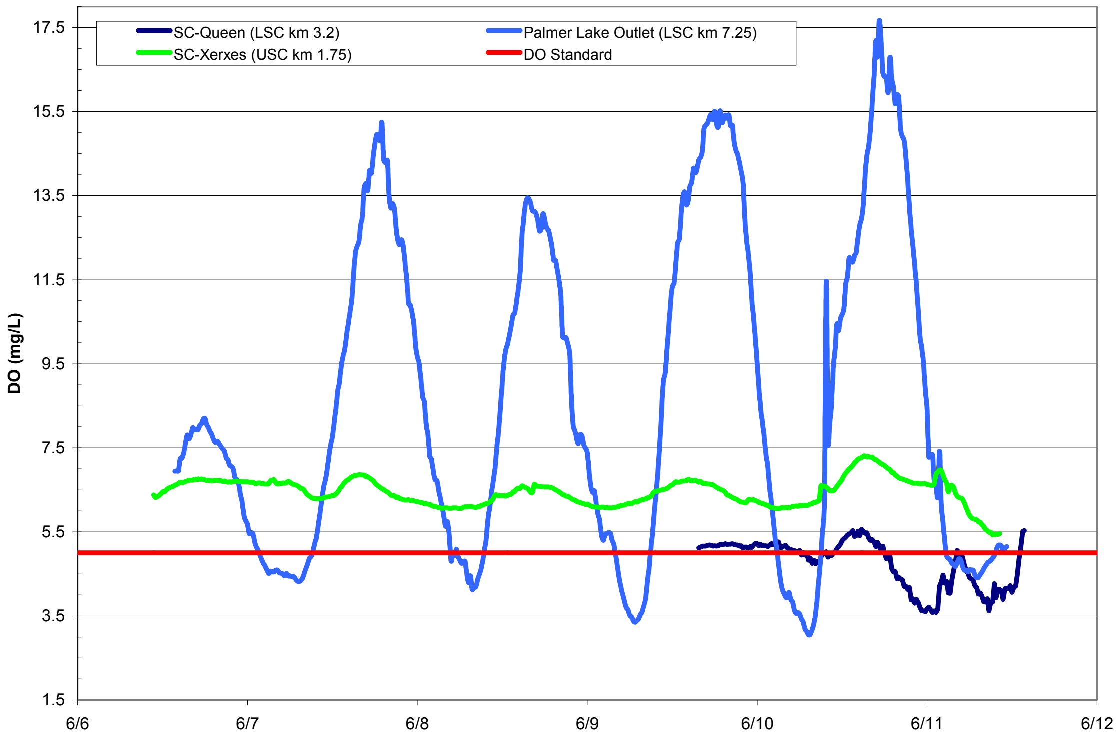
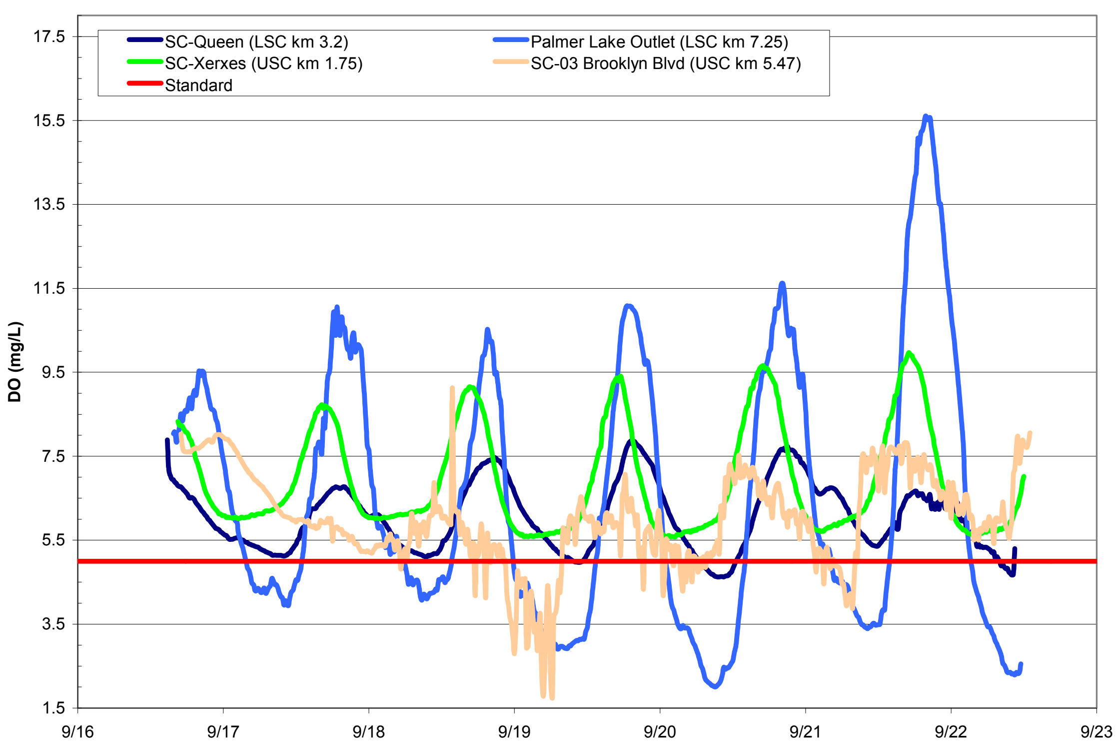


Figure 2.33. September 2008 survey continuous dissolved oxygen concentrations.



2.4.2 Longitudinal Profile

Dissolved oxygen data is plotted longitudinally for Upper and Lower Shingle Creeks in Figures 2.34-2.37. Field grabs of dissolved oxygen were taken using the hand-held YSI (shown in plots as solid squares). The field grabs are labeled with the time of sample collection, if available. Figures 2.34-2.37 also show the continuous dissolved oxygen from Figures 2.32 and 2.33 for June 9 and September 17 (shown in plots as the range of data between minimum and maximum as an "I"). All field grab measurements were taken between 8:00 am-11:00 am for Upper Shingle Creek and 12:00 pm-3:00 pm for Lower Shingle Creek. Upper Shingle Creek profiles show a sag in dissolved oxygen coming out of the I-94 headwater wetland with a steady increase moving downstream toward Palmer Lake. Lower Shingle Creek also displays a dip in dissolved oxygen through the slow-flowing reach downstream of Palmer Lake followed by steady DO levels of 5-7 mg/L between the Brookdale Mall and the outlet of Shingle Creek.

Figure 2.34. Upper Shingle Creek dissolved oxygen field grabs and continuous data collected during the June synoptic surveys.

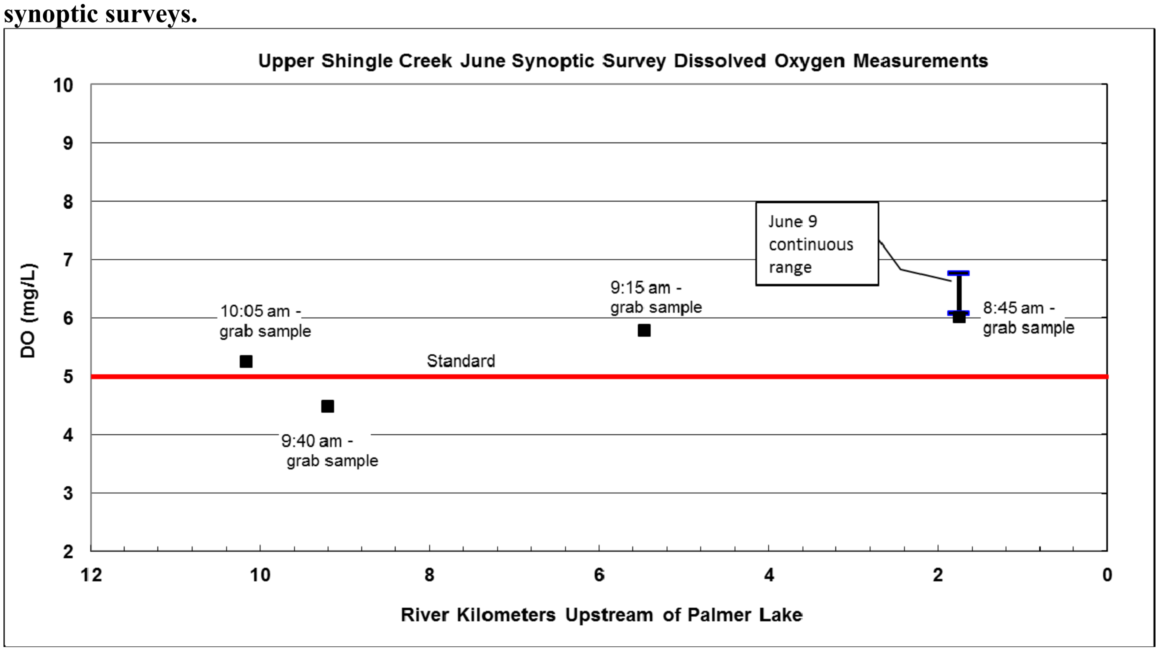


Figure 2.35. Lower Shingle Creek dissolved oxygen field grabs and continuous data collected during the June synoptic surveys.

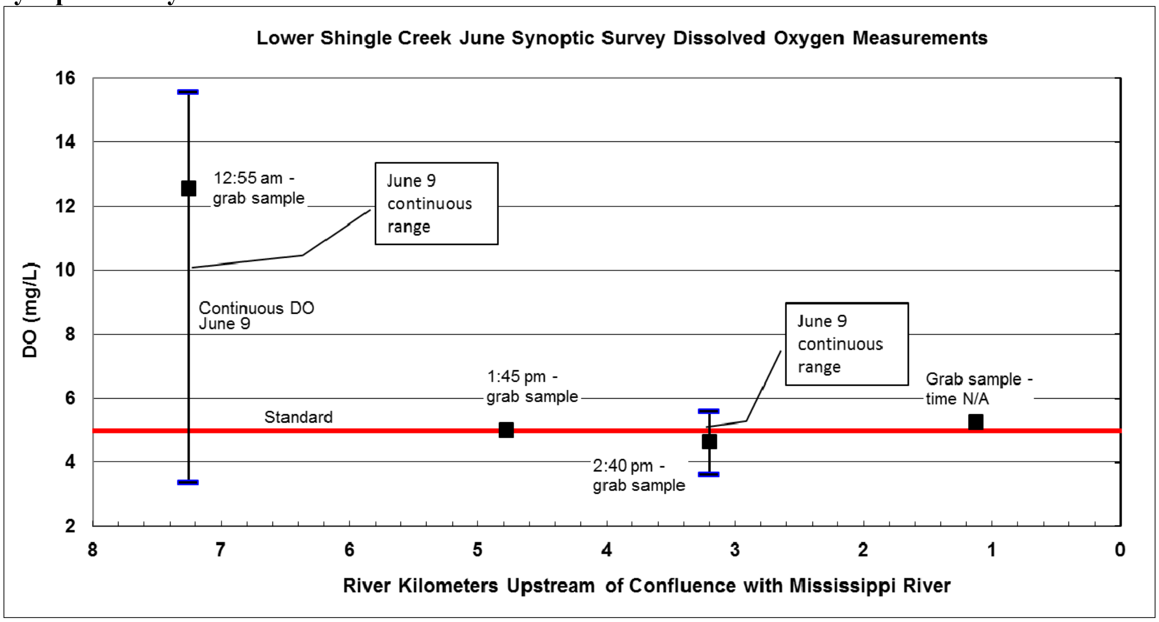


Figure 2.36. Upper Shingle Creek dissolved oxygen field grabs and continuous data collected during the September synoptic surveys.

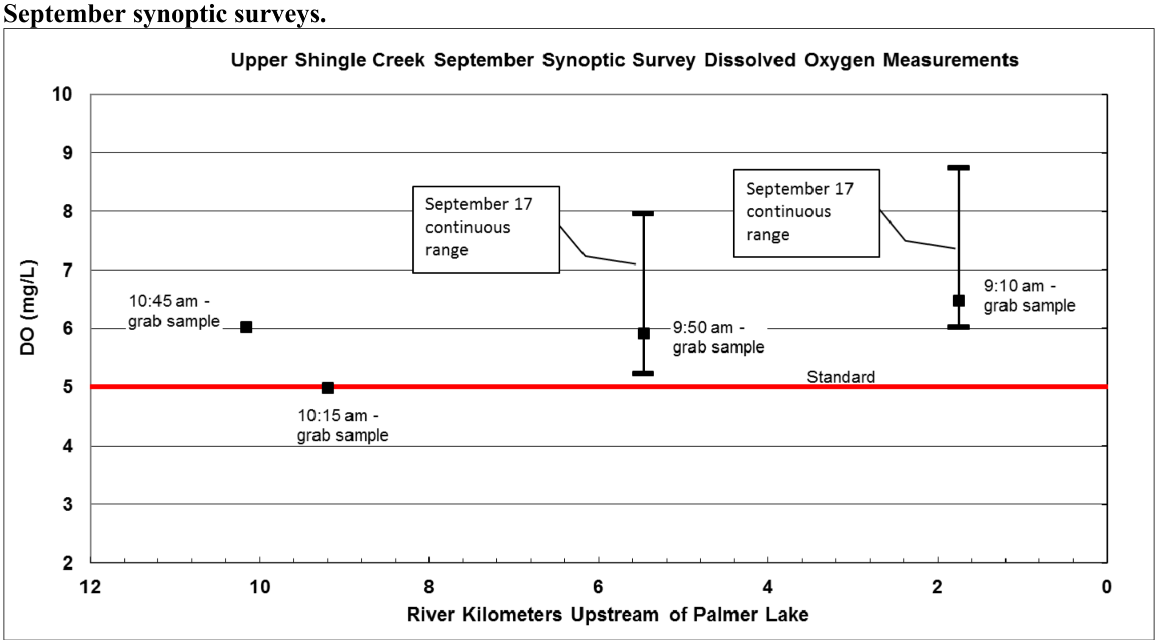
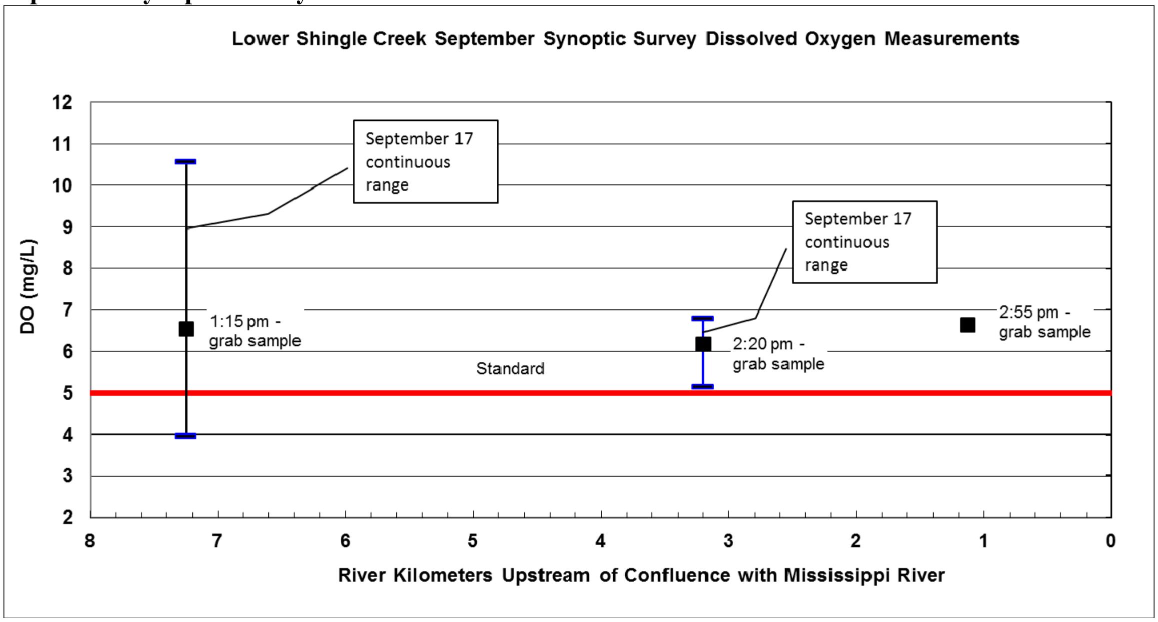


Figure 2.37. Lower Shingle Creek dissolved oxygen field grabs and continuous data collected during the September synoptic surveys.



2.4.3 2007 Longitudinal Survey

All DO field readings for the August 17, 2007 longitudinal survey were collected between 6:00 am and 10:00 am. The profiles are similar to the June and September 2008 synoptic surveys showing lower DO concentrations coming out of the headwater wetlands and gradual increase/reaeration moving downstream (Figures 2.38 and 2.39). The field grabs are labeled with the time of sample collection, if available.

Figure 2.38. Dissolved oxygen concentrations from the August 2007 longitudinal profile of Upper Shingle Creek.

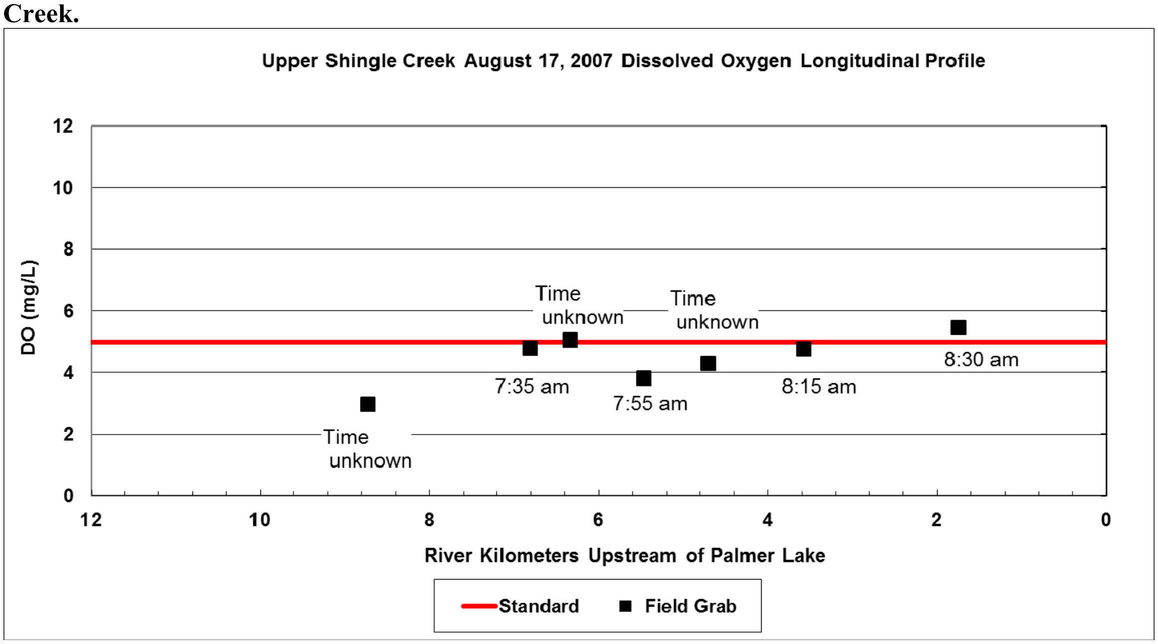
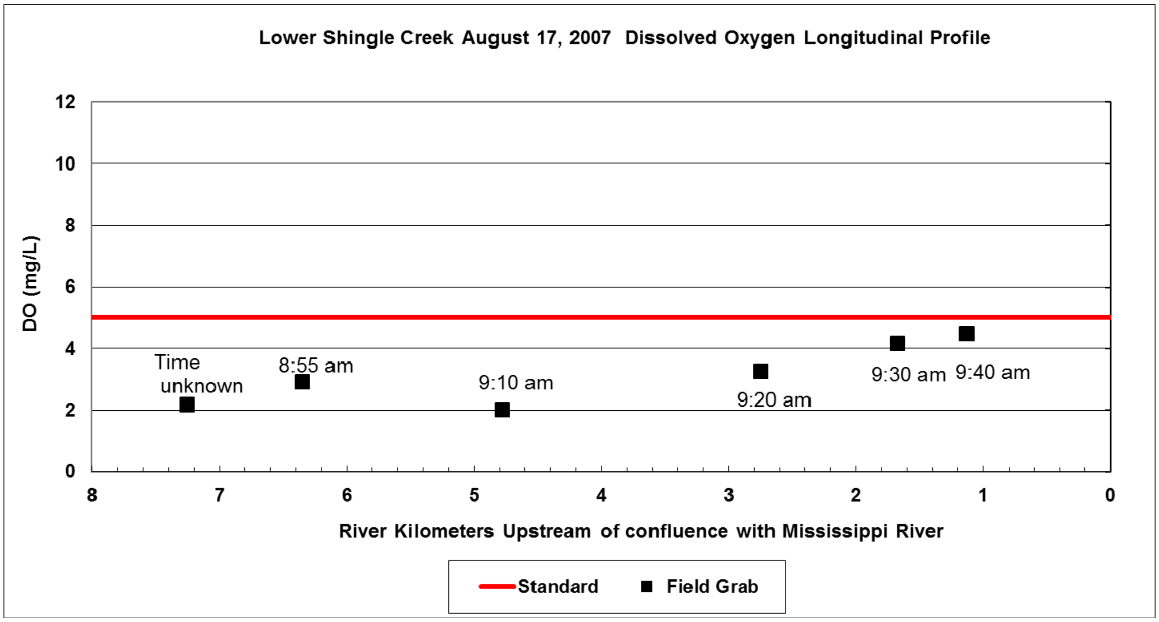


Figure 2.39. Dissolved oxygen concentrations from the August 2007 longitudinal profile of Lower Shingle Creek.



Appendix C
Description of Modeling Method

1.0 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. The model runs within a Microsoft Windows environment programmed with Visual Basic for Applications (VBA) and Excel as the graphical user interface (GUI). QUAL2K was selected to analyze Shingle Creek because it is a public domain model for surface water quality interactions during steady-state conditions.

1.1 GENERAL OVERVIEW OF THE MODELS

The Lower and Upper Shingle Creek models were built using both summer high-flow and fall low-flow synoptic survey data collected on June 9, 2008 and September 17, 2008, respectively. Stream locations 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 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, sediment oxygen demand (SOD) was adjusted for each reach to match observed dissolved oxygen data.

Figures 1.1 and 1.2 depict Lower Shingle Creek and Upper Shingle Creek and their hydraulic reaches. The figures also show the location of water quality monitoring sites that were used to calibrate the models.

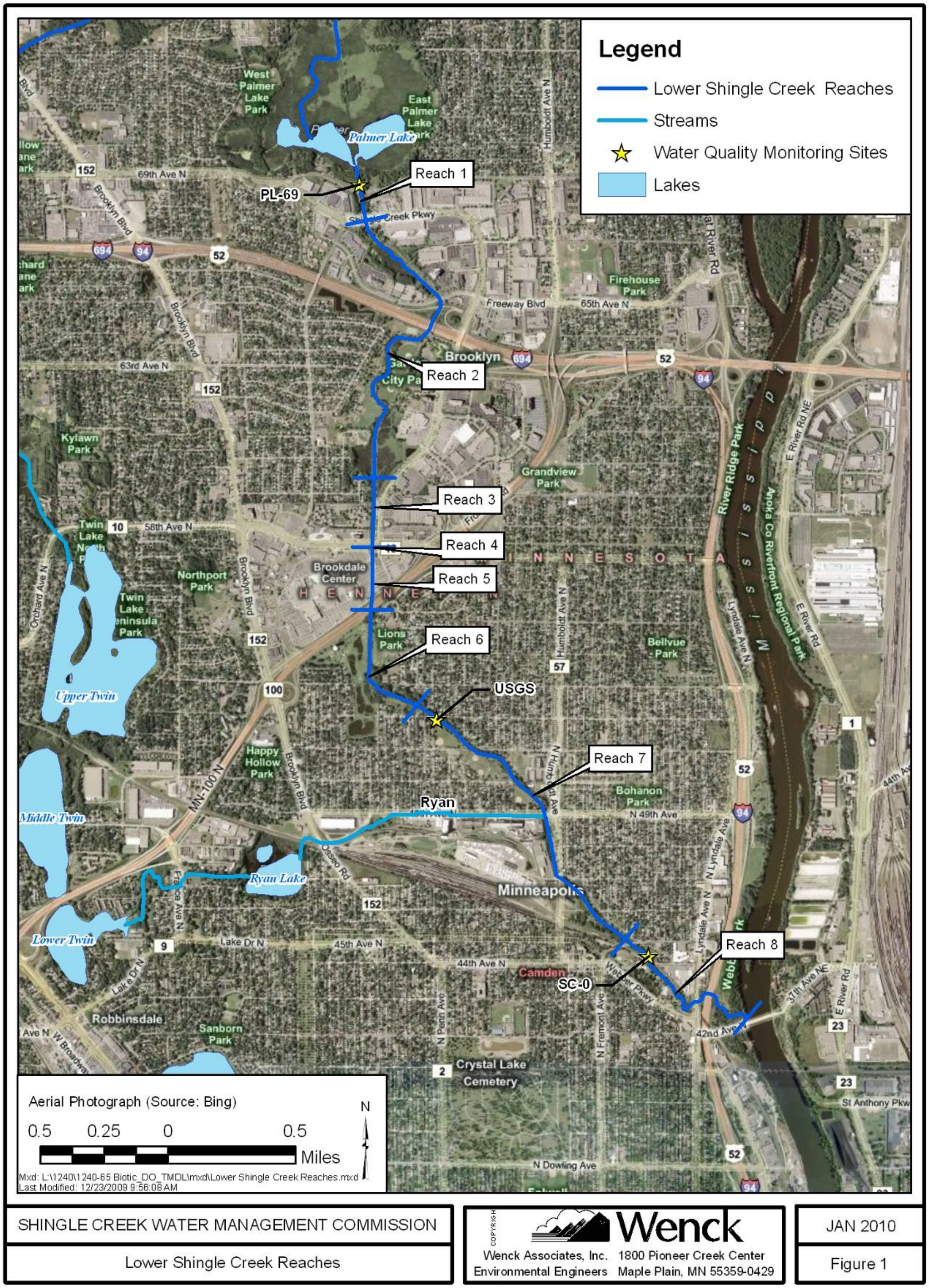


Figure 1.1. Monitoring stations and reaches on Lower Shingle Creek.

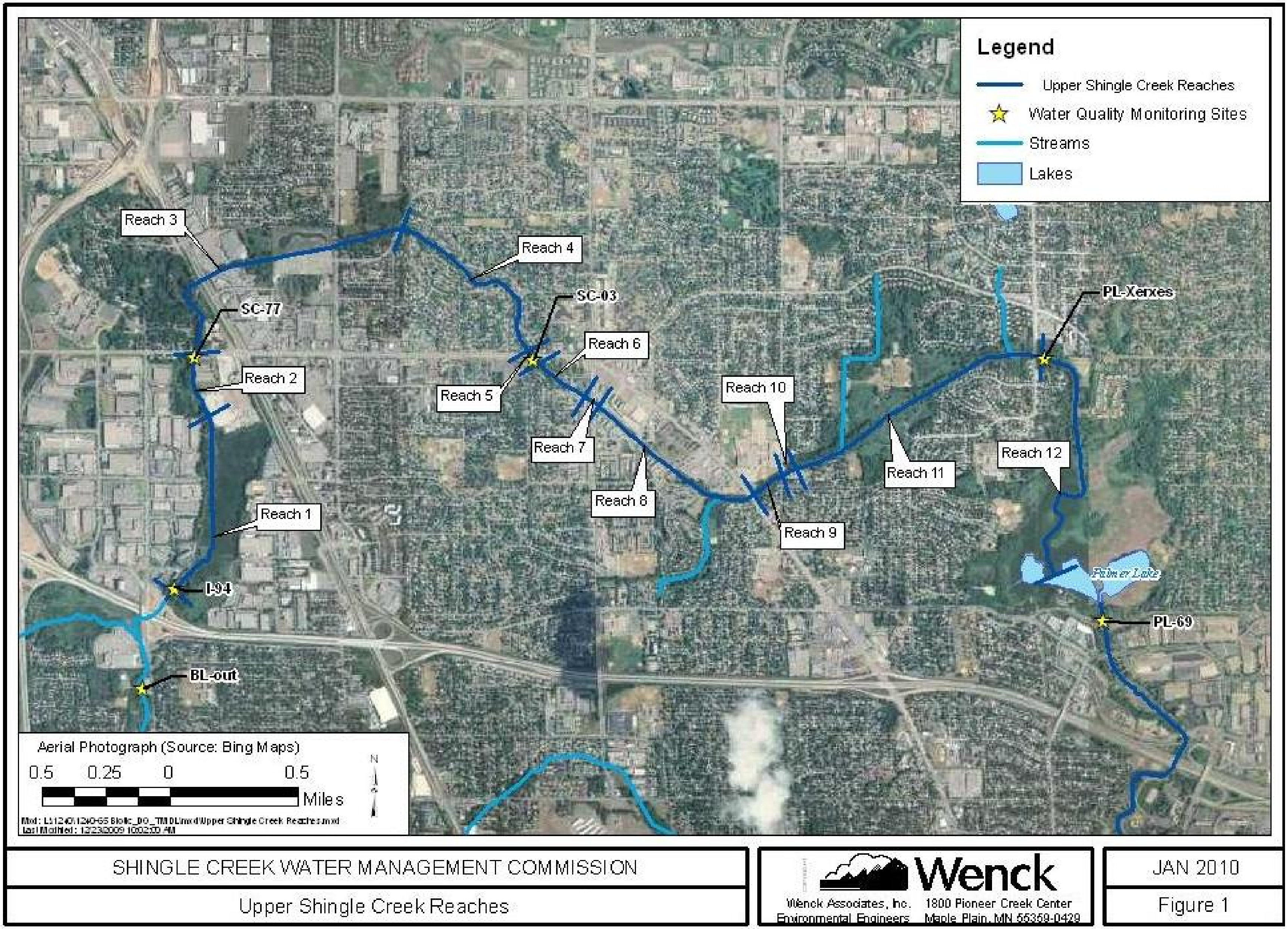


Figure 1.2. Upper Shingle Creek reaches and monitoring stations.

2.0 MODEL SETUP AND INPUTS

2.1 REACH CHARACTERISTICS

2.1.1 Lower Shingle Creek

The Lower Shingle Creek QUAL2K model covers the main stem of Shingle Creek from the Palmer Lake outlet just north of 69th Avenue North in Brooklyn Center to its confluence with the Mississippi River. The Lower Creek as explicitly modeled represents approximately 4.5 miles (7.25 km) as eight individual reaches. The start of each reach correlates with a monitoring station location, road crossing, or physical change in stream hydrology (Figure 1.1, Table 2.1). Monitoring locations are shown on Figure 1.1 and detailed in Table 2.2.

Table 2.1. Lower Shingle Creek model reach characteristics.

Reach	Description	Upstream River km	Downstream River km	Distance (km)	Distance (mile)	Slope (m/m)
1	Palmer Lake Outlet (PLO) to Shingle Creek Pkwy	7.25	7.04	0.21	0.13	0.004
2	Shingle Creek Pkwy to upstream of Bass Lake Road (BLR)	7.04	4.78	2.56	1.59	0.0003
3	Upstream of Bass Lake Road (BLR) to (weir/drop structure)	4.78	4.34	0.45	0.28	0.0003
4	Weir	4.34	4.33	0.01	0.006	~ 0.3 m drop
5	Brookdale Mall to Hwy 100 (Culvert under mall parking lot)	4.33	4.06	0.27	0.17	0.0006
6	Hwy 100 to USGS station at Queen Ave N	4.06	3.20	0.86	0.53	0.0006
7	USGS station at Queen Ave N to Shingle Creek at Webber Park (SC-00)	3.20	1.13	2.07	1.29	0.0006
8	Shingle Creek at Webber Park (SC-00) to Miss. River	1.13	0	1.13	0.70	0.0025

Table 2.2. Lower Shingle Creek monitoring locations.

Reach	Reach Start Monitoring Location ID	Description	Data Collected
1	PLO	Shingle Creek at Palmer Lake Outlet, downstream end of 69th Ave N crossing	Water quality, flow and field parameters
3	BLR (Upstream)	Shingle Creek ~500 ft upstream of Bass Lake Rd crossing	Flow (June and September) and field parameters (June only)
6	USGS	Shingle Creek at upstream end of Queen Ave. N. crossing – USGS monitoring station	Water quality, flow and field parameters
7	SC-00	Shingle Creek at Webber Park in Minneapolis – long-term Shingle Creek Watershed Management Commission's monitoring station	Water quality, flow and field parameters

2.1.2 Upper Shingle Creek

The Upper Shingle Creek QUAL2K model covers the main stem of Shingle Creek from its headwaters just north of I-94 in Brooklyn Park to Palmer Lake in Brooklyn Center. The stretch of the creek as explicitly modeled represents approximately 6.3 miles (10.16 km) as twelve individual reaches. The start of each reach correlates with a monitoring station location, road crossing or a physical change in the creek's landscape or hydrology (Figure 1.2, Table 2.3). Monitoring locations are shown on Figure 1.2 and detailed in Table 2.4.

Table 2.3. Upper Shingle Creek model reach characteristics.

Reach	Description	Upstream	Downstream	Distance		Slope
		River (km)		(km)	(mile)	(m/m)
1	Downstream of I-94 (SC-I94) to outlet of channelized wetland	10.16	9.20	0.96	0.60	0.0005
2	Wetland to 1st Brooklyn Blvd crossing (SC-77)	9.20	8.73	0.47	0.29	0.0005
3	Brooklyn Blvd (SC-77) to Candlewood Avenue	8.73	6.81	1.92	1.19	0.0005
4	Candlewood to Rock Cascade #1	6.81	5.49	1.33	0.82	0.0006
5	Rock Cascade #1 to 2nd Brooklyn Blvd crossing (SC-03)	5.49	5.47	0.15	0.10	0.0230
6	Brooklyn Blvd (SC-03) to Rock Cascade #2	5.47	5.05	0.42	0.26	0.0010
7	Rock Cascade #2 to Zane Ave	5.05	5.04	0.15	0.10	0.0230
8	Zane Ave to 3rd Brooklyn Blvd crossing	5.04	3.84	1.20	0.74	0.0004
9	Brooklyn Blvd to Drop Structure (In Park)	3.84	3.34	0.50	0.31	0.0004
10	Drop Structure (In Park)	3.34	3.33	0.15	0.01	0.0008
11	Drop Structure to Xerxes Ave	3.33	1.75	1.58	0.98	0.0008
12	Xerxes Ave to Palmer Lake	1.75	0	1.75	1.09	0.0008

Table 2.4. Upper Shingle Creek monitoring locations.

Reach	Monitoring Location ID	Description	Data Collected
1	SC-I94	Shingle Creek headwaters in channelized wetland just north of I-94 crossing	Water quality, flow and field parameters
2	SC-77	Shingle Creek at 1st Brooklyn Boulevard crossing west of County Road 81	Water quality, flow and field parameters
4	SC-Candlewood	Shingle Creek at Candlewood Avenue crossing	Flow (high-flow only)
5	SC-03	Shingle Creek at 2nd Brooklyn Boulevard Crossing in Brooklyn Park – long-term Shingle Creek Watershed Management Commission's monitoring station	Water quality, flow and field parameters
8	SC-Xerxes	Shingle Creek at Xerxes Ave crossing	Water quality, flow and field parameters

2.2 HYDRAULIC STRUCTURES

2.2.1 Lower Shingle Creek


Figure 2.1. Reach 4, the Bass Lake Road weir, looking upstream.

Reach 4 represents the large weir between Bass Lake Road (County Road 10) and the Brookdale Mall parking lot (Figure 2.1). Water was constantly flowing over this weir during both synoptic surveys and was built into the model by setting weir height and width equal to water depth (~0.40 m) and width (~11 m) measured upstream of the dam. The weir was defined in the model as a round, broad-crested curved face dam with slight to moderate reservoir water quality pollution.

Reach 5 represents the stretch of the creek that is confined to a 900 foot long, 12 foot by 12 foot dual box culvert that runs beneath the Brookdale Mall parking lot. This reach was modeled using Manning's formulas by setting stream width to 24 feet wide, channel side slopes to 0 (90 degrees) and Manning's roughness to 0.015 (concrete channel bottom). Channel slope was then adjusted to 0.0006 to match time of travel measurements.

2.2.2 Upper Shingle Creek

Reaches 5 and 7 represent two short stretches of the creek where dam/drop structures were removed and replaced by a more gently sloped incline filled with large rocks/boulders. These "rock cascades" were designed to reduce upstream pools and increase reaeration during mid-to high flows. Figures 2.2 and 2.3 show Rock Cascade #2 under low and high flow, respectively.


Figure 2.2. Rock Cascade #2 at Reach 7 at low flow.

Figure 2.3 Rock Cascade #2 at Reach 7 at high flow.

These features were modeled using Manning's formulas based on channel cross sections and survey data. Stream width for this reach was set at 11 meters, channel slope 0.0230 and Manning's η 0.0350 to represent large rocks and riprap (Chow et al. 1988).

Reach 10 represents a small drop structure in the park downstream of Noble Avenue that provides a 2 foot drop in elevation. This structure was built into the model assuming dam/weir width and height equal to the channel width (~7 m) and water depth (~0.38 m) at the closest upstream gauging station. The weir was defined in the model as a flat, broad-rested vertical face dam with slight to moderate reservoir water quality pollution.

2.3 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 Lower Shingle Creek because it is more appropriate than the other options in predicting reaeration for flows below 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)

The channel slope and velocity are variables in calculating reaeration in each reach. Average channel slopes were estimated based on data from a comprehensive channel elevation survey conducted by the engineer for the Shingle Creek Watershed Management Commission in 1998 (Figure 2.4 and Figure 2.5).

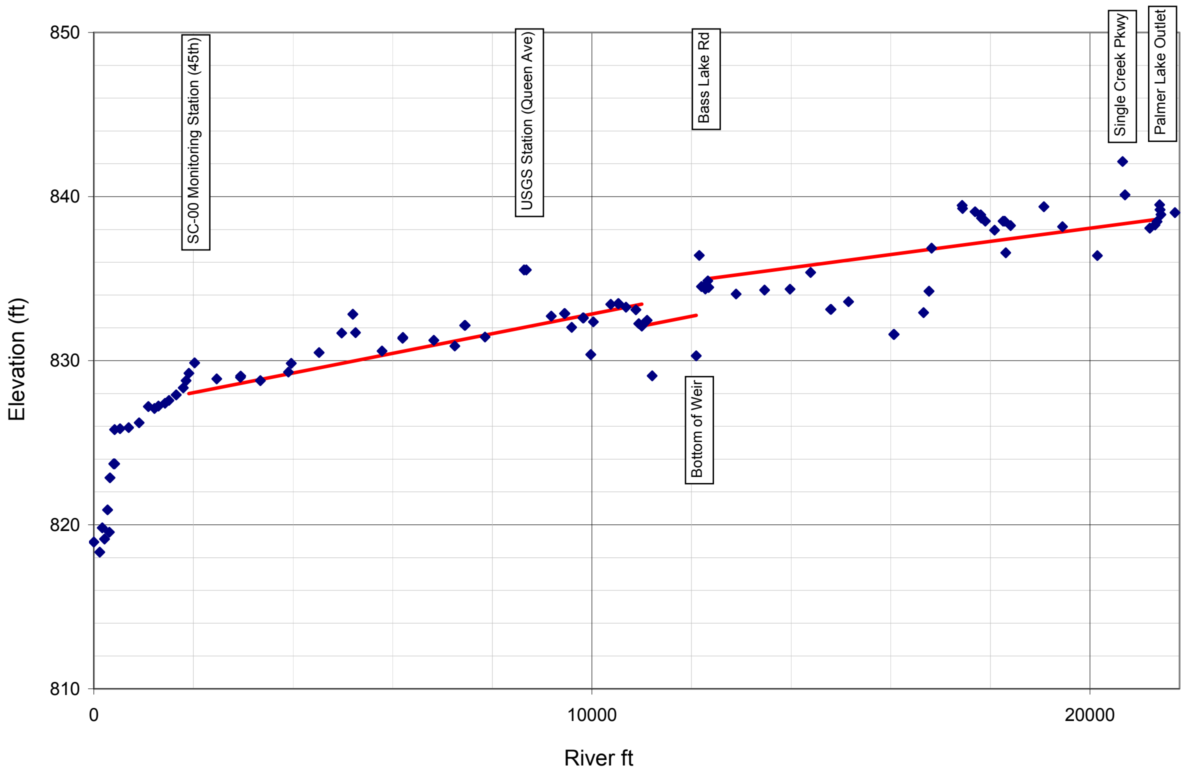


Figure 2.4. Longitudinal elevation survey and modeled reach slopes for Lower Shingle Creek.

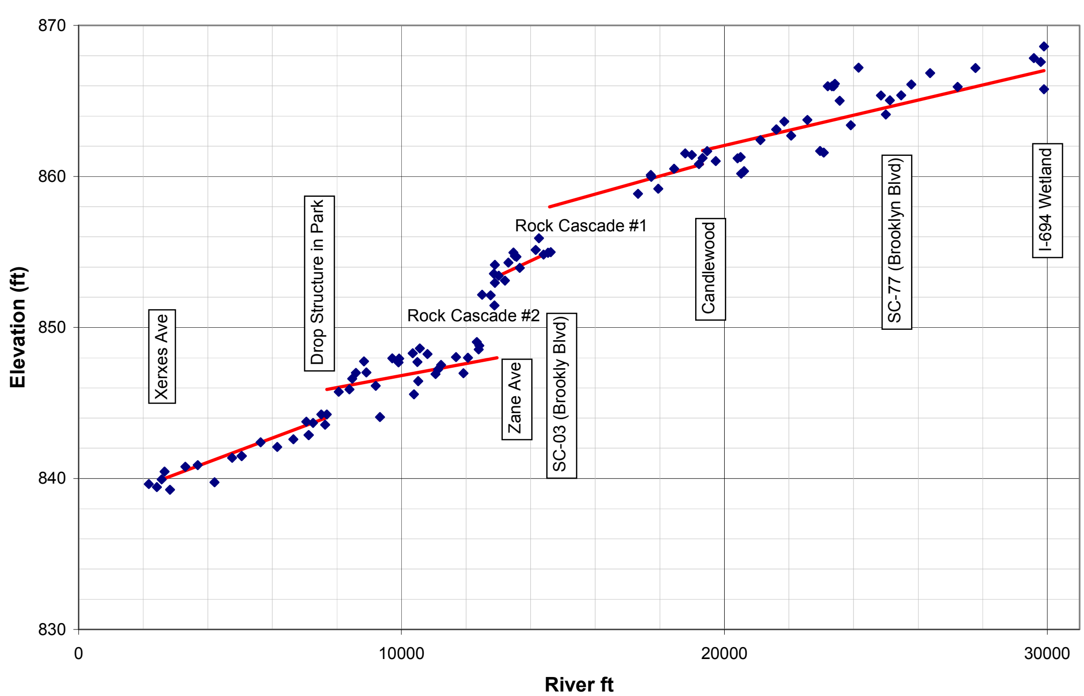


Figure 2.5. Longitudinal elevation survey and modeled reach slopes for Upper Shingle Creek.

2.4 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 Crystal Airport station, which is located about 1½ miles to the west of Shingle Creek. Channel coverage (shading/ canopy cover) was estimated by air photos and field observation. Shading was set to 0% (no cover) for wide wetland reaches and for reaches that enter/exit wide wetland channels, 100% for the Brookdale Mall culvert reach (Lower), and 50% for all moderately shaded reaches. Table 2.5 summarizes how these parameters are defined for all reaches in the Lower Shingle Creek QUAL2K model and Table 2.6 for the Upper Shingle Creek model.

Table 2.5. Weather and physical process variables for Lower Shingle Creek.

QUAL2K Parameter	Reaches	Shading	Justification
Cloud Cover	1-4, 6-8	0% (no cover)	Field observation
	5	100%	Complete cover. Brookdale Mall culvert.
Shading	2-4	0% (no cover)	Entering/exiting wide wetland channels
	1, 6-8	50%	Moderate canopy cover
	5	100%	Complete cover. Brookdale Mall culvert.

Table 2.6: Weather and physical process variables for Upper Shingle Creek..

QUAL2K Parameter	Reaches	Shading	Justification
Cloud Cover	1-12	0% (no cover)	Field observation
Shading	1, 7, 8	0% (no cover)	Entering/exiting wide wetland channels
	2-6, 9-12	50%	Moderate canopy cover

2.5 HEADWATERS

All water quality and flow data collected at the Palmer Lake Outlet (PLO) station on June 9-10, 2008 and September 17-18, 2008 was used to represent the upstream boundary condition/ headwater in the Lower Shingle Creek "high-flow" and "low-flow" models. All water quality and flow data collected at the SC-I94 station near the creek's headwaters on June 9, 2008 and September 17, 2008 was used to represent the upstream boundary condition/headwater in the Upper Shingle Creek high-flow and low-flow models.

2.6 $CBOD_{ULTIMATE}$

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 Shingle Creek synoptic survey. Biochemical oxygen demand (BOD) is a measure of the oxygen consumed by bacteria from the decomposition of organic matter. CBOD only measures oxidation of carbon. 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):

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

The 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 use of 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 June and September surveys. 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 for each reach are modeled using either power function rating curves, weirs (dam/drop structures) or Manning's equations. 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. 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 equals one ($b + d + g = 1.0$), and the product of the coefficients equals one ($a \times c \times f = 1.0$).

3.1.1 Lower Shingle Creek

Gauging stations with similar channel dimensions and flow characteristics were combined into one rating curve to provide more robust velocity/depth versus flow relationships (Figures 3.1 to 3.3). The representative hydraulic rating curves for each reach was selected based on proximity to gauging stations and typical channel dimensions throughout the reach. Coefficients and exponents for each reach are detailed in Table 3.1.

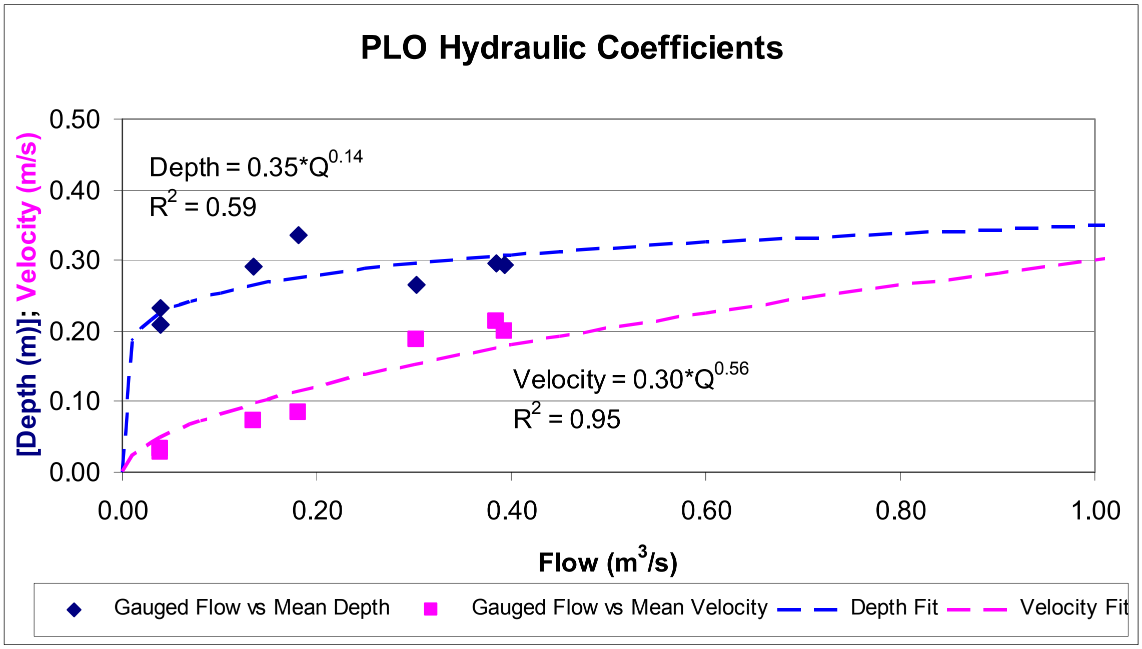


Figure 3.1. Hydraulic rating curve plot for gauging station Palmer Lake Outflow (PLO).

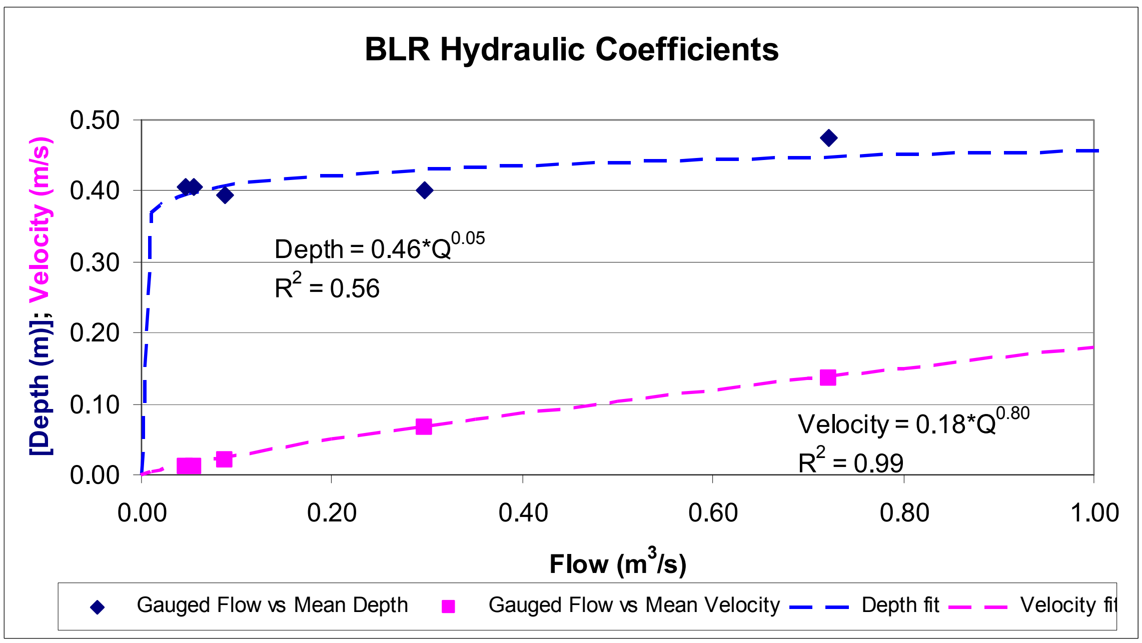


Figure 3.2. Hydraulic rating curve plot for gauging station Bass Lake Road (BLR).

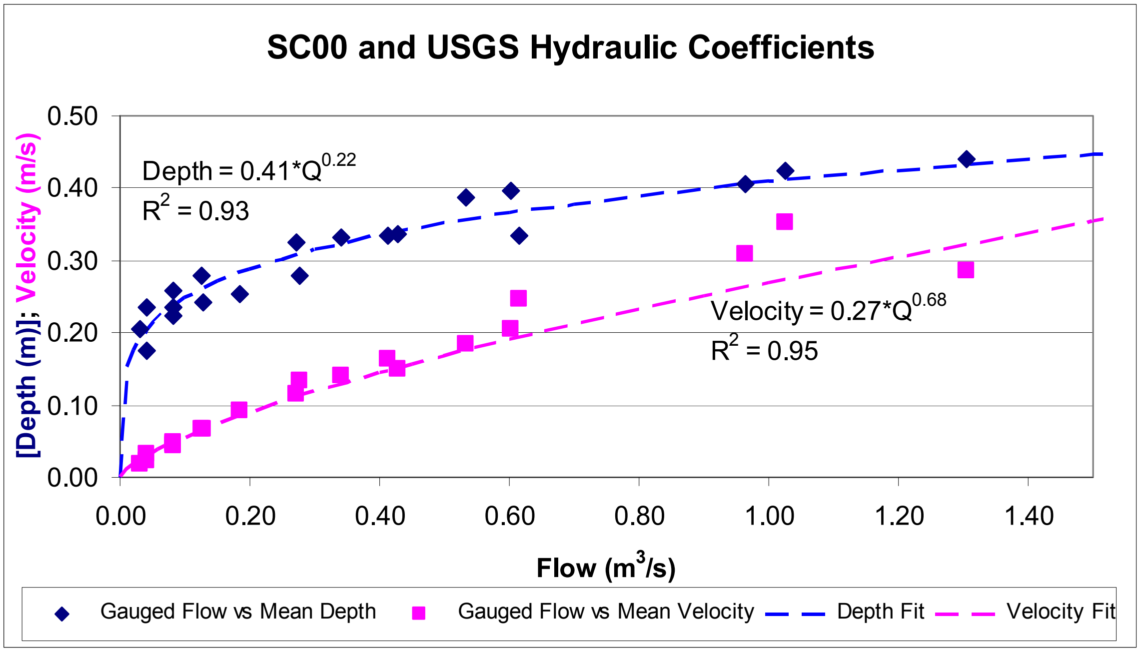


Figure 3.3. Hydraulic rating curve plot for gauging stations Webber Park (SC00) and Queen Avenue North (USGS).

Table 3.1. Hydraulic summary coefficients and exponents assigned to each reach.

Reach	Rating Curve Used	Velocity Coeff.	Velocity Exp.	Depth Coeff.	Depth Exp.	Adjustments
1	PLO*	0.30	0.56	0.35	0.14	None
2	BLR	0.11 Δ	0.80	0.46 Δ	0.05	Velocity and depth coefficients adjusted to meet channel conditions and time of travel
3	BLR*	0.18	0.80	0.46	0.05	None
4	None – Weir	See Table 3.3				Weir height and depth based on channel dimensions
5	None – Manning's	See Table 3.2				Channel dimensions set to culvert specifications and slope adjusted to meet time of travel
6	SC00+USGS	0.27	0.68	0.41	0.22	None
7	SC00+USGS*	0.27	0.68	0.41	0.22	None
8	SC00*+USGS	0.27	0.68	0.41	0.22	None

* The monitoring station is at the upstream end of the reach.

Δ The hydraulic coefficients or exponent were changed.

Table 3.2 details the Manning's equation parameters assigned to Reach 5, the long culvert under the Brookdale Mall parking lot.

Table 3.2. Manning equation parameters assigned.

Reach	Channel Slope (m/m)	Manning η	Bottom Width (m)	Side Slopes (run/rise; m/m)
5	0.003	0.013	7.32	0.0

Reach 4 is the dam/weir between Bass Lake Road and the culvert under the Brookdale Mall parking lot. Table 3.3 details for Reach 4 the QUAL2K parameters ADAM, which is a coefficient representing the current water quality condition behind the dam, and BDAM, which is a factor that describes the dam type. An ADAM coefficient of 1.25 was selected to represent "clear to slightly polluted waters" over an ADAM coefficient of 1.00 for "polluted waters."

Table 3.3. Weir equation parameters assigned.

Reach	Height (m)	Width (m)	ADAM	BDAM
4	0.40	11.0	1.25	0.45

A BDAM coefficient of 0.45 was selected to represent a flat broad-crested curved face, over BDAM coefficients of 0.60 for flat broad-crested vertical face dam/weir, 1.00 for weirs with free fall or 1.30 for steep weirs or cascades.

3.1.2 Upper Shingle Creek

Gauging stations with similar channel dimensions and flow characteristics were combined into one rating curve to provide more robust velocity/depth versus flow relationships (Figures 3.4 to 3.7). The representative hydraulic rating curves for each reach was selected based on proximity to gauging stations and typical channel dimensions throughout the reach. Coefficients and exponents for each reach are detailed in Table 3.4.

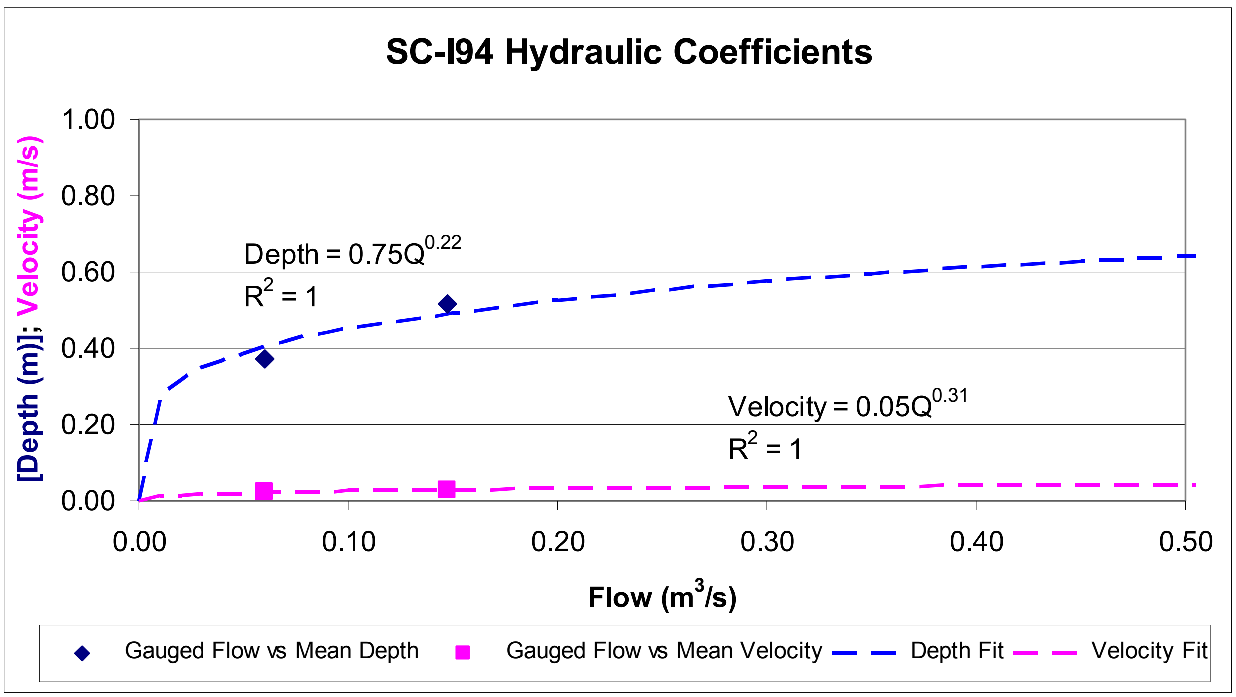


Figure 3.4. Hydraulic rating curve plots for gauging station I-94, the Shingle Creek headwaters.

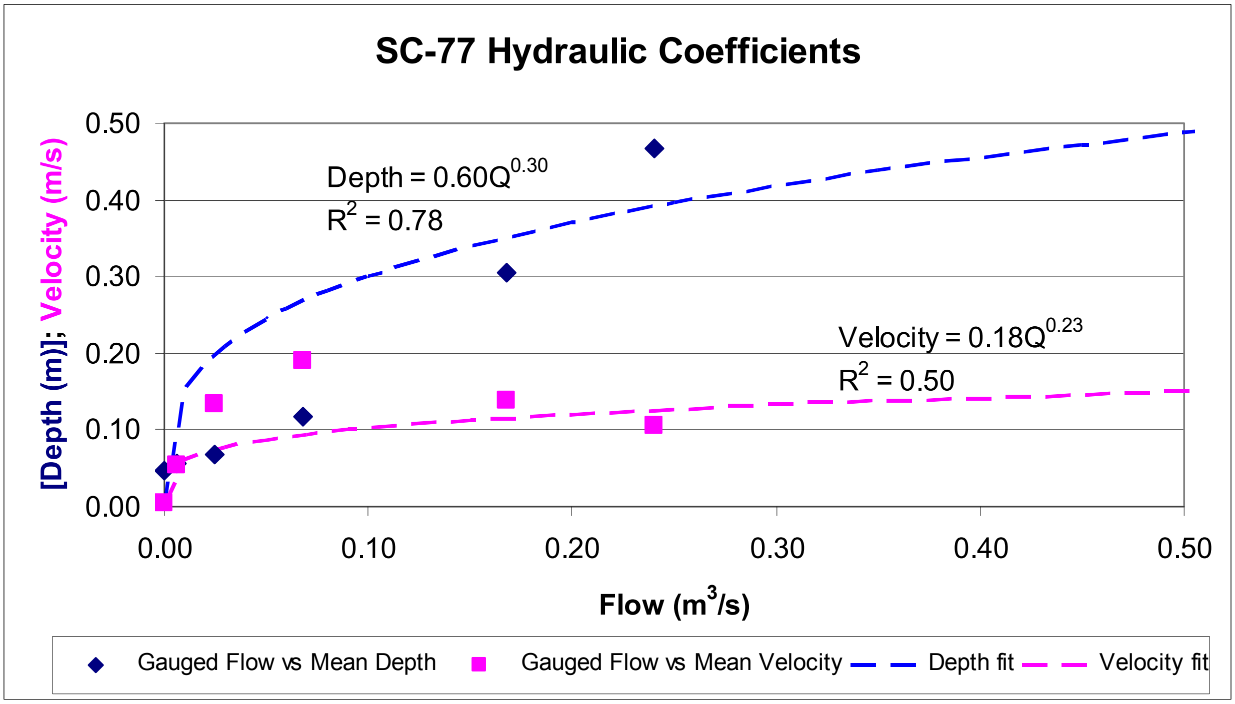


Figure 3.5. Hydraulic rating curve plots for gauging station SC-77.

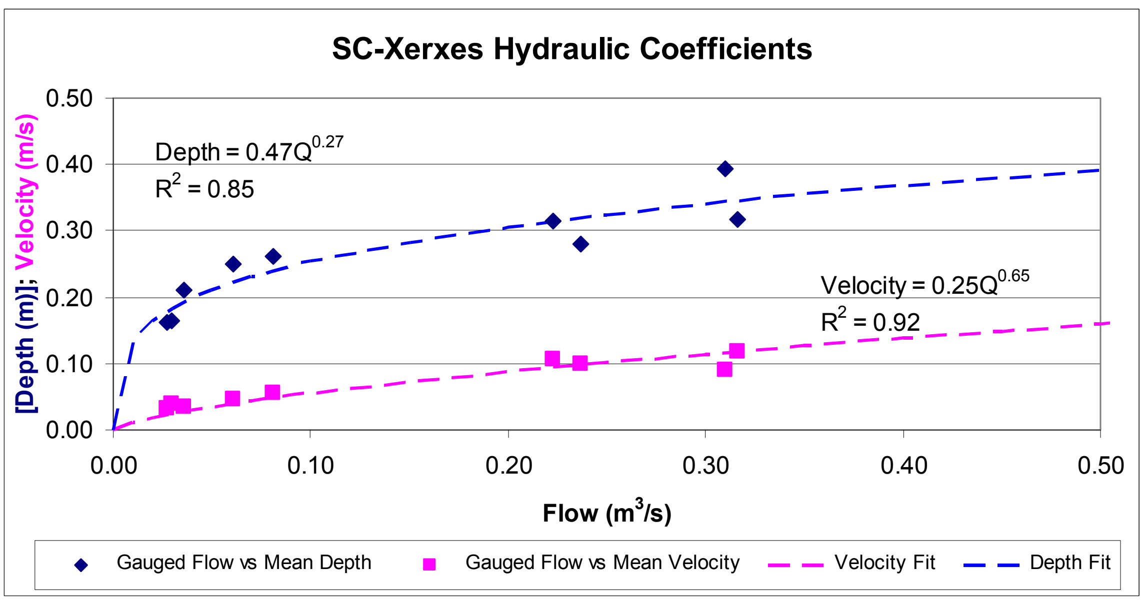


Figure 3.6. Hydraulic rating curve plots for gauging station SC-03.

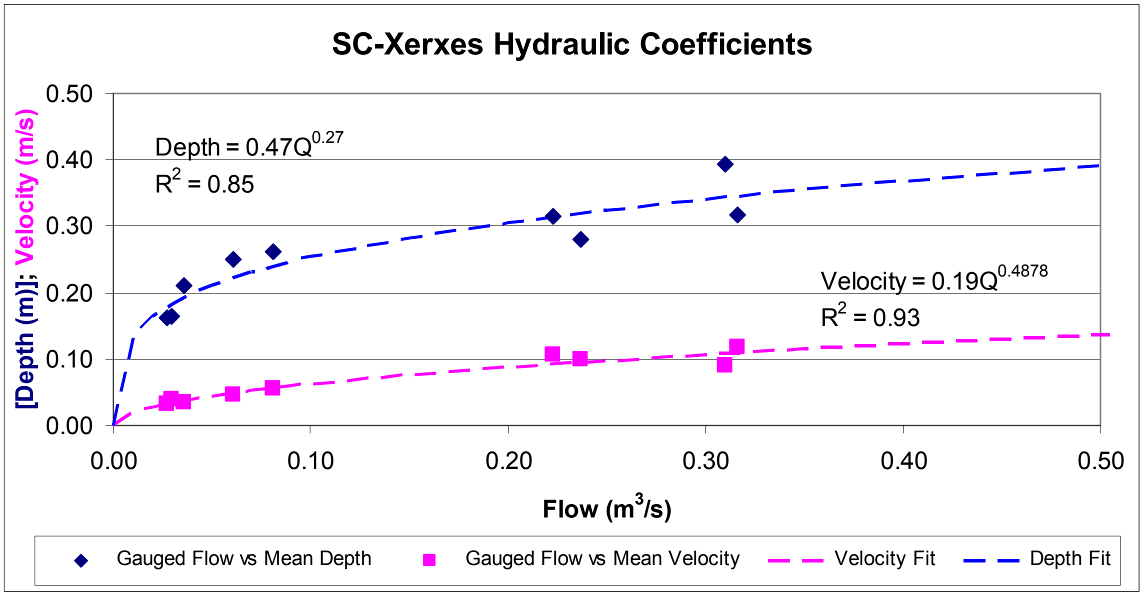


Figure 3.7. Hydraulic rating curve plots for gauging station Xerxes, upstream of Palmer Lake.

Table 3.4. Hydraulic coefficient and exponents assigned to each reach

Reach	Rating Curve used	Velocity Coeff.	Velocity Exp.	Depth Coeff.	Depth Exp.	Adjustments
1	SC-I94	0.05	0.31	0.75	0.22	None
2	SC-77	0.18	0.23	0.60	0.30	None
3	SC-77*	0.18	0.23	0.60	0.30	None
4	SC-03	0.18 Δ	0.65	0.49	0.16	Decreased velocity coefficient to slow flow and represent a wider channel
5	None – Manning's	See Table 3.5				Rock Cascade channel dimensions and slope adjusted to surveyed data
6	SC-03*	0.25	0.65	0.49	0.16	None
7	None – Manning's	See Table 3.5				Channel dimensions and slope set the same as reach 5 cascade
8	SC-03	0.16Δ	0.65	0.49 Δ	0.16	Lowered velocity coefficient by ~1/3 to slow flow to meet travel time
9	Xerxes	0.19	0.49	0.47	0.27	None
10	None – Weir	See Table 3.6				Weir height adjusted to survey results
11	Xerxes	0.19	0.49	0.47	0.27	None
12	Xerxes*	0.19	0.49	0.47	0.27	None

* The monitoring station is at the upstream end of the reach. Δ The hydraulic coefficients or exponent was changed.

Table 3.5 details the Manning's equation parameters assigned to Reaches 5 and 7, which are rock cascade #1 and #2 respectively.

Table 3.5: Manning's equation parameters assigned.

Reach	Channel Slope (m/m)	Manning η	Bottom Width (m)	Side Slopes (run/rise; m/m)
5	0.23	0.035	11	0.35
7	0.23	0.035	11	0.35

Reach 10 is the dam/weir in Brookdale Park between Noble Avenue North and Xerxes Avenue North. Table 3.6 details for Reach 10 the QUAL 2K parameters ADAM, which is a coefficient representing the current water quality condition behind the dam, and BDAM, which is a factor that describes the dam type. An ADAM coefficient of 1.25 was selected to represent "clear to slightly polluted waters" over an ADAM coefficient of 1.00 for "polluted waters."

Table 3.6. Weir equation parameters assigned .

Reach	Height (m)	Width (m)	ADAM	BDAM
10	0.38	7.0	1.25	0.60

A BDAM coefficient of 0.60 was selected to represent a flat broad-crested vertical face dam/weir, over BDAM coefficients of 0.45 for flat broad-crested curved face, 1.00 for weirs with free fall or 1.30 for steep weirs or cascades.

3.2 FLOW CALIBRATION

3.2.1 Lower Shingle Creek

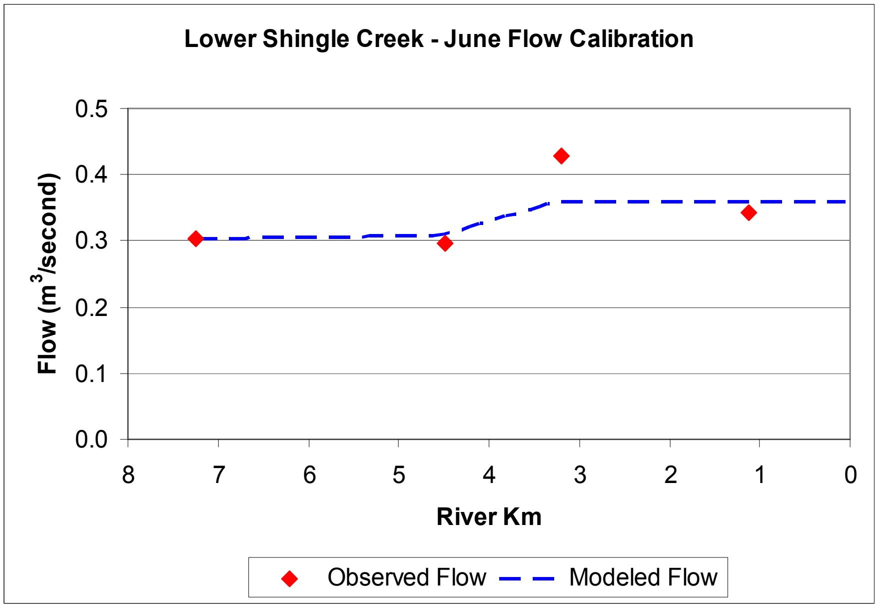
Changes in flow between gauging stations were built into the model as diffuse sources. Ryan Creek flows from Ryan Lake to Shingle Creek near 49th Avenue North in Reach 7 and is the only major tributary that enters Shingle Creek below Palmer Lake. Ryan Creek had a small amount (~ 1 foot depth) of slow flowing water during the June synoptic survey and was dry during the September low-flow survey. Ryan Creek was not sampled or explicitly modeled as it was determined these flow contributions were small compared to flow in the main channel of Shingle Creek. In addition, outflow from Ryan Lake into Ryan Creek is limited by a control structure. It is assumed changes in flow across Shingle Creek are some combination of trapping or release to/from in- and off-channel storage or delayed stormwater and groundwater inflow.

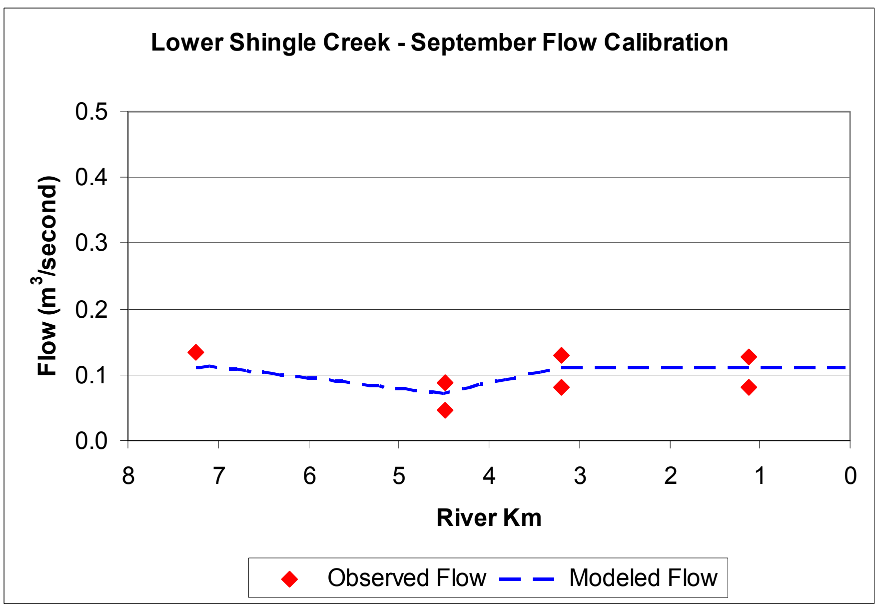
The only calculated increase in gauged flow data during both surveys occurred between the BLR and USGS-Queen Avenue station. A flow abstraction of 0.05 m^3/s (1.59 cfs) was assigned between PLO and BLR to match the September low-flow synoptic survey data. This may be attributed to storage in the wide, sluggish slow-flowing reaches (1-3) upstream of the BLR site. The flow calibration is illustrated in Figures 3.8 and 3.9. The model was deemed hydraulically calibrated for total discharge once all diffuse source flows were built in to the model (Table 3.7).

Table 3.7. Modeled diffuse sources for Shingle Creek.

Reach	Month	Total diffuse flow throughout reach (m^3/s)[a]	Total diffuse flow throughout reach (cfs)[a]	Flow rate (cfs per river mile)[a]	Flow rate (cfs per river kilometer)[a]
Reach 1-3 (PLO to BLR)	June	0.005[b]	0.18[b]	0.102	0.064
Reach 3-6 (BLR to USGS)	June	0.052	1.82	2.289	1.422
Reach 1-3 (PLO to BLR)	September	0.005[b]	0.18[b]	0.102	0.064
Reach 2-3 (SC Pkwy to BLR)	September	-0.045	-1.59	-0.999	-0.621
Reach 3-6 (BLR to USGS)	September	0.038	1.34	1.686	1.048

[a] Negative flow values are abstractions (outflows), while positive flow values are inflows.
[b] Further discussed in Section 4.3.





Figures 3.8 and 3.9. Final Shingle Creek flow calibration plots with diffuse source inflows.

3.2.2 Upper Shingle Creek

Changes in flow between gauging stations were built into the model as diffuse sources. Though no major tributaries enter Shingle Creek in this segment, there are a number of in- and off-channel pools, wetlands and storm ponds that receive and discharge water to the creek during runoff events. In addition, a number of small channels convey stormwater from commercial properties abutting Reach 1 through the wetland to the Creek. It is assumed all changes in flow across Upper Shingle Creek during the synoptic survey are the result of storage discharge from these systems. All of Upper Shingle Creek appeared to be gaining flow between gauging stations during the June survey. The September survey represented more "extreme" low-flow conditions and displayed both losing and gaining reaches. The flow calibration is illustrated in Figures 3.10 and 3.11. The model was deemed hydraulically calibrated for total discharge once all diffuse source flows were built in to the model (Table 3.8).

Table 3.8. Modeled diffuse sources for Upper Shingle Creek.

Reach	Month	Total diffuse flow throughout reach (m^3/s)[a]	Total diffuse flow throughout reach (cfs)[a]	Flow Rate (cfs per River Mile)[a]	Flow Rate (cfs per River kilometer)[a]
Reach 1-2 (SC-I94 to SC-77)	June	0.094	3.32	3.74	2.32
Reach 3-5 (SC-77 to SC-03)	June	0.019	0.67	0.33	0.21
Reach 6-11 (SC-03 to SC-Xerxes)	June	0.056	1.98	0.86	0.53
Reach 1-2 (SC-I94 to SC-77)	September	0.008	0.28	0.32	0.20
Reach 3-5 (SC-77 to SC-03)	September	-0.047	-1.64	-0.81	-0.50
Reach 6-11 (SC-03 to SC-Xerxes)	September	0.040	1.40	0.61	0.38

[a] Negative flow values are abstractions (outflows), while positive flow values are inflows.

It should be mentioned that this stretch of Shingle Creek is driven almost exclusively by urban runoff and discharge from ponds and wetlands and receives little, if any groundwater inputs. Thus, true "steady-state" or "baseflow" conditions are difficult to define. While no rain fell on the day of either survey, approximately 1.5 inches of rainfall was recorded in the week leading up to the June synoptic survey and 0.6" for the September survey. As a result, total discharge was decreasing by approximately ~25% and ~50% per day during the high and low-flow survey, respectively. Channel flow approached zero upstream of SC-03 during the low-flow survey on September 18th trapping the time of travel dye in a series of pools throughout Reaches 3 and 4.

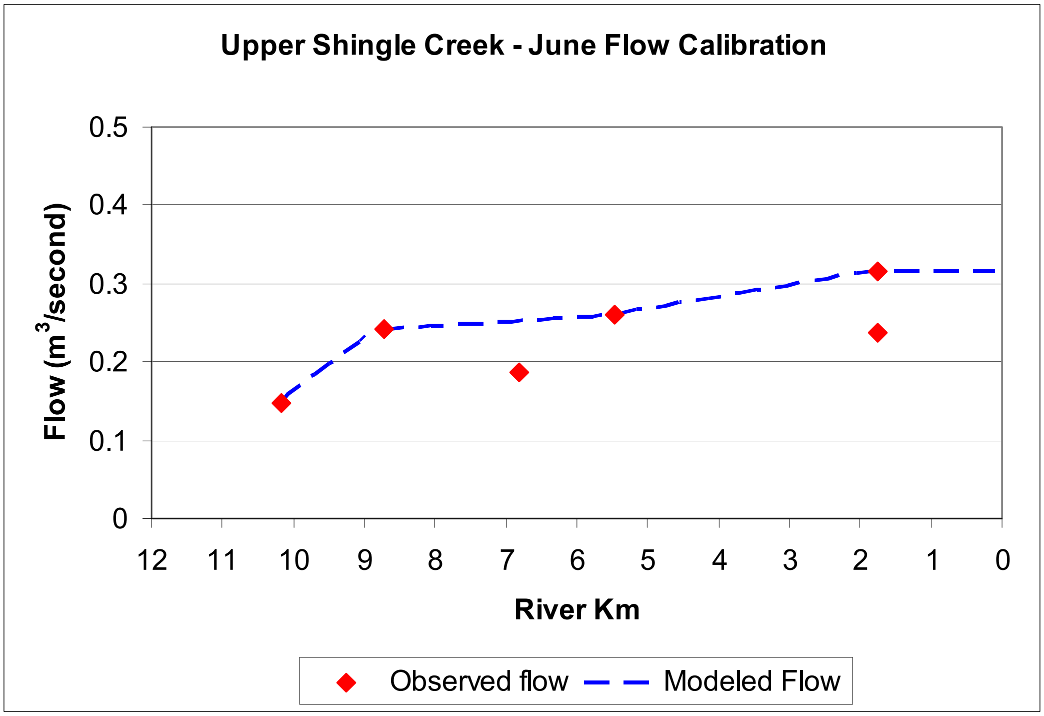


Figure 3.10. Final flow calibration plot for Upper Shingle Creek with diffuse source inflows, June flow calibration.

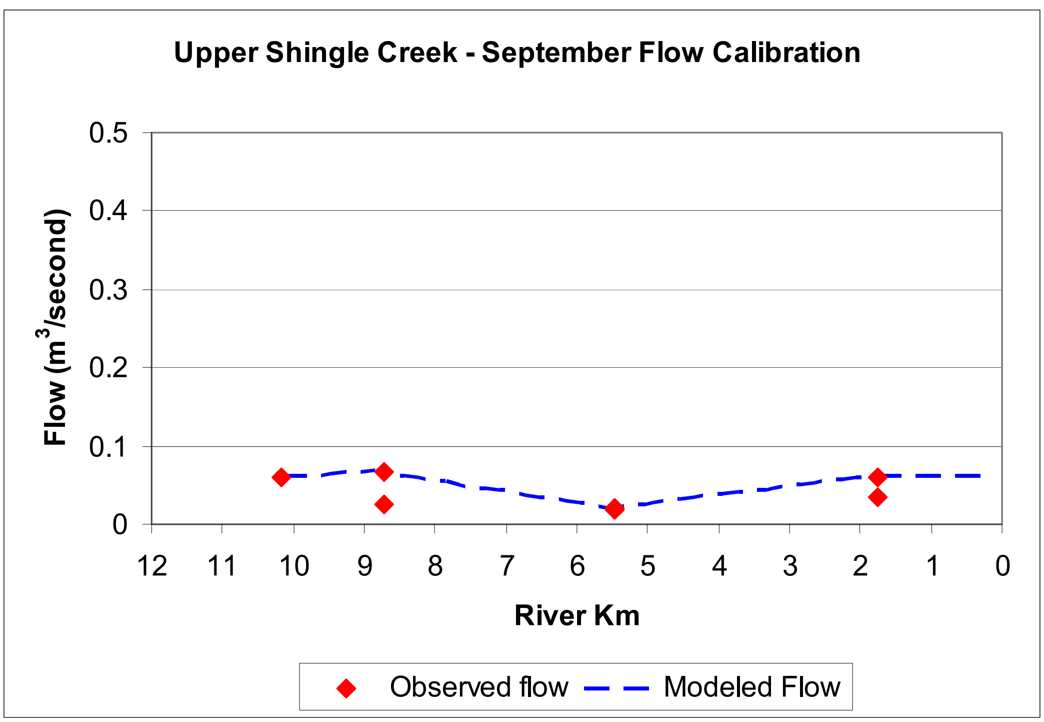


Figure 3.11. Final flow calibration plot for Upper Shingle Creek with diffuse source inflows, September flow calibration.

3.3 TIME OF TRAVEL CALIBRATION

3.3.1 Lower Shingle Creek

With total flow calibrated, rating curve coefficients and exponents were adjusted to meet time of travel times measured during the dye study portion of the synoptic survey. Reaches 1-3 were the only reaches where travel time could not be modeled using gauging station rating curves. Stream velocity decreases as the channel becomes significantly wider in Reach 2 between Shingle Creek Parkway and the Bass Lake Road monitoring station. In the early 1980s about one-half mile of Shingle Creek south of I-94 in Reach 2 was relocated, widened, and meandered to make more room for new softball fields in Brooklyn Center's Central Park. Dye study results support adjusting the velocity and depth hydraulic coefficients for this reach to represent a slower velocity and wider channel than the Bass Lake Road station. The velocity coefficient for this reach was lowered by ~65% and the depth coefficient was adjusted to represent an average water depth of 0.33 meters (Table 3.1). Figures 3.12 and 3.13 show the time of travel calibration.

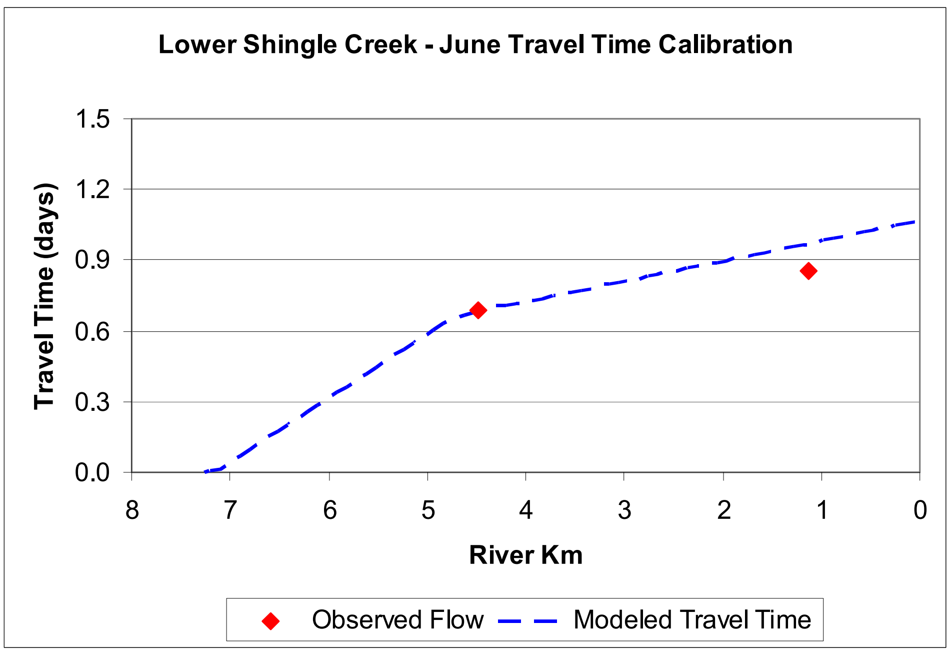


Figure 3.12. Time of travel calibration plot, June travel time calibration

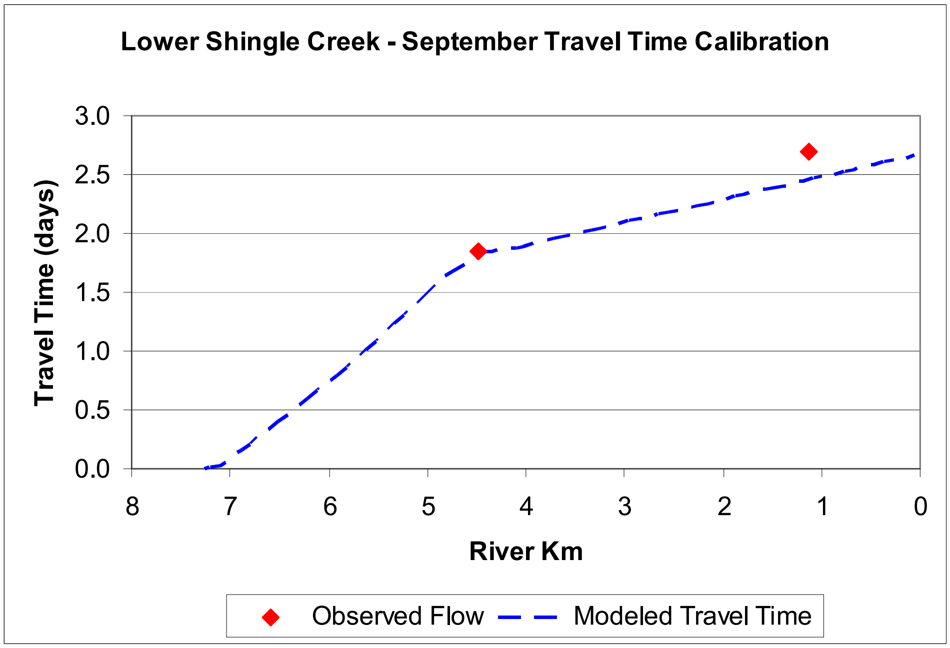


Figure 3.13. Time of travel calibration plot, September travel time calibration

3.3.2 Upper Shingle Creek

With total flow calibrated, rating curve coefficients and exponents were adjusted to meet travel times measured during the dye study portion of the synoptic survey. Slight changes were made to coefficients for Reaches 1, 3, 4 and 8 with no gauging data. These adjustments were done to create deeper and/or wider channels to slow flow and meet time of travel estimates. Figures 3.14 and 3.15 show the time of travel calibration.

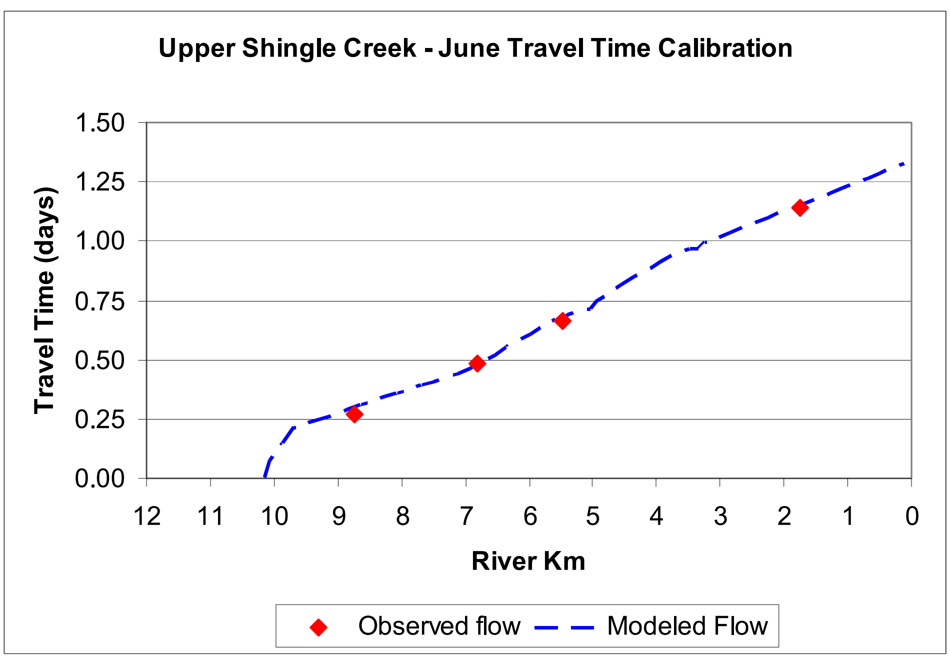


Figure 3.14. Time of travel calibration plot, June travel time calibration.

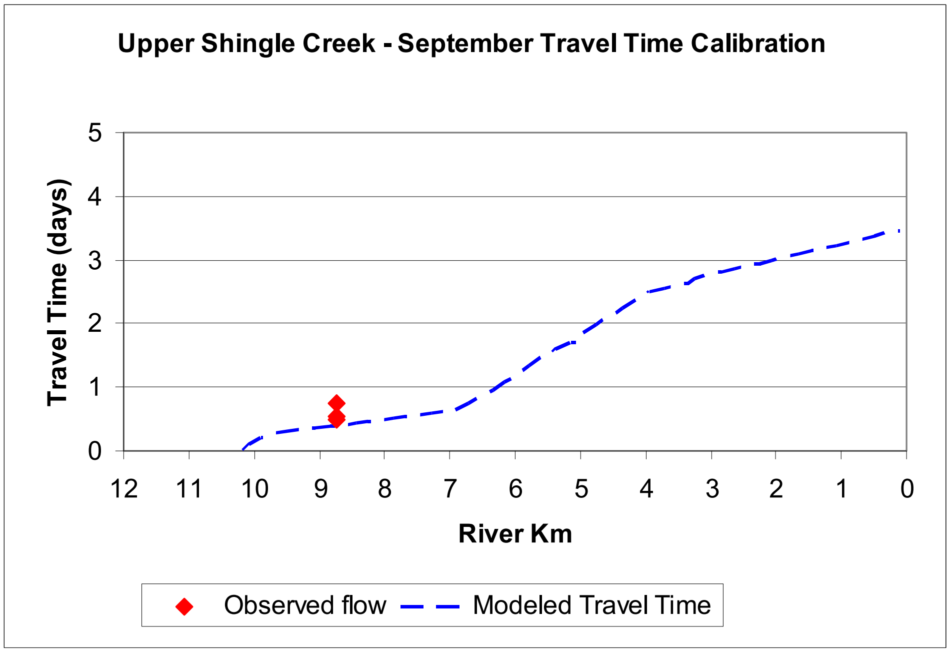


Figure 3.15. Time of travel calibration plot, September travel time calibration.

4.0 WATER QUALITY CALIBRATION

All water quality model inputs were derived from data collected during the June and September synoptic surveys. 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. The model input and calibration adjustments are described in the following sections.

4.1 GENERAL KINETIC RATES

4.1.1 Lower Shingle Creek

Five kinetic rates were adjusted from default values in order to meet longitudinal changes in observed water quality data. Kinetic rate changes were first applied to the September low-flow model and then verified/tested in the June “high-flow” model. While every effort was made to keep kinetic rate changes consistent between the two events, September phytoplankton settling velocity was lowered further from default to keep algae in suspension during the “high-flow” model run. Stream velocity and turbulence were much lower during the low-flow survey creating a more favorable environment for phytoplankton leaving Palmer Lake to survive and remain in suspension near the water surface. While these rates were set to different values, all kinetic rate adjustments were within the range of published values (Table 4.1).

Table 4.1. QUAL2K kinetic rates adjusted from model default values.

Rate	June Calibrated Rate	September Calibrated Rate	Default Rate	Literature Range	Citation/Study Area/Justification
Reaeration Model	Tsivoglou and Neal	Tsivoglou and Neal	User Specified	Thomann and Mueller 1987 cite that Tsivoglou and Neal 1976 is best for small, shallow streams (1-15 cfs)	
$CBOD_u$ oxidation rate (day^{-1})	0.1	0.1	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/day)	0.01	0.01	0.1	(A)	Low suspended particulate organic matter
Organic-P Settling Velocity (m/day)	0.05	0.05	0.1	(A)	Low suspended particulate organic matter
Inorganic-P settling (m/day)	0.25	0.25	2.0	(A)	
Phytoplankton Settling (m/day)	0.50	0.1	0.50	0 – 2	Bowie et al. 1985 Table 6-19 p352 Chen & Orlob 1975 and Smith, 1978

Note: (A) Literature ranges are not available since settling velocities are influenced by a material's size, shape, and density and the speed of water.

4.1.2 Upper Shingle Creek

Six kinetic rates were adjusted from default values in order to meet longitudinal changes in observed water quality data. Due to upstream trapping and extreme variability of the September survey flow regime, kinetic rate changes were calibrated to the June low-flow data and then applied to the September low-flow model. While every effort was made to keep kinetic rate changes consistent between the two events, the September phytoplankton settling velocity was lowered further the value used in June. This was done to keep more algae in suspension during the high-flow (June) model run. Stream velocity and turbulence were much lower throughout Upper Shingle Creek during the low-flow (September) survey. These physical conditions likely created a more favorable environment for the phytoplankton leaving wetlands and ponds to survive and remain in suspension near the water surface. While these rates were set to different values, all kinetic rate adjustments were within the range of published values (Table 4.2).

Table 4.2. QUAL2K kinetic rates adjusted from model default values.

Rate	June Calibrated Rate	Sept. Calibrated Rate	Default Rate	Literature Range	Citation/Study Area/Justification
Reaeration Model	Tsivoglou and Neal	Tsivoglou and Neal	User Specified	Thomann and Mueller 1987 cite that Tsivoglou and Neal 1976 is best for small, shallow streams (1-15 cfs)	
$CBOD_u$ oxidation rate (day^{-1})	0.10	0.10	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

Rate	June Calibrated Rate	Sept. Calibrated Rate	Default Rate	Literature Range	Citation/Study Area/Justification
Organic-N Settling Velocity (m/d)	0.01	0.01	0.10	(A)	Low suspended particulate organic matter
Organic-P Settling Velocity (m/d)	0.01	0.01	0.10	(A)	Low suspended particulate organic matter
Inorganic-P settling (m/d)	0.25	0.25	2.00	(A)	
Phytoplankton Settling (m/d)	0.3	0.1	0.5	0 – 2	Bowie et al., 1985, Table 6-19 p.352; Chen & Orlob, 1975 and Smith, 1978

Note: (A) Literature ranges are not available since settling velocities are influenced by a material's size, shape, and density and the speed of water.

4.2 REACH SPECIFIC RATES

4.2.1 Lower Shingle Creek

In addition to global changes to kinetic rates, individual reaches required specific kinetic rate adjustments to calibrate to in-stream water quality data. Nitrate was overpredicted in all reaches under default nitrogen series kinetic rates. This suggests breakdown of organic nitrogen is too fast, or there is a loss of nitrate from the system. In order to test the former, organic nitrogen hydrolysis and nitrification kinetic rates were lowered to meet in-stream conditions. These adjustments resulted in a small decrease in nitrate and left too much nitrogen in organic and reduced forms. Denitrification is common in eutrophic lakes, littoral areas, wetlands and other anaerobic environments. Reaches 1-3 downstream of Palmer Lake are wide, slow moving reaches with little reaeration and significant wetland vegetation and sediment. The sediment denitrification transfer coefficient was set to 1.0 in Reaches 1-3 to reflect potential denitrification in these reaches and calibrate to monitored nitrate levels in the downstream reaches of Shingle Creek (Table 4.3).

Table 4.3. Summary of reach specific sediment fluxes and kinetic rates.

Reach	Rate	Reach Specific Rate	Default Rate	Justification
1-3 (PLO to BLR)	Sediment denitrification transfer coefficient (m/d)	1.0	0	Wide, slow moving reaches with muddy bottom and wetland vegetation. Evidence of anaerobic conditions and high denitrification rates supported by (Bowie et al., 1985 Table 5-4 p 262 Rate Coefficient Range 0.0-1.0 m/d; Baca & Arnett, 1976)

4.2.2 Upper Shingle Creek

In addition to global changes to kinetic rates, individual reaches in Upper Shingle Creek required specific kinetic rate adjustments to calibrate to in-stream water quality data. Chlorophyll-a concentrations decreased rapidly between the SC-I94 and SC-77 station, suggesting much of the phytoplankton in suspension near the headwaters settles out and is not transported downstream. Phytoplankton settling velocities were increased to 1.25 m/d in Reaches 1 and 2 to meet observed conditions (Table 4.4).

Table 4.4. Summary of reach specific sediment fluxes and kinetic rates.

Reach	Rate	Reach Specific Rate	Default Rate	Justification
1 and 2 (SC-I94 to CR 81)	Phytoplankton Settling Velocity (m/d)	1.25 (June only)	0.50	Wetland reach with elevated phytoplankton settling rates early in the season during higher flows. Supported by Bowie et al., 1985

4.3 IN-STREAM LOADINGS

Another source of nutrients into water bodies is the release from bottom sediments (internal loading). In a wetland setting, sediments can have high organic content, the decay of which uses available oxygen, causing anoxic conditions. Anoxia is a condition of low dissolved oxygen in the overlying water column above the sediment surface. Research has shown that this weakens and destroys the chemical bonding of nutrients within the sediment, releasing nitrogen and phosphorus into the water in a form readily available for algae and other plant growth. The rate phosphorus is released from sediments depends on the type of phosphorus (e.g. iron-bound), the pH and dissolved oxygen. Iron bacteria consume increased amounts of iron under anoxic conditions, releasing iron-bound phosphorus into the overlying water column. The release rates are further increased when the pH is above 8.5. Decomposition of submersed and emergent vegetation releases phosphorus into the water column. Based on these factors, we expect sediment phosphorus release under anoxic conditions and phosphorus release from plants during decomposition.

As discussed previously, nitrogen cycling throughout Lower Shingle Creek was not in equilibrium during the two surveys. June and September longitudinal mass loading profiles suggest inputs of organic nitrogen and ammonia in the upper reaches (1-3) of Lower Shingle Creek that cannot be calibrated by adjusting kinetic rates or diffuse sources. Near-stream sources, macrophytes and organic-rich sediments are often major contributors of dissolved organic nitrogen and ammonia to rivers and streams (Wetzel 2001). QUAL2K, in its present form, is not suited to model the geochemical affects of growth and breakdown of macrophytes and riparian vegetation. In order to model in-stream loading of organic nitrogen, a diffuse source with a small inflow and high organic nitrogen concentration was placed in wetland Reach 2. In-stream ammonia mass loading can be modeled in QUAL2K by prescribing NH_4 sediment fluxes. Ammonia sediment flux can range from 20-325 mg N/m^2/day depending on season/temperature, sediment biogeochemistry and aerobic conditions. Prescribed fluxes assigned to Reaches 1 and 2 (Table 4.5) were on the mid to high end of this range in order to calibrate to downstream monitoring. These high fluxes can be attributed to a channel-sediment surface area that is wider than modeled and contains sediment high in organic matter and low dissolved oxygen.

Table 4.5. Summary of in-stream loadings.

Reach	Flux	June	September	Justification
Reach 3-6 (BLR to USGS)	Ammonia	Prescribed sediment NH_4 flux (125 mg N/m^2/day)	Prescribed sediment NH_4 flux (75 mg N/m^2/day	Wide, deep slow moving reach containing sediment with high organic matter content (rate supported by Thomann and Mueller 1987)
Reach 1-3 (PLO to BLR)	Organic Nitrogen	Small flow diffuse source with high organic-N (6000 µg N/L)	Small flow diffuse source with high organic-N (6000 µg N/L)	Release of dissolved organic-nitrogen from macrophytes and riparian vegetation (Wetzel 2001)
Reach 1-3 (PLO to BLR)	CBOD	Small flow diffuse source with CBOD (150 mg O_2 /L)	None	Discharge of CBOD from macrophytes and riparian vegetation

4.4 DIFFUSE SOURCES LOADINGS

4.4.1 Lower Shingle Creek

Initially, all flow increases were assigned typical groundwater water quality values and then adjusted upward to meet monitored in-stream water quality results (Table 4.6). Temperature, specific conductance and dissolved oxygen were the only parameters adjusted to meet in-stream conditions.

Table 4.6. Modeled diffuse input parameters for reaches 4-5 (Bass Lake Road to USGS-Queen Ave station).

Parameter	June	September	Justification
Temp (C)	30	25	Calibrated adjustment to in-stream conditions
Specific Conductance (umhos)	900	550	Calibrated adjustment to in-stream conditions
DO	5	5	Calibrated adjustment to in-stream conditions
Nitrate (µg/L)	500	500	Typical MN GW literature value (MPCA 1998)
Organic-P (µg/L)	11.20	11.20	Typical MN GW literature value (MPCA 1999)
Inorganic-P (µg/L)	44.80	44.80	Typical MN GW literature value (MPCA 1999)

4.4.2 Upper Shingle Creek

Initially, all flow increases were assigned typical groundwater water quality values and then adjusted upward to meet monitored in-stream water quality results (Table 4.7). Many of the phosphorus and nitrogen diffuse input concentrations were adjusted above typical groundwater values (Table 4.8). This is further evidence that inflow to Upper Shingle Creek comes from pond discharge and direct stormwater runoff rather than groundwater inputs.

Table 4.7. Modeled diffuse input parameters for June and September.

Parameter	June Reaches 1-2 (SC-I94 to SC-77)	June Reaches 3-4 (SC-77 to SC-03)	June Reaches 4-7 (SC-03 to SC-Xerxes)	Sept. Reaches 1-2 (SC-I94 to SC-77)	Sept. Reaches 3-4 (SC-77 to SC-03)	Sept. Reaches 4-7 (SC-03 to SC-Xerxes)
Location (km to km)	10.16 to 8.73	8.73 to 5.47	5.47 to 1.75	10.16 to 8.73	8.73 to 5.47	5.47 to 1.75

Parameter	June Reaches 1-2 (SC-I94 to SC-77)	June Reaches 3-4 (SC-77 to SC-03)	June Reaches 4-7 (SC-03 to SC-Xerxes)	Sept. Reaches 1-2 (SC-I94 to SC-77)	Sept. Reaches 3-4 (SC-77 to SC-03)	Sept. Reaches 4-7 (SC-03 to SC-Xerxes)
Inflow (m^3/s)	0.094	0.019	0.056	0.008	-0.047 (abstraction)	0.040
Temp (C)	20	20	25	20	n/a	20
Specific conductance (umhos)	800	800	1,500	--	n/a	1,100
DO (mg/L)	--	--	2.5	--	n/a	5.0
$CBOD_u$ (mg/L)	5.00	20.00	--	--	n/a	--
Organic-N (µg/L)	800	800	2000	800	n/a	800
Ammonia (µg/L)	--	--	1500	1000	n/a	1250
Nitrate (µg/L)	--	--	1500*	--	n/a	400
Organic-P (µg/L)	65*	65*	200*	--	n/a	90*
Inorganic-P (µg/L)	100*	100*	44.8	500*	n/a	44.8
Phytoplankton (µgA/L)	--	--	15	--	n/a	6

* denotes above what was expected from typical groundwater sources

Table 4.8: Typical Minnesota surficial (or Quaternary) groundwater literature values

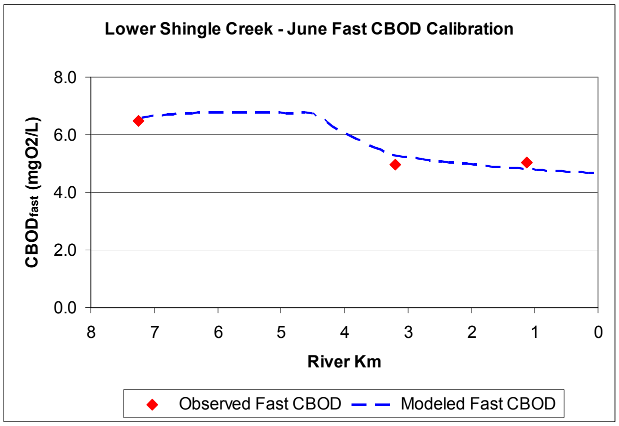
Parameter	Value
Nitrate (µg/L)	500
Organic-P (µg/L)	11.20
Inorganic-P (µg/L)	44.80

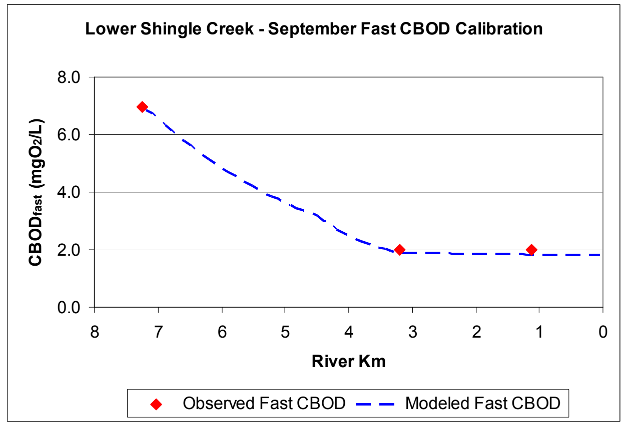
Source: MPCA 1998 and MPCA 1999.

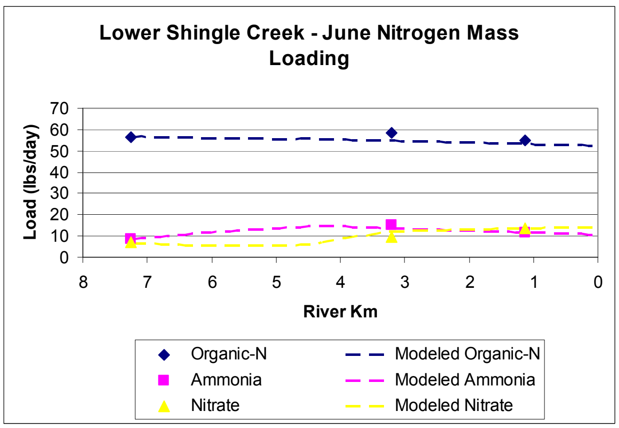
5.0 FINAL WATER QUALITY CALIBRATION

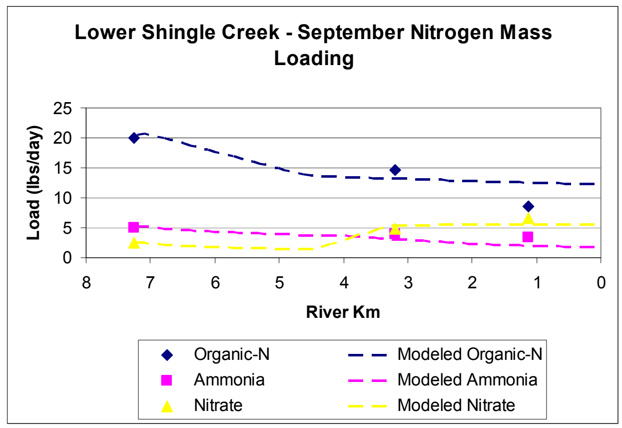
CBOD, chlorophyll a and all forms of nitrogen and phosphorus were calibrated once all diffuse source water quality parameters and kinetic rates are properly incorporated into the model. The models performed well in predicting loads and concentrations of the primary water quality parameters that affect dissolved oxygen. Figures 5.1 to 5.8 are calibration plots for the Lower Shingle Creek model and Figures 5.9 to 5.16 are similar plots for the Upper Shingle Creek model.

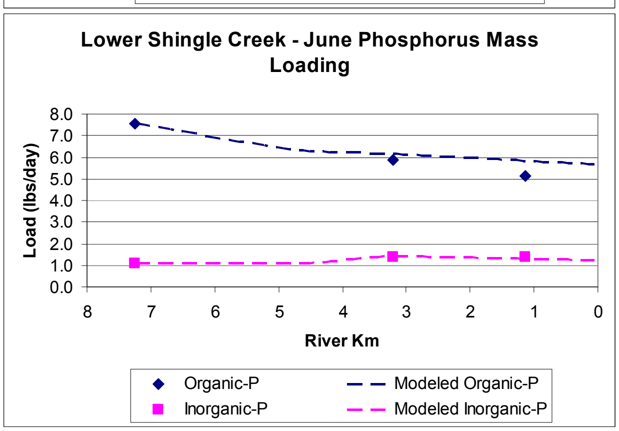
Figures 5.1 to 5.8. Final water quality calibration plots for Lower Shingle Creek.

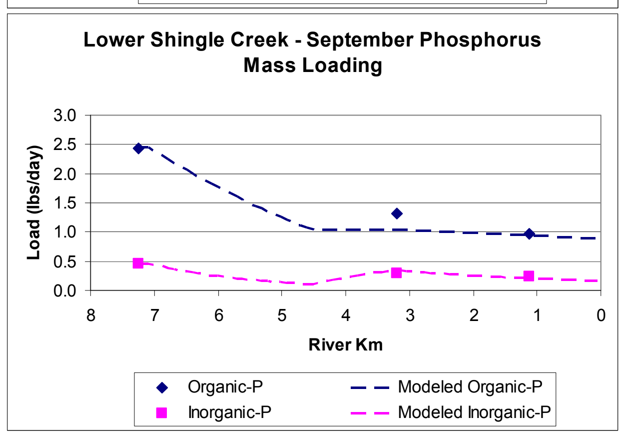


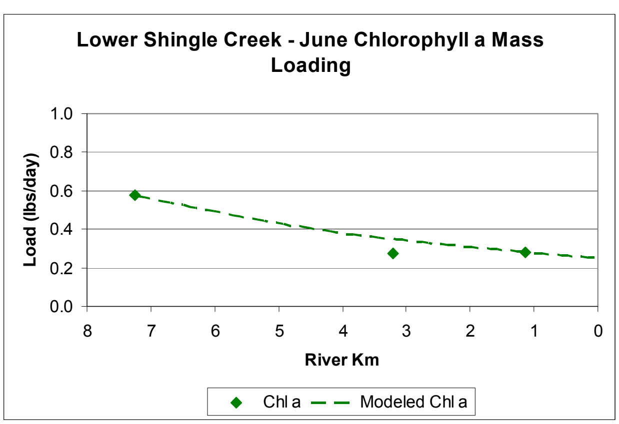


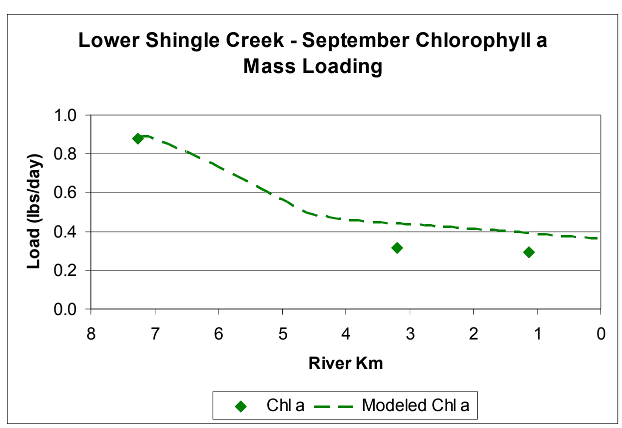




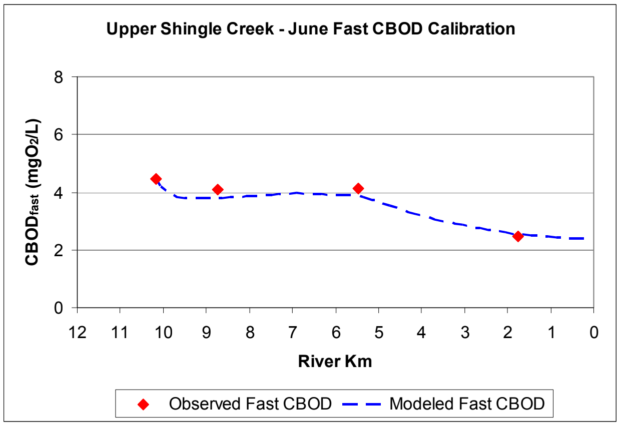


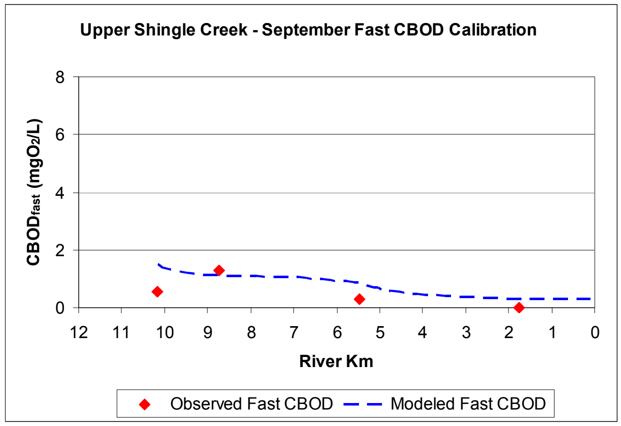


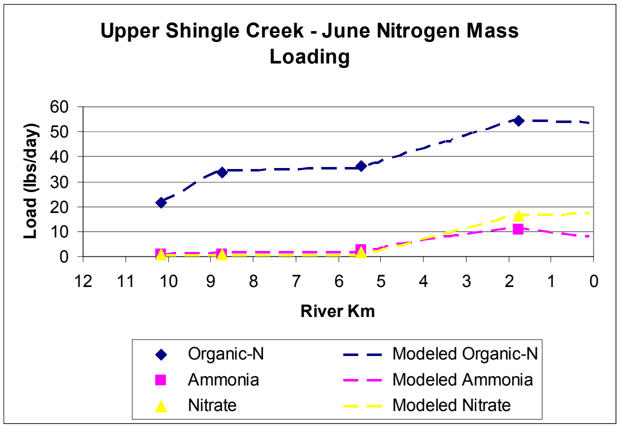


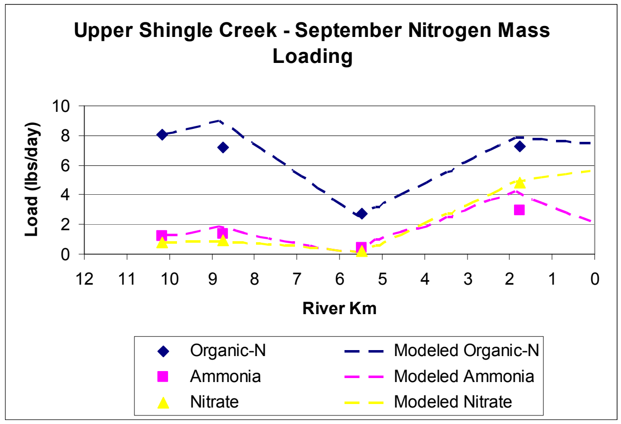


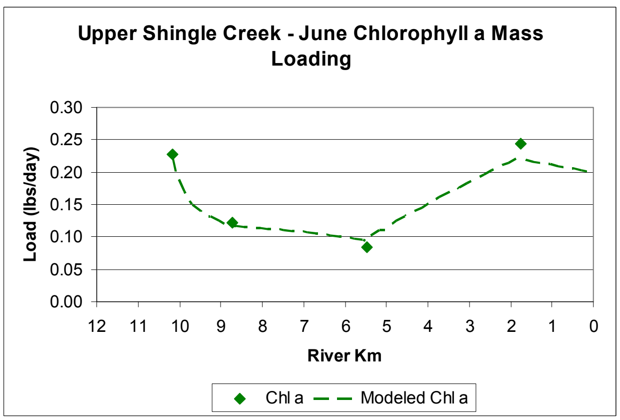
Figures 5.9 to 5.16. Final water quality calibration plots for Upper Shingle Creek.

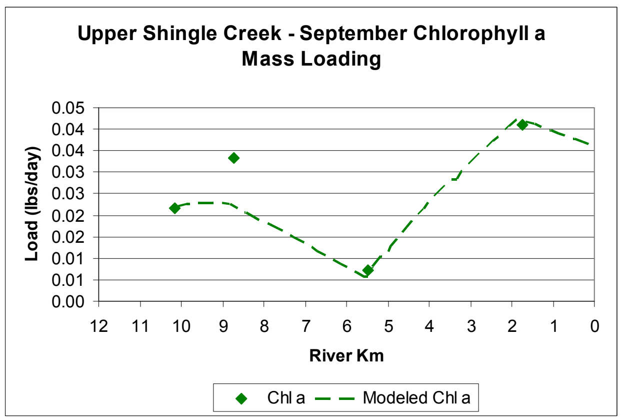


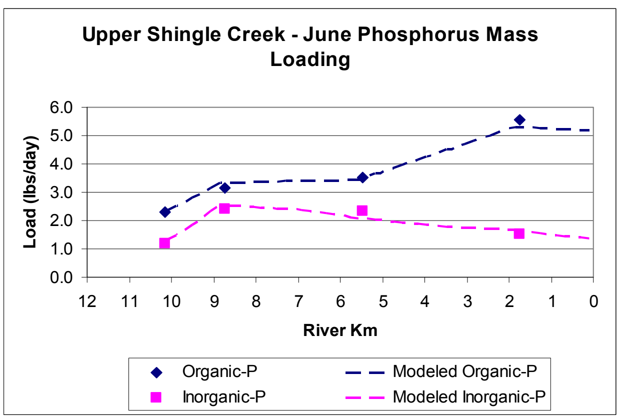


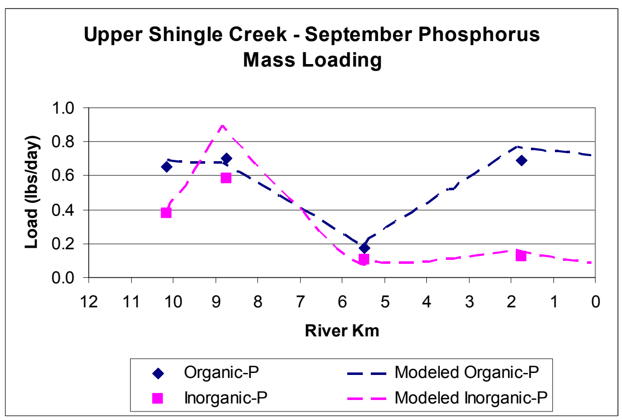












6.0 DISSOLVED OXYGEN CALIBRATION

6.1 SEDIMENT OXYGEN DEMAND/NUTRIENT RELEASE

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 storm 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).

6.1.1 Lower Shingle Creek

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/nutrient calibrated model were close to averaged monitored values for the low-flow synoptic survey and no additional SOD rates were prescribed. Modeled dissolved oxygen concentrations for the June survey were higher than observed using model-predicted SOD rates. The stream was wider in Reaches 1-3 during the June survey when the creek had access to part of its flood plain and riparian vegetation. A prescribed SOD of 2.5 g O_2/m^2/day was assigned to this stretch in order to account for a higher than-modeled sediment surface area and additional SOD from riparian vegetation. These prescribed SOD rates effectively lowered mean oxygen concentrations closer to observed values.

6.1.2 Upper Shingle Creek

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/nutrient calibrated models were consistently higher than average monitored values. Model-predicted SOD is greater than 1.0 g O_2/m^2/day in Reaches 1-3 where phytoplankton settling velocity is high, but quickly drops below 1.0 g O_2/m^2/day for downstream Reaches 4-12. These reaches all contain some slow-moving wetland/depositional stretches with mud and silt-sediment substrate. Additional SOD was applied to Reaches 4-12 to account for breakdown of wetland/riparian vegetation and sediment deposited during non-steady state storm events. SOD rates were prescribed for each reach to keep SOD throughout Upper Shingle Creek close to 1.0 g O_2/m^2/day. These prescribed SOD rates effectively lowered mean oxygen concentrations close to observed.

6.2 FINAL DISSOLVED OXYGEN CALIBRATION

Figures 6.1 through 6.4 show final calibration results for model-predicted and observed dissolved oxygen concentrations. All observed measurements (squares) were collected during the June and September synoptic surveys. Daily minimums and maximums (open squares) are based on continuous DO data from YSI sensor data loggers. Field measurements (solid squares) were collected using a hand-held YSI sensor between 12:00 pm and 3:00 pm during each synoptic survey.

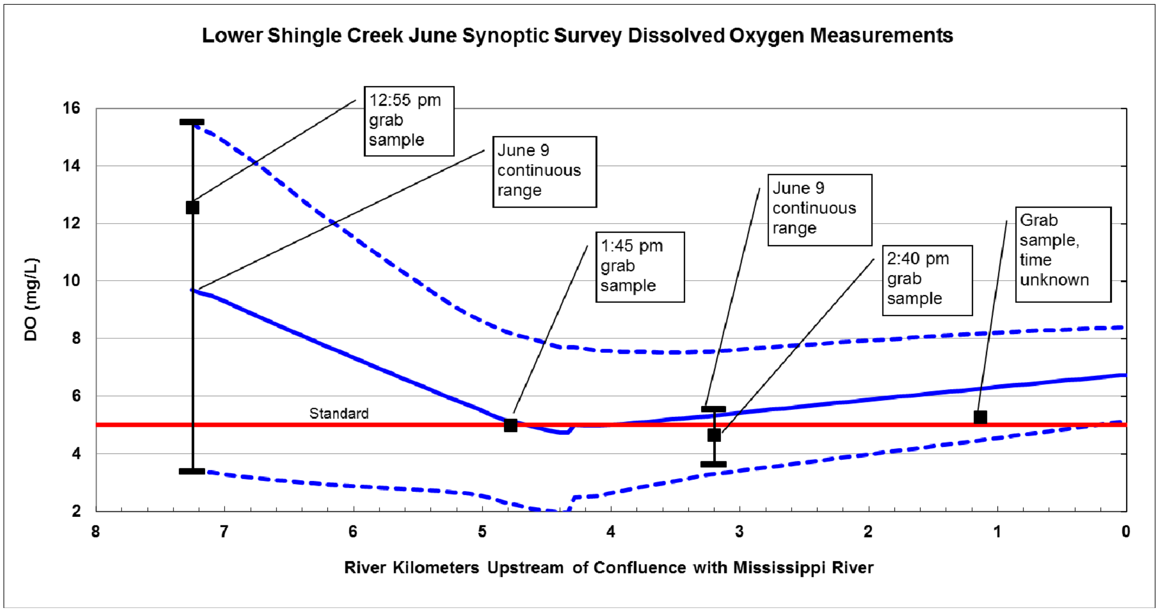


Figure 6.1. June calibrated dissolved oxygen longitudinal profile.
Note: dashed lines are modeled maximum and minimum.

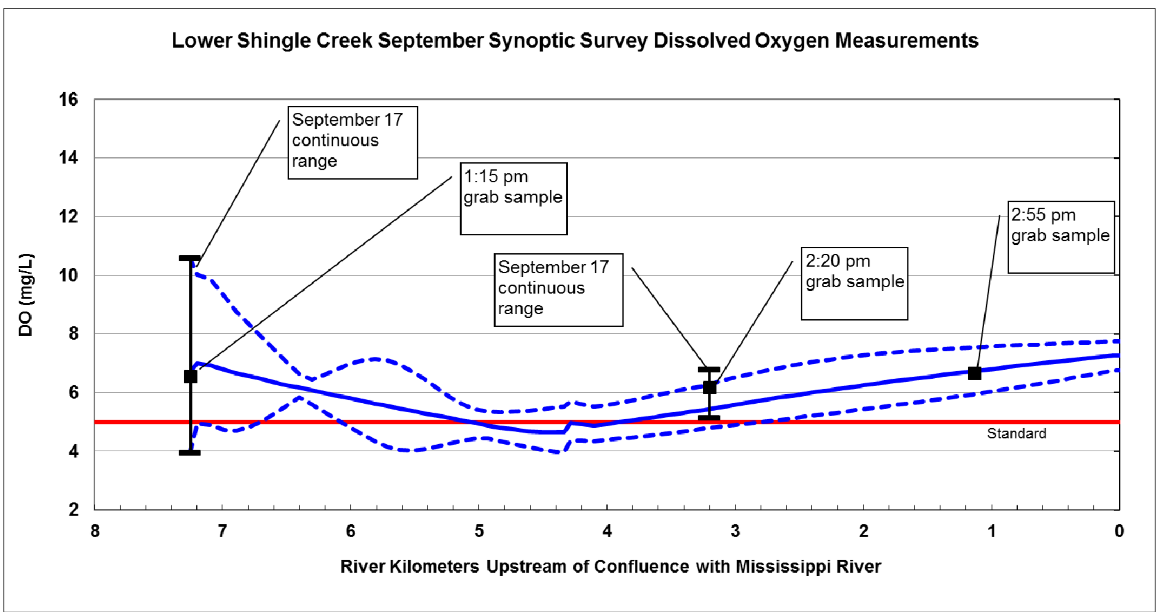


Figure 6.2. September calibrated dissolved oxygen longitudinal profile.
Note: dashed lines are modeled maximum and minimum.

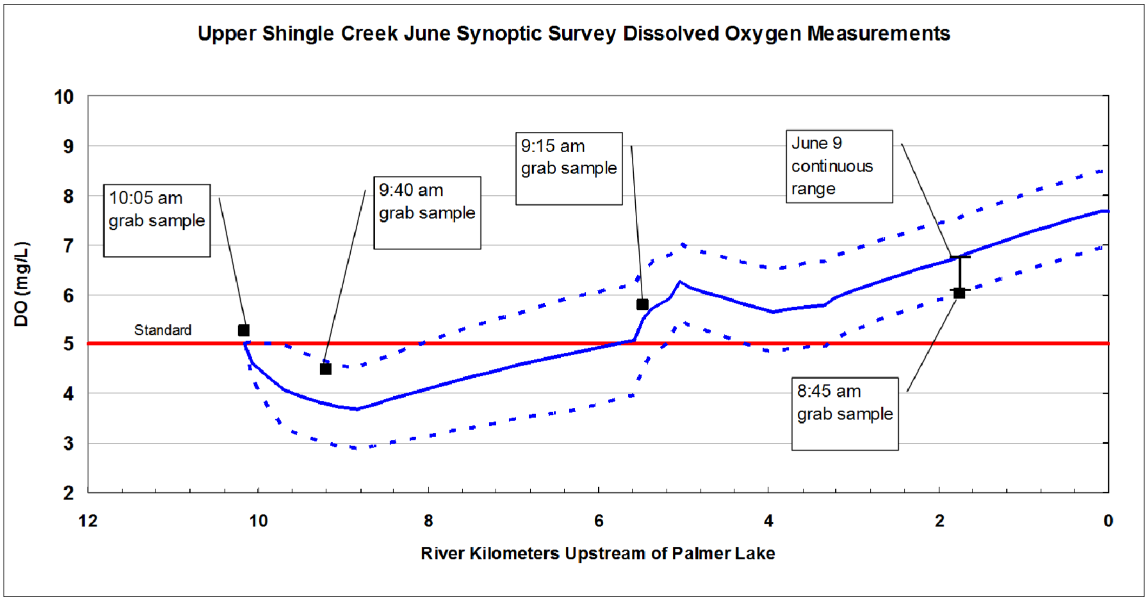


Figure 6.3. June calibrated dissolved oxygen longitudinal profile.

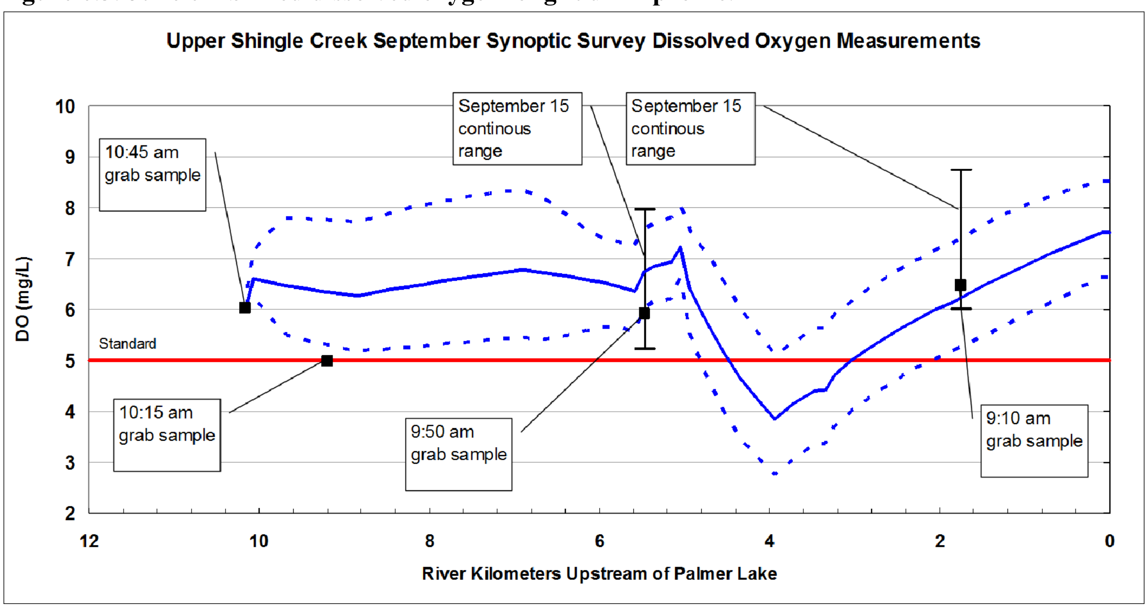


Figure 6.4. September calibrated dissolved oxygen longitudinal profile.

7.0 MODEL VALIDATION

The high-flow and low-flow calibrated models were validated using dissolved oxygen data collected during a Shingle Creek longitudinal dissolved oxygen profile on August 16, 2007.

7.1.1 Lower Shingle Creek

All observed measurements (squares) were collected between the hours of 8:30 am and 10:00 am. The goal of the validation was to substantiate the model for another event without making changes to the calibrated kinetic rates and constants. Average daily flow at the USGS station during the longitudinal survey was 0.23 m^3/s, which is in between the June high flow (0.34 m^3/s)

and the September low-flow events (0.11 m^3/s). Headwater and diffuse source flow rates for the validation runs were raised or lowered by the percent difference in flow at the USGS station during the validation survey and each calibration run. The headwater and diffuse source water quality concentrations and kinetic rates were left the same as the calibrated runs. Model predicted dissolved oxygen concentrations were lower than observed using the June high-flow calibrated model for validation, so the prescribed SOD from Reaches 1-3 was removed for the August 2007 validation run using the high-flow model brings model-predicted dissolved oxygen concentrations closer to observed data (Figure 7.1). Model predicted dissolved oxygen concentrations were slightly higher when using the September low-flow model (Figure 7.2).

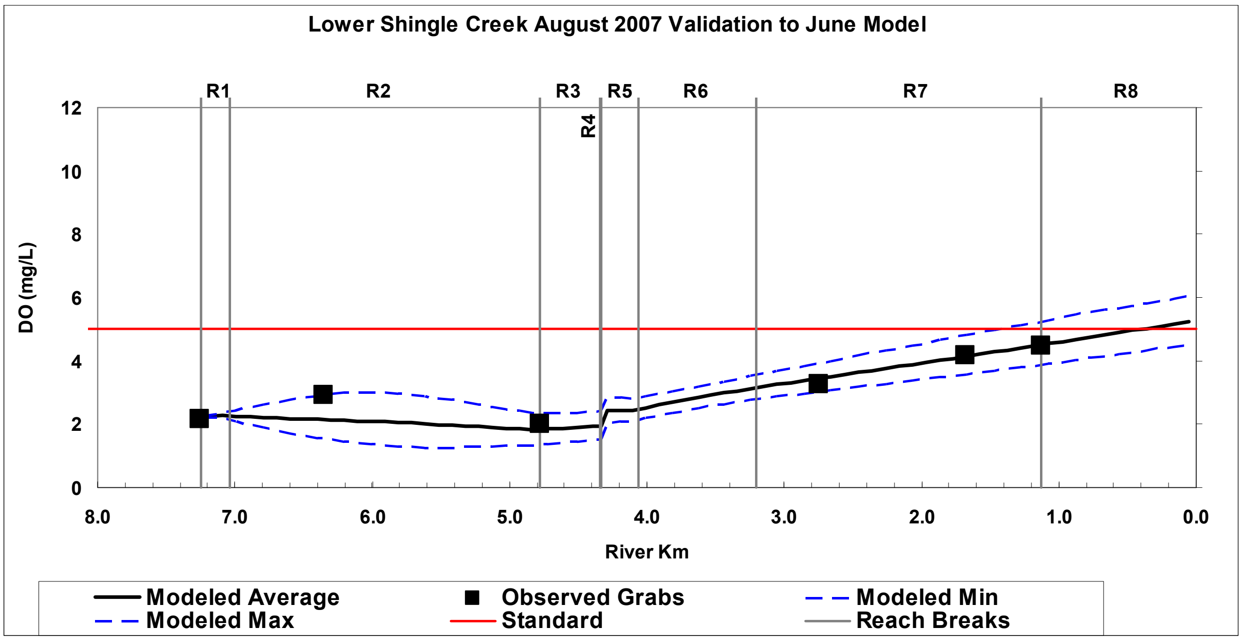


Figure 7.1. August 2007 validation run using "high-flow" calibrated model (prescribed SOD removed).

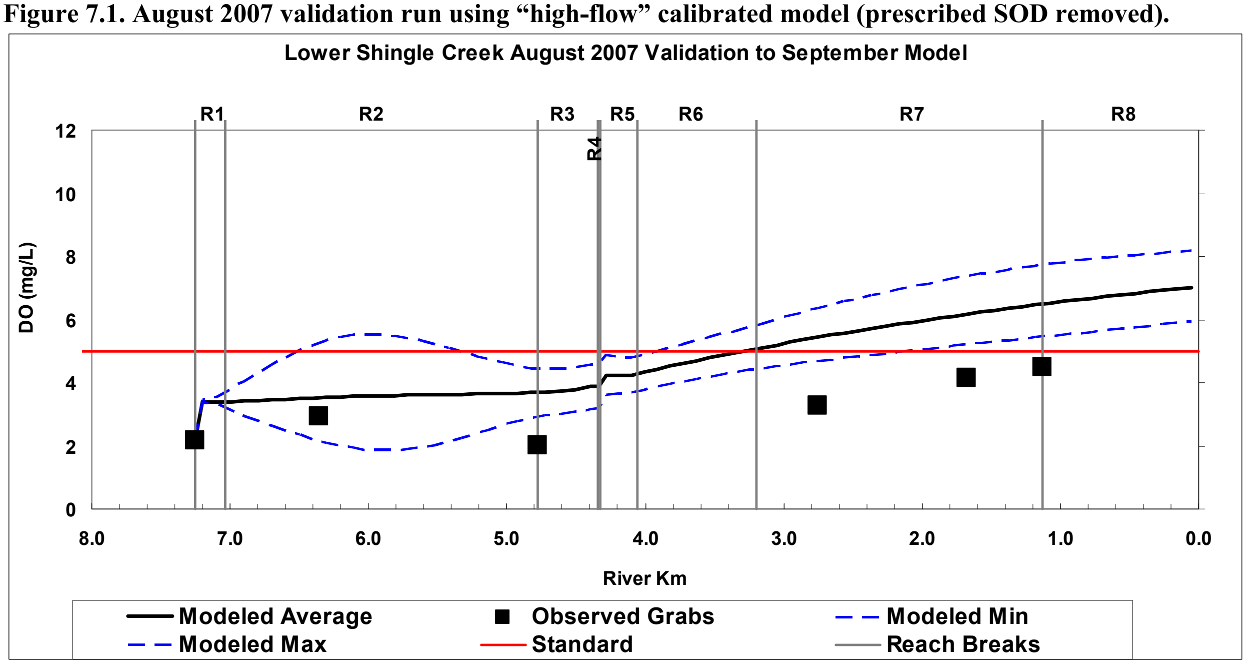


Figure 7.2. August 2007 validation run using "low-flow" calibrated model.

7.1.2 Upper Shingle Creek

All the data collected for the August 16, 2007 validation event was collected between the hours of 6:00 am and 8:30 am. The goal of the validation was to substantiate the model's predictive power. Average daily flow at the SC-03 station during the longitudinal survey was 0.25 m^3/s, which is 4% different from the June 9th synoptic survey gauged flow (0.26 m^3/s). June high-flow model headwater and diffuse source flow rates were lowered 4% to account for the difference in flow at the SC-03 station on August 16, 2007 and June 9, 2008. All headwater and diffuse source water quality concentrations and kinetic rates were left the same as the June high-flow calibrated run. Model-predicted dissolved oxygen concentrations were within the range of observed values on August 16, 2007, thus validating the June high-flow calibrated model (Figure 7.3).

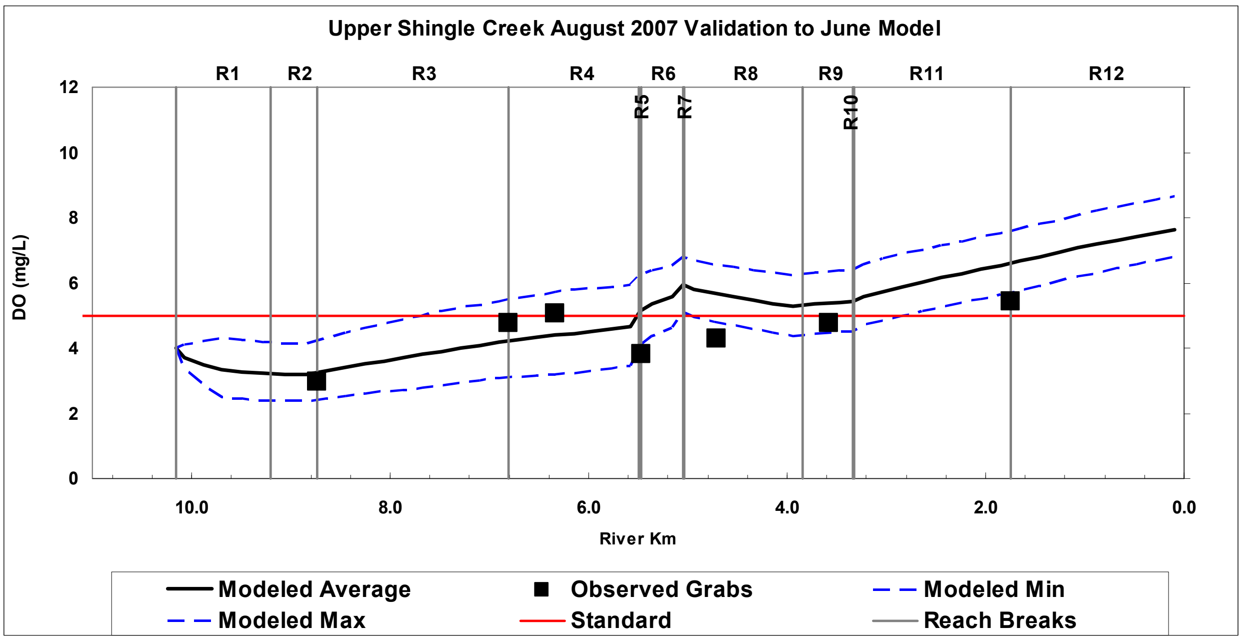


Figure 7.3. August 2007 validation run using the "high-flow" calibrated model.

8.0 SENSITIVITY ANALYSIS

To evaluate the sensitivity of model-predicted dissolved oxygen to changes in model variables, seven kinetic rates, three reach specific rates, and channel slopes were removed or adjusted by specific percentages.

8.1 LOWER SHINGLE CREEK

Tables 8.1 to 8.3 summarize the affect model changes have on dissolved oxygen concentrations as a percentage of the average model calibrated value for the entire segment of Lower Shingle Creek. Results show DO throughout the system is most sensitive to the kinetic rates driving SOD levels (nutrient and phytoplankton settling) and the SOD settings themselves. CBOD oxidation and nutrient hydrolysis rates are less sensitive to dissolved oxygen throughout Lower Shingle Creek. Sensitivity to channel slope also show model predicted dissolved oxygen is sensitive to this parameter. This exercise suggests sediment processes play a bigger role than water column processes in consuming dissolved oxygen during these two calibration/sampling events.

Table 8.1. DO sensitivity to kinetic rates.

Kinetic Rate	+25%		-25%		Default Value	
	June	Sept.	June	Sept.	June	Sept.
$CBOD_u$ oxidation rate (day^{-1})	-0.1%	-0.1%	0.1%	0.1%	-4.7%	-2.5%
Organic-N Hydrolysis (day^{-1})	-0.4%	-1.6%	0.4%	1.5%	--	--
Organic-N Settling (m/d)	-0.1%	-0.2%	0.0%	0.3%	-1.7%	-7.5%
Organic-P Hydrolysis (day^{-1})	0.1%	2.6%	-0.2%	-3.5%	--	--
Organic-P Settling (m/d)	0.0%	-0.4%	0.0%	0.4%	0.0%	-1.4%
Inorganic-P Settling (m/d)	-0.1%	-2.2%	0.1%	2.0%	-6.4%	-32.2%
Phytoplankton Settling (m/d)	-1.1%	-4.6%	1.4%	6.0%	0.0%	-24.3%

Table 8.2: DO sensitivity to reach rates.

Action	DO Sensitivity	
	June	September
Remove Sediment Denitrification Transfer Coefficient in Reaches 1 and 2	0.4%	2.4%
Remove prescribed ammonia sediment flux in Reaches 1 and 2	3.0%	9.7%
Remove prescribed SOD in all reaches	39.7%	6.6%
Remove all SOD by setting SOD channel coverage to 0%	70.6%	93.8%

Table 8.3. DO sensitivity to channel slope.

Channel Slope	DO Sensitivity	
	June	Sept.
Increased by 25%	4.7%	6.2%
Decreased by 25%	-5.4%	-7.1%

8.2 UPPER SHINGLE CREEK

Tables 8.4 to 8.6 summarize the affect model changes have on dissolved oxygen concentrations as a percentage of the average model calibrated value for the entire segment. Results show DO throughout the system is most sensitive to the kinetic rates driving SOD levels (nitrogen and phosphorus settling) and the SOD settings themselves. CBOD oxidation and nutrient hydrolysis rates are less sensitive to dissolved oxygen throughout Upper Shingle Creek. Sensitivity to channel slope also show model predicted dissolved oxygen is sensitive to this parameter. This exercise suggests sediment processes play a bigger role than water column processes in consuming dissolved oxygen during these two calibration/sampling events.

Table 8.4. DO sensitivity to kinetic rates.

Kinetic Rate	+25%		-25%		Default value	
	June	Sept.	June	Sept.	June	Sept.
$CBOD_u$ oxidation rate (day^{-1})	-1.6%	-0.6%	1.7%	0.7%	3.9%	1.8%
Organic-N Hydrolosis (day^{-1})	-0.1%	-0.5%	0.1%	0.6%	--	--
Organic-N Settling (m/d)	-0.1%	-0.2%	0.1%	0.1%	-1.7%	-5.9%
Organic-P Hydrolosis (day^{-1})	0.0%	0.6%	0.0%	-0.7%	--	--
Organic-P Settling (m/d)	0.0%	-0.1%	0.0%	0.0%	0.0%	-1.3%
Inorganic-P Settling (m/d)	0.0%	-2.1%	0.0%	1.9%	-2.4%	-35.6%
Phytoplankton Settling (m/d)	-0.4%	-0.2%	0.4%	0.3%	-0.9%	-1.5%

Table 8.5: DO sensitivity to reach rates.

Action	DO Sensitivity	
	June	Sept.
Remove reach specific phytoplankton settling velocity in Reaches 1+2	-0.5%	--
Remove prescribed SOD in all reaches	9.5%	83.0%
Remove all SOD by setting SOD channel coverage to 0%	18.6%	98.2%

Table 8.6. DO sensitivity to channel slope.

Channel Slope	DO Sensitivity	
	June	Sept.
Increased by 25%	8.6%	7.0%
Decreased by 25%	-11.4%	-8.1%

9.0 REFERENCES

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Appendix D
Summary of Management Scenario Modeling

1.0 SCENARIO DESCRIPTIONS

Various loading/management scenarios were modeled on both Upper and Lower Shingle Creeks to evaluate load reduction alternatives, and the TMDL. The following three scenarios were developed and analyzed:

1. Headwater boundary conditions;
2. Sediment oxygen demand; and
3. Channel form, drop structures and re-meandering the stream.

These three scenarios were incorporated individually and in combination into the QUAL2K model to predict the DO in both the Upper and Lower Shingle Creek.

1.1 HEADWATER BOUNDARY CONDITIONS

The headwater boundary condition of the:

- Upper Shingle Creek model is the widened wetland reach at the confluence of Bass and Eagle Creeks just north of I-94 in Brooklyn Park
- Lower Shingle Creek model is the outflow of Palmer Lake in Brooklyn Center

This scenario evaluates what the headwater water quality conditions should be to meet the 5 mg/L DO standard downstream.

1.2 SEDIMENT OXYGEN DEMAND (SOD)

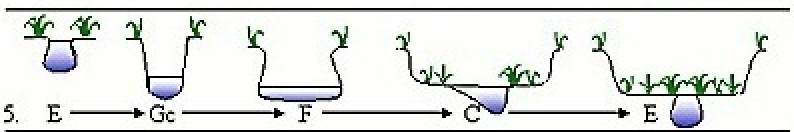
Sediments in the wetland and slow-flowing depositional reaches typically have high organic content, the decay of which consumes available oxygen within the sediments and overlying water column. The model suggests SOD is high enough in certain reaches of Shingle Creek to lower dissolved oxygen to an anoxic state. Under these conditions, phosphorus and reduced forms of nitrogen may be released from the sediments and become available to algae and other aquatic plants for primary production. This scenario quantifies the SOD reduction/removal necessary to achieve a 5 mg/L DO daily minimum throughout all reaches of Shingle Creek.

1.3 LOW FLOW CHANNEL FORM

The longitudinal profile is a graph of elevation versus distance. Over time factors such as anthropogenic influences, discharge, velocity, channel width and shape, reach slope, and size and type of particles in the water and in the channel influence the longitudinal profile and stability of a channel's form.

In the case of Shingle Creek, many factors contribute to the wide trapezoidal channel form seen today. According to the 1855 public land survey, Shingle Creek was once a narrow meandering creek in an oak savannah. Dramatic changes in land use toward urban and loss of the creek's meander are evident when reviewing the 1947 to 2010 aerial photography. Increases in runoff discharge rates, peaking factors, and runoff volumes are the direct result of urban development and channel straightening, resulting in changes in channel form until a new state of channel form equilibrium is found.

The following graphic shows an example of channel form evolution ultimately reaching equilibrium under a change in hydrology and hydraulics of a stream.



Source: Rosgen 1996, evolution of stream type 5.

Shingle Creek through natural and human-induced causes has evolved into a stage 3-stage 4 stream. This scenario evaluates the effect a stage 5 channel form will have on dissolved oxygen. These proposed changes in channel form do not specify any changes to the flat channel slope common throughout much of Shingle Creek.

The introduction of a small low flow channel would increase flow velocities resulting in increased reaeration. Applying the principals of hydraulic geometry (Leopold and Maddock 1953) and selecting a non-erodible design velocity based on the channel sediments (using pebble count data collected), the low-flow width and depth of the channel are determined using the permissible velocity design method.

The flow gauging cross-sections were modeled in XP-SWMM using the QUAL2K model reach data. The cross-sections were modified to represent the creation of a low flow channel with side slopes of 3 horizontal to 1 vertical (assume sandy loam channel wall material). The low-flow width and depth of the channel was determined using a maximum permissible velocity of 1.5 ft/s (assume fine sand). A range of flow rates were simulated in XP-SWMM to estimate QUAL2K hydraulic power function rating curves coefficients and exponents to define reach hydraulics, as follows:

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

The resulting changes increase the velocity, which in turn increases reaeration with no change in channel slope as shown in the reaeration model formula below (Tsivoglou and Neal 1972; Thomann and Mueller 1987)

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

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)

This scenario evaluates the effect of modifying the channel form on reaeration.

2.0 LOWER SHINGLE CREEK

2.1 HIGHER FLOW SCENARIO RESULTS

The higher flow model was developed using June 2008 synoptic survey results.

2.1.1 Scenario 1: Headwater Adjustments

Specific headwater water quality parameters were adjusted to meet water quality standards (Table 2.1, Figure 2.1).

Table 2.1. Higher flow scenario Lower Shingle Creek model parameter adjustments.

Parameter	Calibrated Model Value	Scenario Value	Justification
Diurnal DO curve	Observed – data sonde (Figure 2.1)	Typical DO profile (Figure 2.1)	Adjusted headwater DO profile so that minimum daily DO does not fall below 5.0 mg/L

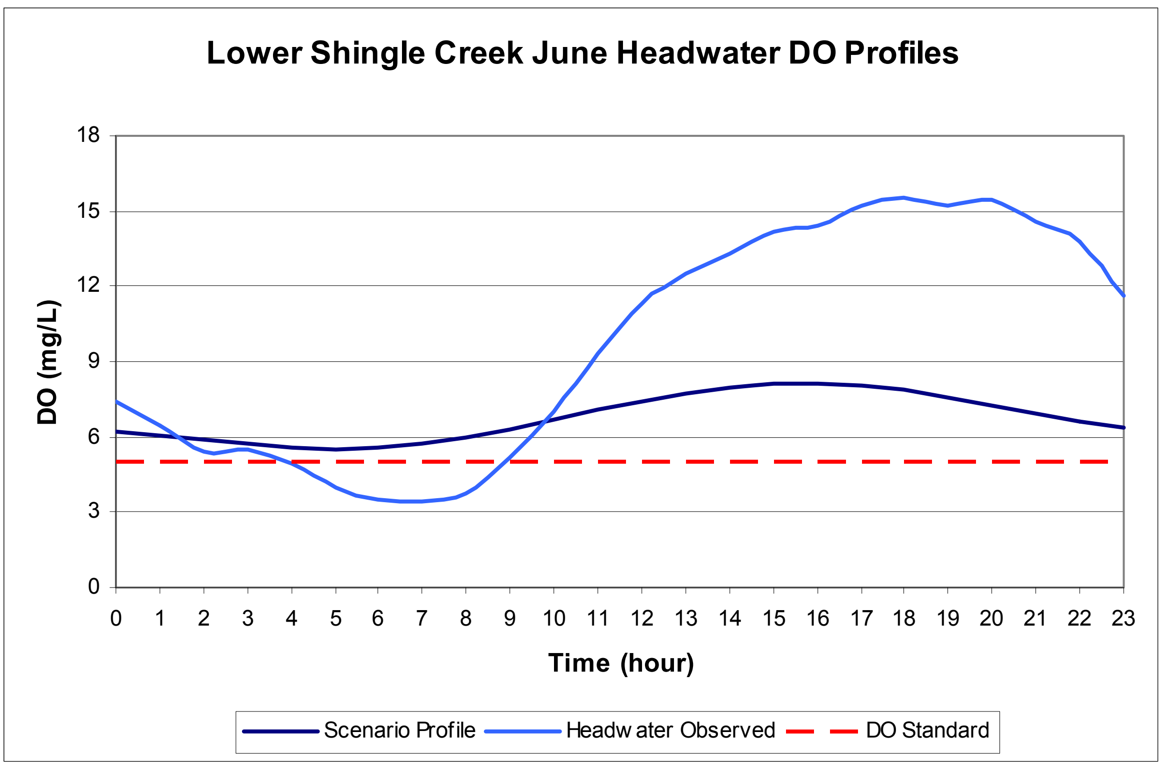


Figure 2.1. Higher flow scenario 1 DO headwater profile.

2.1.2 Scenario 2: SOD Adjustments

Prescribed SOD was adjusted to achieve the DO standard (Table 2.2).

Table 2.2. Higher flow scenario 2 adjustments to prescribed SOD and bottom coverage.

Reach	Calibration Prescribed SOD ($g\ O_2/m^2/day$)	Scenario Prescribed SOD ($g\ O_2/m^2/day$)	Calibration SOD bottom coverage (%)	Scenario SOD bottom coverage (%)
1	2.5	**0.0**	100	**100**
2	2.5	**0.0**	100	**100**
3	2.5	**0.0**	100	**100**
4	0.1	**0.0**	100	**100**
5	0.1	**0.0**	100	**100**
6	0.1	**0.0**	100	**100**
7	0.1	**0.0**	100	**100**
8	0.1	**0.0**	100	**100**

2.1.3 Final Scenario Combination Output

Each scenario (1 and 2) was applied step-wise until minimum dissolved oxygen did not fall below the 5.0 mg/L standard anywhere throughout Lower Shingle Creek (Table 2.3 and Figure 2.2). The combination of removal of prescribed SOD and increased headwater DO was sufficient to meet the required SOD reductions and increase minimum daily DO for Lower Shingle Creek. No adjustments to channel form were required.

Table 2.3 Higher flows combined scenarios results.

Scenario	Minimum DO (mg/L)	Minimum DO location (River Km)
Calibrated Model	1.96	4.40
1	2.38	4.40
2	5.05	5.91

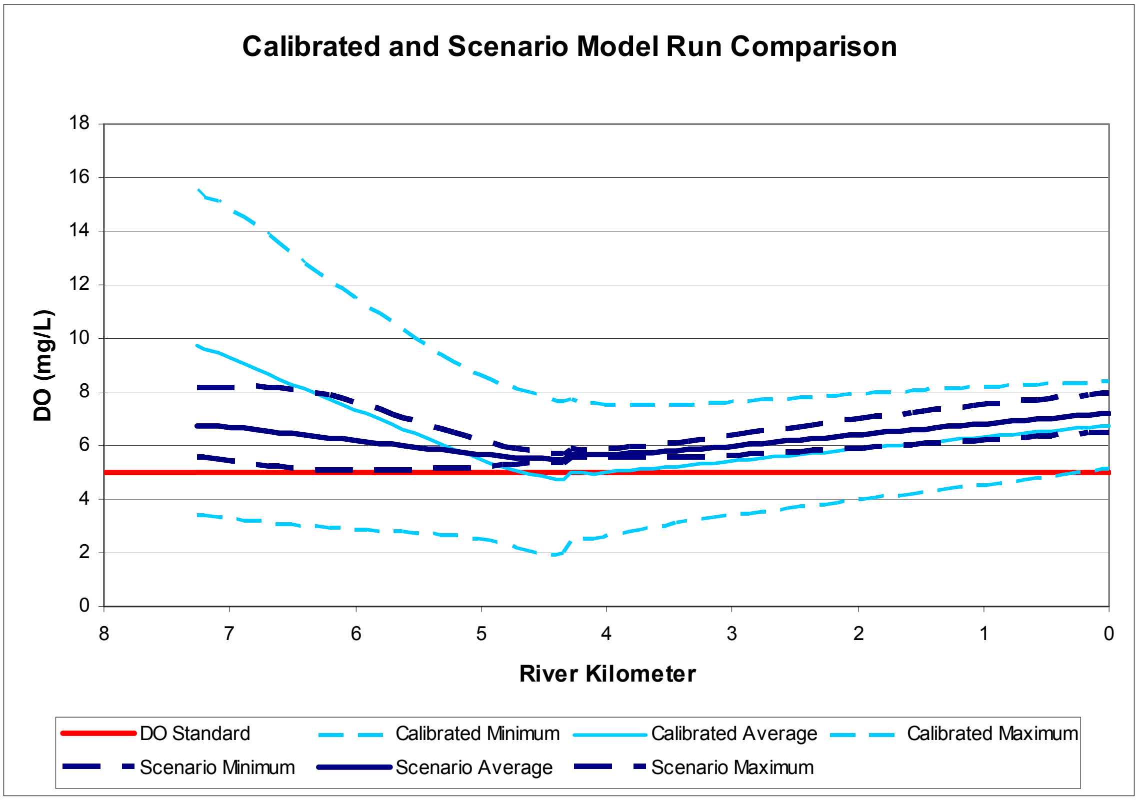


Figure 2.2. Higher flows combined scenarios DO profile.

2.2 LOWER FLOW SCENARIO RESULTS

The lower flow model was developed using September synoptic survey results.

2.2.1 Scenario 1: Headwater Adjustments

Specific headwater water quality parameters were adjusted to meet water quality standards (Table 2.4, Figure 2.3).

Table 2.4. Lower flow scenario Lower Shingle Creek model parameter adjustments.

Parameter	**Calibrated Model Value**	**Scenario Value**	**Justification**
Diurnal DO curve	Observed – data sonde (Figure 3.1)	Typical DO profile (Figure 3.1)	Adjusted headwater DO profile so that minimum daily DO does not fall below 5.0 mg/L
Chlorophyll-a	Observed – 42 ug/L	20 ug/L	Adjusted to meet NCHF shallow lake chlorophyll-a standard

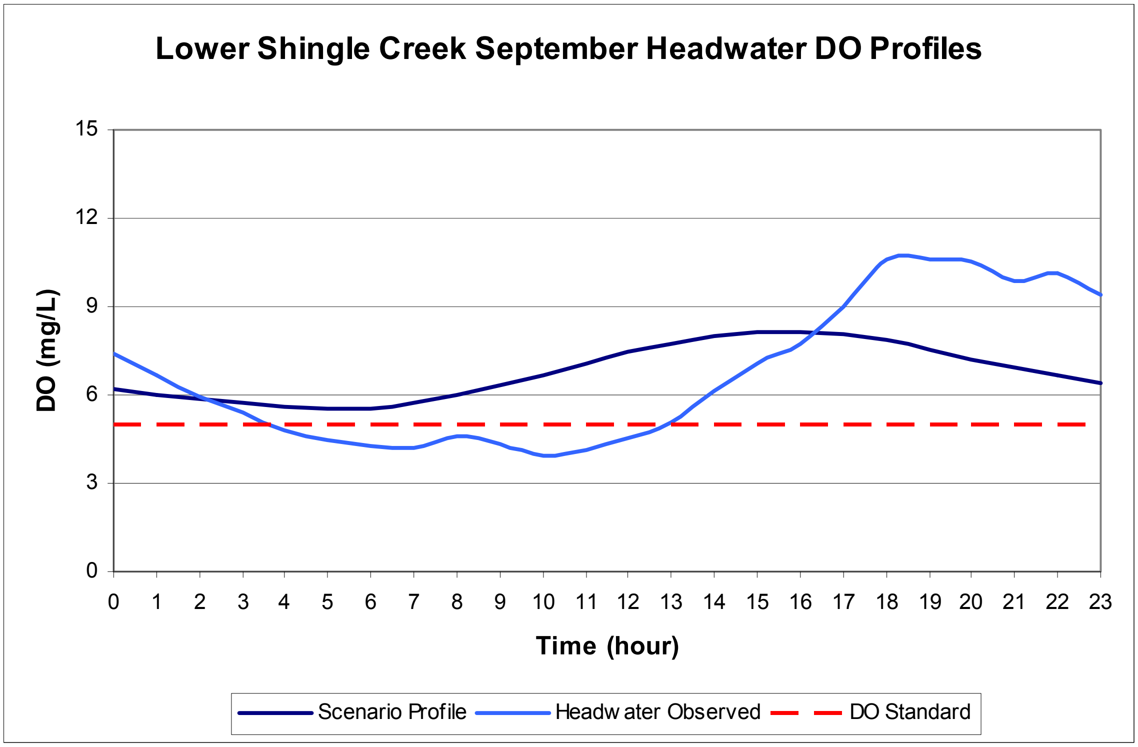


Figure 2.3. Lower flow scenario 1 DO headwater profile.

2.2.2 Scenario 2: Channel Form Adjustment

Hydraulic coefficients were adjusted (Tables 2.5 and 2.6) to create narrower, low-flow channels when flow is below 10 cfs.

Table 2.5. Lower Shingle Creek calibrated hydraulic coefficient and exponents assigned to each reach.

Reach	Rating Curve Used	Velocity		Depth		Width	
		Coeff.	Exp.	Coeff.	Exp.	Coeff.	Exp.
1	PLO*	0.30	0.56	0.35	0.14	9.52	0.30
2	BLR	0.11 Δ	0.80	0.46	0.05	12.21	0.15
3	BLR*	0.18	0.80	0.46	0.05	12.21	0.15
4	None – Weir	Appendix C					
5	None – Manning's	Appendix C					
6	SC00+USGS	0.27	0.68	0.41	0.22	9.06	0.10
7	SC00+USGS*	0.27	0.68	0.41	0.22	9.06	0.10
8	SC00*+USGS	0.27	0.68	0.41	0.22	9.06	0.10

* The monitoring station is at the upstream end of the reach.

Δ The hydraulic coefficients or exponent were changed.

Table 2.6. Lower Shingle Creek channel form scenario.

Reach	Rating Curve Used	Velocity		Depth		Width	
		Coeff.	Exp.	Coeff.	Exp.	Coeff.	Exp.
1	PLO*	**0.22**	**0.35**	**1.50**	**0.45**	**3.03**	**0.20**
2	BLR	**0.40**	0.80	0.46	0.05	**5.49**	0.15

Reach	Rating Curve Used	Velocity		Depth		Width	
		Coeff.	Exp.	Coeff.	Exp.	Coeff.	Exp.
3	BLR*	**0.40**	0.80	0.46	0.05	**5.49**	0.15
4	None – Weir	No change for channel form scenario					
5	None – Manning's	No change for channel form scenario					
6	SC00+USGS	**0.40**	0.68	**0.80**	0.22	**3.13**	0.10
7	SC00+USGS*	**0.40**	0.68	**0.80**	0.22	**3.13**	0.10
8	SC00*+USGS	**0.40**	0.68	**0.80**	0.22	**3.13**	0.10

* The monitoring station is at the upstream end of the reach.

Δ The hydraulic coefficients or exponent were changed.

Bold denotes a change in hydraulic coefficients or exponent for low flow channel form scenario

2.2.3 Scenario 3: SOD Adjustments

Prescribed SOD and bottom coverage SOD was adjusted to achieve DO standard (Table 2.7).

Table 2.7. Scenario 3 adjustments to prescribed SOD and bottom coverage.

Reach	Calibration Prescribed SOD (g O_2/m^2/day)	Scenario Prescribed SOD (g O_2/m^2/day)	Calibration SOD bottom coverage (%)	Scenario SOD bottom coverage (%)
1	0.1	**0.0**	100	**95**
2	0.1	**0.0**	100	**95**
3	0.1	**0.0**	100	**95**
4	0.1	**0.0**	100	**95**
5	0.1	**0.0**	100	**95**
6	0.1	**0.0**	100	**95**
7	0.1	**0.0**	100	**95**
8	0.1	**0.0**	100	**95**

2.2.4 Combined Scenarios Results

Each scenario (1-3) was applied step-wise until minimum dissolved oxygen did not fall below the 5.0 mg/L standard anywhere throughout Lower Shingle Creek (Table 2.8 and Figure 2.4). The combination of removal of prescribed SOD, increased headwater DO, and low-flow channel alterations was sufficient to meet the required SOD reductions and increase minimum daily DO for Lower Shingle Creek.

Table 2.8. Lower flows combined scenarios results.

Scenario	Minimum DO (mg/L)	Minimum DO location (River Km)
Calibrated Model	3.96	7.25
1	4.46	5.03
2	4.88	5.52
3	5.01	5.52

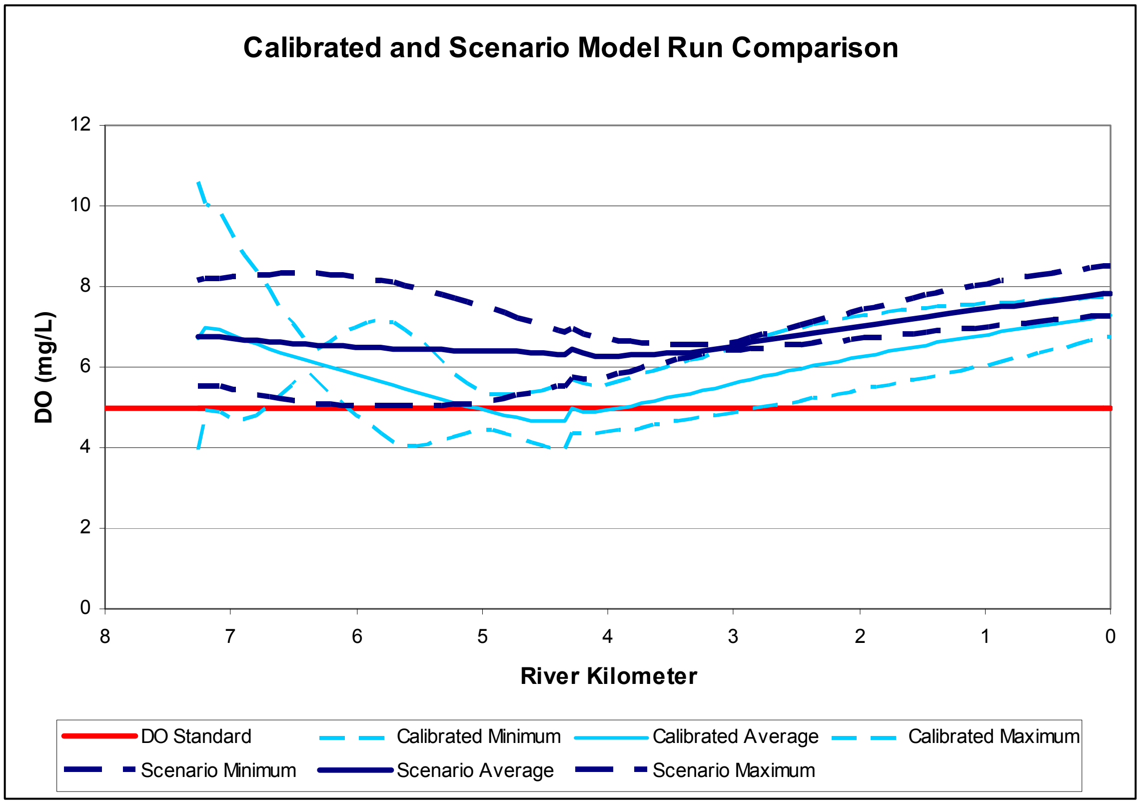


Figure 2.4. Lower flows combined scenarios DO profile.

3.0 UPPER SHINGLE CREEK

3.1 HIGHER FLOW SCENARIO RESULTS

The higher flow model was developed using June synoptic survey results.

3.1.1 Scenario 1: Headwater Adjustments

Specific headwater water quality parameters were adjusted to meet water quality standards (Table 3.1, Figure 3.1). Because no continuous dissolved oxygen data was available at the I-94 Wetland outlet, the calibrated model assumed that the wetland was always discharging at 5.0 mg/L, the average of the available sampling data. This scenario assumed that dissolved oxygen concentration followed a typical diurnal profile that did not fall below 5.0 mg/L.

Table 3.1. Higher flow scenario Upper Shingle Creek model parameter adjustments.

Parameter	Calibrated Model Value	Scenario Value	Justification
Diurnal DO curve	Average of observed data = 5.0 mg/L (Figure 2.1)	Typical DO profile (Figure 2.1)	Adjusted headwater DO profile so that minimum daily DO does not fall below 5.0 mg/L

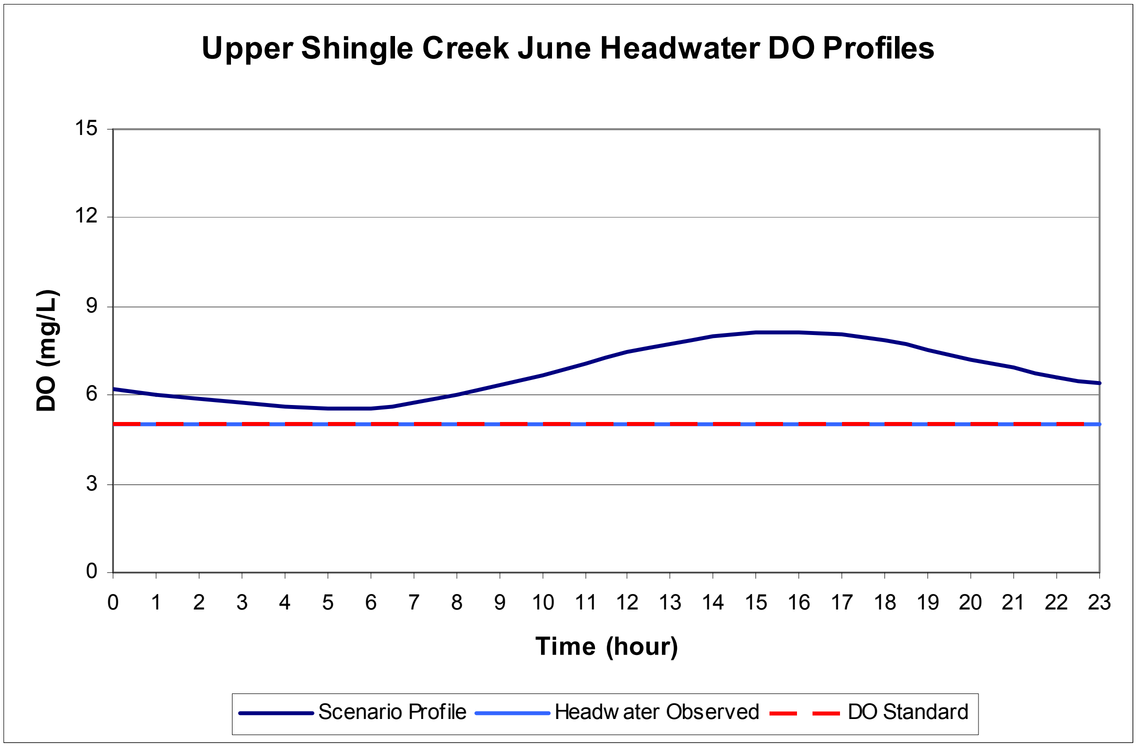


Figure 3.1. Higher flow scenario 1 DO headwater profile.

3.1.2 Scenario 2: Diffuse Flow

DO diffuse inflow through wetland reaches 1-2 was set to 0.0 mg/L. Concentration was set to the standard, 5.0 mg/L.

3.1.3 Final Scenario Combination Output

Each scenario (1 and 2) was applied step-wise until minimum dissolved oxygen did not fall below the 5.0 mg/L standard anywhere throughout Upper Shingle Creek (Table 3.2 and Figure 3.2). The combination of removal of prescribed SOD and increased headwater DO was sufficient to meet the required SOD reductions and increase minimum daily DO for Upper Shingle Creek. No adjustments to channel form were required.

Table 3.2. Higher flows combined scenarios results.

Scenario	Minimum DO (mg/L)	Minimum DO location (River Km)
Calibrated Model	2.88	8.84
1	3.59	8.84
2	5.06	9.69

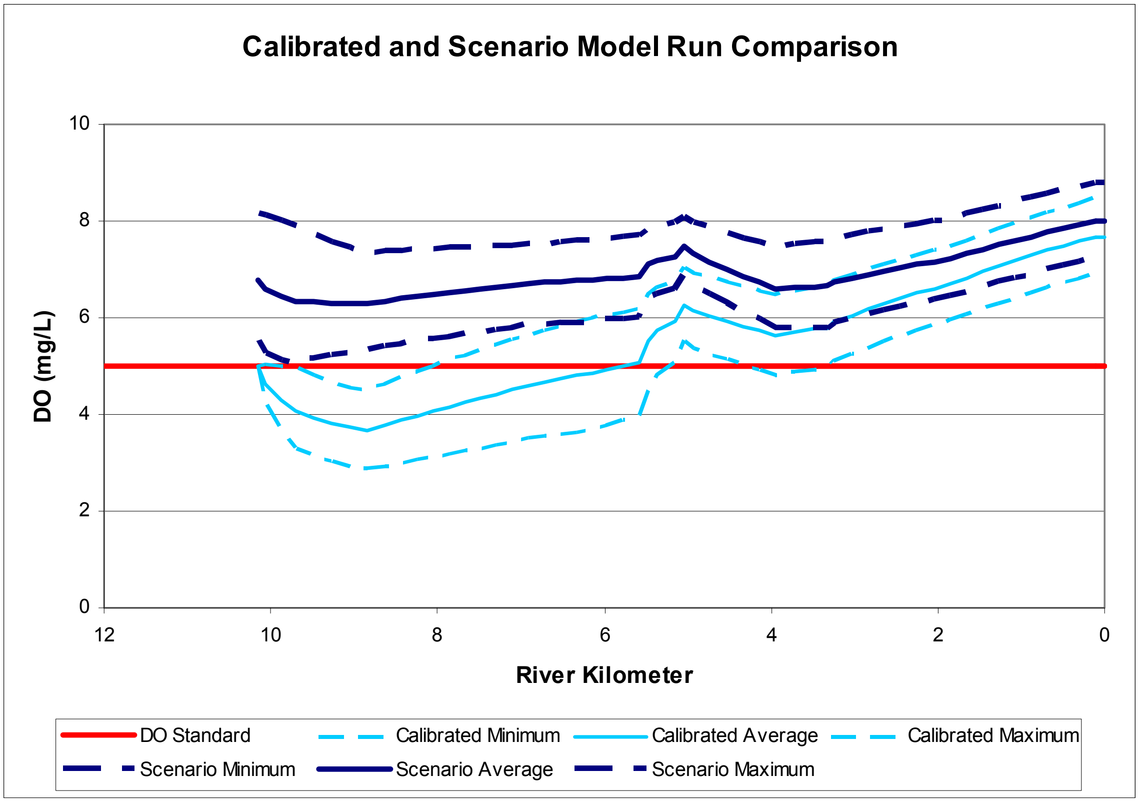


Figure 3.2. Higher flows combined scenarios DO profile.

3.2 LOWER FLOW SCENARIO RESULTS

The lower flow model was developed using September synoptic survey results.

3.2.1 Scenario 1: Headwater Adjustments

Specific headwater water quality parameters were adjusted to meet water quality standards (Table 3.3, Figure 3.3). Because no continuous dissolved oxygen data was available at the I94 Wetland outlet, the calibrated model assumed that the wetland was always discharging at 6.02 mg/L, the average of the available sampling data. This scenario assumed that dissolved oxygen concentration followed a typical diurnal profile that did not fall below 5.0 mg/L.

Table 3.3. Lower flow scenario Upper Shingle Creek model parameter adjustments.

Parameter	Calibrated Model Value	Scenario Value	Justification
Diurnal DO curve	6.02 mg/L – average of observed values (Figure 3.1)	Typical DO profile (Figure 3.1)	Adjusted headwater DO profile is a typical diurnal profile that does not fall below 5.0 mg/L

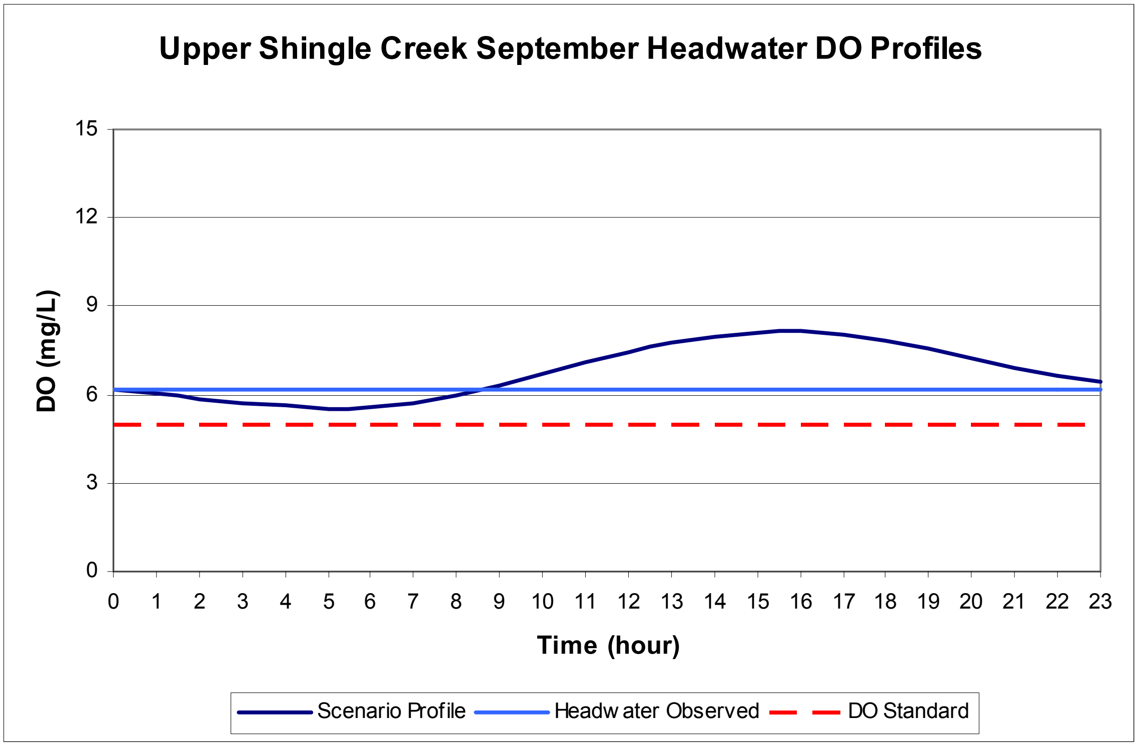


Figure 3.3. Lower flow scenario 1 DO headwater profile.

3.2.2 Scenario 2: Channel Form Adjustment

Hydraulic coefficients were adjusted (Tables 3.4 and 3.5) to create narrower, low-flow channels when flow is below 10 cfs.

Table 3.4. Upper Shingle Creek calibrated hydraulic coefficient and exponents assigned to each reach.

Reach	Rating Curve Used	Velocity		Depth		Width	
		Coeff.	Exp.	Coeff.	Exp.	Coeff.	Exp.
1	SC-I94	0.05	0.31	0.75	0.22	25.16	0.47
2	SC-77	0.18	0.23	0.60	0.30	9.52	0.47
3	SC-77*	0.18	0.23	0.60	0.30	9.52	0.47
4	SC-03	0.18 Δ	0.65	0.49	0.16	8.22	0.19
5	None – Manning's	Appendix C					
6	SC-03*	0.25	0.65	0.49	0.16	8.22	0.19
7	None – Manning's	Appendix C					
8	SC-03	0.16Δ	0.65	0.49	0.16	8.22	0.19
9	Xerxes	0.19	0.49	0.47	0.27	11.15	0.24
10	None – Weir	Appendix C					
11	Xerxes	0.19	11	Xerxes	0.19	11	Xerxes
12	Xerxes*	0.19	12	Xerxes*	0.19	12	Xerxes*

* The monitoring station is at the upstream end of the reach.

Δ The hydraulic coefficients or exponent were changed.

Table 3.5. Upper Shingle Creek channel form scenario.

Reach	Rating Curve Used	Velocity		Depth		Width	
		Coeff.	Exp.	Coeff.	Exp.	Coeff.	Exp.
1	SC-I94	**0.08**	0.31	**1.40**	0.22	**8.98**	0.47
2	SC-77	**0.31**	0.23	**1.00**	0.30	**3.23**	0.47
3	SC-77*	**0.31**	0.23	**1.00**	0.30	**3.23**	0.47
4	SC-03	**0.43**	0.65	**1.00**	0.16	**2.33**	0.19
5	None-Manning's	No change for channel form scenario					
6	SC-03*	**0.43**	0.65	**1.00**	0.16	**2.33**	0.19
7	None-Manning's	No change for channel form scenario					
8	SC-03	**0.43**	0.65	**1.00**	0.16	**2.33**	0.19
9	Xerxes	**0.30**	0.49	**0.90**	**0.25**	**3.70**	**0.26**
10	None – Weir	No change for channel form scenario					
11	Xerxes	**0.30**	0.49	**0.90**	**0.25**	**3.70**	**0.26**
12	Xerxes*	**0.30**	0.49	**0.90**	**0.25**	**3.70**	**0.26**

* The monitoring station is at the upstream end of the reach.

Δ The hydraulic coefficients or exponent were changed.

Bold denotes a change in hydraulic coefficients or exponent for low flow channel form scenario

3.2.3 Scenario 3: SOD Adjustments

It was assumed that a low-flow channel should increase low-flow velocity enough to transport sediment particles contributing to SOD through each reach, thus lowering SOD and the justification for prescribing more SOD to the models. Scenario 3 removes all prescribed SOD (Table 3.6).

Table 3.6. Scenario 3 adjustments to prescribed SOD and bottom coverage.

Reach	Calibration Prescribed SOD (g O_2/m^2/day)	Scenario Prescribed SOD (g O_2/m^2/day)	Calibration SOD bottom coverage (%)	Scenario SOD bottom coverage (%)
1	1.00	**0.0**	100	**100**
2	1.00	**0.0**	100	**100**
3	1.00	**0.0**	100	**100**
4	1.00	**0.0**	100	**100**
5	0.30	**0.0**	100	**100**
6	0.30	**0.0**	100	**100**
7	0.30	**0.0**	100	**100**
8	2.00	**0.0**	100	**100**
9	0.30	**0.0**	100	**100**
10	0.30	**0.0**	100	**100**
11	0.30	**0.0**	100	**100**
12	0.30	**0.0**	100	**100**

3.2.4 Combined Scenarios Results

Each scenario (1-3) was applied step-wise until minimum dissolved oxygen did not fall below the 5.0 mg/L standard anywhere throughout Upper Shingle Creek (Table 3.7 and Figure 3.4). The combination of removal of prescribed SOD, increased headwater DO, and low-flow channel alterations was sufficient to meet the required SOD reductions and increase minimum daily DO for Upper Shingle Creek.

Table 3.7. Lower flows combined scenarios results.

Scenario	Minimum DO (mg/L)	Minimum DO location (River Km)
Calibrated Model	2.75	3.94
1	2.83	3.94
2	5.39	9.69
3	5.52	10.16

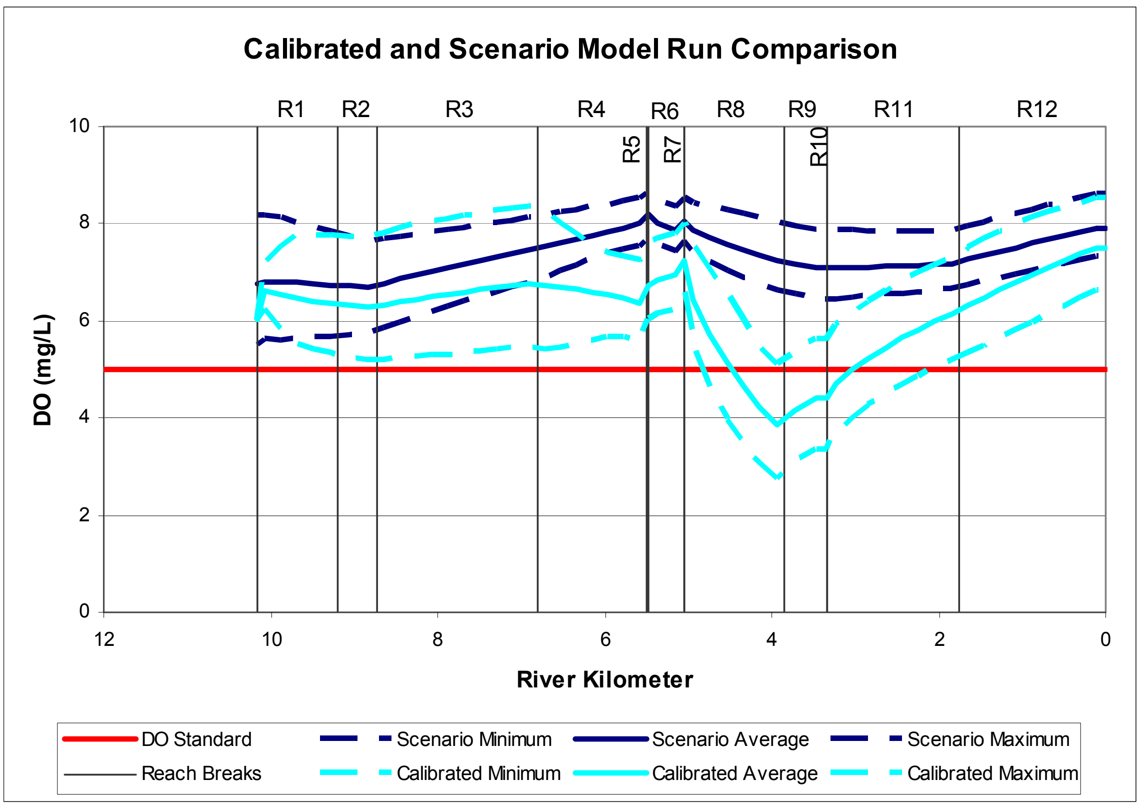


Figure 3.4. Lower flows combined scenarios DO profile.

4.0 REFERENCES

Leopold, L.B. and Maddock, T. (1953). The hydraulic geometry of stream channels and some physiographic implications. U.S. Geol. Survey, Professional Paper,