Wenck Associates, Inc.
1800 Pioneer Creek Center
P.O. Box 249
Maple Plain, MN 55359-0249

800-472-2232
(763) 479-4200
Fax (763) 479-4242
wenckmp@wenck.com
www.wenck.com

TECHNICAL MEMORANDUM

TO: Minnesota Pollution Control Agency
Pioneer- Sarah Creek Watershed Management Organization

FROM: Jeff Strom and Diane Spector

DATE: April 2015

SUBJECT: Unnamed Creek Historic Dissolved Oxygen Data Summary

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This technical memorandum summarizes all historic dissolved oxygen (DO) and relevant water quality data collected throughout the Unnamed Creek impaired reach (AUID 07010205-593) since 2010. The reach of Unnamed Creek from Mud Lake to the creek's outlet to Rice Lake is expected to be placed on the 2016 303(d) list of impaired waters for DO. To help determine the cause of the DO violations, historical DO data from the reach were obtained from the Minnesota Pollution Control Agency's (MPCA's) EQuIS database and compared to continuous flow, nitrogen, biochemical oxygen demand (BOD), phosphorus and chlorophyll-*a* (chl-*a*) data.

1.0 WATERSHED DESCRIPTION

The Unnamed Creek DO impaired reach is approximately 3.3 miles in length in the South Fork Crow River watershed (Figure 1-1). The watershed of the impaired reach, including land upstream of the reach headwaters, covers approximately 9,669 acres in Carver and Hennepin Counties. Only a small fraction of the watershed land cover is urbanized or roads. About half the watershed is in agricultural use, and the other half is forested, wetlands, or open water (Table 1-1).

Table 1-1. Land cover in the Unnamed Creek impaired reach watershed.

[1]Landuse Type	Unnamed Creek Direct Watershed	Unnamed Creek Watershed - All
Total area (acres)	4,122	9,669
Wetlands and Open Water	29%	29%
Corn/Soybeans	26%	27%
Hay and Pasture	19%	18%
Forest and Shrubland	15%	18%
Urban/Roads	6%	4%
Grains and other Crops	5%	4%

[1] Source: 2011 National Agriculture Statistics Services (NASS) land cover dataset.

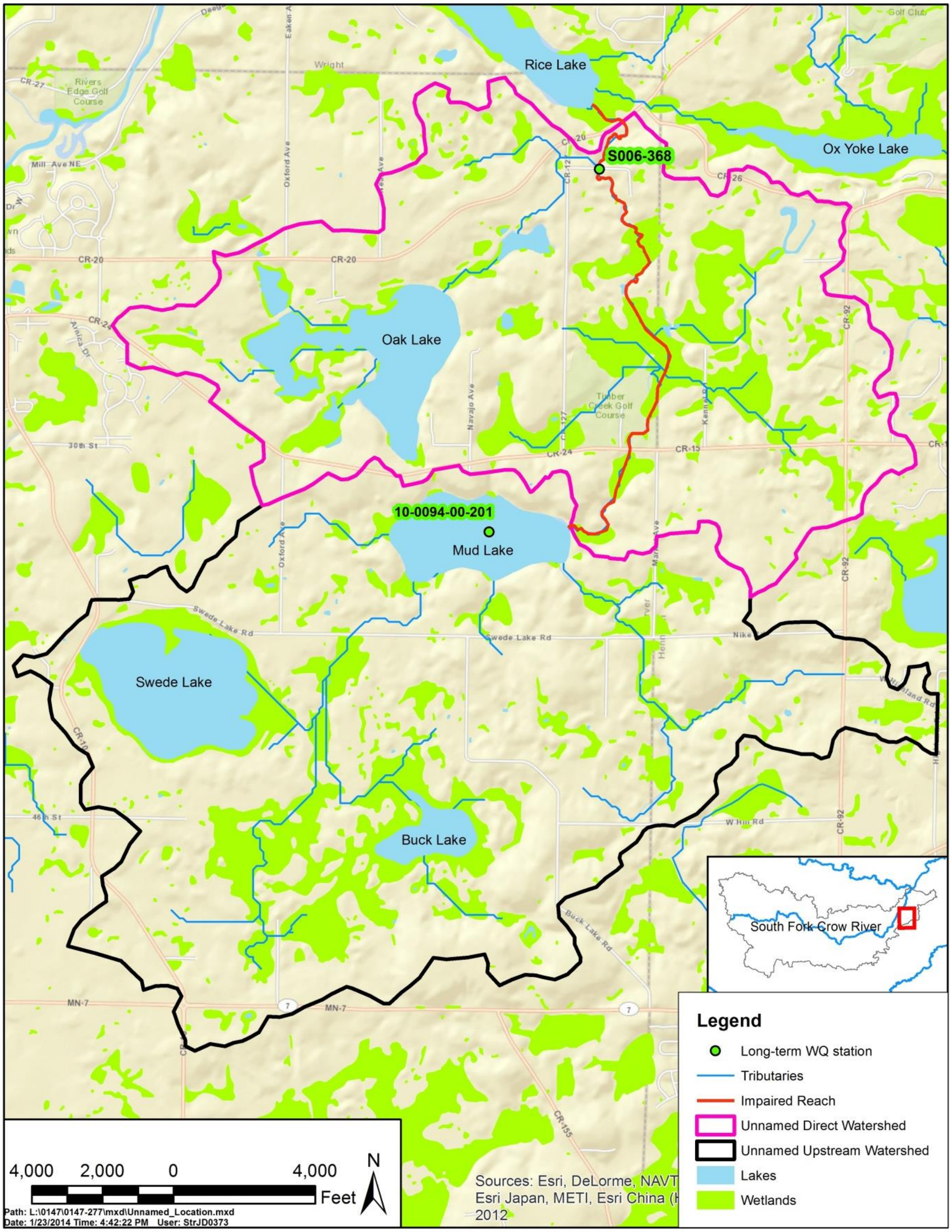

Figure 1-1. Deer Creek DO impaired reach.

The headwaters of Unnamed Creek are located at the outlet of Mud Lake, south of County Road 24 and east of Watertown, Minnesota. The Unnamed Creek DO impaired reach flows through a series of golf course ponds (Figure 1-2) and one major wetland complex between County Road 24 and Hainlin Road (Figure 1-3). The wetland complex is a 350-acre wetland located upstream (south) of the long-term monitoring station at Hainlin Road. Air photos suggest there is no distinct channel thorough much of this wetland complex and the wetland is characterized by dense cattails and a series of shallow ponds and areas of standing water during wet conditions. It should be noted that riparian wetland stretches tend to have slow velocities, long travel times and high sediment oxygen demand (SOD) due to the high organic content of wetland peat deposits.

Figure 1-2. Unnamed Creek impaired reach through the Timber Creek Golf Course.

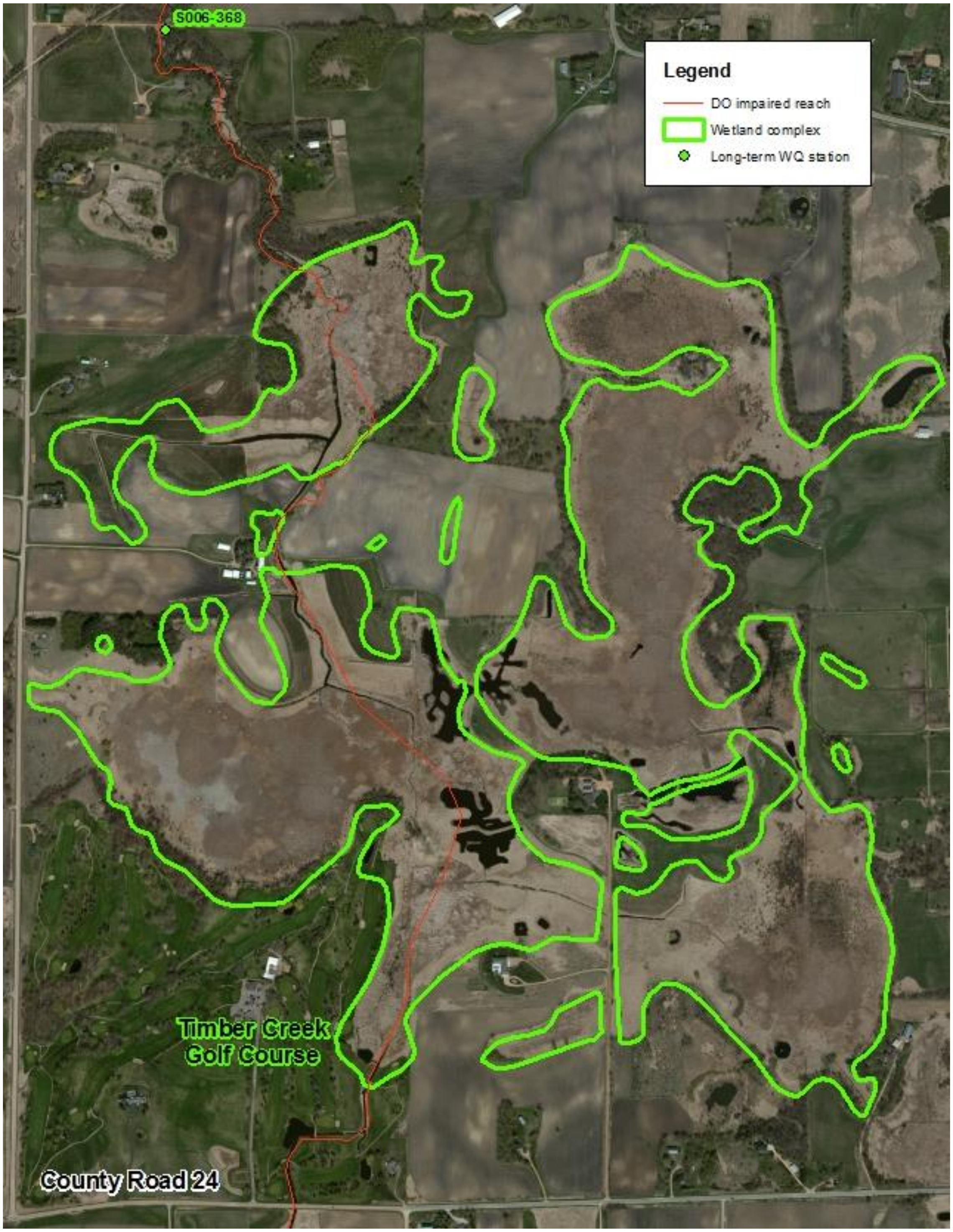

Figure 1-3. Large wetland complex upstream of the long-term Unnamed Creek monitoring station.

2.0 REVIEW OF UNNAMED CREEK DISSOLVED OXYGEN DATA

Minnesota Pollution Control Agency (MPCA) and Three Rivers Park District staff have collected DO data at one station (S006-368) on the Unnamed Creek DO impaired reach since 2010 (Figure 1-1 and Table 2-1). Continuous stream flow data are available at Unnamed Creek station S006-368 from 2009-2013.

2.1 DISSOLVED OXYGEN GRABS/FIELD MEASUREMENTS

The Unnamed Creek impaired reach is designated by state statute as a beneficial-use Class 2B warm water stream. This designation states that DO concentrations shall not fall below 5.0 mg/L as a daily minimum in order to support the aquatic life and recreation of the ecosystem. Approximately 65% of the May-September DO observations collected at the S006-368 station were below the 5.0 mg/L DO standard (Table 2-1 and Figure 2-1). Only 1 of the 34 individual DO measurements was collected prior to 9:00 am (Figure 2-2), and time of day records are unavailable for a few of the samples. The MPCA protocol states that measurements taken after 9:00 am do not represent daily minimums, and measurements greater than 5.0 mg/L DO later in the day are no longer considered to be indications that a stream is meeting state standards. The only DO sample collected before 9:00 am was less than the DO standard. By comparison, 20 of the 32 (63%) measurements recorded after 9:00 am were less than the DO standard, suggesting DO violations are common throughout the impaired reach regardless of the time of day. Additional DO measurements should be collected prior to 9:00 am to fully assess DO in Unnamed Creek according to the new DO protocol. Monthly plots (Figure 2-3) show a majority of the violations were recorded during the warmer summer months (June through August).

Table 2-1. Unnamed Creek (07010205-593) May through September DO data summary.

EQuIS ID	Location	Impaired Reach River Mile	DO Observations	DO Violations (<5 mg/L)	Years
S006-368	Unnamed Creek at Hainlin Road	0.6	34	22	2010-2013

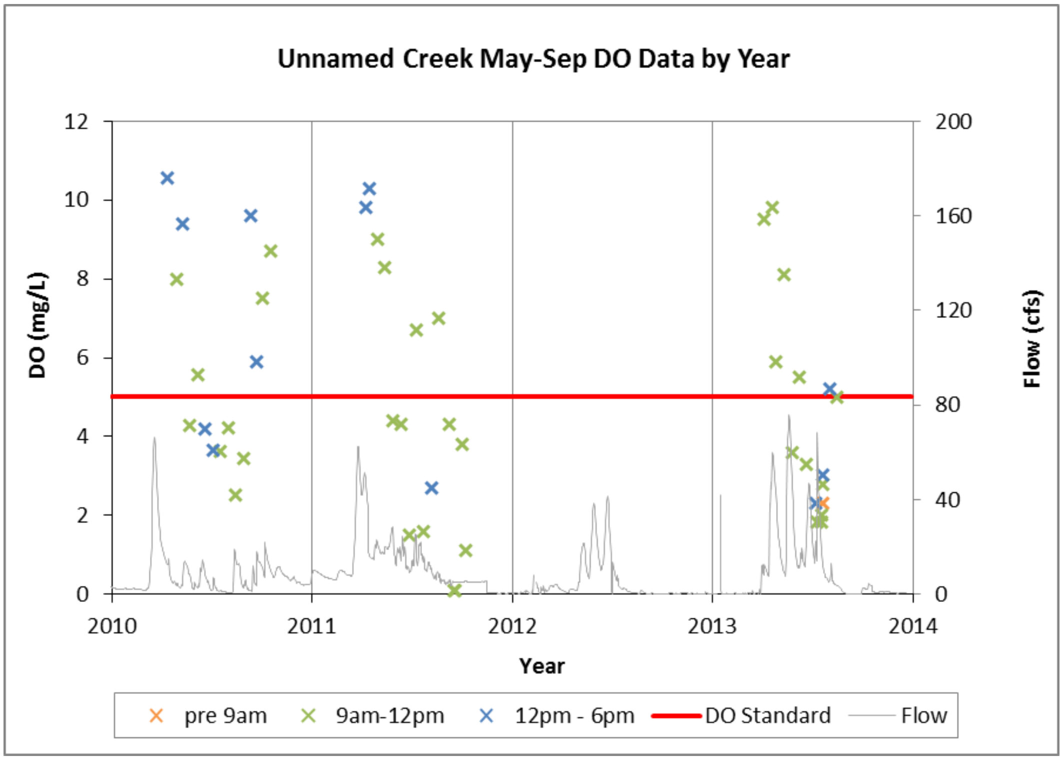

Figure 2-1. DO and flow data for the Unnamed Creek impaired reach by year, color coded by time of day.

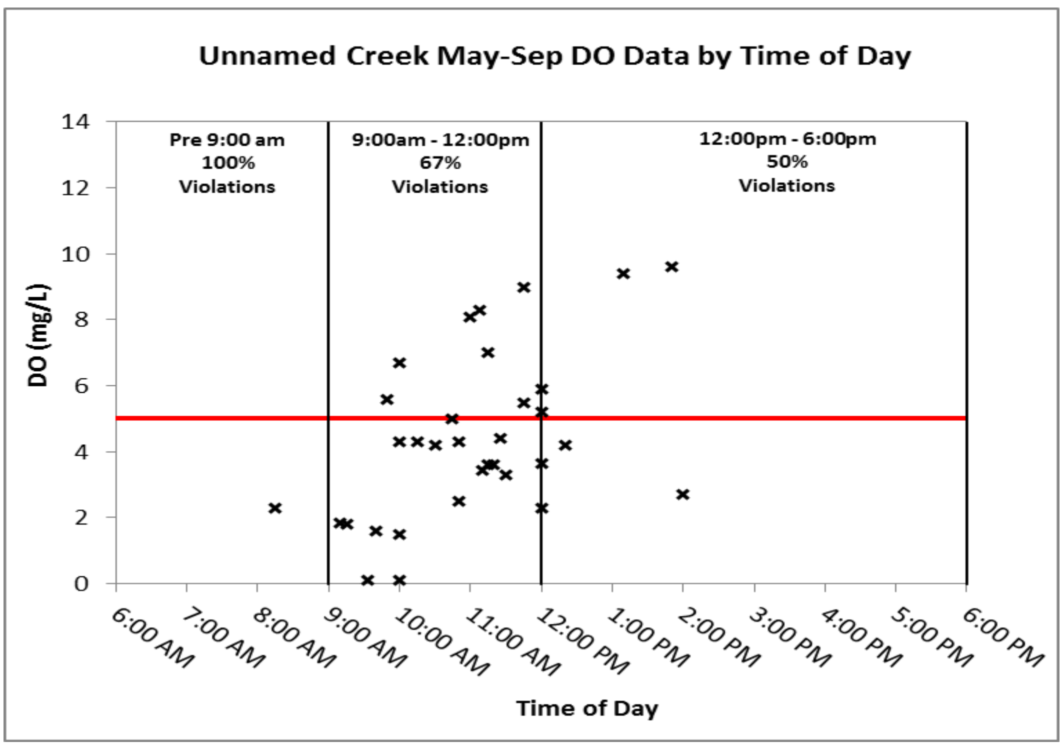

Figure 2-2. Unnamed Creek DO data (May-Sep) by time of day.

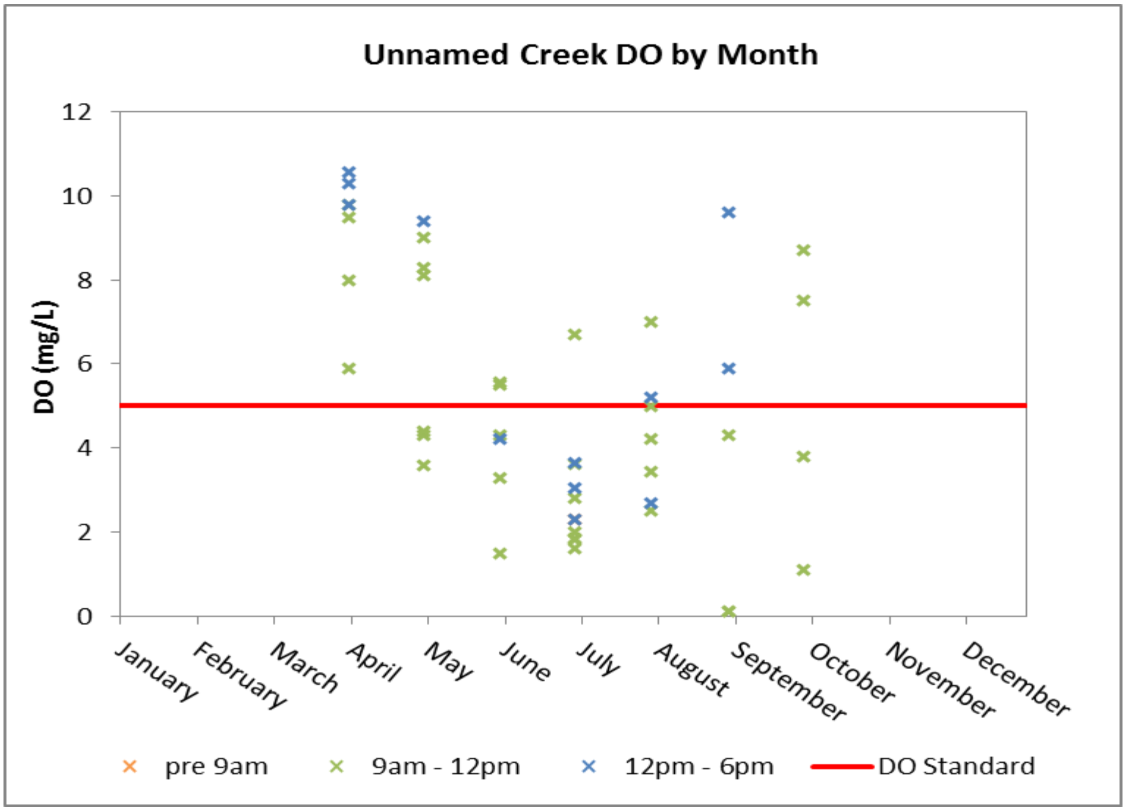

Figure 2-3. Unnamed Creek DO data by month.

2.2 DISSOLVED OXYGEN RELATION TO FLOW

Average daily flow for Unnamed Creek was compared to Unnamed Creek DO measurements. Representing DO measurements on flow duration plots show DO violations occur across all flow conditions (Figure 2-4). This reach, which is fed by outflow from Mud Lake and several wetland systems has been observed to stop flowing during late summer and fall drought conditions (MPCA, personal communication) which likely explains the lack of DO measurements during dry and low-flow conditions.

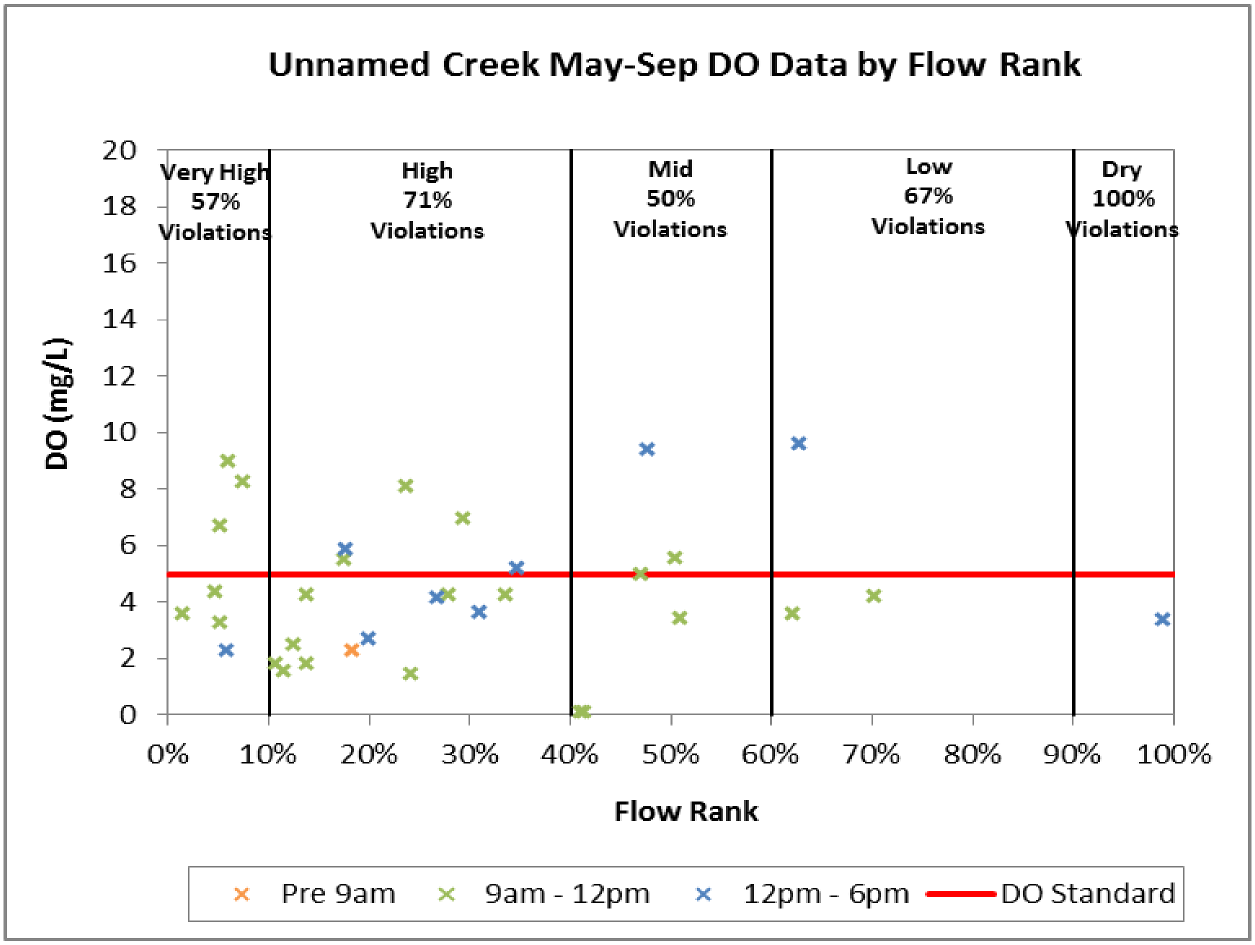

Figure 2-4. Unnamed Creek DO by flow condition.
Flow duration was constructed using continuous average daily flow data from the Unnamed Creek monitoring station.

2.3 2013 DISSOLVED OXYGEN MONITORING

One data sonde with internal logging capability was deployed by Three Rivers Park staff at the long-term Unnamed Creek monitoring station from 5/1/2013 through 7/18/2013 (Figure 2-5). The data sonde was programed to monitor continuous DO and temperature at 15-minute intervals. Results indicate Unnamed Creek daily minimum DO concentrations were below 5.0 mg/L for 73 of the 79 days the sonde was deployed. Daily minimum DO violations were common across all monitored flow conditions (Figure 2-6).

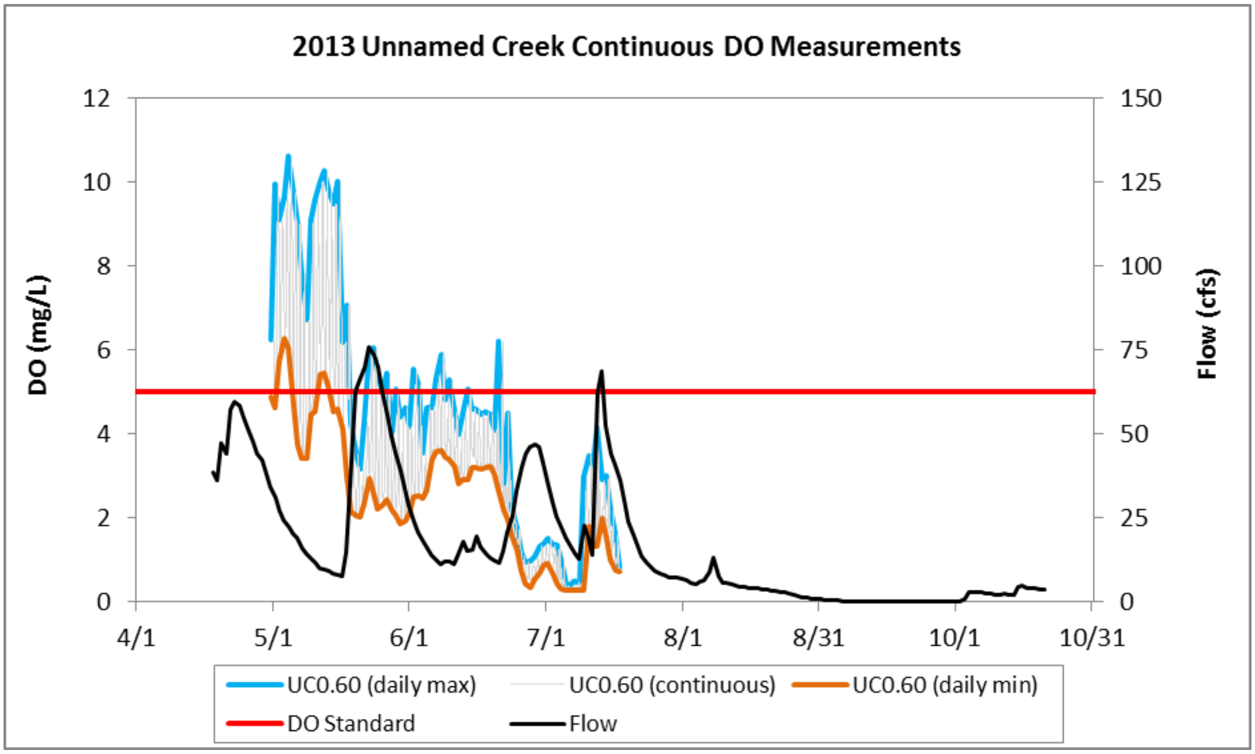

Figure 2-5. Unnamed Creek 2013 continuous DO measurements.

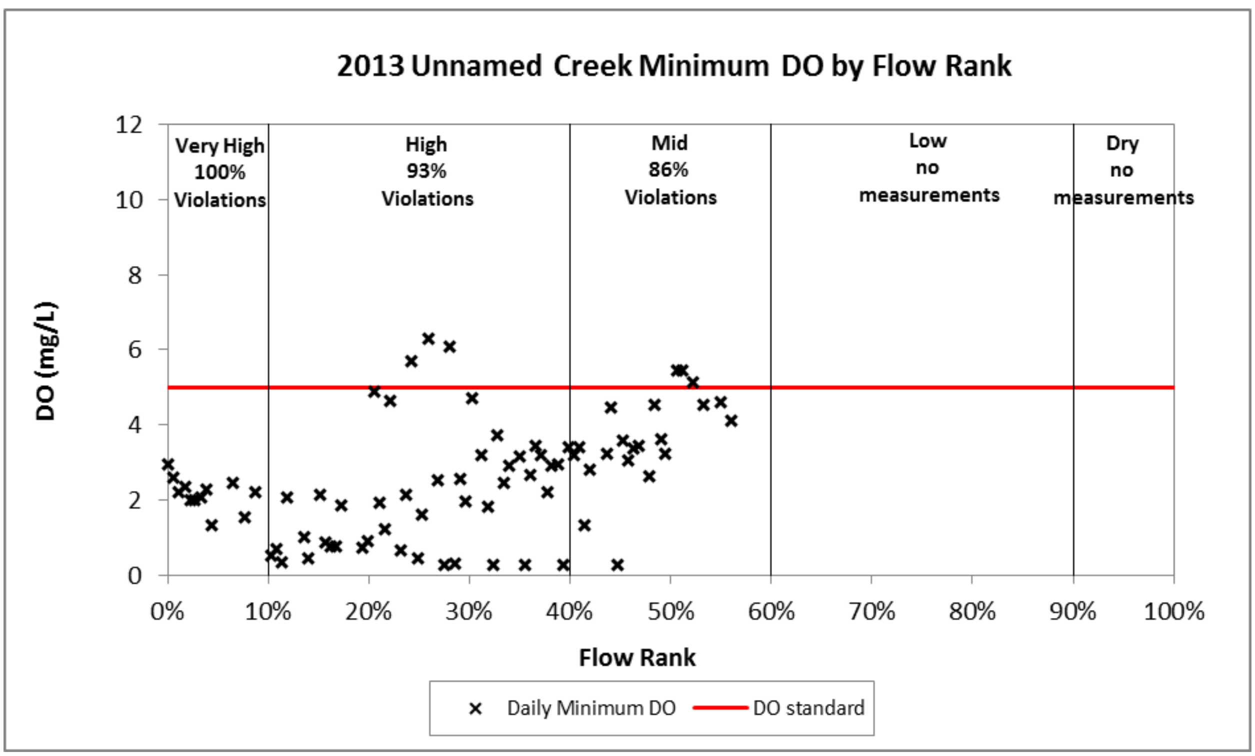

Figure 2-6. Unnamed Creek 2013 daily minimum DO from data sonde deployment.

3.0 WATER QUALITY PARAMETERS AFFECTING DISSOLVED OXYGEN

Daily dissolved oxygen swings are affected by biological activities such as photosynthesis and respiration by algae and submerged vegetation. Stream DO, however, can also be 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).

Biochemical oxygen demand (BOD) from the breakdown of organic compounds can be measured directly through laboratory incubation (typically 5-days). The nitrogen component of BOD can also be measured directly through lab incubations, or estimated by measuring nitrogen-series parameters within the system. This section provides an analysis of the water quality parameters that may be affecting DO conditions in the Unnamed Creek impaired reach.

3.1 BIOCHEMICAL OXYGEN DEMAND

5-day BOD sampling in Unnamed Creek is limited to only 19 samples from 2010-2013. Results indicate BOD_5 ranges from below detection limit (<2.0 mg/L) to 9.0 mg/L (Figures 3-1 and 3-2). These values are relatively low and are within the typical range (1.5 – 3.2 mg/L) for streams in the North Central Hardwood Forest ecoregion. MPCA's Nutrient Criteria Development for Rivers in the central region suggest BOD_5 levels greater than 2.0 mg/L indicate potential eutrophication and impacts to biologic communities (MPCA, 2013). The 9.0 mg/L BOD measurement was collected on September 3, 2013 when chlorophyll-*a* levels in Deer Creek were over 200 µg/L. To date, there have been five BOD_5 measurements (26%) greater than 2.0 mg/L, one each during the very high and high flow conditions and three samples during low flow conditions.

Since there are no industrial or wastewater treatment facilities in the Unnamed Creek watershed, elevated levels of BOD_5 likely come from algae loading from upstream lakes and wetlands or watershed runoff during storm events.

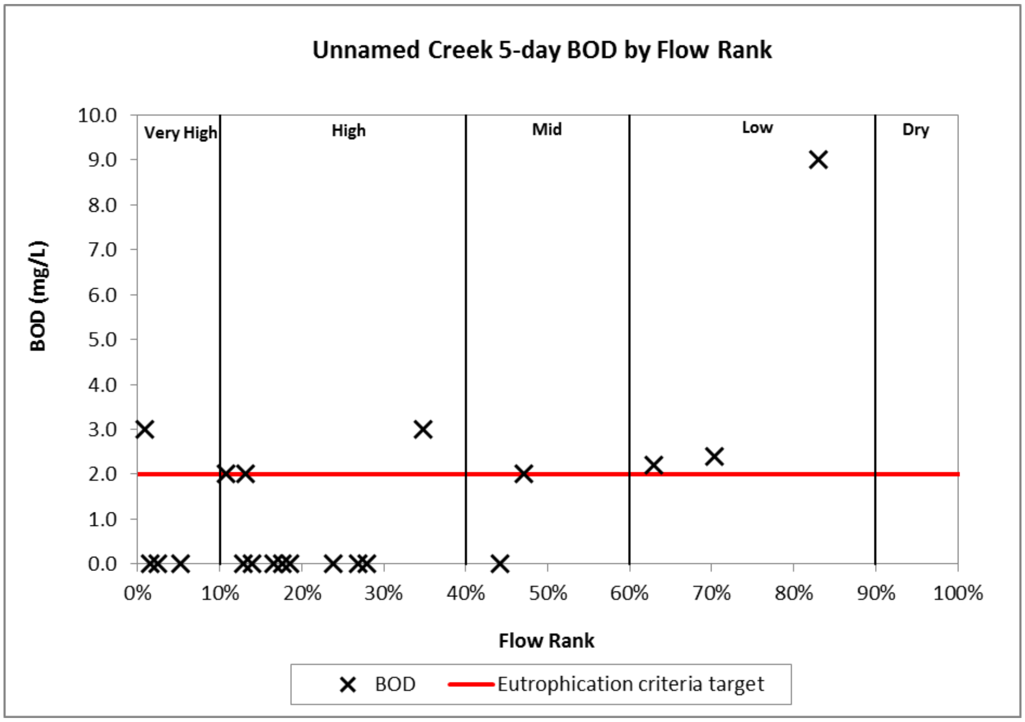

Figure 3-1. Unnamed Creek BOD by flow condition.
Note: Samples below detection limit (<2.0 mg/L) are shown on the figure as 0.0 mg/L.

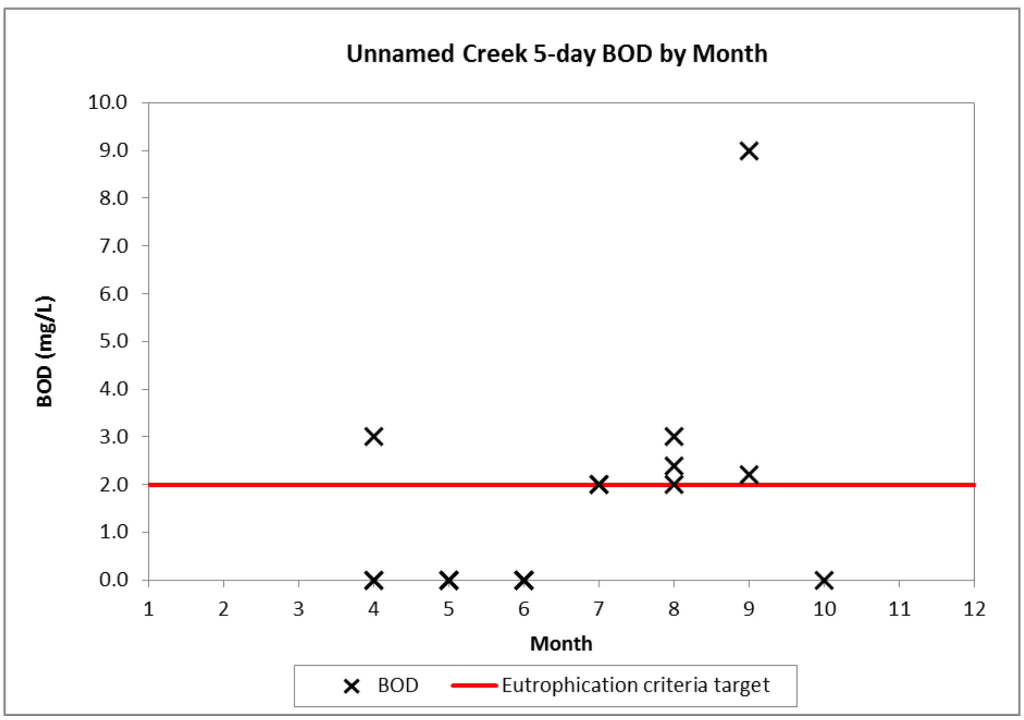

Figure 3-2. Unnamed Creek BOD data by month.
Note: Samples below detection limit (<2.0 mg/L) are shown on the figure as 0.0 mg/L.

3.2 NITROGEN

Total nitrogen (TN) is the sum of organic nitrogen (ON), ammonia (NH_3) and ammonium (NH_4^+), nitrate (NO_3^-) and nitrite (NO_2^-). Of the nitrogen components, NH_3 and NH_4^+ break down quickly in natural systems and are rapidly converted to nitrate by nitrifying bacteria, a process which consumes oxygen. TN data has been collected in Unnamed Creek since 2010 and ammonia-N (NH_3 + NH_4^+-N) data were collected in 2013. Additionally, TN samples have been collected in Mud Lake (headwaters of the Unnamed Creek impaired reach) in 2010 and 2011. Total nitrogen concentrations in the Unnamed Creek impaired reach and Mud Lake ranged from 0.56-5.40 mg/L and 1.84-5.67 mg/L, respectively. Overall, Unnamed Creek and Mud Lake average TN concentrations were very similar. Unnamed Creek ammonia-N results indicate 8 of the 12 samples collected were below detection limit (<0.050 mg/L). Thus, almost all of the nitrogen in Unnamed Creek is some combination of ON and NO_3^--N + NO_2^--N. Total nitrogen is typically highest in Unnamed Creek during April, July and August and during high flow conditions (Figures 3-3 and 3-4).

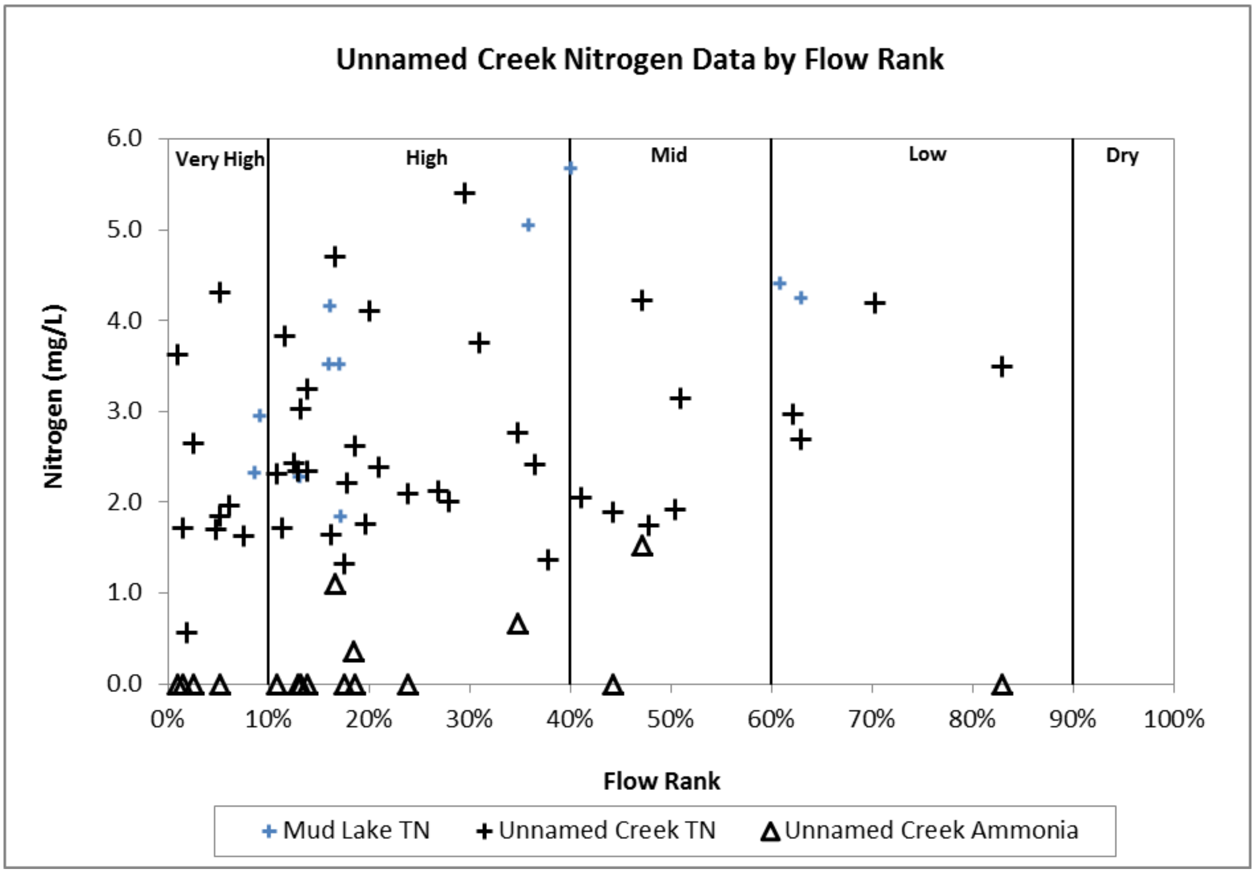

Figure 3-3. Unnamed Creek and Mud Lake total nitrogen and ammonia-N data by flow condition.
Note: Samples below detection limit (<0.050 mg/L) are shown on the figure as 0.0 mg/L.

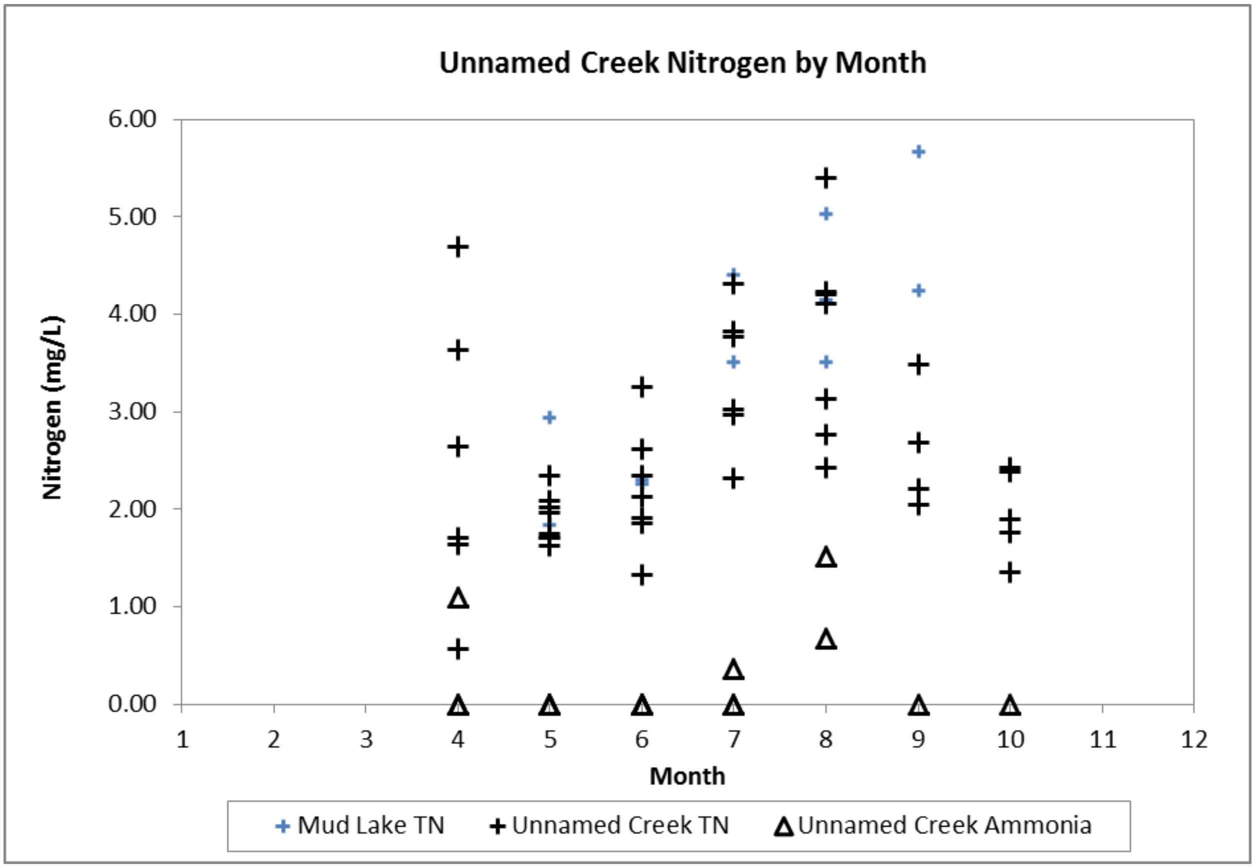

Figure 3-4. Unnamed Creek and Mud Lake total nitrogen and ammonia-N data by month.
Note: Samples below detection limit (<0.050 mg/L) are shown on the figure as 0.0 mg/L.

3.3 PHOSPHORUS

High nutrient concentrations, particularly phosphorus, can accelerate eutrophication, thus increasing diurnal DO concentration swings and biochemical oxygen demand (BOD) after the organic matter dies off. Total phosphorus was measured in Unnamed Creek from 2010-2013. Total phosphorus sampling was conducted in Mud Lake in 2010-2011. Total phosphorus concentrations in Unnamed Creek and Mud Lake ranged from 62-691 µg/L and 76-246 µg/L, respectively. Unnamed Creek TP concentrations were high and often exceeded the 100 µg/L proposed central region river/stream eutrophication standard (MPCA, 2013). Mud Lake TP concentrations were generally lower than Unnamed Creek; however summer averages did exceed the 60 µg/L standard for shallow lakes in the NCHF Ecoregion.

The higher average TP concentrations in Unnamed Creek indicate TP loading occurs downstream of Mud Lake, likely from the large in-channel wetland complex between Mud Lake and the Unnamed Creek monitoring site (Figures 1-1 through 1-3). Ortho-phosphorus concentrations in Unnamed Creek were also very high and accounted for, on average, about 64% of the total phosphorus in the stream. High ortho-phosphorus concentrations in streams indicate loading from illicit point sources (e.g. failing septic systems), agricultural runoff, or internal loading from channel/wetland sediment that is exposed to anoxic conditions. Total phosphorus and ortho-phosphorus concentrations in Unnamed Creek were high across all flow regimes suggesting phosphorus inputs may be a combination of all of the previously mentioned sources (Figures 3-5 and 3-6).

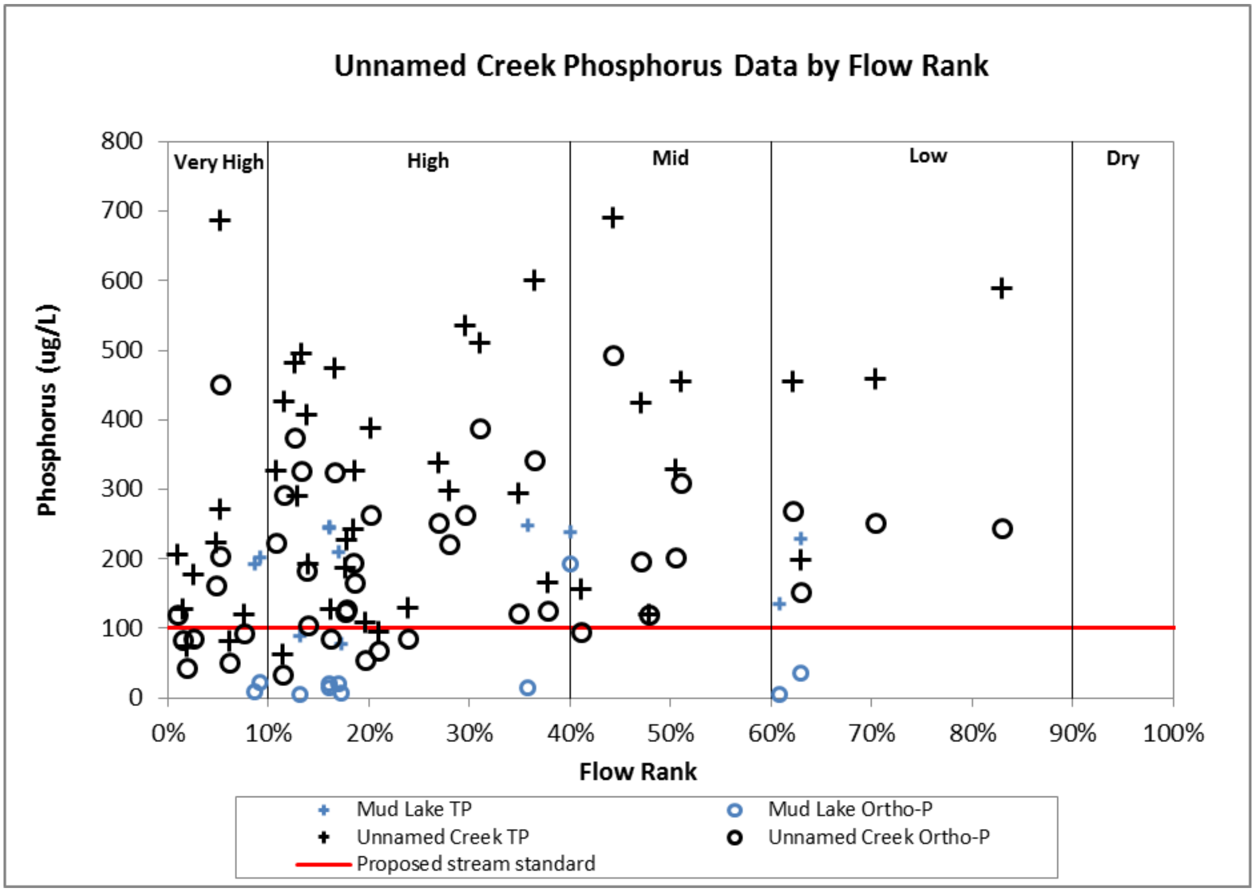

Figure 3-5. Unnamed Creek and Mud Lake TP and orthophosphate data by flow condition.

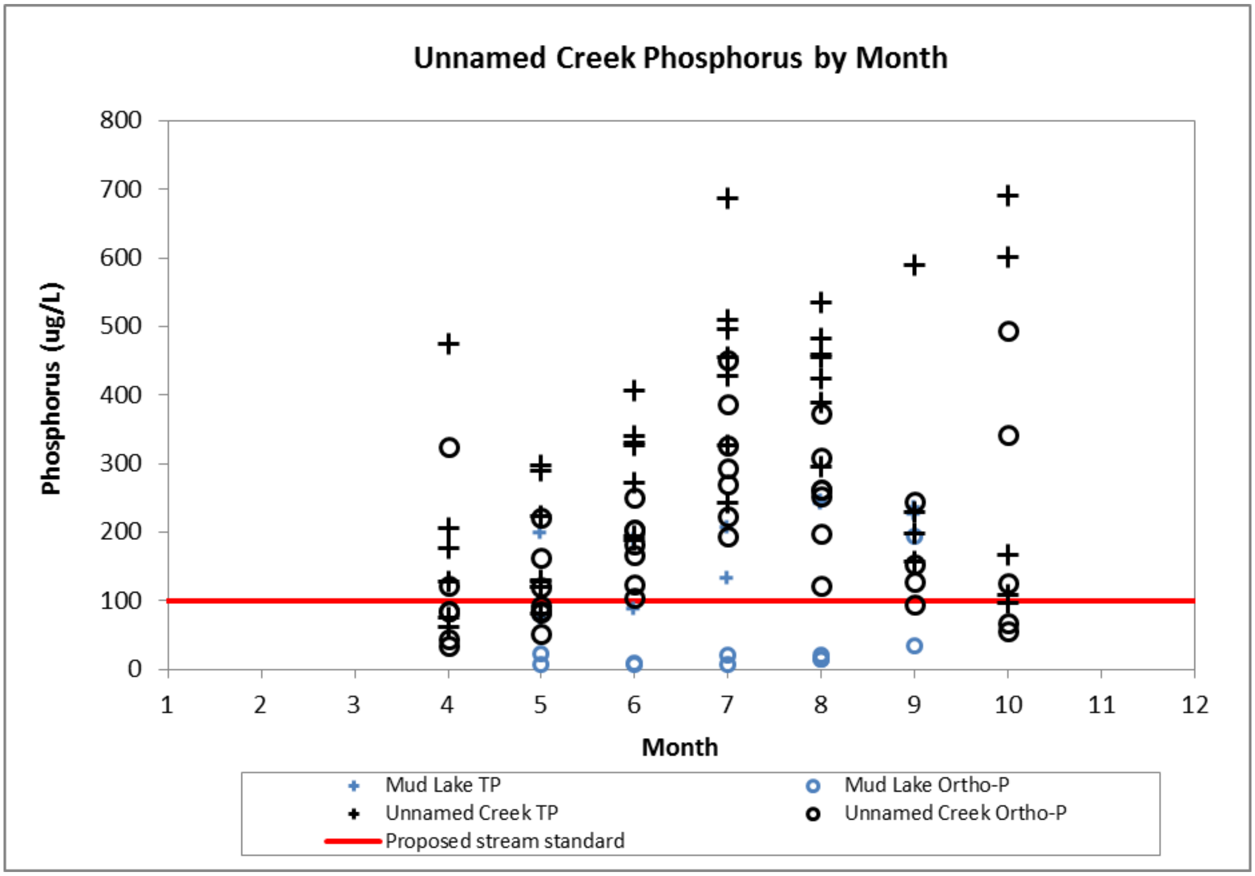

Figure 3-6. Unnamed Creek and Mud Lake TP and orthophosphate data by month.

3.4 CHLOROPHYLL-A

Chlorophyll-*a* is the primary pigment in aquatic algae and has been shown to have a direct correlation with algal biomass. Since chlorophyll-*a* is an inexpensive, and simple measurement, it is often used to evaluate algal abundance. Chlorophyll-*a* measurements are often paired with TP and transparency to assess trophic status in lakes and streams. Thirteen chlorophyll-*a* samples were collected in the impaired reach of Unnamed Creek in 2013 and concentrations ranged from below detection limit (<5 µg/L) to 211 µg/L (Figures 3-7 and 3-8). Five of the 13 samples collected in 2013 were below detection limit. Elevated levels of chlorophyll-*a* were also measured in Unnamed stream; 4 of the 13 samples were above the MPCA's 20 µg/L chlorophyll-*a* proposed standard for river/streams in Minnesota's central region according to the MPCA's Nutrient Criteria Development for Rivers (MPCA, 2013). Three of the four chlorophyll-*a* samples that exceeded the proposed nutrient criteria were collected in April, while the other sample (211 µg/L) was collected in early September.

Chlorophyll-*a* was also assessed in Mud Lake in 2010-2011. Chlorophyll-*a* concentrations in Mud Lake ranged from 10-233 µg/L with annual summer (June – September) averages ranging from 21-45 µg/L. These chlorophyll-*a* levels exceed state standards for shallow (20 µg/L) and deep (14 µg/L) lakes in the NCHF Ecoregion and suggest a significant amount of algae is discharged to Unnamed Creek during the summer months. During low-flow conditions, it appears most of the algae that enters Unnamed Creek dies and/or settles out near the creek's headwaters or in the wetland complex since chlorophyll-*a* concentrations are lower at the Unnamed Creek monitoring station which is approximately 2.7 miles downstream of the lake.

3.5 TEMPERATURE

Temperature also has a significant effect on stream DO concentrations. Dissolved oxygen solubility in water is temperature-dependent in that cold water holds more DO than warmer water. Summer water temperatures for the Unnamed Creek impaired reach are occasionally high and exceed the upper end of typical NCHF streams (2-21°C) during the summer months (June-August; Figure 3-9).

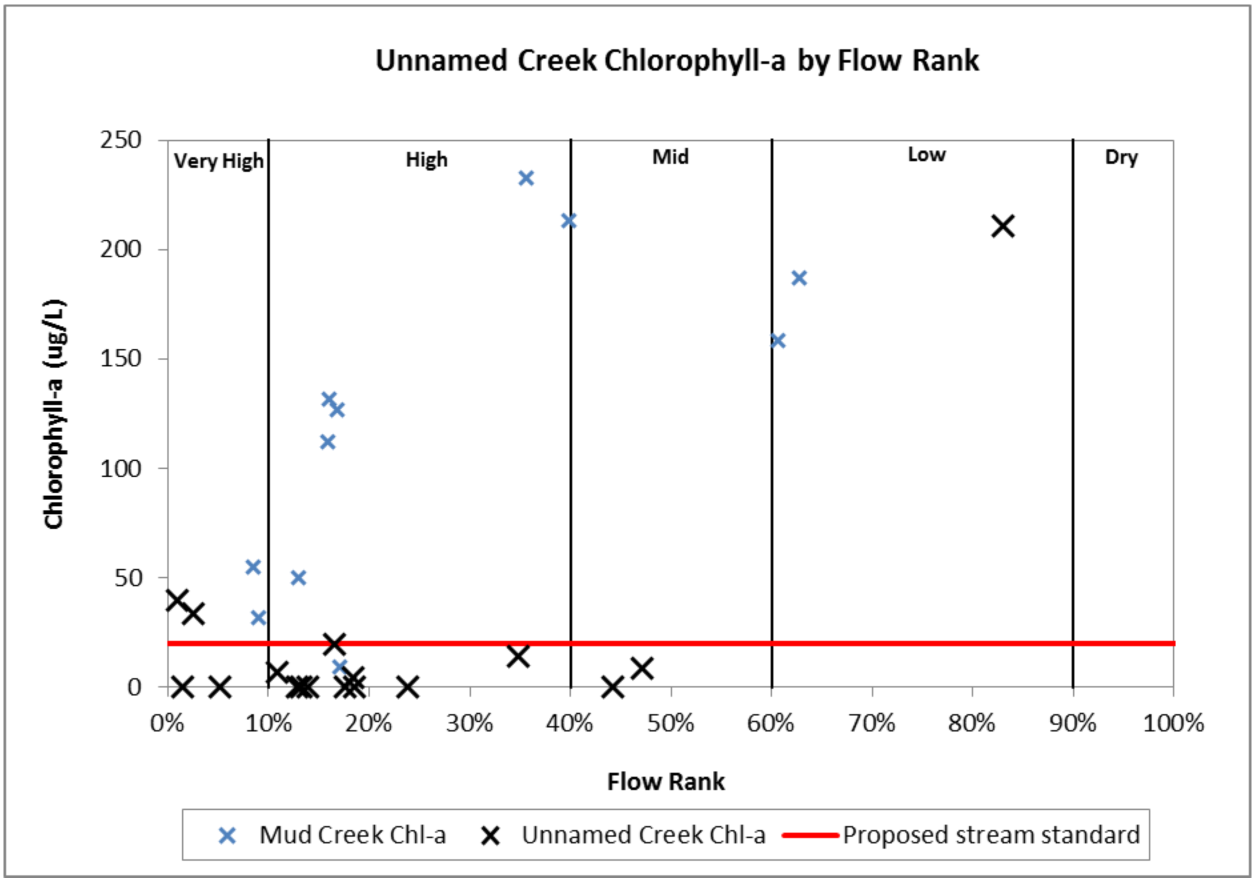

Figure 3-7. Unnamed Creek and Mud Lake chlorophyll-*a* data by flow condition.
Note: Samples below detection limit (<5 µg/L) are shown on the figure as 0 µg/L.

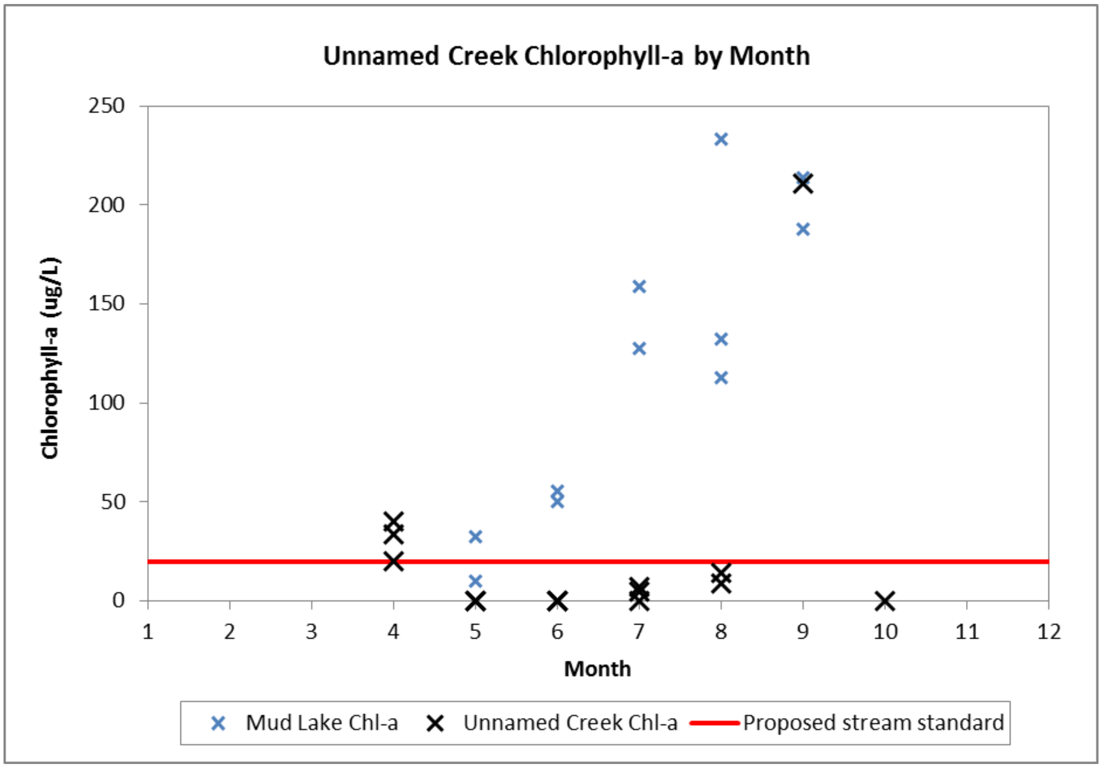

Figure 3-1. Unnamed Creek and Mud Lake chlorophyll-a data by month.

Note: Samples below detection limit (<5 µg/L) are shown on the figure as 0 µg/L.

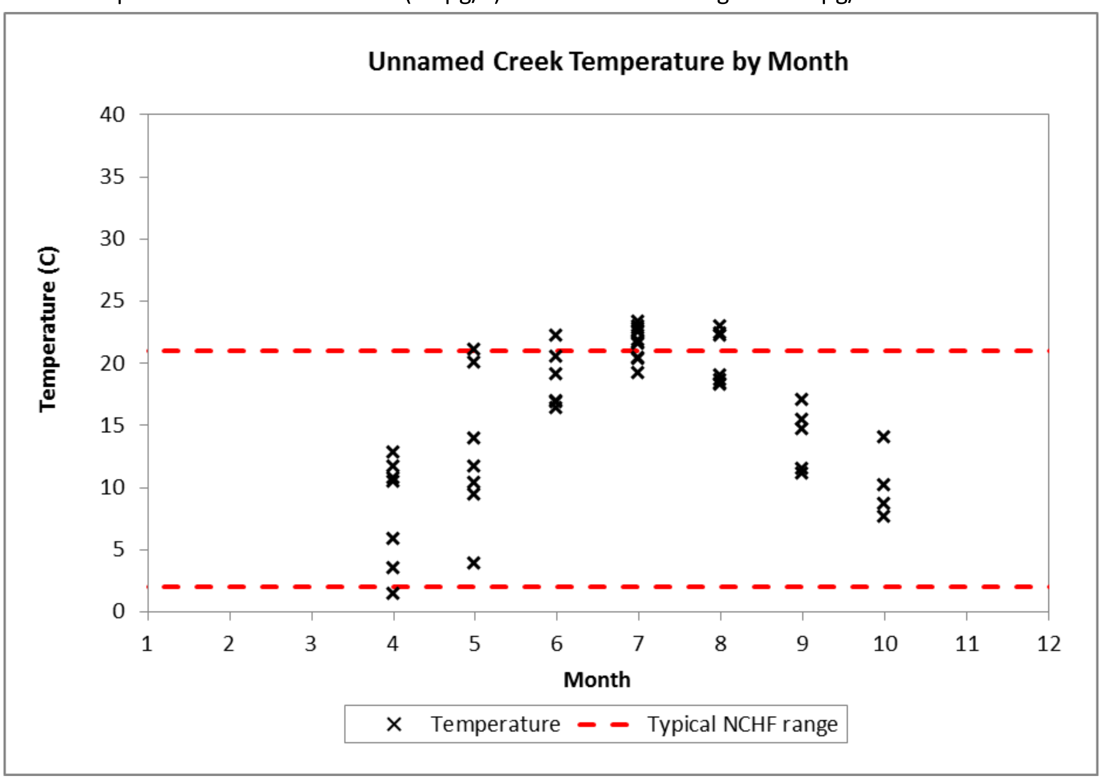

Figure 3-2. Unnamed Creek temperature data by month.

4.0 CONCLUSIONS

Unnamed Creek DO measurements indicate violations occur throughout all summer months regardless of time of day or flow condition. Further analysis of water quality parameters that affect DO suggest eutrophication in Mud Lake likely contributes to the phosphorus, nitrogen, BOD and algae loading to the headwaters of Unnamed which likely affect DO levels measured downstream in the impaired reach. Unnamed Creek's in-channel wetland complex located between County Road 24 and Hainlin Road also appears to be a major source of nutrient loading and low DO levels in Unnamed Creek through SOD, sediment nutrient release and low reaeration rates.

There are a number of potential dissolved oxygen drivers including:

1. Headwater conditions in Mud Lake likely play a role in the dissolved oxygen dynamics in Unnamed Creek. Mud Lake is hypereutrophic and discharges high concentrations of phosphorus, nitrogen, BOD and chlorophyll-*a* to the headwaters of Unnamed Creek upstream of County Road 24.

2. Chlorophyll-*a* levels in Mud Lake are high, while chlorophyll-*a* in Unnamed Creek are typically low. However, chlorophyll-*a* concentrations are occasionally above the proposed nutrient criteria standards during high flow conditions. Thus, algae discharged from Mud Lake do not appear to survive in Unnamed Creek under most flow conditions and likely settle out in the stream channel and contribute to SOD in the impaired reach.

3. Low reaeration and high levels of SOD are likely throughout the large in-stream wetland complex between County Road 24 and Hainlin Road.

5.0 REFERENCES

Minnesota Pollution Control Agency (MPCA). 2013. Minnesota Nutrient Criteria Development for Rivers (Draft). http://www.pca.state.mn.us/index.php/view-document.html?gid=14947

Wenck Associates, Inc.
1800 Pioneer Creek Center
P.O. Box 249
Maple Plain, MN 55359-0249

800-472-2232
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www.wenck.com

TECHNICAL MEMORANDUM

TO: Minnesota Pollution Control Agency
Pioneer-Sarah Creek Watershed Management Organization

FROM: Jeff Strom and Diane Spector

DATE: April 2015

SUBJECT: Unnamed Creek Synoptic Survey Methods and Results

1.0 PURPOSE

This technical memorandum summarizes the data collection methods and results for the July 24, 2013 Unnamed Creek synoptic survey. This survey was conducted to obtain the data needed to construct and calibrate a River and Stream Water Quality Model (QUAL2K) to address the Unnamed Creek dissolved oxygen (DO) impairment.

1.1 STUDY AREA LOCATION

This synoptic survey covered the Unnamed Creek DO impaired reach from the outlet of Mud Lake to the creek's outlet to Rice Lake downstream of County Road 20 in Watertown Township (AUID 07010205-593). This reach is considered a beneficial Class 2B warm water stream that spans a total of 3.35 river miles. Monitoring locations were distributed relatively evenly throughout the impaired reach. All sampling stations referred to in this memo are shown in Figure 1-1 and described in Table 1-1.

Table 1-1. Unnamed Creek synoptic survey monitoring locations.

Station ID	EQuIS ID	Description	River Mile	WQ/Flow Monitoring	Continuous DO	Dye Injection	Dye Monitoring
UC2.60	S007-715	Unnamed Creek at County Road 24	2.60	Yes	No	No	No
UC1.55	S007-699	Unnamed Creek east of County Road 127	1.55	Yes	No	Yes	No
UC0.60	S006-368	Unnamed Creek at Hainlin Road	0.60	Yes	Yes	No	Yes
UC0.20	S007-705	Unnamed Creek at County Road 20	0.20	Yes	No	No	Yes
TRIB2.05	S007-708	Tributary to unnamed Creek Kennel Road		Yes	No	No	No

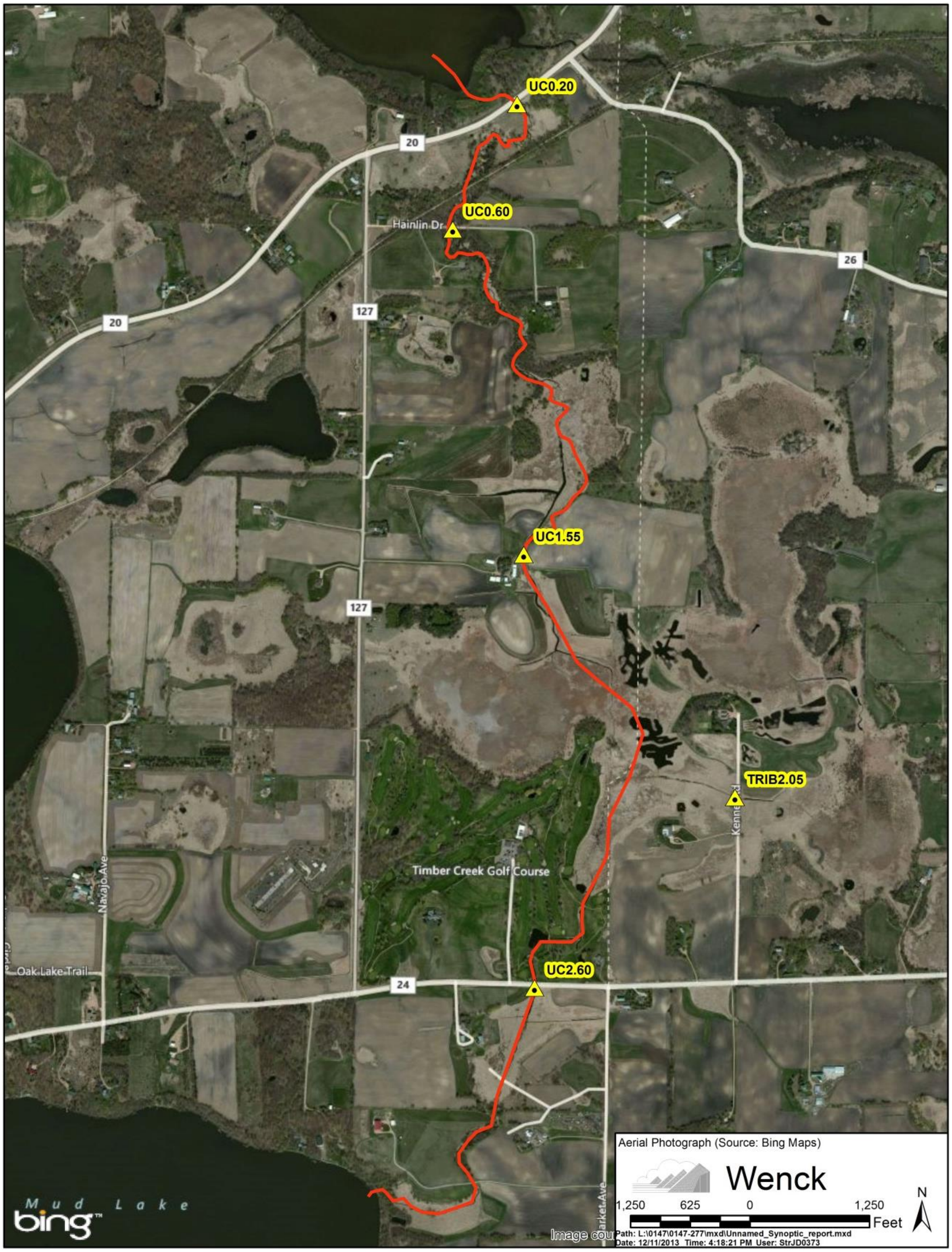

Figure 1-1. Unnamed Creek DO impaired reach and synoptic survey sampling locations.

1.2 Dye Study

Dye travel through the impaired reach was measured during the July 24 synoptic survey from stations UC1.55 to UC0.20. Dye travel was not measured between UC2.60 and UC1.55 due to a series of large in-line ponds and wetlands that would have made dye travel impossible. A slug of a tracer (Rhodamine WT dye) was injected at UC1.55 and water samples were collected downstream at UC0.60 and UC0.20 using ISCO automatic samplers. The ISCO samplers were programmed and left running until it was determined the dye cloud passed. Dye concentrations were measured using an Aquafluor handheld fluorometer.

Figures 1-2 and 1-3 are time series concentration plots for station UC0.60 and UC0.20. Estimated travel time between stations was calculated based on timing of the concentration peaks (Table 1-2). Average velocity from station UC1.55 to station UC0.60 was 0.19 feet/second while velocity from UC0.60 to UC0.20 was 0.23 feet/second. The creek flows through a large ditched wetland complex between the Timber Creek Golf Course (river mile 2.30) and river mile 1.00. Flow through this wetland complex is slow before speeding up considerably once it leaves the ditched wetland upstream of station UC0.60.

Table 1-2. July 24 dye study estimated travel times.

Sub Reach	Description	Reach Length (miles)	Injection Time	Dye Peak Time	Reach Flow (cfs)	Estimated Travel Time (hrs)	Average Velocity (ft/s)
1	UC1.55 to UC0.60	0.95	7/24 10:50	7/24 18:00	2.10 (UC1.55) 4.44 (UC0.60)	7:10	0.19
	UC1.55 to UC0.20	1.53	7/24 10:50	7/24 20:30	2.10 (UC1.55) 4.55 (UC0.20)	9:40	0.20
2	UC0.60 to UC0.20	0.40	NA	NA	4.44 (UC0.60) 4.55 (UC0.20)	2:30	0.23

Note: Travel times estimated by calculating the time between upstream injection and peak concentration measured downstream.

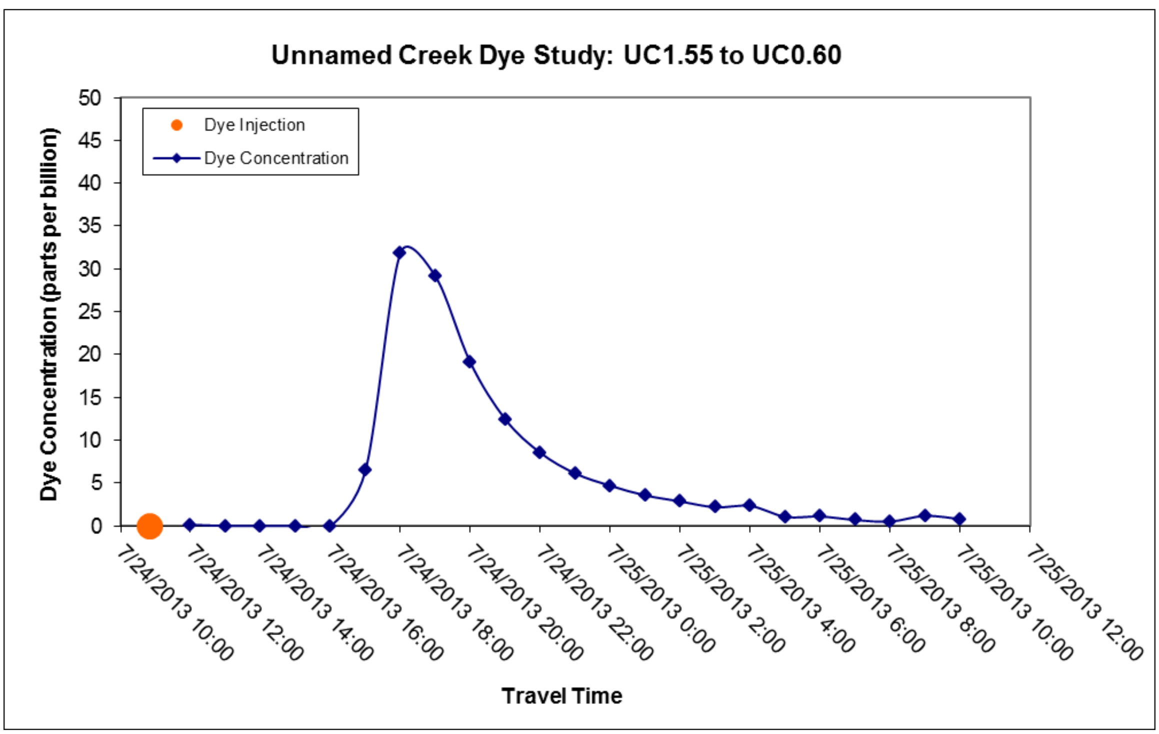

Figure 1-2. UC1.55 to UC0.60 dye study measurements.

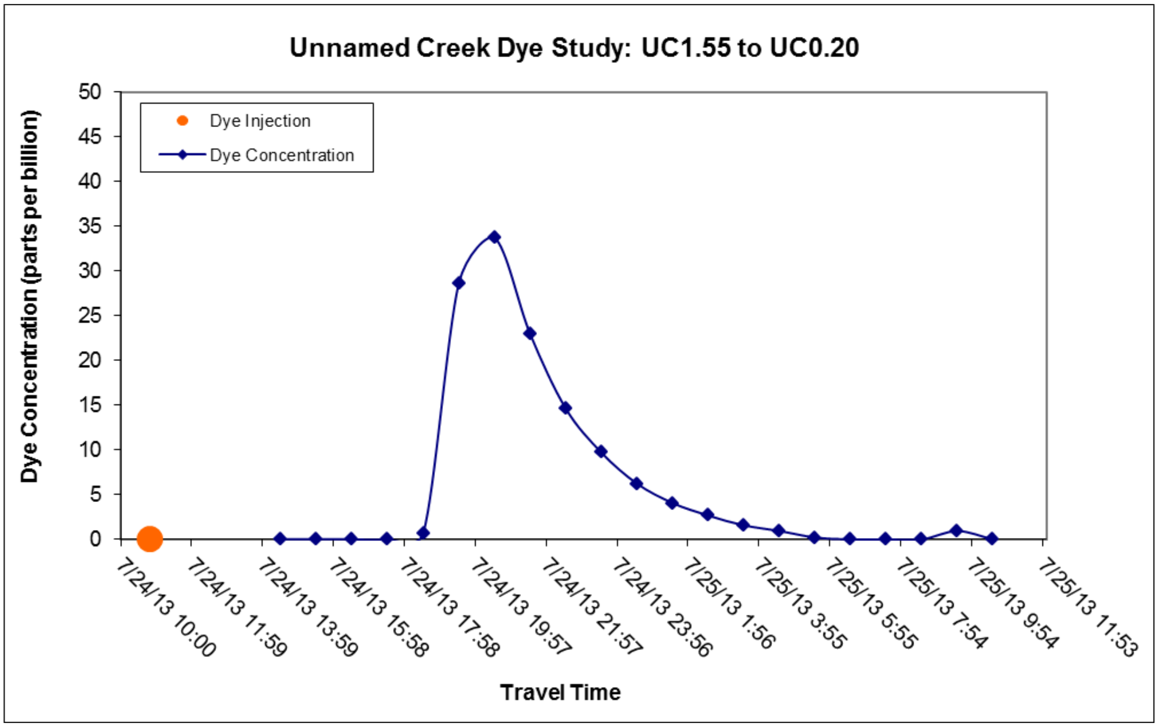

Figure 1-3. UC1.55 to UC0.20 dye study measurements.

1.3 Flow Gauging

Flow gauging was conducted at each water quality and dye monitoring station during the July synoptic survey. Flow was recorded using SonTek Flow Tracker handheld digital velocity meters with an accuracy of 0.001 cubic feet per second (cfs). Velocity measurements were taken at 60 percent of the total depth. Horizontal spacing of velocity measurements was set so less than 10 percent of total discharge is accounted for by any single velocity measurement.

Results from all stream flow measurements during the July survey are illustrated in Figure 1-4 and summarized in Table 1-3. The flow data shows Unnamed Creek is a gaining stream between UC2.60 and UC0.20. Approximately 0.20 inches of rain was recorded in the week leading up to the start of this survey (7/17 – 7/23).

Table 1-3. Gauged flow measurements during the July 24 synoptic survey.

Station	River Mile	Flow (cfs)	Average Velocity (ft/s)	Average Depth (ft)	Channel Width (ft)
UC2.60	2.60	1.04	0.07	2.18	6.8
UC1.55	1.55	2.10	0.04	2.64	18.0
UC0.60	0.60	4.44	0.17	1.88	14.0
UC0.20	0.20	4.55	0.08	5.83	10.0
TRIB2.05		0.19	0.18	0.54	2.0

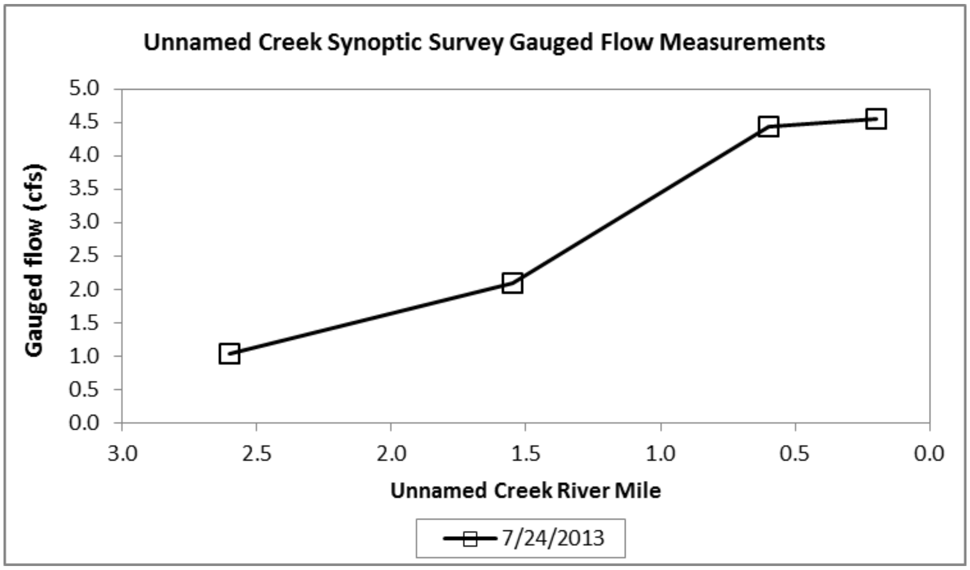

Figure 1-4. Gauged flow measurements during the July 24 synoptic survey.

1.4 Water Quality Sampling

Water quality data were collected by Wenck staff at three main-stem sites (Figure 1-1 and Table 1-1) during the July synoptic survey. One water sample (grab) was collected at each station on 7/24 and preserved for lab analysis through the Minnesota Department of Health laboratory. Samples were analyzed for the following parameters: total phosphorus (TP), ortho-phosphorus (Ortho-P), total Kjeldahl nitrogen (TKN), ammonia-N (NH_3), nitrate+nitrite - N (NO_3+ NO_2-N), 5-day carbonaceous biochemical oxygen demand ($CBOD_5$), chlorophyll-*a*, total suspended solids (TSS), and volatile suspended solids (VSS). Data sondes were used in the field to collect the following water quality parameters at the three main-stem stations and one tributary site: temperature, conductivity, pH, oxidation reduction potential (ORP), and dissolved oxygen (DO).

Lab and field water quality results are summarized in Table 1-4 and illustrated in Figures 1-5 through 1-9. TKN, CBOD, chlorophyll-*a*, TSS and VSS are all higher at the upstream station (UC2.60) compared to downstream stations. Station UC2.60 is highly influenced from outflow from Mud Lake, a eutrophic lake with high algae and nutrient concentrations. TP, ortho-P and ammonia-N were significantly higher at the downstream stations, UC1.55 and UC0.60. Nutrient loading at the downstream stations is likely from tributary inputs and export from the golf course and large wetland complex located between monitoring stations UC2.60 and UC1.55.

Table 1-4. July 24, 2013 synoptic survey water quality results.

Parameter	UC2.60	UC1.55	UC0.60	UC0.20	TRIB2.05
Temperature (Celsius)	22.53	20.77	20.42	20.31	17.45
Sp. Conductivity (µmhos/cm)	357	405	407	407	593
DO (mg/L) grab **Time**	3.47 7:50	1.99 8:00	2.30 8:15	4.46 8:20	0.59 7:40
pH	7.53	7.03	7.28	7.33	6.79
ORP (mV?)	6.4	-11.7	4.2	13.4	-4.7
Total Phosphorus (µg/L)	137	270	243	--	--
Orthophosphate (µg/L)	68	211	194	--	--
TKN (mg/L)	2.13	1.64	1.83	--	--
NH_3-N (mg/L)	0.06	0.47	0.36	--	--
Nitrate+Nitrite - N (mg/L)	<0.05	<0.05	<0.05	--	--
5-day CBOD (mg/L)	5.4	2.8	2.1	--	--
Chlorophyll-*a* (ug/L)	92.1	6.4	4.6	--	--
Total Suspended Solids (mg/L)	35.0	4.4	3.2	--	--
Volatile Suspended Solids (mg/L)	24.0	4.4	3.2	--	--

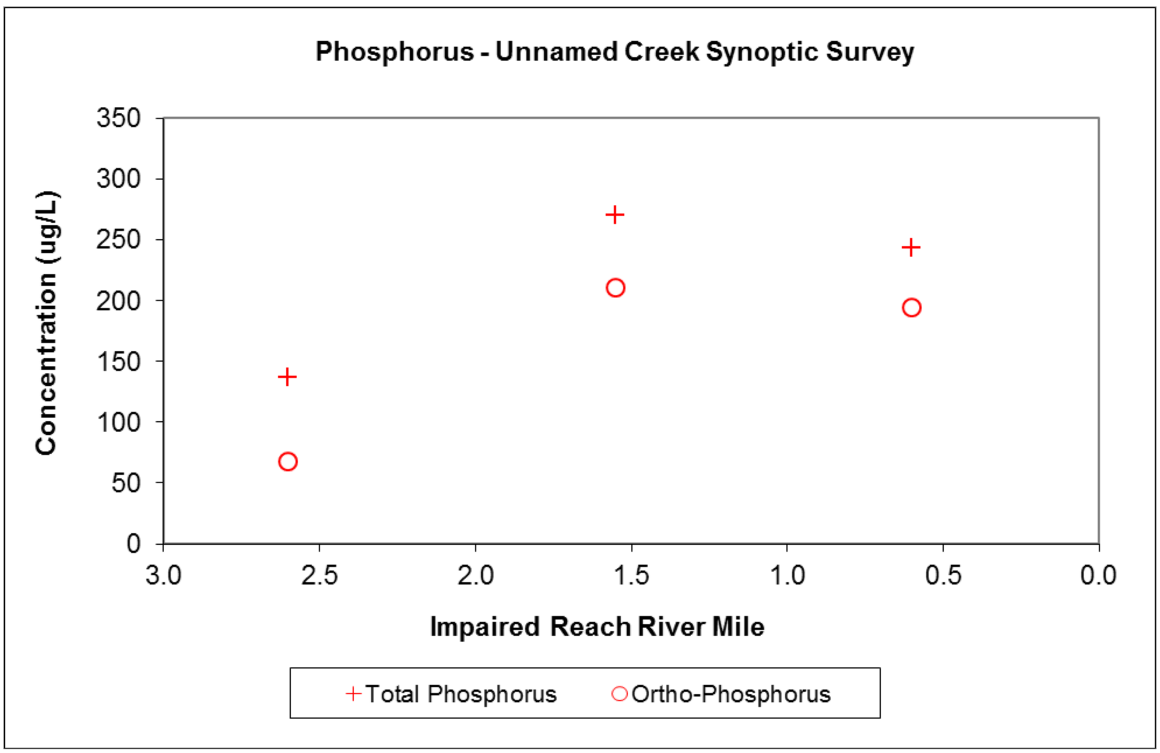

Figure 1-5. Main-stem synoptic survey phosphorus sampling results.

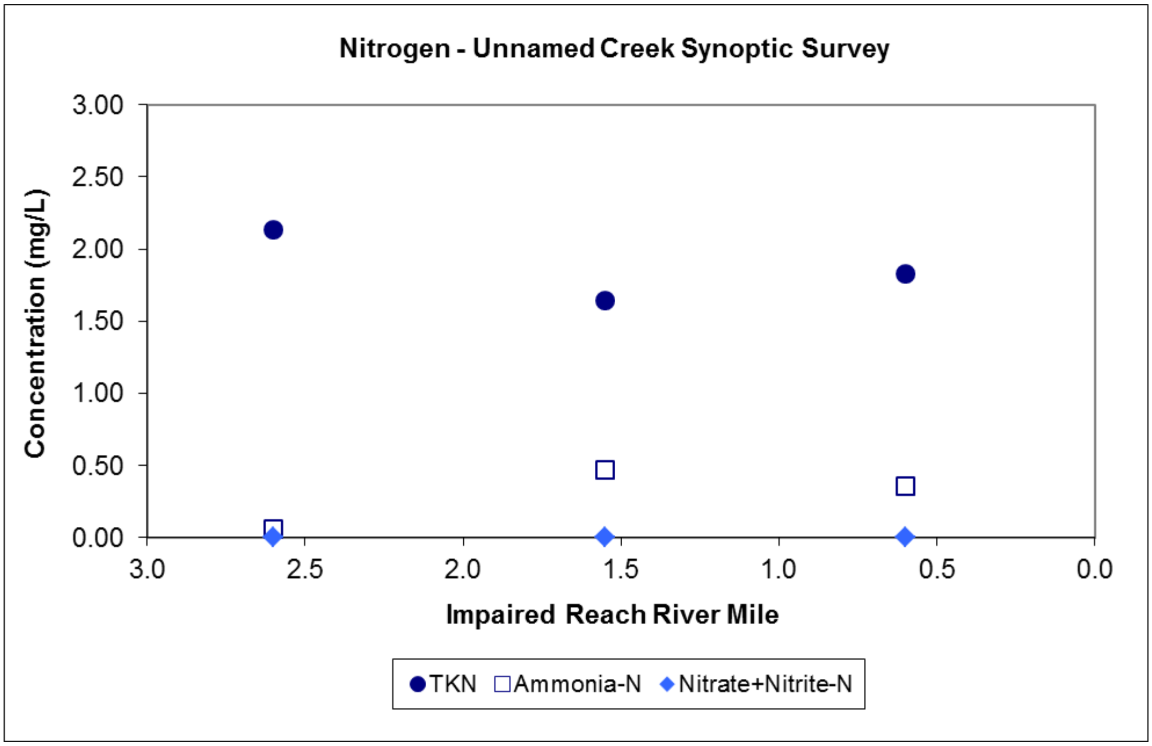

Figure 1-6. Main-stem synoptic survey nitrogen sampling results.

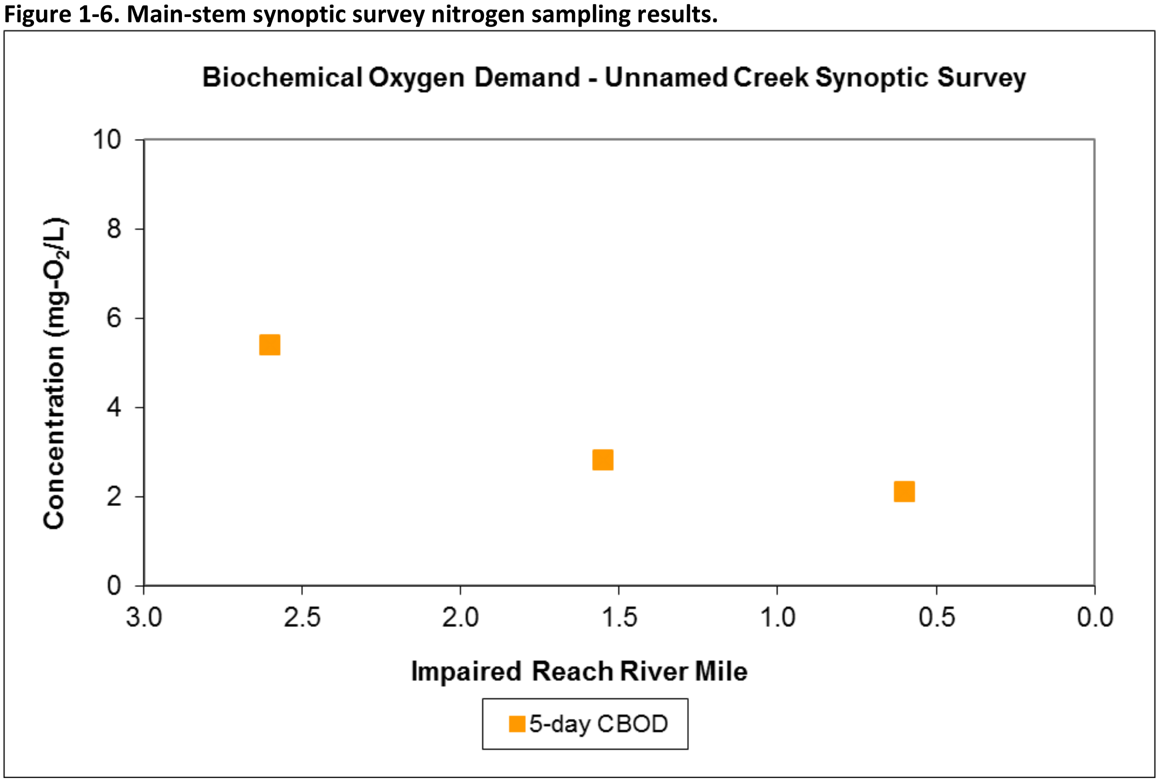

Figure 1-7. Main-stem synoptic survey biochemical oxygen demand sampling results.

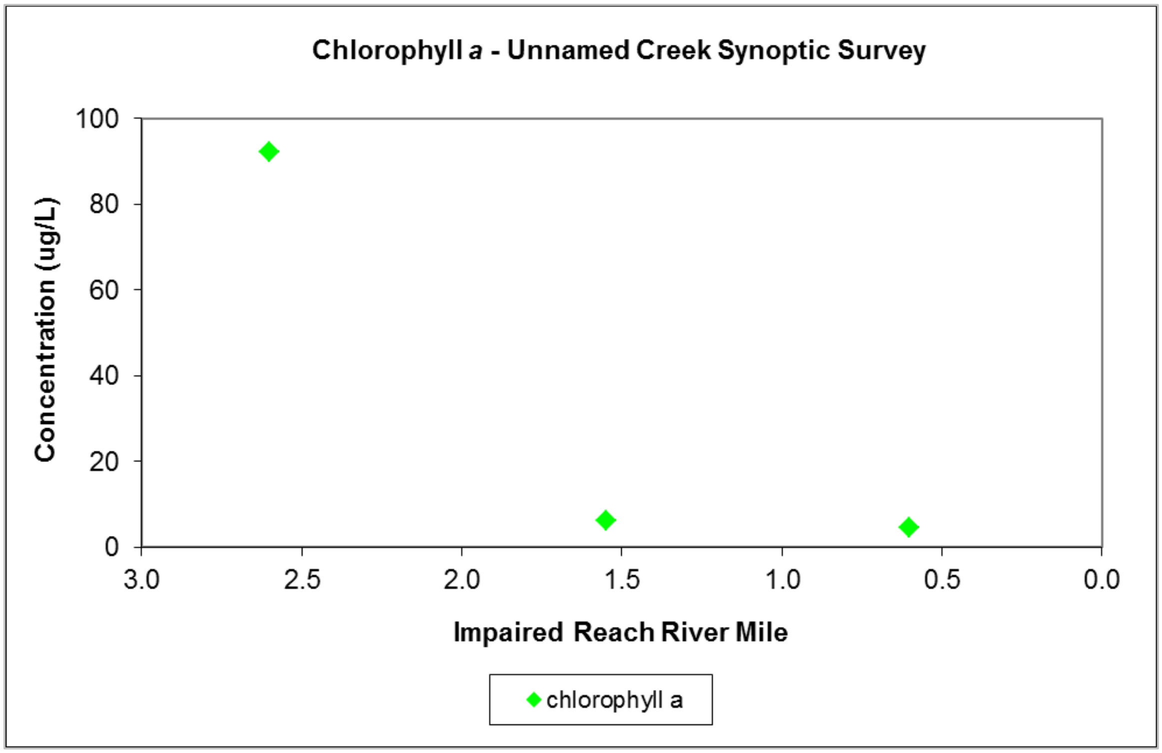

Figure 1-8. Main-stem synoptic survey chlorophyll-*a* results.

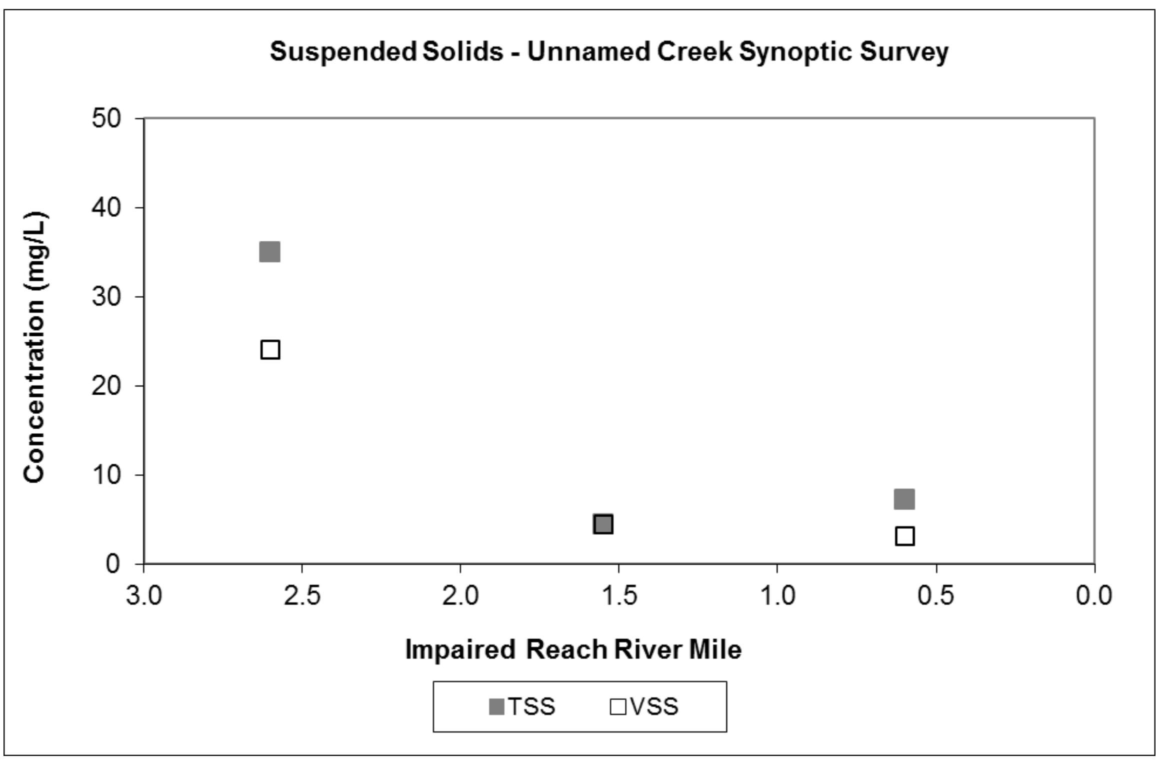

Figure 1-9. Main-stem synoptic survey suspended solids sampling results.

1.5 Longitudinal DO Profile

Results of three early morning (pre 9:00 am) DO longitudinal profiles are shown in Figure 1-10. These profiles suggest minimum daily DO is consistently below the standard throughout the entire Unnamed Creek impaired reach. The profiles show minimum DO levels decrease between stations UC2.60 and UC0.60 as the creek flows through the Timber Creek Golf Course and the large wetland complex downstream of station UC2.60.

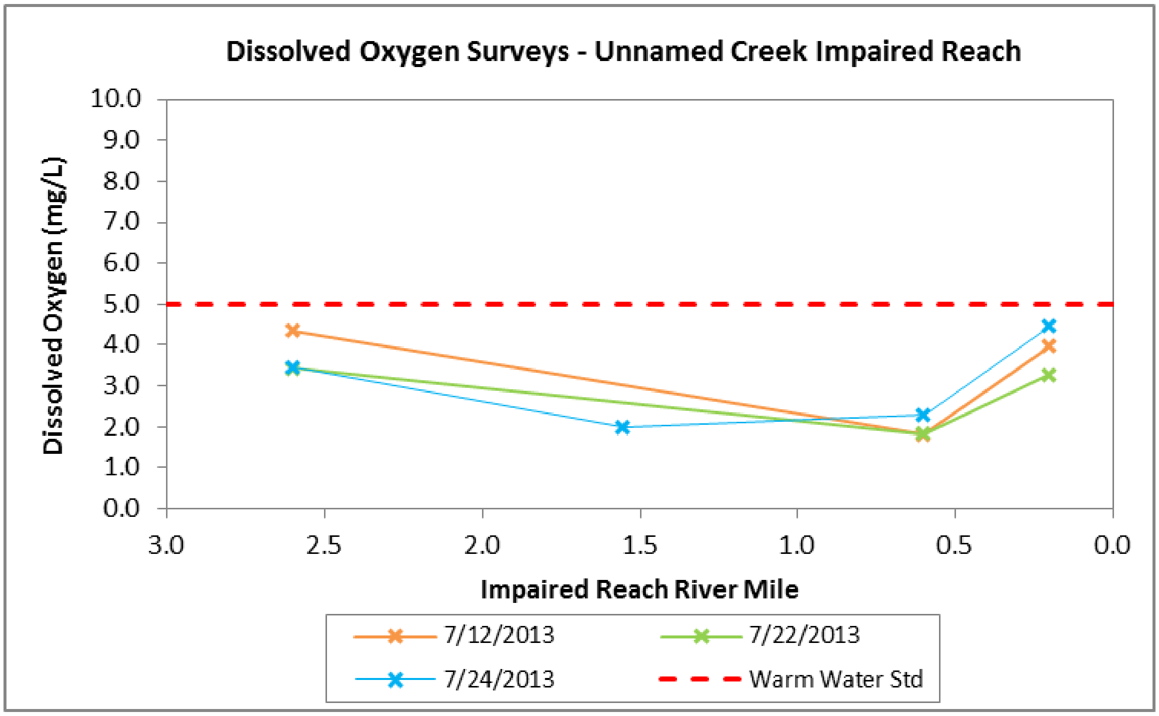

Figure 1-10. Unnamed Creek DO longitudinal profiles measured before and during the July 2013 synoptic survey.

Wenck
Engineers • Scientists
Business Professionals

Wenck Associates, Inc.
1800 Pioneer Creek Center
P.O. Box 249
Maple Plain, MN 55359-0249

800-472-2232
(763) 479-4200
Fax (763) 479-4242
wenckmp@wenck.com
www.wenck.com

TECHNICAL MEMORANDUM

TO:	Pioneer- Sarah Creek Watershed Management Organization Minnesota Pollution Control Agency
FROM:	Jeff Strom, Erik Megow and Diane Spector
DATE:	April 2015
SUBJECT:	Unnamed Creek QUAL2K Modeling Methods and Results

Wenck Associates, Inc. has developed and calibrated a low-flow QUAL2K model for Unnamed Creek dissolved oxygen (DO) impaired reach AUID 07010205-563 from the outlet of Mud Lake to the inlet of Rice Lake. The purpose of this technical memorandum is to describe the methods and assumptions used to create and calibrate the QUAL2K model.

1.0 INTRODUCTION

1.1 Model Selection

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

1.2 General Overview of the Model

The model was built using late summer synoptic survey data collected on July 24, 2013. Stream locations and physical features were built in to the model first before proceeding to hydraulic calibration. Once tributary and diffuse inflow (groundwater) were quantified and incorporated into the model, the temperature and conductivity were calibrated to synoptic survey data by adjusting stream shading and groundwater input parameters. Then, chlorophyll-*a* (phytoplankton production), nutrients (phosphorus and nitrogen components), and carbonaceous biochemical oxygen demand (CBOD) were calibrated by adjusting tributary contributions and/or kinetic coefficients within the range of published values. Finally, bottom algae coverage was adjusted for each reach to match observed DO data.

2.0 MODEL SETUP AND INPUTS

The QUAL2K model covers the main stem of Unnamed Creek from the outlet of Mud Lake to the end of the impaired reach at the inlet of Rice Lake. This stretch of Unnamed Creek, explicitly modeled, is approximately 3.3 river miles long and was represented in the model as six individual reaches. The start of each reach correlates with a monitoring station location, road crossing, or physical change in stream morphology (Tables 2.1 and 2.2, Figure 2.1).

These final "modeled" channel slopes were adjusted and are different than those measured during the channel survey. The surveyed slopes did not work well in the model and grossly under-estimated travel time and over-estimated observed velocities in the field. The slope was used as a calibration adjustment to accurately model hydraulics and match observed data on travel time and velocity.

Table 1.1. Model reach characteristics.

Reach	Description	Upstream River Mile	Downstream River Mile	Reach Length (miles)	Channel Slope[1] (ft/ft)
1	Mud Lake (UC3.30) to CR 16 (UC2.60)	3.30	2.60	0.70	0.00015
2	CR 16 (UC2.60)to Outlet of Golf Course Lake (UC2.45)	2.60	2.45	0.15	0.00005
3	Outlet of Golf Course Lake (UC2.45) to Farm Road Crossing (UC1.55)	2.45	1.55	0.90	0.00003
4	Farm Road Crossing (UC1.55)) to Outlet of Wetland (UC1.20)	1.55	1.20	0.35	0.00040
5	Outlet of Wetland (UC1.20) to Hainlin Avenue (UC0.60)	1.20	0.60	0.60	0.00050
6	Hainlin Avenue (UC0.60) to Rice Lake (UC0.00)	0.60	0.00	0.60	0.00020

[1]The channel slopes listed in Table 2.1 are the modeled channel slopes for each reach.

Table 1.2. Monitoring locations and available data.

Reach	Monitoring Location ID	Description	Data Collected
1	UC2.60	Unnamed Creek at CR 15	Q, Field, Grab
3	UC1.55	Unnamed Creek at Farm Road Crossing	Q, Field, Grab
5	UC0.60	Unnamed Creek at CR 6	Q, Field, Grab, DO, ToT
6	UC0.20	Unnamed Creek at Hainlin Avenue	Q, Field, ToT

Q = Gaged flow.
ToT = Time of travel determined from dye study.
Grab = Water quality grab sample collected and lab analyzed for standard pollutants: total Kjeldahl nitrogen (TKN), ammonia nitrogen (NH_4-N), nitrate nitrogen (NO_2-N), 5-day carbonaceous biological oxygen demand ($CBOD_5$) and ultimate biochemical oxygen demand (BOD_u), total phosphorus (TP), ortho-phosphorus (soluble reactive phosphorus), total organic carbon (TOC), and chlorophyll-*a*.
Field = In-field measurement of temperature, conductivity, pH, and dissolved oxygen (DO).
DO = Data sondes deployed to collect continuous measurements of DO, temperature, pH and conductivity.

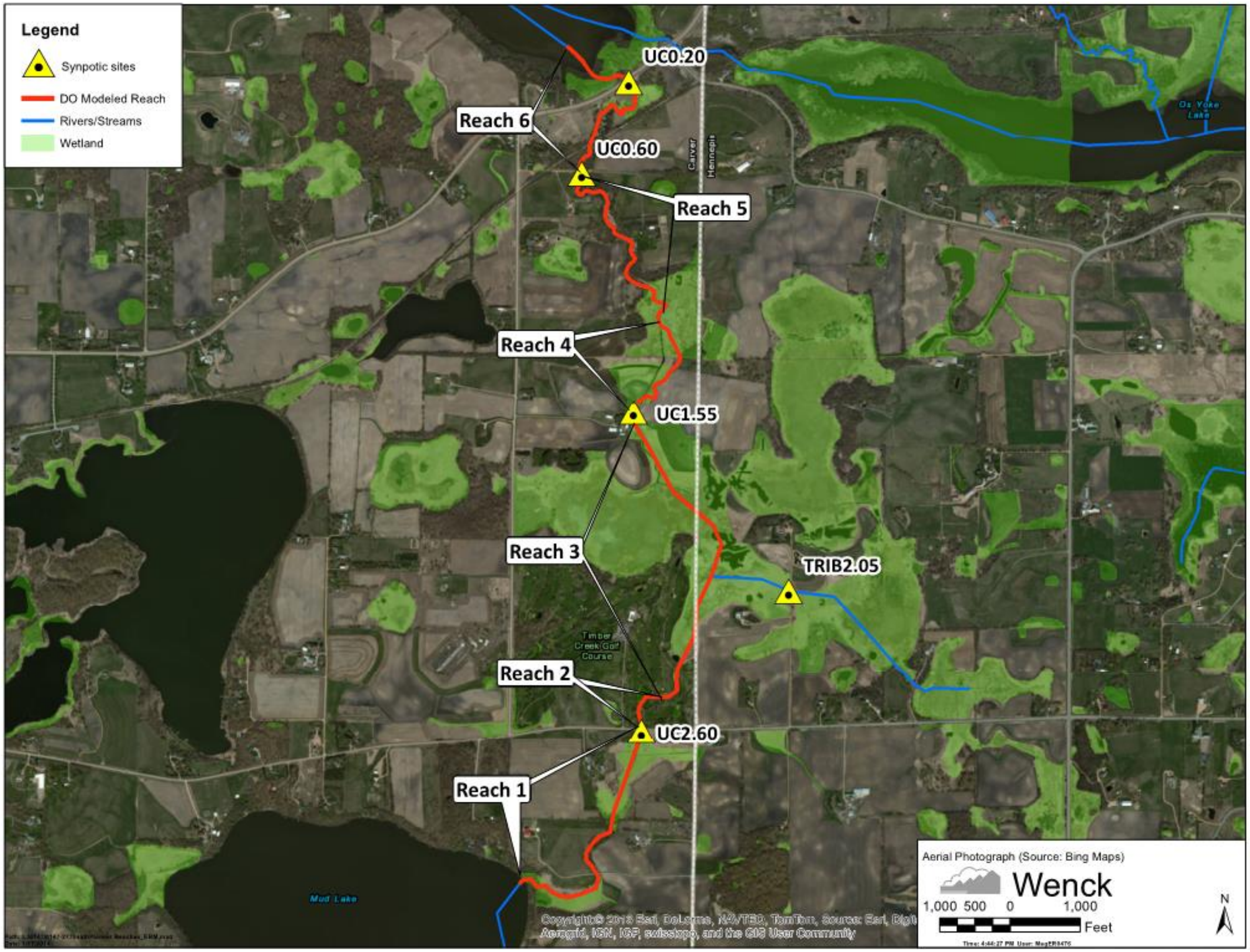

Figure 1.1. Unnamed Creek monitoring stations and modeled reaches.

2.1 Channel Slope

Reaeration in QUAL2K may be prescribed by the user or calculated using one of eight hydraulic-based reaeration formulas built into the model. The Tsivoglou-Neal reaeration model was selected for Unnamed River because it performs well in predicting reaeration in low-flow and low gradient rivers/streams (Tsivoglou and Neal, 1976; Thomann and Mueller, 1987). This model calculates reaeration using stream velocity. Modeled channel slopes were assigned based on data from an elevation survey conducted by Wenck in the fall of 2013. However, applying the surveyed channel slopes greatly underestimated observed travel times and over-estimated field velocity measurements. Therefore, modeled channel slopes had to be adjusted downward to meet the observed measurements. It is believed the final channel slope adjustments more accurately reflect the average slope of each reach. These slopes were verified using MN LiDAR, air photos, wetland locations, and general field observations (Table 2.1).

2.2 Weather and Physical Processes

Hourly weather measurements of temperature, cloud conditions, relative humidity and wind speed were downloaded from a long-term Minneapolis station from Minnesota's Automated Surface Observing Systems (ASOS) website. Channel coverage, canopy and shading were set based on inspection of recent air photographs in GIS.

2.3 Headwaters

The headwater of the Unnamed Creek impaired reach is Mud Lake. During the synoptic survey, the station at UC2.60 had measurable flow (1.04 cfs) and the water quality data collected at this station on July 24, 2013 was used to represent the upstream boundary condition/headwater in the model. Three field measurements from Station UC2.60 (EQuISS007-715) on July 24 were used to model DO, temperature, conductivity, and pH. The field measurements were taken at 7:50 am, 9:45 am, and 5:25 pm (17:25) and therefore represented the range of headwater DO observed throughout the day. These field samples were supplemented by a water quality grab sample that was used to model headwater chemistry.

2.4 Carbonaceous Biochemical Oxygen Demand (CBOD)

QUAL2K calculates nitrogenous oxygen demand separate from ultimate carbonaceous biochemical oxygen demand (CBOD). To do this, QUAL2K requires individual inputs of CBOD and organic nitrogen plus ammonia-nitrogen (TKN – reduced nitrogen). CBOD samples were collected at UC2.60, UC1.55, and UC0.60 on July 24, 2013. These CBOD measurements were used to represent the breakdown of organic carbon in the model.

3.0 HYDRAULIC CALIBRATION

Manning's Equation was used to model the hydraulics of Unnamed Creek. The model assumes steady flow conditions in each reach and uses the following Manning's Equation to model the flow in each reach:

$$Q = \frac{S_0^{1/2}}{n} \cdot \frac{A_c^{5/3}}{P^{2/3}},$$

where Q is the flow, S_0 is the bottom slope, n is the Manning roughness coefficient, A_c is the cross-sectional area, and P is the wetted perimeter.

For the QUAL2K model, the necessary inputs for Manning's equation are side slopes (z_1 and z_2), bottom width (W_b), channel slope (S_0), and roughness coefficient (n). The side slopes and width are used to calculate the wetted perimeter (P) and cross-sectional area (A_c) in the equation above.

Reach channel slopes, side slopes and bottom widths are shown in Table 3.1. The bottom width and side slopes were calculated by approximating a trapezoidal channel to match cross-section survey data from one location within each reach. Final channel slopes were determined by calibrating to synoptic survey travel time and velocity measurements.

Table 1.3. Manning's equation inputs and assumptions.

Reach	*n*	W_0 (ft)	Channel Slope (ft/ft)	Side Slope *(Z_1)*	Side Slope *(Z_2)*
1	0.080[1]	10.0	0.00015	0.86	3.28
2	0.080	32.8	0.00005	0.86	3.28
3	0.080	9.8	0.00003	1.03	1.15
4	0.080	9.0	0.00040	1.03	1.15
5	0.080	7.5	0.00050	1.00	2.23
6	0.080	7.5	0.00020	2.73	3.03

[1]Roughness is assumed based on literature values (Mays, 2005)

3.1 Flow and Travel Time Calibration

Gauged flow data for Unnamed Creek was collected on July 24, 2013 at three sites along the impaired reach. The measured flows are listed in Table 3.2.

Table 1.4. Unnamed Creek gauged flow data, July 24, 2013.

Site	Timestamp	Flow (cfs)	Flow (m^3/s)
UC2.60	9:45	1.04	0.029
UC1.55	10:40	2.10	0.059
UC0.60	11:15	4.44	0.126
UC0.20	12:00	4.55	0.129
TRIB2.05	12:30	0.19	0.005

Incremental increases in flow between gauging stations were built into the model as diffuse sources and/or point sources where appropriate. Diffuse sources were modeled as groundwater, while point sources were modeled as tributaries.

Groundwater was estimated using 32 inches of annual rainfall and based on a unit-area hydrograph for each reach. Based on literature values, an estimated 2.2% of rainfall over each reaches watershed area is delivered to the stream as groundwater (Baker et al, 1979). Table 3.3 lists the estimated groundwater entering each reach.

Table 1.5. Unnamed Creek estimated groundwater as diffuse flow for each modeled reach.

Reach	Watershed Area (ac)	Groundwater Inflows			
		Inch/yr	Acre-feet/yr	Inflow (CFS)	Inflow (m^3/s)
1	212	0.7	12	0.017	0.0005
2	282	0.7	16	0.023	0.0006
3	1606	0.7	94	0.129	0.0037
4	86	0.7	5	0.007	0.0002
5	166	0.7	10	0.013	0.0004
6	1771	0.7	103	0.143	0.0040

After groundwater sources were calculated and incorporated into the model, additional increases in flow between gauging stations was modeled as tributaries at locations determined through aerial imagery. Table 3.4 lists the modeled inflows, both tributary (point sources) and groundwater (diffuse sources) for each reach.

Table 1.6. Unnamed Creek modeled tributary (point source) and groundwater (diffuse source) inflows.

Reach	Groundwater Inflow (m^3/s)	Tributary Inflow (m^3/s)	Tributary Location
1	0.0005	0.0000	None
2	0.0006	0.0000	None
3	0.0037	0.0252	RM 2.1
4	0.0002	0.0654	RM 1.4
5	0.0004	0.0000	None
6	0.0040	0.0000	None

The model was deemed calibrated for total flow once the headwater, tributaries and the groundwater diffuse source inflow were built in to the model (Figure 3.1.).

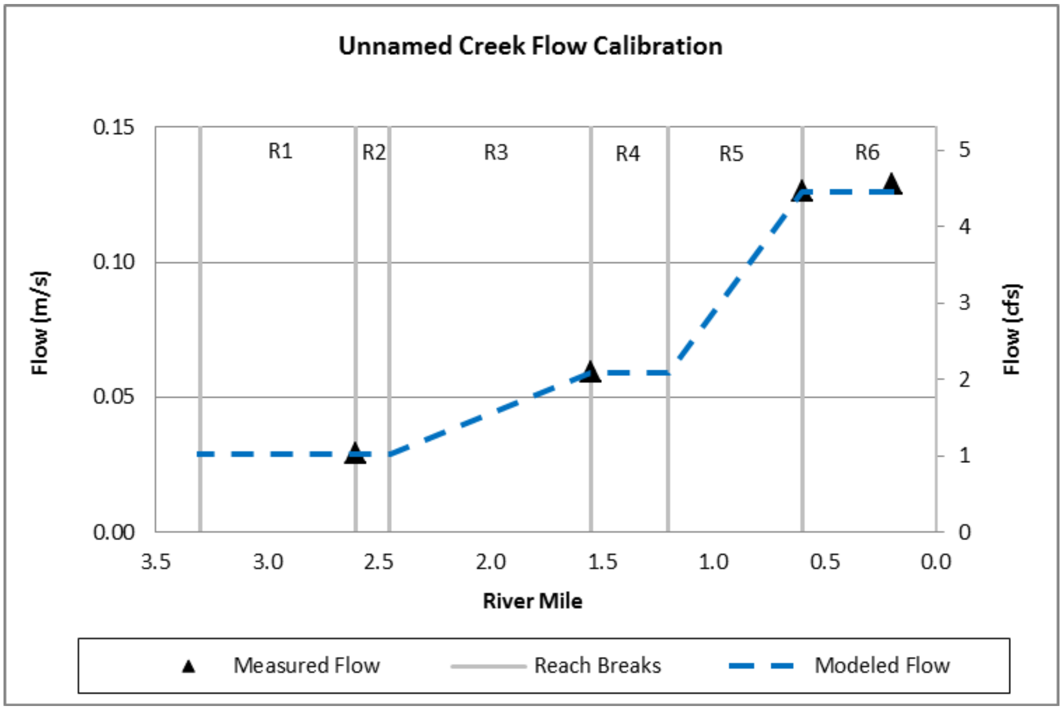

Figure 1.2. Unnamed Creek QUAL2K flow calibration with headwater, tributary and groundwater diffuse inflows.

Model predicted travel time throughout the impaired reach matched observed travel time data once the tributary and diffuse sources were properly incorporated into the model (Figure 3.2). Manning's inputs, specifically reach slope and width, were calibrated based on MN LiDAR, air photos, travel time and average reach velocity observations.

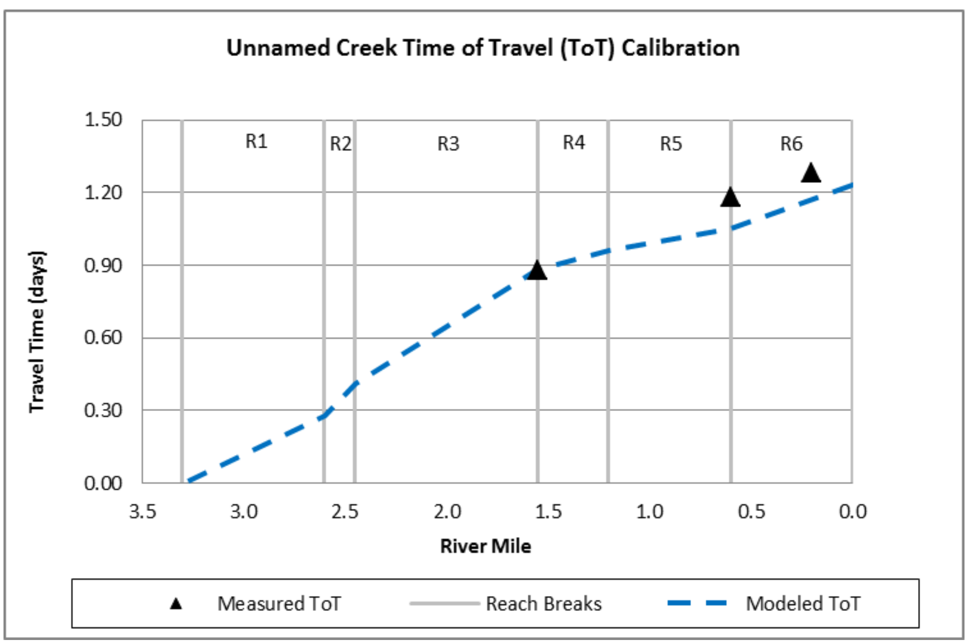

Figure 1.3. Unnamed Creek QUAL2K travel time calibration.

4.0 WATER QUALITY CALIBRATION

All headwater and tributary water quality model inputs were derived from data collected during the July 24, 2013 synoptic survey. Groundwater diffuse source water quality parameters were estimated based on literature values and calibration to in-stream water quality data. The QUAL2K model was set up to predict flow, travel time, depth, temperature, conductivity, pH, DO, organic nitrogen (ON), ammonia-nitrogen (NH_3-N), nitrate/nitrite-nitrogen (NO_2/ NO_3-N), $CBOD_u$, sediment oxygen demand (SOD), organic and inorganic phosphorus and chlorophyll-*a*. All model changes to global and reach specific kinetic rates as well as the groundwater diffuse source settings are discussed in this section.

4.1 General Kinetic Rates

Nine kinetic rates were considered during water quality calibration to meet longitudinal changes in the observed data. Organic nitrogen hydrolysis and settling, organic phosphorus hydrolysis, ammonia (NH4) flux, inorganic phosphorus flux, and phytoplankton settling were the only kinetic rates adjusted from default rates. All kinetic rate adjustments were within the range of published values (Table 4.1).

Table 1.7. Unnamed Creek QUAL2K kinetic rates adjustments.

Rate	Calibrated Rate	Default Rate	Literature Range	Citation/Study Area
Reaeration (day^{-1})	0.0 – 3.0 (model calculated)	Tsivoglou and Neal, 1976		
CBOD oxidation rate (day^{-1})	0.20	0.20	0.02 – 0.60 0.56 – 3.37	Bowie et al., 1985, Table 3-17 p. 152 Kansas (6 rivers) Michigan (3 rivers) reported by Bansal, 1975
Organic-N Hydrolysis (day^{-1})	0.10	0.20	0.02 – 0.10 0.03 – 0.20	Bowie et al., 1985, Table 5-3 p. 259 Scavia, 1980 Di Toro & Matystik, 1980
Nitrification (day^{-1})	0.20	0.20	0.09 – 0.20	Thomann et al., 1982; Di Toro et al., 1980
Organic-N Settling Velocity (m/d)	0.01	0.05	Influenced by the amount of particulate organic matter and its size, shape and density and velocity of stream	
Inorganic-P settling Velocity (m/d)	0.01	0.01	Influenced by the amount of particulate organic matter and its size, shape and density and velocity of stream	
Organic-P Hydrolysis (day^{-1})	0.02	0.05	0.02 – 0.80	Bowie et al., 1985, Table 5-5 p. 266 Jorgenson, 1976 Bowie et al., 1980
Organic-P Settling Velocity (m/d)	2.0	2.0	Influenced by the amount of particulate organic matter and its size, shape and density and velocity of stream	
Sediment Inorganic-P Flux (mg P/m^2/d)	95	Model Calculated	9.6-95	Fillos and Swanson, 1975
Sediment NH4 Flux (mg N/m^2/d)	300	Model Calculated	20-325	Thomann and Mueller, 1987
Phytoplankton Settling (m/d)	0.40	0.25	0 – 2	Bowie et al., 1985 Table 6-19 p352 Chen & Orlob, 1975 and Smith, 1978

4.2 Diffuse Groundwater Quality Inputs

Diffuse groundwater inputs were assigned typical groundwater quality values for the Franconia aquifer (CFRN) based on MPCA's 1999 baseline groundwater report (MPCA, 1999). Organic nitrogen and $CBOD_u$ diffuse inputs had to be assumed as these parameters were not monitored during the MPCA's 1999 study. Table 4.2 lists the values used for modeling groundwater quality parameters.

Table 1.8. Groundwater parameter model assumptions and literature values.

Parameter	Modeled Value	Groundwater Literature Values[1]	Notes
Temp (C)	10.3	9.1 – 11.5	Used mean groundwater value for Franconia aquifer (MPCA 1999)
Sp. Cond (umhos/cm)	718	421 - 951	Used mean groundwater value for Franconia aquifer (MPCA 1999)
pH	7.39	6.92 – 7.96	Used mean groundwater value for Franconia aquifer (MPCA 1999)
DO	0.3	0.30 – 5.78	Used median groundwater value for Franconia aquifer (MPCA, 1999)
Organic- N (µg/L)	500	NA	Calibrated adjustment to in-stream conditions (no published data available)
Nitrate (µg/L)	500	<500 – 6,900	Used median groundwater value for Franconia aquifer (MPCA 1999)
Organic-P (µg/L)	48	19 - 293	Used mean groundwater value for Franconia aquifer (MPCA 1999)
Inorganic-P (µg/L)	25	<20 – 630	Used mean groundwater value for Franconia aquifer (MPCA 1999)
$CBOD_u$ (mg O_2/L)	0	NA	Calibrated adjustment to in-stream conditions (no published data available)

[1] Typical groundwater quality literature values for the Franconia aquifer (MPCA, 1999)

4.3 Tributary Water Quality Inputs

Tributary (point source) water quality values were modeled using the average values measured along the main-stem during the July 24, 2013 longitudinal sampling. If needed, the average values were then adjusted within the range of typical Minnesota water quality conditions for the North Central Hardwood Forest ecoregion values to better match main-stem water quality results. Table 4.3 summarizes the modeled water quality parameters for each tributary.

Table 4.3. Tributary parameter model assumptions and literature values

Parameter	In-stream Values		Tributaries		Justification
	Range[1]	Average	RM 2.1	RM 1.4	
Temp (C)	20.3 - 27.2	22.0	22.0	22.0	Adjusted within main-stem values
Sp. Cond (µmhos/cm)	357 - 407	394	394	394	Adjusted within main-stem values
CBOD (mg/L)	2.1 - 5.4	3.4	3.4	3.4	Adjusted within main-stem values
DO (mg/L)	0.5 - 5.6	3.3	0.6	4.0	Adjusted within main-stem values and TRIB2.05 measured value
Organic- N (µg/L)	1,124 – 1,437	1,323	1,323	1,437	Adjusted within main-stem values
Nitrate+Nitrite-N (µg/L)	0	0	0	0	Adjusted within main-stem values
Ammonia-N (µg/L)	60 - 470	297	470	297	Adjusted within main-stem values
Organic-P (µg/L)	0 -53	32	500	100	Tributary values adjusted above main-stem range to reflect increased organic phosphorus load observed at UC0.60 during survey
Inorganic-P (µg/L)	68 - 211	158	90	68	Adjusted within main-stem values
pH	7.03 – 7.53	7.29	7.29	7.29	Adjusted within main-stem values

4.4 Final Water Quality Calibration

CBOD, chlorophyll-*a* and all forms of nitrogen and phosphorus were deemed calibrated after diffuse source water quality parameters and kinetic rates were properly incorporated and adjusted within the model. The model performed well in predicting monitored concentrations of the primary water quality parameters that affect DO.

5.0 DISSOLVED OXYGEN CALIBRATION

5.1 Diurnal Dissolved Oxygen Calibration

The Unnamed Creek QUAL2K model applies half saturation formulations defining the relationship of light penetration through the water column and effects on algae and photosynthesis. It was assumed water column algae is accurately depicted in the model since modeled chlorophyll-a concentrations closely match observed values throughout the impaired reach during the synoptic survey. However, early model runs did not accurately predict daily minimum and maximum DO observations, suggesting there was in-situ primary production (photosynthesis and respiration) not accounted for or under-represented. QUAL2K has a bottom algae component that simulates photosynthesis and nutrient uptake of any non-suspended algae and/or plants. In the Unnamed Creek model, the bottom algae channel coverage was adjusted by reach to match observed swings in the continuous DO data observed throughout the July 24 synoptic survey (Table 5.1). It is assumed that this bottom algae component represents all elements of primary production (attached algae, submerged macrophytes, rooted aquatic vegetation) that could not be measured or quantified in the field.

Table 1.9. Prescribed bottom algae coverage.

Reach	Bottom Algae Coverage (%)
1	0
2	3
3	7
4	7
5	2
6	2

5.2 Final Dissolved Oxygen Calibration

Figure 5.1 shows the model-predicted and observed DO for the Unnamed Creek QUAL2K calibrated model run. Field DO grabs were measured three times at each of the four field sites in the early morning, midday, and afternoon on July 24th using a hand-held YSI. These three measurements aimed to capture the diurnal pattern of DO at each site (Table 5.3).

Table 1.3. Longitudinal DO data for July 24, 2013

Location	Monitored DO Concentrations (mg/L)		
	Morning (7:50-8:20)	Mid-day (9:45-11:25)	Afternoon (17:25-17:50)
UC2.60	3.47	4.30	5.67
UC1.55	1.99	0.52	1.25
UC0.60	2.30	2.80	3.04
UC0.20	4.46	4.70	4.76

The model performed well in predicting monitored DO concentrations (black squares) and diurnal patterns (daily minimum and maximum, shown in plots as blue dashed lines) at the four monitoring stations with DO measurements. The model and data show that DO decreases through the first three slow moving reaches, bottoming out in Reaches 3 and 4 where the creek travels through a large wetland complex. DO increases due to increased reaeration, velocity and flow in reaches 5 and 6.

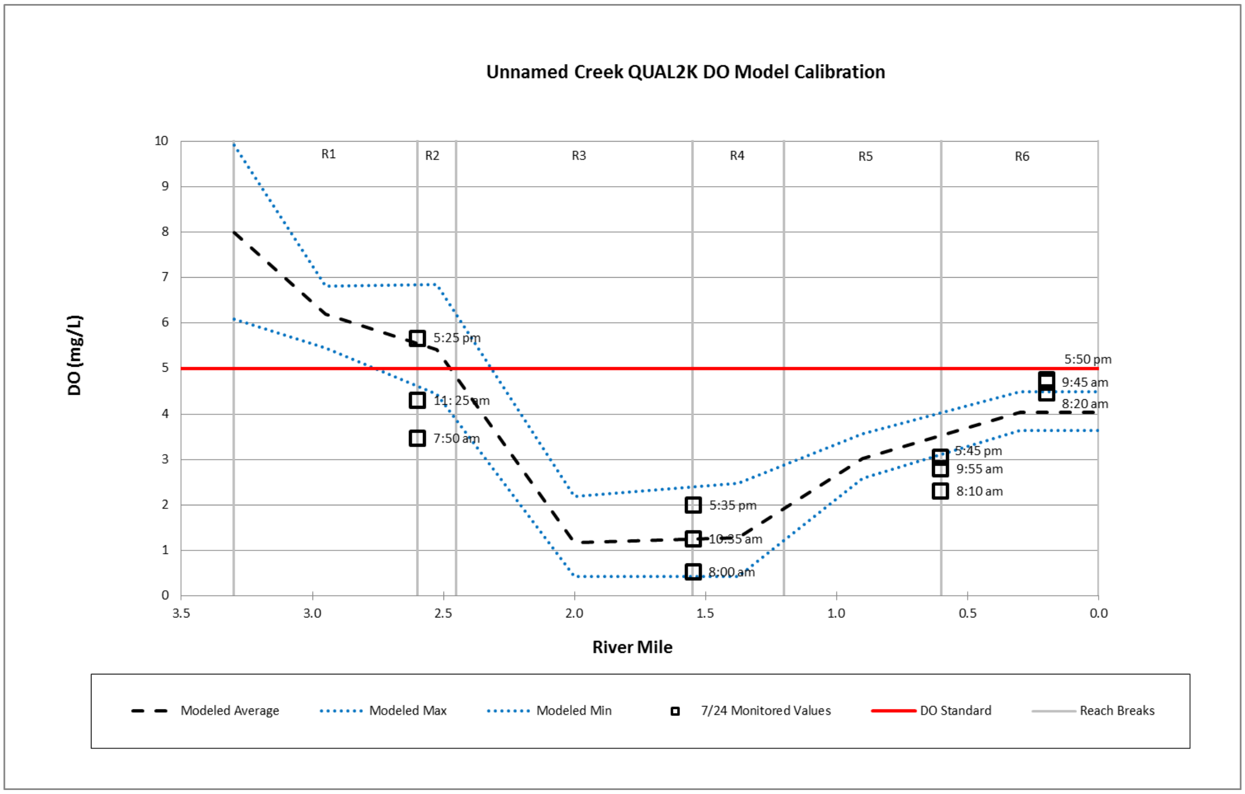

Figure 1.4. DO longitudinal profile for the Unnamed Creek QUAL2K calibrated model run.

6.0 SENSITIVITY ANALYSIS

To evaluate the sensitivity of model-predicted DO to changes in model variables, four kinetic rates (Table 6.1), three reach specific rates (Table 6.2), and channel slopes (Table 6.3) were removed or adjusted by specific percentages. The following tables summarize the affect these changes have on the average model-predicted DO concentration for the entire modeled stretch of Unnamed Creek. Results show that DO throughout the system is not sensitive to kinetic rates and only slightly sensitive to the sediment NH_4 flux, bottom algae and channel slope adjustments. This exercise suggests that DO levels below the 5.0 mg/L standard observed in reaches 2-4 during the synoptic survey were most affected by reaeration and bottom algae coverage throughout the wetland reach.

Table 1.10. DO sensitivity to kinetic rates.

Kinetic rate	+25%	-25%	Default
Organic-N Hydrolysis (day^{-1})	-0.8%	1.1%	-3.2%
Organic-N Settling (m/d)	-0.8%	0.8%	-6.1%
Organic-P Hydrolysis (day^{-1})	0.0%	0.0%	0.0%
Phytoplankton Settling (m/d)	-0.3%	0.5%	0.5%

Table 1.11. DO sensitivity to reach rates.

Action	DO Sensitivity
Remove Sediment Inorganic-P Flux	0.0%
Remove Sediment NH_4 Flux	4.8%
Remove Bottom Algae Coverage	-6.3%

Table 1.12. DO sensitivity to channel slope.

Channel Slope	DO Sensitivity
Increased by 25 percent	5.6%
Decreased by 25 percent	-6.5%

7.0 REFERENCES

Bansal, M.K., 1975. Deoxygenation in Natural Systems. Water Resources Bulletin 11: 491-504.

Bowie, G.L., C.W. Chen, and D.H. Dykstra. 1980. Lake Ontario Ecological Modeling, Phase III. Tetra Tech, Inc., Lafayette, California. For National Oceanic and Atmospheric Administration, Great Lakes Environmental Research Laboratory, Ann Arbor, Michigan.

Bowie, G.L., et al., 1985. « Rates, constants and kinetic formulations in surface water quality modeling (2nd Edition.)" USEPA

Chapra, S.C., Pelletier, G.J. and H. Tao. 2007. QUAL2K: A Modeling Framework for Simulating River and Stream Water Quality, Version 2.07: Documentation and Users Manual. Civil and Environmental Engineering Dept., Tufts University, Medford, MA.

Chen, C.W. and G.T. Orlob. 1975. Ecological simulation for aquatic environments. Systems Analysis and Simulation in Ecology, Volume 3. Academic Press, New York, New York. pp. 476-588.

Di Toro, D.M. and W.F. Matystik, Jr. 1980. Mathematical Models of Water Quality in Large Lakes. PartII: Lake Erie. U.S. Environmental Protection Agency, Ecological Research Series. EPA-600/3-3-80-065.

Jorgensen, S.E.. 1976. A Eutrophication Model for a Lake. Ecol. Modeling, 2: 147-165.

Minnesota Pollution Control Agency. 1999. Baseline Water Quality of Minnesota's Principal Aquifers – Region 6, Twin Cities Metropolitan Area. http://www.pca.state.mn.us/index.php/view- document.html?gid=6296

Olsen, B. 2011. Groundwater – Surface Water Interactions Along the Vermillion River. Dakota County Water Resources Deprtment.

Scavia, D. 1980. An Ecological Model of Lake Ontario. Ecol. Modeling, 8: 49-78.

Smith, D.J. 1978. Water quality for river-reservoir systems. Resource Management Associates, Inc., Lafayette, California. For U.S. Army Corps of Engineers, Hydrologic Engineer Center, Davis, California.

Thomann, R. V., Mueller, J. A., 1987. "Principles of Surface Water Quality Modeling and Control." Harper Collins Publishers Inc.

Tsivoglou, E.C., and Neal, L.A. 1976. "Tracer Measurement of Reaeration. III. Predicting the Reaeration Capacity of Inland Streams." Journal of the Water Pollution Control Federation, 48(12): 2669-2689.