St. Louis River Watershed Total Maximum Daily Load Report

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Abbreviations

AFO	animal feeding operation
AUID	assessment unit identification
AWWDF	average wet weather design flow
BMP	best management practice
BWSR	Board of Water and Soil Resources
CAFO	concentrated animal feeding operation
CALM	consolidated assessment and listing
chl-*a*	chlorophyll-*a*
CIRSSD	Central Iron Range Sanitary Sewer District
DMR	discharge monitoring report
DNR	Minnesota Department of Natural Resources
DO	dissolved oxygen
E. coli	*Escherichia coli*
EPA	Environmental Protection Agency
EQuIS	Environmental Quality Information System
HSPF	Hydrologic Simulation Program–Fortran
HUC	hydrologic unit code
IPHT	imminent public health threat
Kcal	kilocalories
L	liter
LA	load allocation
lb	pound
m	meter
MGD	million gallons per day
mg	milligrams
mL	milliliter
MnDOT	Minnesota Department of Transportation
MOS	margin of safety
MPCA	Minnesota Pollution Control Agency
MS4	municipal separate storm sewer system

n.d.	no date
NLCD	National Land Cover Database
NPDES	National Pollutant Discharge Elimination System
NRCS	Natural Resources Conservation Service
NVSS	nonvolatile suspended solids
org	organisms
PCB	polychlorinated biphenyl
SDS	state disposal system
SID	stressor identification
SSTS	subsurface sewage treatment systems
SWCD	soil and water conservation district
SWPPP	MS4 Stormwater Pollution Prevention Program
TMDL	total maximum daily load
TP	total phosphorus
TSI	trophic status index
TSS	total suspended solids
µg/L	micrograms per liter
µmhos/cm	micromhos per centimeter
USDA	United States Department of Agriculture
USGS	United States Geological Survey
VSS	volatile suspended solids
WLA	wasteload allocation
WQ	water quality
WQBEL	water quality based effluent limit
WRAPS	watershed restoration and protection strategy
WWTF	wastewater treatment facility

Executive Summary

The Clean Water Act, Section 303(d) requires total maximum daily loads (TMDLs) to be produced for surface waters that do not meet applicable water quality standards necessary to support their designated uses. A TMDL determines the maximum amount of a pollutant a receiving water body can assimilate while still achieving water quality standards and assigns load reductions needed to meet water quality standards. This TMDL study addresses the stream and lake impairments in the St. Louis River Watershed in northeastern Minnesota that are tributary to the St. Louis River above the Fond du Lac Dam. Below the Fond du Lac Dam are several smaller streams considered urban streams in and around the urbanized Duluth area. These urban streams are being addressed as part of a separate effort. The causes of impairment in the watershed include high levels of total suspended solids (TSS), Escherichia coli (*E. coli)*, and nutrients, in addition to high temperature and low dissolved oxygen (DO), affecting aquatic life and aquatic recreation designated uses. Fifteen stream TMDLs and two lake TMDLs are provided: eleven *E. coli* TMDLs, two TSS TMDLs, one phosphorus stream TMDL, two phosphorus lake TMDLs, and one temperature stream TMDL.

Much of the watershed is undeveloped but does contain multiple cities, including numerous small cities in the Mesabi Iron Range. Historic and current land use changes throughout the watershed have degraded many lakes, rivers, and streams. Mining of iron ore in the Iron Range has dramatically altered natural hydrology (surface and subsurface) in the area, most significantly in several of the headwater subwatersheds. Although mining along the Iron Range has dramatically altered surface and subsurface hydrology in the region, the impairments for which TMDLs are developed in this report are not heavily influenced by pollutant sources related to mining.

Potential sources of pollutants include watershed runoff (both regulated and unregulated), near-channel sources (e.g., bank failures and channel erosion), municipal and industrial wastewater, aging sanitary and storm sewer infrastructure, septic systems and untreated wastewater, livestock, atmospheric deposition (lakes), internal loading (lakes), wildlife, and pets. Potential causes of high temperature include natural factors such as low gradient wetlands and beaver ponds and anthropogenic factors such as mine pits and ponded water.

The pollutant load capacity of the impaired streams was determined through the use of load duration curves for the conventional pollutants (i.e., *E. coli*, TSS, and phosphorus). These curves represent the allowable pollutant load at any given flow condition. Water quality data were compared with the load duration curves to determine load reduction needs. A stream water quality model, QUAL2K, was used to develop the temperature TMDL. QUAL2K is a steady state (but diurnally variable), one-dimensional model that can simulate in-stream water temperatures and DO concentrations on an hourly time step. The nutrient loading capacity for each impaired lake was calculated using BATHTUB, an empirical model of reservoir eutrophication developed by the U.S. Army Corps of Engineers. The models were calibrated to existing water quality data. A 10% explicit margin of safety (MOS) was incorporated into all TMDLs to account for uncertainty, with the exception of Wyman Creek, which has an implicit MOS.

The implementation strategy highlights an adaptive management process to achieving water quality standards and restoring beneficial uses. Implementation strategies include reducing loading of pathogens from urban stormwater; addressing private wastewater systems; feedlot, pasture, and livestock management; stream restoration; improved altered watercourse management; lake internal load management; reduction of municipal wastewater phosphorus loading; and shade and beaver management. A core team of staff from local, state, federal, and tribal resource management agencies supported the TMDL process and provided valuable input and review. In addition, public participation included meetings with watershed stakeholders to present data and TMDL elements. The TMDL study is supported by previous work including the *St. Louis River Watershed Monitoring and Assessment Report* (MPCA 2013), *St. Louis River Watershed Stressor Identification (SID) Report* (MPCA 2016), and the St. Louis River Watershed hydrology and water quality model (Tetra Tech 2016a and 2016b). A companion Watershed Restoration and Protection Strategies (WRAPS) report that provides more details on implementation strategies was produced simultaneously with this report and is also available (MPCA 2017a).

1. Project Overview

1.1 Purpose

The Clean Water Act and U.S. Environmental Protection Agency (EPA) regulations require that TMDLs be developed for waters that do not support their designated uses. In simple terms, a TMDL study is a report on what is needed to attain and maintain water quality standards in waters that are not currently meeting them. This report addresses a portion of the St. Louis River Watershed (SLRW; United States Geological Survey (USGS) Hydrologic Unit Code [HUC] 8 04010201) in northeastern Minnesota (Figure 1). The SLRW TMDL study addresses only the impairments that are tributary to the St. Louis River above the Fond du Lac Dam (Figure 1). Below the Fond du Lac Dam are several smaller streams considered urban streams in and around the urbanized Duluth area. These urban streams are being addressed as part of a separate effort.

The project area covers portions of St. Louis County, Carlton County, Aitkin County, and Itasca County. A small portion of the St. Louis River Watershed near the river's mouth extends into Wisconsin (2%). In this report, the phrase "St. Louis River Watershed (SLRW)" refers to the Minnesota portion of the watershed ("St. Louis River WRAPS Project Area" in Figure 1), not including the subwatersheds in the Duluth area ("Duluth Urban WRAPS Project Area" in Figure 1).

This TMDL report addresses water bodies that have impaired aquatic life and aquatic recreation designated uses. These types of TMDLs address "conventional pollutants" such as excessive nutrients, bacteria, turbidity, or stressors not related to bioaccumulative toxins such as mercury and polychlorinated biphenyls (PCBs). Some of the aquatic life and recreation impairments in the watershed are being deferred because the pollutants identified as stressors for these impairments do not have applicable numeric water quality standards or because the primary stressors are unknown (see Section 1.4).

There are also water bodies with impaired aquatic consumption designated uses in the SLRW; these impairments are due to high levels of toxins such as mercury or PCBs in fish tissue or in the water column and are not addressed in this report. For more information on mercury impairments, see the statewide mercury TMDL (MPCA 2007a).

This TMDL report is a component of a larger effort led by the Minnesota Pollution Control Agency (MPCA) to develop WRAPS for the SLRW. Other components of this larger effort include the *St. Louis River Watershed Monitoring and Assessment Report* (MPCA 2013), the *St. Louis River Watershed Stressor Identification Report* (MPCA 2016), the St. Louis River Hydrologic Simulation Program—FORTRAN (HSPF) watershed model (Tetra Tech 2016a and 2016b), and the *St. Louis River WRAPS* (MPCA 2017a). These reports are available on the MPCA's St. Louis River Watershed website.

There are many other ongoing efforts in the watershed to protect and improve water quality; these efforts involve citizens, civic organizations, businesses, and government organizations. For example, part of the SLRW is in the St. Louis River Area of Concern, designated under the United States and Canada Great Lakes Water Quality Agreement in 1987. The EPA and other federal and state agencies are working to restore the beneficial uses within the Area of Concern. In addition, the Fond du Lac Band of Lake Superior Chippewa has federal Clean Water Act jurisdiction for waters of the reservation, which is located in the downstream portion of the SLRW, adjacent to the Wisconsin border, and is active in watershed management and water quality restoration in the area. The Fond du Lac Band has established water quality standards for its waters and implements a water quality monitoring, assessment, protection, and restoration program on the reservation. The state does not have authority to assess or list impairments for waters in Indian Country; this state-led TMDL study does not address waters of the Fond du Lac Reservation.

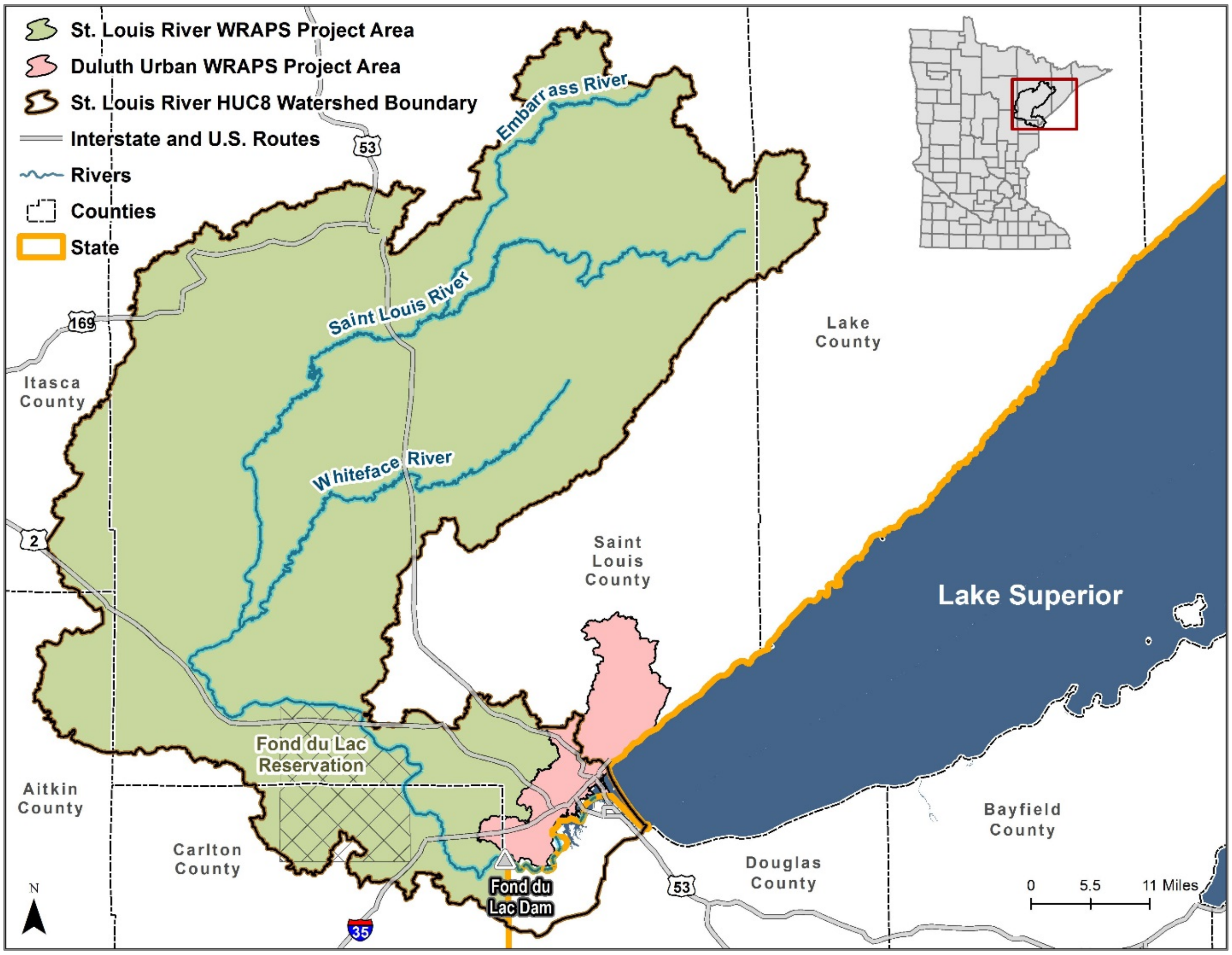

Figure 1. St. Louis River Watershed location map

1.2 Identification of Water Bodies

There are aquatic life and/or aquatic recreation impairments on 32 stream reaches (Table 1) and 7 lakes (Table 2) in the SLRW. These impairments are on the MPCA's final 2012 303(d) list and the proposed 2016 303(d) list of impaired water bodies and are based on high levels of turbidity or *E. coli*, aquatic macroinvertebrate or fish bioassessments, and/or eutrophication biological indicators.

Table 1. Streams with an aquatic recreation or aquatic life impairment in the St. Louis River TMDL project area. Does not include streams with an impaired aquatic consumption designated use. TMDLs are developed in this report for the reaches that are shaded in the table below; see sections 1.4 and 1.5 for information on the selection of reaches for TMDL development. Reaches are ordered alphabetically within watershed zone; watershed zones from MPCA (2016).

Water-shed Zone	Reach Name	Reach Description	Year Added to List	Assessment Unit Identification (AUID), (04010201-###)	Use Classif-ication [a]	Affected Designated Use	Pollutant or Stressor
Swan River–Hibbing	Barber Creek (East Swan River)	T57 R20W S28, east line to Dempsey Cr	2012	569	2A	Aquatic Recreation	*Escherichia coli*
	Barber Creek (East Swan River)	T57 R20W S2, north line to T57 R20W S27, west line	2012	641	2B	Aquatic Recreation	*Escherichia coli*
	Buhl Creek	T58 R19W S30, east line to Six Mile Lk	2012	580	2B	Aquatic Recreation	*Escherichia coli*
	Dempsey Creek	Six Mile Lk to T56 R20W S12, west line	2012	582	2B	Aquatic Recreation	*Escherichia coli*
	East Swan River	Barber Cr to Swan R	2012	558	2A	Aquatic Life	TSS / Turbidity [b]
	Penobscot Creek	T57 R20W S28, north line to East Swan R	2012	936	2A	Aquatic Recreation	*Escherichia coli*
	Unnamed creek	Unnamed cr to T56 R20W S9, east line	2012	542	2B	Aquatic Recreation	*Escherichia coli*
	Unnamed creek	Unnamed cr to Unnamed cr	2012	A22	2B	Aquatic Recreation	*Escherichia coli*
	Unnamed creek (East Swan Creek)	T56 R20W S5, north line to East Swan R	2012	888	2A	Aquatic Life	Aquatic Macroinvertebrate Bioassessments
						Aquatic Recreation	*Escherichia coli*

Water-shed Zone	Reach Name	Reach Description	Year Added to List	Assessment Unit Identification (AUID), (04010201-###)	Use Classif-ication [a]	Affected Designated Use	Pollutant or Stressor
West Two–McQuade Moraine	Unnamed creek	Unnamed cr to McQuade Lk	2012	551	2B	Aquatic Life	Aquatic Macroinvertebrate Bioassessments
	West Two River	West Two R Reservoir to McQuade Lk outlet	2012	535	2B	Aquatic Life	Aquatic Macroinvertebrate Bioassessments
Virginia Mesabi Range	Elbow Creek	T57 R18W S12, north line to Elbow Lk	2012	518	2B	Aquatic Life	Aquatic Macroinvertebrate Bioassessments Fishes Bioassessments
	Elbow Creek	Unnamed ditch to St Louis R	2012	570	2B	Aquatic Life	Aquatic Macroinvertebrate Bioassessments
	Unnamed branch (also known as Manganika Creek)	Manganika Lk to East Two R	2012	548	2B	Aquatic Life	Aquatic Macroinvertebrate Bioassessments Fishes Bioassessments
Nashwauk Uplands–Embarrass River	Ely Creek	Headwaters (Ely 69-0660-00) to Unnamed cr	2012	A26	2B	Aquatic Life	Fishes Bioassessments
	Embarrass River	Headwaters to Embarrass Lk	2012	579	2B	Aquatic Life	Fishes Bioassessments
	Spring Mine Creek	Ridge Cr to Embarrass R	2012	A42	2B	Aquatic Life	Aquatic Macroinvertebrate Bioassessments Fishes Bioassessments
Laurentian Uplands–Partridge River	Wyman Creek	Headwaters to Colby Lk	2012	942	2A	Aquatic Life	Fishes Bioassessments

Water-shed Zone	Reach Name	Reach Description	Year Added to List	Assessment Unit Identification (AUID), (04010201-###)	Use Classif-ication [a]	Affected Designated Use	Pollutant or Stressor
Meadowlands Floodwood Peat Bog	Sand Creek	Unnamed cr to St Louis R	2012	607	2B	Aquatic Life	Fishes Bioassessments
	Skunk Creek	Unnamed cr to St Louis R	2012	A18	2B	Aquatic Life	Aquatic Macroinvertebrate Bioassessments Fishes Bioassessments
	St Louis River	Whiteface R to Floodwood R	2012	508	2B	Aquatic Life	Aquatic Macroinvertebrate Bioassessments
	Stony Creek	Unnamed cr to Unnamed cr	2012	963	2B	Aquatic Life	Aquatic Macroinvertebrate Bioassessments Fishes Bioassessments
	Unnamed creek	Unnamed ditch to St Louis R	2012	A17	2B	Aquatic Life	Aquatic Macroinvertebrate Bioassessments
	Unnamed creek (Little Swan Creek)	Headwaters to East Swan R	2012	891	2A	Aquatic Life	Fishes Bioassessments
	Vaara Creek	Unnamed cr to Floodwood R	2012	623	2B	Aquatic Life	Aquatic Macroinvertebrate Bioassessments Fishes Bioassessments
Makinen Lakes	Paleface Creek	Unnamed cr to Paleface R	2012	A24	2B	Aquatic Life	Aquatic Macroinvertebrate Bioassessments Fishes Bioassessments
	Water Hen Creek	Unnamed cr to Mud Hen Cr	2012	A31	2B	Aquatic Life	Aquatic Macroinvertebrate Bioassessments
	Water Hen Creek	Unnamed cr to S Br Water Hen Cr	2012	A35	2B	Aquatic Life	Aquatic Macroinvertebrate Bioassessments

Water-shed Zone	Reach Name	Reach Description	Year Added to List	Assessment Unit Identification (AUID), (04010201-###)	Use Classif-ication [a]	Affected Designated Use	Pollutant or Stressor
Mille Lacs–North Shore Highlands	Hay Creek	Unnamed cr to Midway R	2012	751	2A	Aquatic Recreation	*Escherichia coli*
	Otter Creek	Little Otter Cr to T48 R16W S7, east line	2012	629	2A	Aquatic Life	Aquatic Macroinvertebrate Bioassessments
	Pine River (White Pine River)	T50 R16W S4, north line to St Louis R	2012	543	2A	Aquatic Recreation	*Escherichia coli*
	Unnamed creek (also known as West Rocky Run)	T50 R16W S11, north line to Midway R	2012	625	2A	Aquatic Recreation	*Escherichia coli*

a. Class 2A streams are also classified as 1B, 3B, 3C, 4A, 4B, 5, and 6. Class 2B streams are also classified as 3C, 4A, 4B, 5, and 6.

b. East Swan River was listed in 2012 with a turbidity impairment; this impairment is addressed with a TSS TMDL.

Table 2. Lakes with aquatic recreation impairment due to nutrient/eutrophication biological indicators

TMDLs are developed in this report for the shaded lakes; see sections 1.4 and 1.5 for information on the selection of lakes for TMDL development.

Watershed Zone	Name	Lake ID	Year Added to List	Lake Classification [a]
West Two–McQuade Moraine	McQuade	69-0775-00	2012	Shallow lake
	West Two Rivers Reservoir	69-0994-00	2012	Lake
Virginia Mesabi Range	Manganika	69-0726-00	2008	Shallow lake
Toimi Uplands–Whiteface Headwaters	Strand	69-0529-00	2012	Shallow lake
Makinen Lakes	Dinham	69-0544-00	2012	Lake
	Long	69-0495-00	2012	Shallow lake
	Mud Hen	69-0494-00	2012	Shallow lake

a. Classification as a shallow lake takes into account basin depth, littoral area, and other ecological characteristics. Shallow lakes typically have a mean depth < 15 feet and a littoral area that is > 80% of the lake surface area (MPCA 2017b).

1.3 Priority Ranking

The MPCA's schedule for TMDL completions, as indicated on the 303(d) impaired waters list, reflects Minnesota's priority ranking of this TMDL. The MPCA has aligned TMDL priorities with the watershed approach and WRAPS cycle. The schedule for TMDL completion corresponds to the WRAPS report completion on the 10-year cycle. The MPCA developed a state plan Minnesota's TMDL Priority Framework Report to meet the needs of the EPA's national measure (WQ-27) under EPA's Long-Term Vision for Assessment, Restoration and Protection under the Clean Water Act Section 303(d) Program. As part of these efforts, the MPCA identified water quality impaired segments that will be addressed by TMDLs by 2022. The SLRW waters addressed by this TMDL are part of that MPCA prioritization plan to meet the EPA's national measure.

1.4 Stressor Identification and Pollutants for TMDL Analysis

The pollutant selected for TMDL development is based on the 303(d) listing, and, in the case of the biota impairments, on the St. Louis River Watershed SID Report (MPCA 2016), referred to as the "SID" herein.

This section summarizes the SID to show the connection from the entire list of impairments to the list of reaches chosen for TMDL development. Even though TMDLs were not developed for some of these reaches, it is important for this report section to serve as the link between the SID and the TMDLs developed in this report.

Phosphorus TMDLs were developed for two of the lakes with aquatic recreation impairments based on nutrient/eutrophication indicators. Phosphorus is often the main limiting nutrient of primary production in Minnesota lakes. Increases in phosphorus loads to a lake can lead to increases in algal growth (measured as chlorophyll-*a* (chl-*a*)), which in turn decreases water transparency (measured as Secchi depth transparency). The five remaining impaired lakes are shallow lakes (Table 2). Because the MPCA is considering developing new standards for shallow lakes in the Northern Lakes and Forests ecoregion, these five TMDLs are being deferred until shallow lakes standards are developed.

E. coli TMDLs were developed for the aquatic recreation impairments due to high *E. coli* concentrations. A TSS TMDL was developed for the turbidity impairment, based on the recently promulgated TSS standard.

For biota impaired streams (i.e., aquatic macroinvertebrate bioassessments and fishes bioassessments), TMDLs were developed for load-based pollutants based on information contained within the SID. The goal of the SID is to identify the factors that cause the biota impairments. The SID evaluated the following stressors: poor physical habitat conditions, altered hydrology, low DO, high daily DO range, elevated water temperature, elevated pH, high specific conductivity, sulfate toxicity, elevated TSS, iron toxicity/precipitate, ammonia toxicity, and nitrate toxicity.

The SID categorized the stressors based on the strength of evidence. Stressors that were identified as diagnosed, probable, or confirmed are considered here to be primary stressors. Other stressors were identified as potential stressors or focus areas for additional monitoring; these stressors are not considered further for TMDL development but are addressed as part of the WRAPS report (MPCA 2017a). The SID identified seven primary stressors to the biota in the SLRW:

- High TSS

- Poor habitat
- Altered hydrology and/or loss of hydrologic connectivity
- Low DO
- High daily DO range
- High temperature
- Nitrate toxicity

Many of the identified stressors are not load-based, and there is no pollutant on which to base the TMDL (i.e., poor habitat, altered hydrology, low DO, and temperature). In the case of low DO, load-based stressors such as nutrients and BOD were evaluated in the SID, but there was no evidence for a link between the load-based stressors and low DO conditions in the water bodies. For the non-load-based stressors documented in the SID (MPCA 2016), alternate classification is recommended under EPA's Consolidated Assessment and Listing Methodology (CALM) 4C classification: impaired, but a TMDL study is not required because the impairment is not caused by a pollutant. Guidance for the 4C classification is provided in EPA's integrated report guidance (EPA 2015). TMDLs were not developed for these water bodies, and they will be considered impaired until they meet water quality standards. Restoration strategies to address the impairments are recommended in the WRAPS report. One exception is that a temperature TMDL was developed for Wyman Creek.

TMDLs were completed for impairments that identify high TSS, high DO flux due to eutrophication, and high temperature as primary stressors. The MPCA is deferring TMDLs for nitrate toxicity because the state does not have applicable numeric water quality standards for nitrate.

Three reaches (Unnamed Tributary/Kinney Creek, Spring Mine Creek, and Water Hen Creek) were identified as having a high daily DO range (often referred to as DO flux); however, the reason for the high DO range is not clear. There is no evidence for eutrophication in these streams and therefore a phosphorus TMDL is not appropriate at this time. Other processes need to be further investigated to determine the cause of high DO range in these three reaches. These three reaches will be investigated in the second WRAPS cycle, scheduled to start in 2019.

Primary stressors were not identified in Otter Creek, and input from local partners suggests that this reach may not have an impaired biotic assemblage. The MPCA will re-evaluate the macroinvertebrate bioassessment listing for Otter Creek in the second WRAPS cycle, scheduled to start in 2019.

Table 3 summarizes the recommended approaches to pollutant selection for TMDL development. Table 4 summarizes the primary stressors for each biota impairment and the TMDL pollutants. TMDLs are presented in this report for the pollutants listed in the "TMDL Pollutant" column in Table 4. For the impairments that do not have a listed TMDL pollutant, the TMDL is either deferred or the impairment is considered not to be due to a pollutant.

Table 3. Approach to address TMDL listings, including selection of TMDL pollutant based on primary stressor

Primary Stressor	Approach to Address TMDL Listing
High TSS	· Develop TSS TMDL.
Poor habitat	· Impairment is typically due to a combination of poor substrate, lack of riffle and glide features, bank erosion, channel incision, and embeddedness. Classify impairment as EPA CALM 4C [a].
Altered hydrology	· Impairment is typically due to impoundments, ditching, perched culverts, withdrawals, and other hydrologic alteration. Classify impairment as EPA CALM 4C [a].
Low dissolved oxygen	· Impairment is often due to the contribution of low DO water from wetlands or impoundments and a low gradient that results in lack of aeration. Classify impairment as EPA CALM 4C [a]. · If cause of low DO is unknown, defer DO TMDL.
High dissolved oxygen range	· Impairment could be due to eutrophication; develop phosphorus TMDL if eutrophication is the cause. · Where phosphorus is not high and eutrophication is unlikely, defer TMDL until the cause of impairment is identified.
High temperature	· Impairment could be due to impoundments (e.g., beaver dams, mine pits) and lack of shading; develop temperature TMDL if there is a mix of natural and anthropogenic causes. · If impairment is solely due to beaver dams, classify impairment as EPA CALM 4C [a].
Nitrate toxicity	· Defer TMDL due to lack of numeric water quality standards.

a. EPA CALM 4C: impaired, but a TMDL study is not required because the impairment is not caused by a pollutant

Table 4. Primary stressors and TMDL pollutant selection for biota impairments

Reach name	AUID (0401 0201-###)	Primary Stressor									TMDL Pollutant	Non-Pollutant Stressors Only	TMDL Deferred
		High TSS	Poor Habitat	Altered Hydrology	Loss of Connectivity	Low DO	High DO Range	High Temperature	Nitrate Toxicity	No Diagnosed Stressors			
Elbow Cr (upper reach)	518					ü					–	ü	ü [a]
Elbow Cr (lower reach)	570		ü								–	ü	
Ely Cr	A26		ü	ü		ü					–	ü	
Embarrass R	579					ü					–	ü	
Otter Cr	629									ü	–		ü
Paleface Cr	A24					ü					–	ü	
Sand Cr	607		ü								–	ü	
Skunk Cr	A18		ü			ü					–	ü	
Spring Mine Cr	A42						ü				–		ü
St. Louis R	508		ü								–	ü	
Stony Cr	963	ü	ü			ü					TSS		

Reach name	AUID (0401 0201-###)	Primary Stressor									TMDL Pollutant	Non-Pollutant Stressors Only	TMDL Deferred
		High TSS	Poor Habitat	Altered Hydrology	Loss of Connectivity	Low DO	High DO Range	High Temperature	Nitrate Toxicity	No Diagnosed Stressors			
Unnamed Branch (Manganika Cr)	548	ü				ü					–		ü[b]
Unnamed Cr (Kinney Cr)	551						ü				–		ü
Unnamed Cr	A17		ü								–	ü	
Unnamed Cr (East Swan Cr)	888								ü		–		ü
Unnamed Cr (Little Swan Cr)	891		ü			ü		ü			–	ü	
Vaara Cr	623		ü			ü					–	ü	
Water Hen Cr (lower reach)	A31					ü					–	ü	
Water Hen Cr (upper reach)	A35					ü	ü				–		ü
West Two R	535					ü	ü				Phosphorus		
Wyman Cr	942				ü	ü		ü			Temperature (addresses low DO)[c]		

a. SID inconclusive regarding cause of low DO.

b. Phosphorus TMDL to be developed to address low DO. TMDL is deferred until upstream Lake Manganika phosphorus TMDL is developed; Lake Manganika TMDL is deferred until shallow lake standards are developed). TSS is due to algae from Lake Manganika's upstream eutrophication impairment that will be addressed by a phosphorus TMDL; TSS TMDL not needed.

c. Decreasing temperatures in Wyman Creek will increase DO due to the water's increased capacity for DO.

"– " in the TMDL pollutant column indicates that a TMDL is not developed in this report.

1.5 Impairments Addressed in this Study

TMDLs for 2 lakes and 15 stream reaches are presented in this report (Table 5). TMDLs for the remaining impairments in Table 1 and Table 2 are not addressed in this report because they are either due to nonpollutant stressors or are being deferred (see Section 1.4).

Table 5. Impairments addressed in this study

Water Body Name	Reach Description	Lake ID or River AUID (04010201-###)	Affected Designated Use	Pollutant or Stressor	TMDL Pollutant
Lakes					
Dinham Lake	NA	69-0544-00	Aquatic Recreation	Nutrient/eutrophication biological indicators	Phosphorus
West Two Rivers Reservoir	NA	69-0994-00	Aquatic Recreation	Nutrient/eutrophication biological indicators	Phosphorus
Streams					
Barber Creek (East Swan River)	T57 R20W S28, east line to Dempsey Cr	569	Aquatic Recreation	*E. coli*	*E. coli*
Barber Creek (East Swan River)	T57 R20W S2, north line to T57 R20W S27, west line	641	Aquatic Recreation	*E. coli*	*E. coli*
Buhl Creek	T58 R19W S30, east line to Six Mile Lk	580	Aquatic Recreation	*E. coli*	*E. coli*
Dempsey Creek	Six Mile Lk to T56 R20W S12, west line	582	Aquatic Recreation	*E. coli*	*E. coli*
East Swan River	Barber Cr to Swan R	558	Aquatic Life	Turbidity	TSS
Hay Creek	Unnamed cr to Midway R	751	Aquatic Recreation	*E. coli*	*E. coli*
Penobscot Creek	T57 R20W S28, north line to East Swan R	936	Aquatic Recreation	*E. coli*	*E. coli*
Pine River (White Pine River)	T50 R16W S4, north line to St Louis R	543	Aquatic Recreation	*E. coli*	*E. coli*
Stony Creek	Unnamed cr to Unnamed cr	963	Aquatic Life	Aquatic macroinvertebrate bioassessments and fishes bioassessments	TSS
Unnamed creek	Unnamed cr to T56 R20W S9, east line	542	Aquatic Recreation	*E. coli*	*E. coli*
Unnamed creek (also known as West Rocky Run)	T50 R16W S11, north line to Midway R	625	Aquatic Recreation	*E. coli*	*E. coli*

Water Body Name	Reach Description	Lake ID or River AUID (04010201-###)	Affected Designated Use	Pollutant or Stressor	TMDL Pollutant
Unnamed creek	Unnamed cr to Unnamed cr	A22	Aquatic Recreation	*E. coli*	*E. coli*
Unnamed creek (East Swan Creek)	T56 R20W S5, north line to East Swan R	888	Aquatic Recreation	*E. coli*	*E. coli*
West Two River	West Two R Reservoir to McQuade Lk outlet	535	Aquatic Life	Aquatic macroinvertebrate bioassessments	Phosphorus
Wyman Creek	Headwaters to Colby Lk	942	Aquatic Life	Fishes bioassessments	Temperature

2. Applicable Water Quality Standards and Numeric Water Quality Targets

Water quality standards are designed to protect designated uses (e.g., fishable, swimmable, etc.). The standards consist of the designated uses, criteria to protect the uses, and other provisions such as antidegradation policies that protect the water body.

2.1 Designated Uses

Use classifications are defined in Minn. R. 7050.0140, and water use classifications for individual water bodies are provided in Minn. R. 7050.0470, 7050.0425, and 7050.0430. The impaired streams in this report are either classified as Class 2A or 2B waters (Table 1). The Class 2A streams are also classified as 1B, 3B, 3C, 4A, 4B, 5, and 6; the Class 2B streams are also classified as 3C, 4A, 4B, 5, and 6. The lakes addressed in this report are classified as Class 2B, 3C, 4A, 4B, 5, and 6 waters. This TMDL report addresses the water bodies that do not meet the standards for Class 2 waters, which are protected for aquatic life and recreation designated uses.

Class 2A waters are protected for the propagation and maintenance of a healthy community of cold water sport or commercial fish and associated aquatic life and their habitats. Class 2B waters are protected for the propagation and maintenance of a healthy community of cool or warm water sport or commercial fish and associated aquatic life and their habitats. Both Class 2A and 2B waters are also protected for aquatic recreation activities including swimming.

2.2 Water Quality Standards

Water quality standards for Class 2 waters are defined in Minn. R. 7050.0222. The water quality parameters addressed in this TMDL are phosphorus, *E. coli*, TSS, DO, and water temperature.

Exceedances of the phosphorus standards in lakes indicate that the lake does not meet the aquatic recreation designated use. The numeric water quality standards for phosphorus in lakes in the Northern Lakes and Forests ecoregion (Table 6) will serve as targets for the SLRW lake TMDLs. In addition to meeting phosphorus limits, lake chl-*a* and Secchi transparency standards must also be met. In developing the lake nutrient standards for Minnesota lakes (Minn. R. 7050), the MPCA evaluated data from a large cross-section of lakes within each of the state's ecoregions (MPCA 2005). Clear relationships were established between the causal factor total phosphorus (TP) and the response variables chl-*a* and Secchi transparency. Based on these relationships, it is expected that by meeting the phosphorus target in each lake, the chl-*a* and Secchi transparency standards (Table 6) will likewise be met.

Table 6. Eutrophication standards for Class 2B lakes, shallow lakes, and reservoirs in Northern Lakes and Forests ecoregion

Parameter	Water Quality Standard
Phosphorus, total	≤ 30 µg/L
Chlorophyll-*a*	≤ 9 µg/L
Secchi Transparency	≥ 2.0 meters (m)

In Minnesota, *E. coli* is used as an indicator species of potential water pathogens, and exceedances of the *E. coli* standard indicate that a water body does not meet the aquatic recreation designated use. There are two *E. coli* standards—one is applied to monthly *E. coli* geometric mean concentrations, and the other is applied to individual samples (Table 7).

Exceedances of the TSS standards indicate that a water body does not meet the aquatic life designated use. The numeric water quality standards for TSS (Table 7) will serve as targets for the applicable SLRW TMDLs.

Violations of the DO standard indicate that a water body does not meet the aquatic life designated use. The numeric water quality standard for DO in Class 2A streams (Table 7) is the target for the Wyman Creek TMDL.

Minnesota does not have a numeric standard for temperature; the temperature standard requires "no material increase." The narrative standard for Class 2 waters states that the aquatic habitat "shall not be degraded in any material manner," and that "the normal fishery and lower aquatic biota upon which it is dependent and the use thereof shall not be seriously impaired or endangered, the species composition shall not be altered materially, and the propagation or migration of the fish and other biota normally present shall not be prevented or hindered by the discharge of any sewage, industrial waste, or other wastes to the waters" (Minn. R. 7050.0150, subp. 3). For Wyman Creek, where temperature was identified as a primary stressor, the SID focused on the temperature needs for brook trout—at least 70% of the time the water temperature should be between 7.8 and 20 degrees Celsius to support growth (MPCA 2016, Section 5.14.2, Page 270). Because high water temperatures impact the fish assemblage, the numeric temperature target for the Wyman Creek TMDL is 20 degrees Celsius.

Table 7. Water quality standards for TMDL parameters in streams

Water Body Type	Parameter	Water Quality Standard	Numeric Standard/Target
Class 2 (A and B) streams	*E. coli*	Not to exceed 126 organisms per 100 milliliters (org/100 mL) as a geometric mean of not less than five samples representative of conditions within any calendar month, nor shall more than 10% of all samples taken during any calendar month individually exceed 1,260 organisms per 100 milliliters. The standard applies only between April 1 and October 31.	≤ 126 organisms / 100 mL water (monthly geometric mean) ≤ 1,260 organisms / 100 mL water (individual sample)
Class 2A streams	TSS	10 milligrams per liter (mg/L); TSS standards for Class 2A may be exceeded for no more than 10% of the time. This standard applies April 1 through September 30.	≤ 10 mg/L
Class 2B streams in North River Nutrient Region	TSS	15 mg/L; TSS standards for Class 2B may be exceeded for no more than 10% of the time. This standard applies April 1 through September 30.	≤ 15 mg/L
Class 2A streams	Dissolved oxygen	7.0 mg/L as a daily minimum; requires compliance with the standard 50% of the days at which the flow of the receiving water is equal to the $7Q_{10}$[a].	≥ 7.0 mg/L
Class 2A streams	Temperature	No material increase.	20 deg. Celsius
Class 2 (A and B) streams, North River Nutrient region	Phosphorus	Less than or equal to 50 micrograms per liter (µg/L)	≤ 50 µg/L

a. The lowest 7-day average flow that occurs on average once every 10 years

3. Watershed and Water Body Characterization

The *St. Louis River Watershed Monitoring and Assessment Report* (MPCA 2013) provides a description of the watershed, including discussions of land cover, surface hydrology, and precipitation. The watershed modeling report (Tetra Tech 2016a) provides information on soils, geology, slope, hydrology, and groundwater.

3.1 Lakes

Of the seven impaired lakes in the watershed, TMDLs for two of the lakes were developed. Dinham Lake has a surface area of 200 acres (ac) and West Two Rivers Reservoir is 726 acres (Table 8). The mean depths are 3.7 and 3.6 meters. An evaluation of the five lakes for which TMDL development is being deferred can be found in Appendix A.

Table 8. Lake morphometry and watershed area

Lake Name	Assessment Unit ID	Surface Area (ac)	Mean Depth (m)	Max Depth (m)	Watershed Area (incl. lake surface area; ac)	Watershed Area : Surface Area	Littoral Area (% total area less than 15 feet deep)
Dinham	69-0544-00	200	3.7	7.5	4,569	23:1	63
West Two Rivers Reservoir	69-0994-00	726	3.6	8.2	19,938	27:1	70

Surface area, mean depth, maximum depth, and littoral area from the *St. Louis River Monitoring and Assessment Report* (MPCA 2013). Watershed areas were derived for this TMDL (Section 3.3).

3.2 Streams

The watersheds that drain to impaired streams range from 2,286 acres (3.6 square miles) to 94,536 acres (148 square miles; Table 9). Many of the impairments are nested, in that impairments contribute to impairments downstream. The watershed areas in Table 9 include all drainage area to the impairment, including from upstream assessment units.

Table 9. Watershed areas of impaired streams addressed in this report

Reach Name	AUID (04010201-###)	Watershed Area (ac)
Barber Creek (East Swan River)	569	30,451
Barber Creek (East Swan River)	641	23,910
Buhl Creek	580	4,598
Dempsey Creek	582	22,955
East Swan River	558	94,536
Hay Creek	751	7,788
Penobscot Creek	936	2,982
Pine River (White Pine River)	543	29,764
Stony Creek	963	15,158
Unnamed creek	542	5,142
Unnamed creek (West Rocky Run)	625	5,781
Unnamed creek	A22	2,286
Unnamed creek (East Swan Creek)	888	10,997
West Two River	535	26,434
Wyman Creek	942	7,075

3.3 Watershed Boundaries

The watershed boundaries of the impaired water bodies were developed using multiple data sources, including watershed delineations from the HSPF model application of the SLRW (Tetra Tech 2016a), which are based on HUC12 subwatershed boundaries and modified as needed to accommodate calibration sites and water bodies of interest; Minnesota Department of Natural Resources (DNR) Level 8 and Level 9 watershed boundaries; and a 10-meter digital elevation model.

Mining of iron ore along the Iron Range has dramatically altered natural hydrology (surface and subsurface) in the area, most significantly in several of the headwater subwatersheds. As part of the development of the HSPF model application, an analysis of the interaction of mining operations with surface and groundwater hydrology was completed for a focus area, which includes the watersheds of Unnamed creek (-551), McQuade Lake, West Two Rivers Reservoir, West Two River, Lake Manganika, Unnamed branch/Manganika Creek, and Elbow Creek (Tetra Tech 2016c). In some cases, both surface and groundwater flows are intercepted and diverted from headwater streams by actively pumped mine pits. Much of this water is used in taconite processing with a portion ultimately discharging in other locations. In parts of the focus area, subsurface flow is intercepted and diverted, but surface flow is not. Other drainage areas pass through abandoned, unpumped mine pits. The watershed boundaries and flows used in the TMDL take into account the analysis of the mining hydrology. Additional details can be found in *Upper St. Louis River Watershed Mining Area Hydrology* (Tetra Tech 2016c).

An overview of the impairments and watershed boundaries is provided in Figure 2. Watershed boundaries, cities and townships, and monitoring stations for the *E. coli* TMDLs are presented in Figure 3 and Figure 4. Figure 5 displays the information for the TSS TMDLs, and Figure 6 and Figure 7 display the information for the phosphorus TMDLs. The information for the Wyman Creek temperature TMDL is provided in Figure 47.

The delineation of the upper part of the West Two Rivers Reservoir Subwatershed (Figure 6) is based on HUC12 watershed boundaries. However, the majority of the barren land (see Figure 11) in this subwatershed drains to mine pits, which are dewatered and discharged as industrial wastewater discharge; these discharges do not necessarily follow HUC12 subwatershed boundaries. The receiving watersheds of the wastewater discharges are represented in the model based on information provided by the MPCA and DNR staff; details can be found in the model report (Tetra Tech 2016a). Whereas the watershed boundaries displayed in Figure 6 do not take the into account the locations of industrial wastewater discharges, the estimates of flow and pollutant loading to impaired water bodies in the source assessment (Section 3.6) and TMDLs (Section 4) *do* take into account the drainage alterations that are represented in the HSPF model.

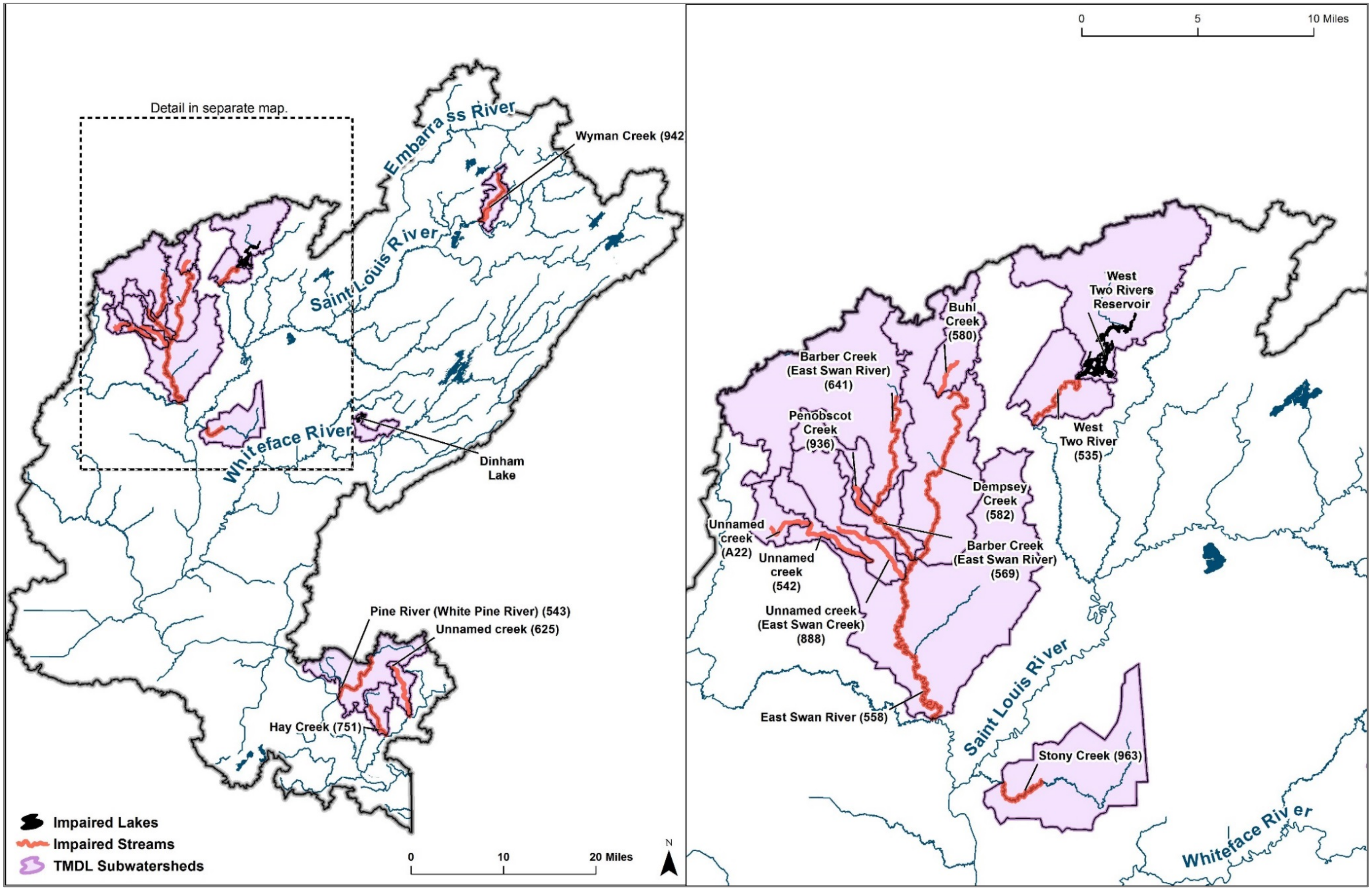

Figure 2. Watershed boundaries of impaired water bodies for which TMDLs were developed

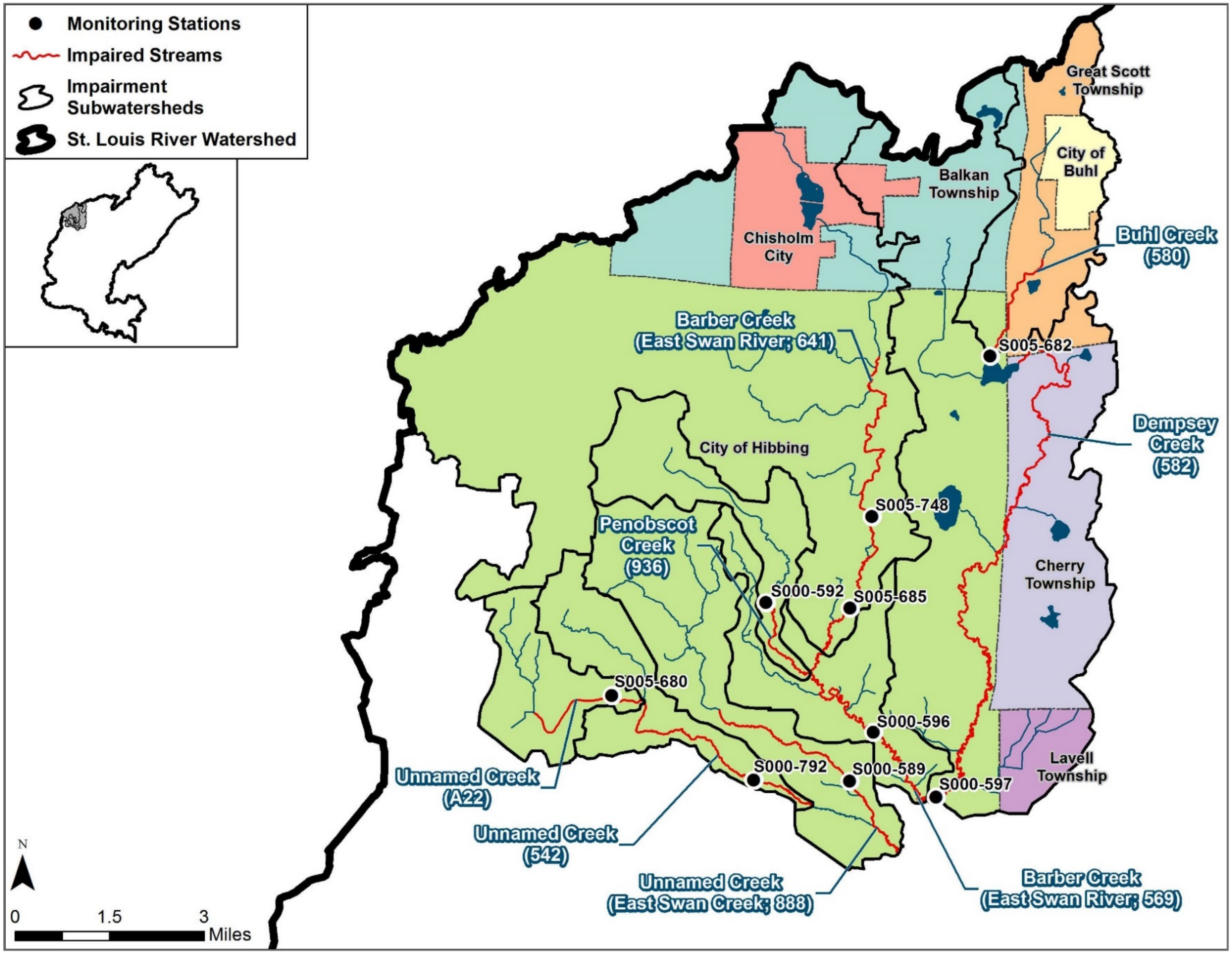

Figure 3. Watershed boundaries, cities and townships, and monitoring stations for upper watershed *E. coli* TMDLs

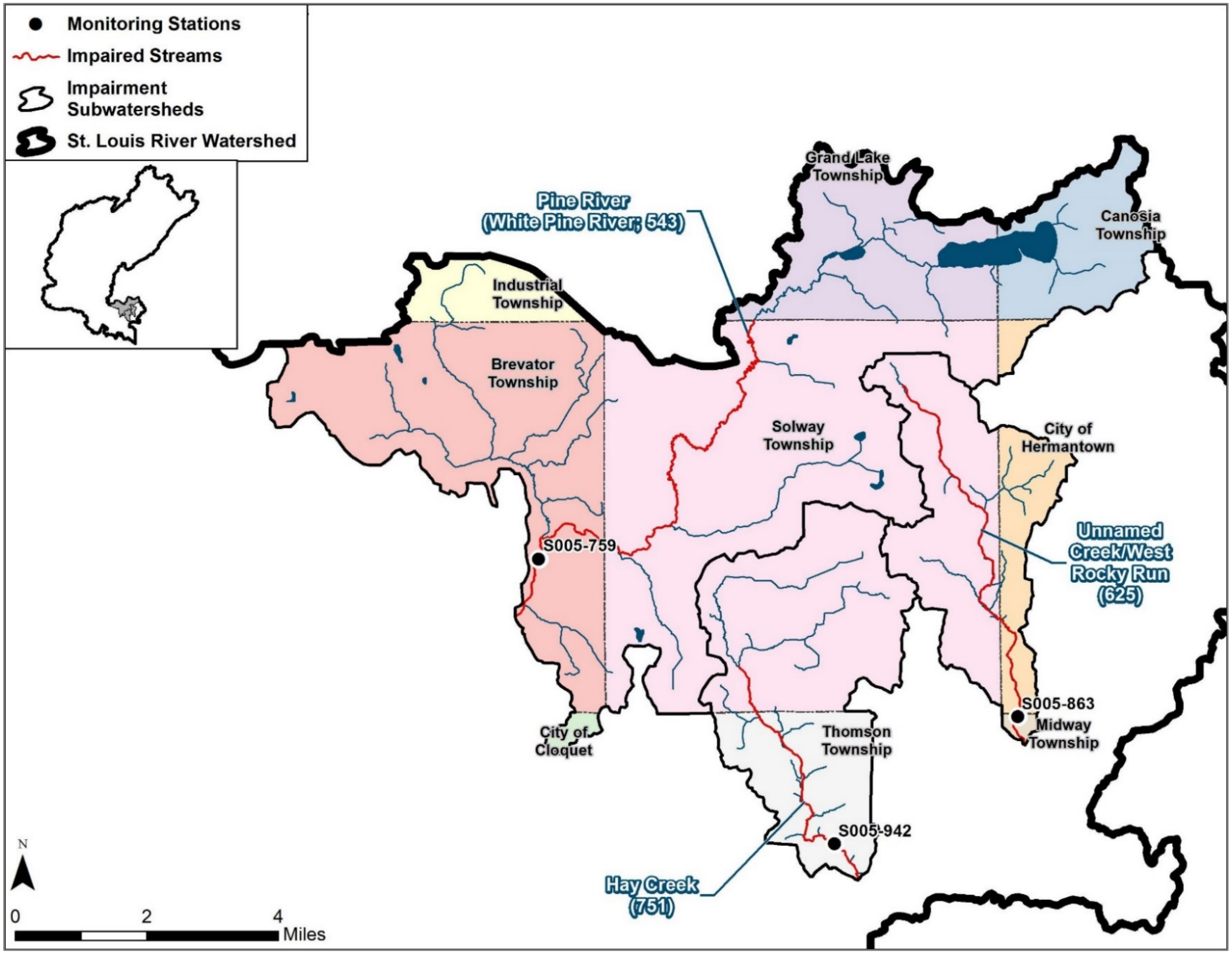

Figure 4. Watershed boundaries, cities and townships, and monitoring stations for lower watershed *E. coli* TMDLs

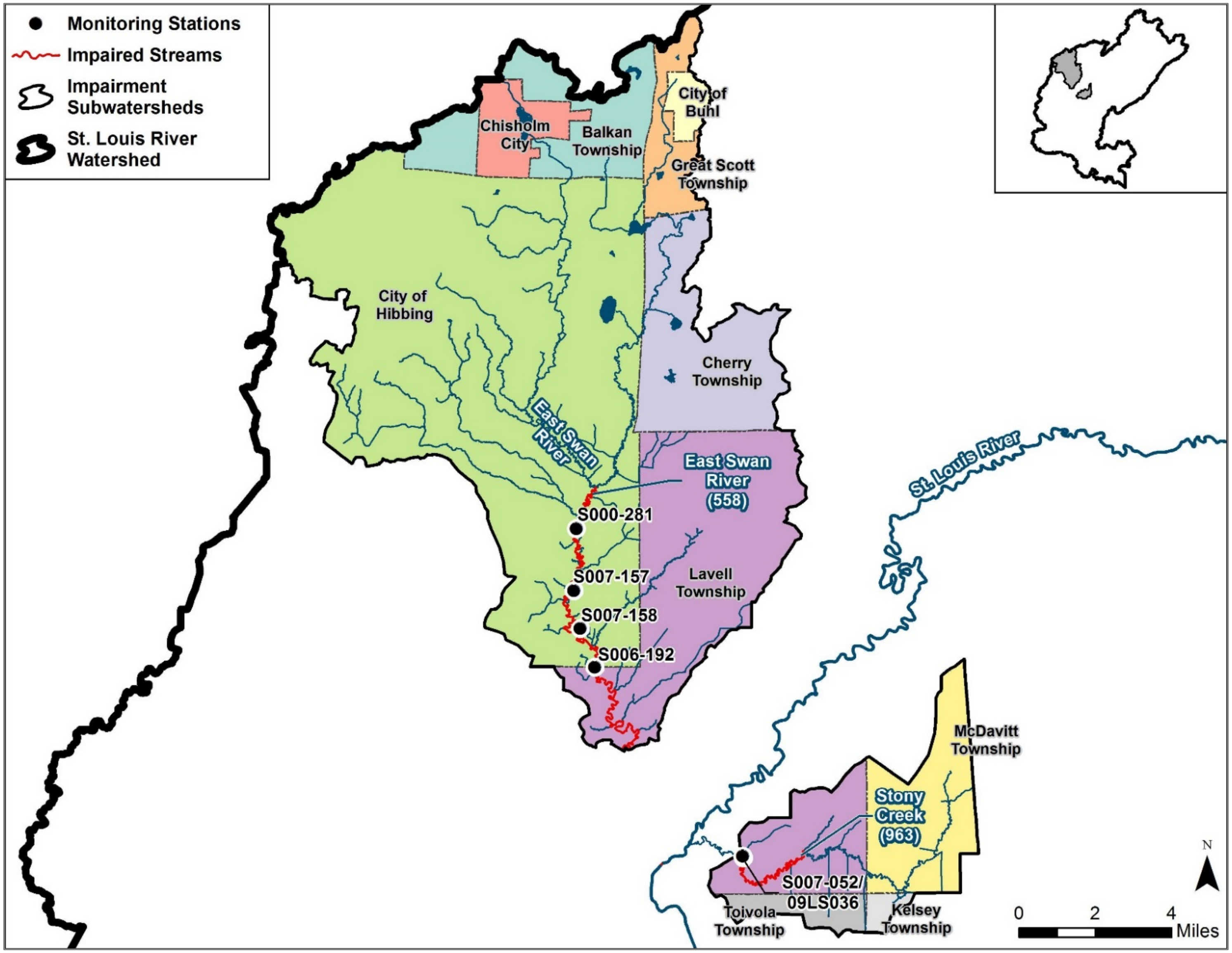

Figure 5. Watershed boundaries, cities and townships, and monitoring stations for East Swan River and Stony Creek TSS TMDLs

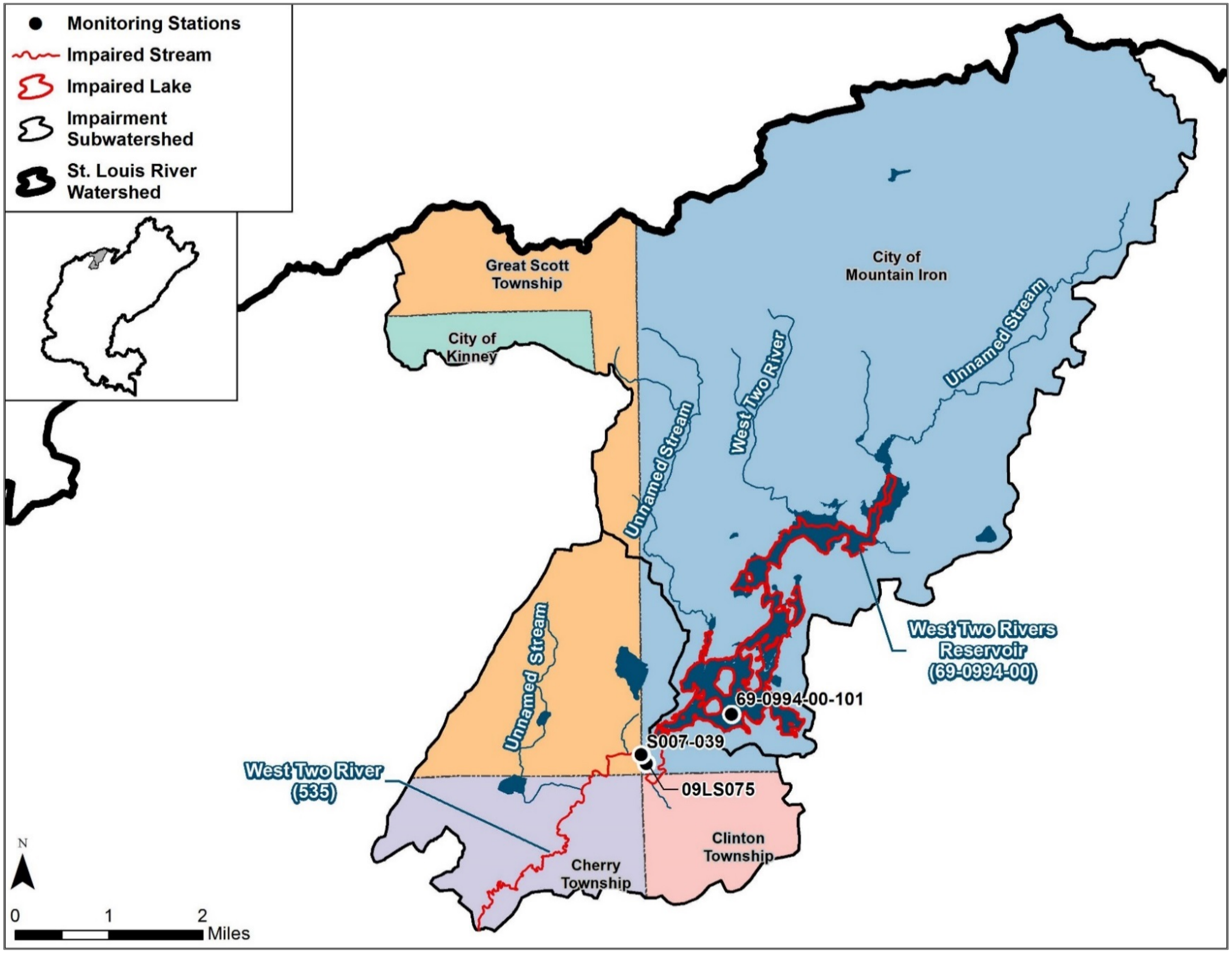

Figure 6. Watershed boundaries, cities and townships, and monitoring stations for West Two Rivers Reservoir and West Two River phosphorus TMDLs

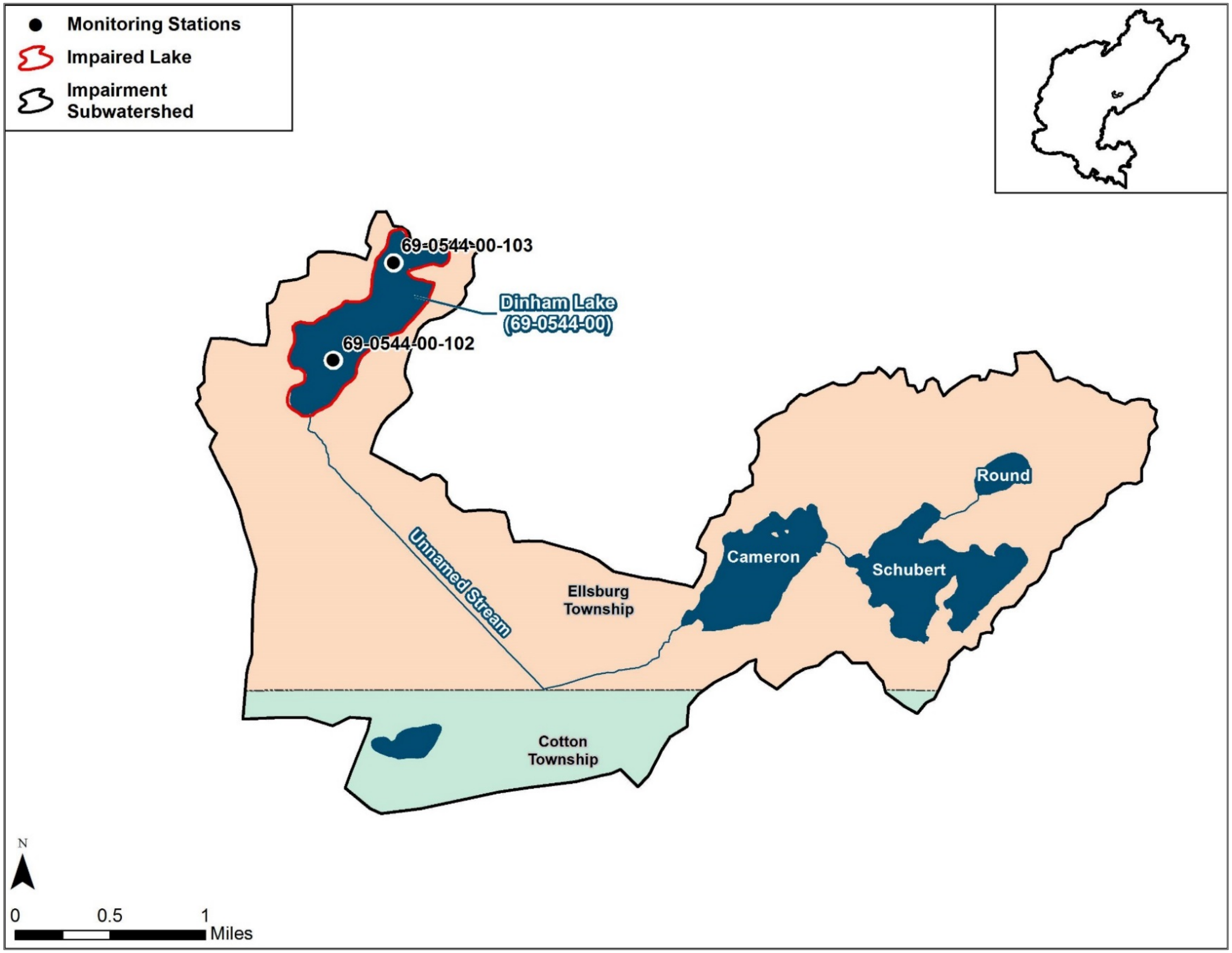

Figure 7. Watershed boundaries, cities and townships, and monitoring stations for Dinham Lake phosphorus TMDL

3.4 Land Cover

Data from the Landscape, Fire, and Resource Management Planning Tools (LANDFIRE) program of the United States Department of Agriculture (USDA) Forest Service and the United States Department of the Interior were used to characterize land cover in the watershed. The LANDFIRE data are based on the same Landsat satellite imagery as the National Land Cover Database's (NLCD) data, yet LANDFIRE provides additional information on tree canopy type and is more accurate than NLCD in differentiating grassland and shrubland from forest cover.

The dominant land covers in the impaired watersheds are wetlands and forest (Table 10; Figure 8 through Figure 13). Shrub, pasture, crop, barren, developed, roads, and open water each make up less than 5% of the area as a whole. Unnamed Creek/West Rocky Run (625), Hay Creek (751), and Unnamed Creek (A22) have substantial areas in pasture. West Two Rivers Reservoir, Barber Creek/East Swan River (569), Buhl Creek (580), Barber Creek/East Swan River (641), and Wyman Creek (942) also contain large areas of barren land[1]. These subwatersheds intersect the mining area along the Mesabi Iron Range, and the barren land primarily consists of taconite pits, natural ore pits, and taconite tailings (Figure 14). The Mesabi Iron Range historically has been mined for taconite, which is an iron-bearing sedimentary rock. Taconite mining declined in the mid-1970s and has more recently rebounded.

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[1] Barren land is where land covers such as bedrock, glacial debris, gravel pits and other accumulations of earthen material exist. Vegetation generally accounts for less than 15%of total land cover.

Table 10. Land cover (LANDFIRE 2008).

Values rounded to nearest whole number.

Water Body Name (AUID)	Percent of Watershed (%)									Watershed Area (square miles)
	Forest	Shrub	Pasture	Crop	Barren	Developed	Roads	Wetland	Water [a]	
Lakes										
Dinham Lake (69-0544-00)	44	1	0	0	0	0	1	41	13	7
West Two Rivers Reservoir (69-0994-00)	28	1	1	0	38	2	2	21	7	31
Streams										
Barber Creek (East Swan River; 04010201-569)	26	2	4	1	29	6	4	23	5	48
Barber Creek (East Swan River; 04010201-641)	25	2	3	0	38	4	3	19	6	37
Buhl Creek (04010201-580)	41	2	4	0	23	3	3	17	7	7
Dempsey Creek (04010201-582)	40	2	5	1	10	2	2	32	6	36
East Swan River (04010201-558)	32	2	4	1	12	4	3	39	3	148
Hay Creek (04010201-751)	58	2	19	1	0	1	3	16	0	12
Penobscot Creek (04010201-936)	21	4	6	1	13	21	13	21	0	5
Pine River (White Pine River; 04010201-543)	68	1	7	1	1	2	3	14	3	47
Stony Creek (04010201-963)	38	0	1	0	0	0	1	60	0	24
Unnamed Creek (04010201-542)	49	3	16	2	0	8	5	17	0	8
Unnamed Creek / West Rocky Run (04010201-625)	64	2	17	0	0	2	4	11	0	9
Unnamed Creek (04010201-A22)	40	2	27	4	0	3	5	19	0	4
Unnamed Creek (East Swan Creek; 04010201-888)	39	4	10	2	0	12	8	25	0	17
West Two River (04010201-535)	35	1	2	0	28	1	2	25	6	41
Wyman Creek (04010201-942)	39	1	0	0	20	0	0	39	1	11
All impairments, St. Louis River Watershed in MN	**43**	**1**	**4**	**1**	**8**	**2**	**2**	**36**	**3**	**418**

a. Includes lake surface area

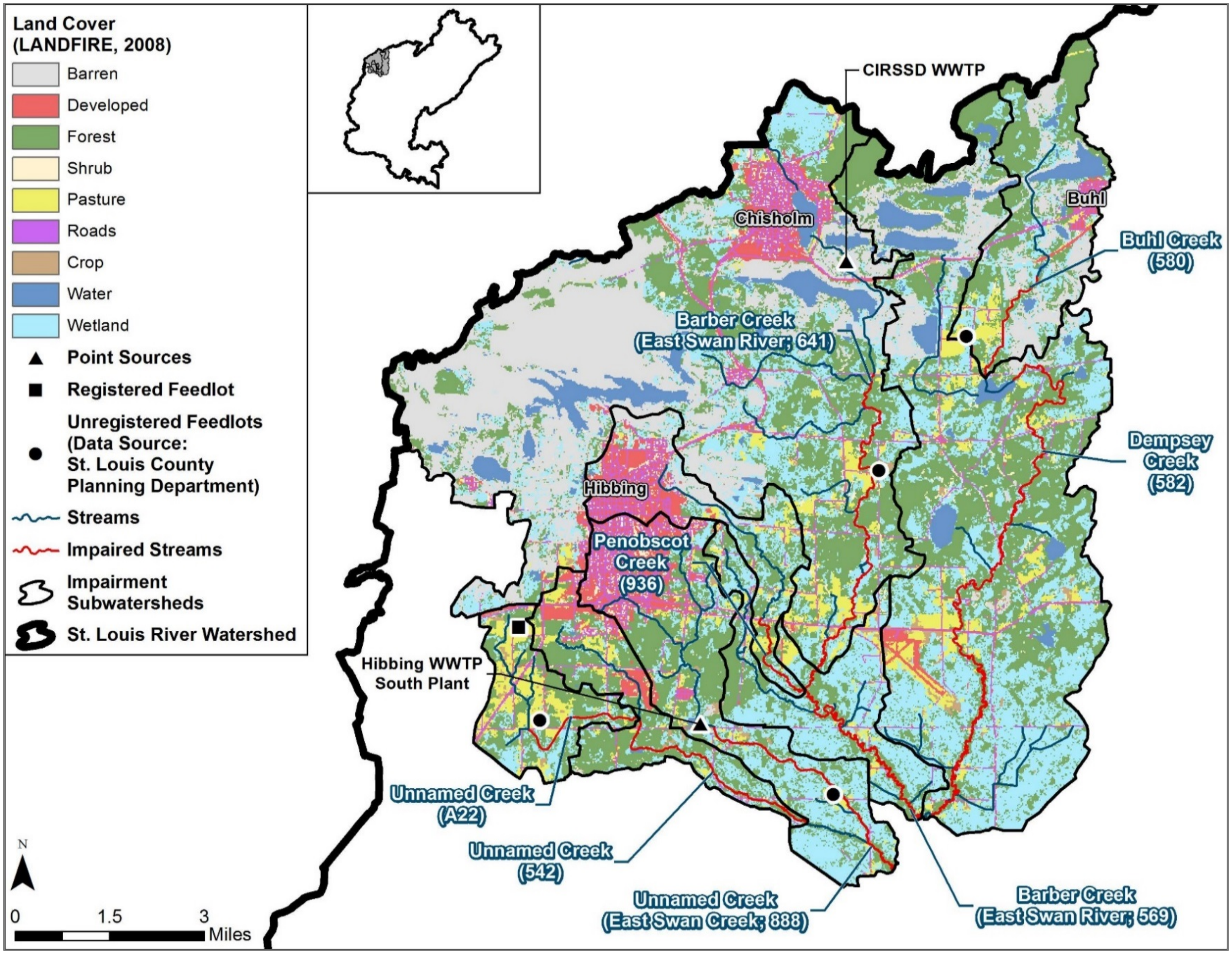


Figure 8. Land cover, point source locations, and feedlot locations for upper watershed *E. coli* TMDLs

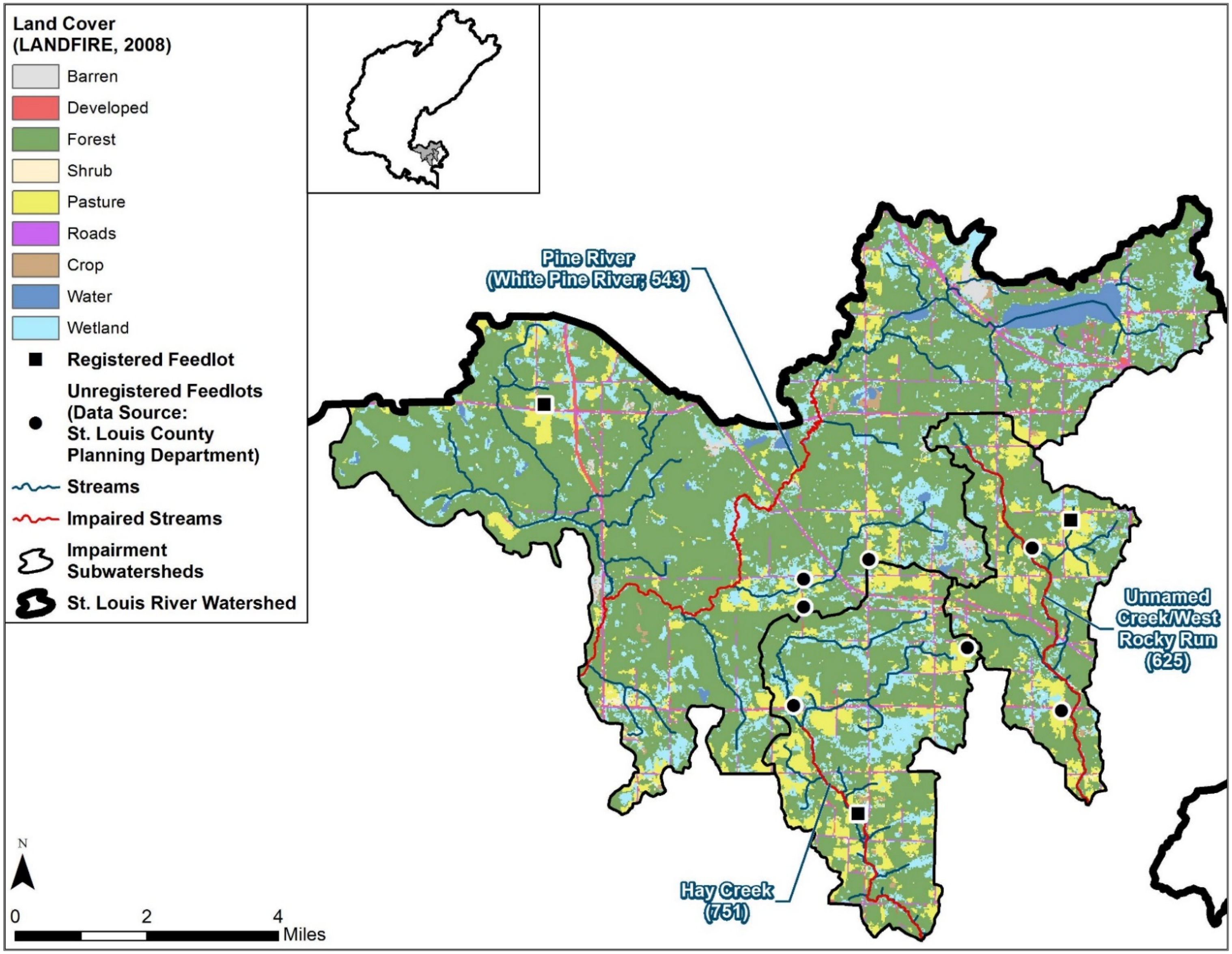


Figure 9. Land cover, point source locations, and feedlot locations for lower watershed *E. coli* TMDLs

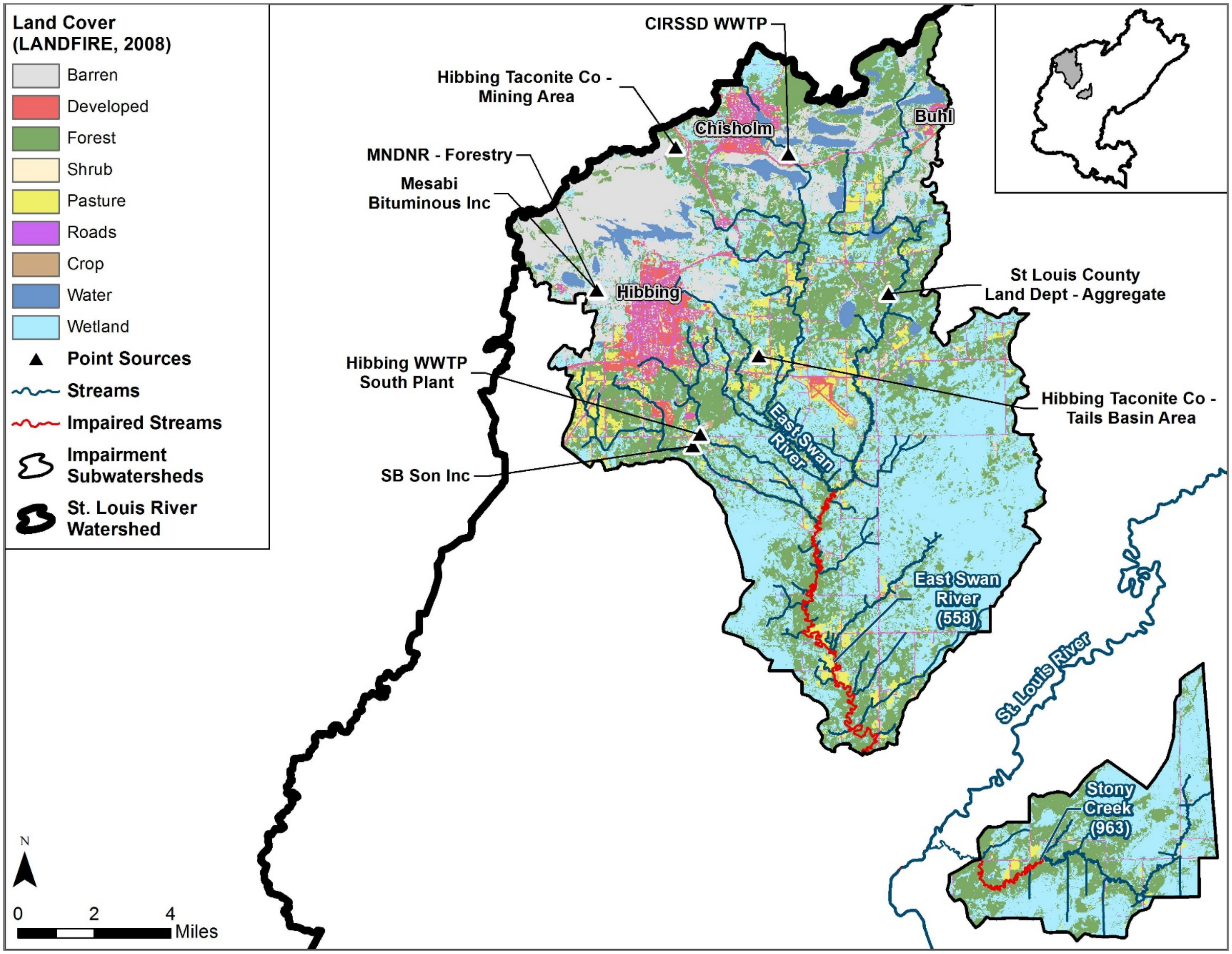
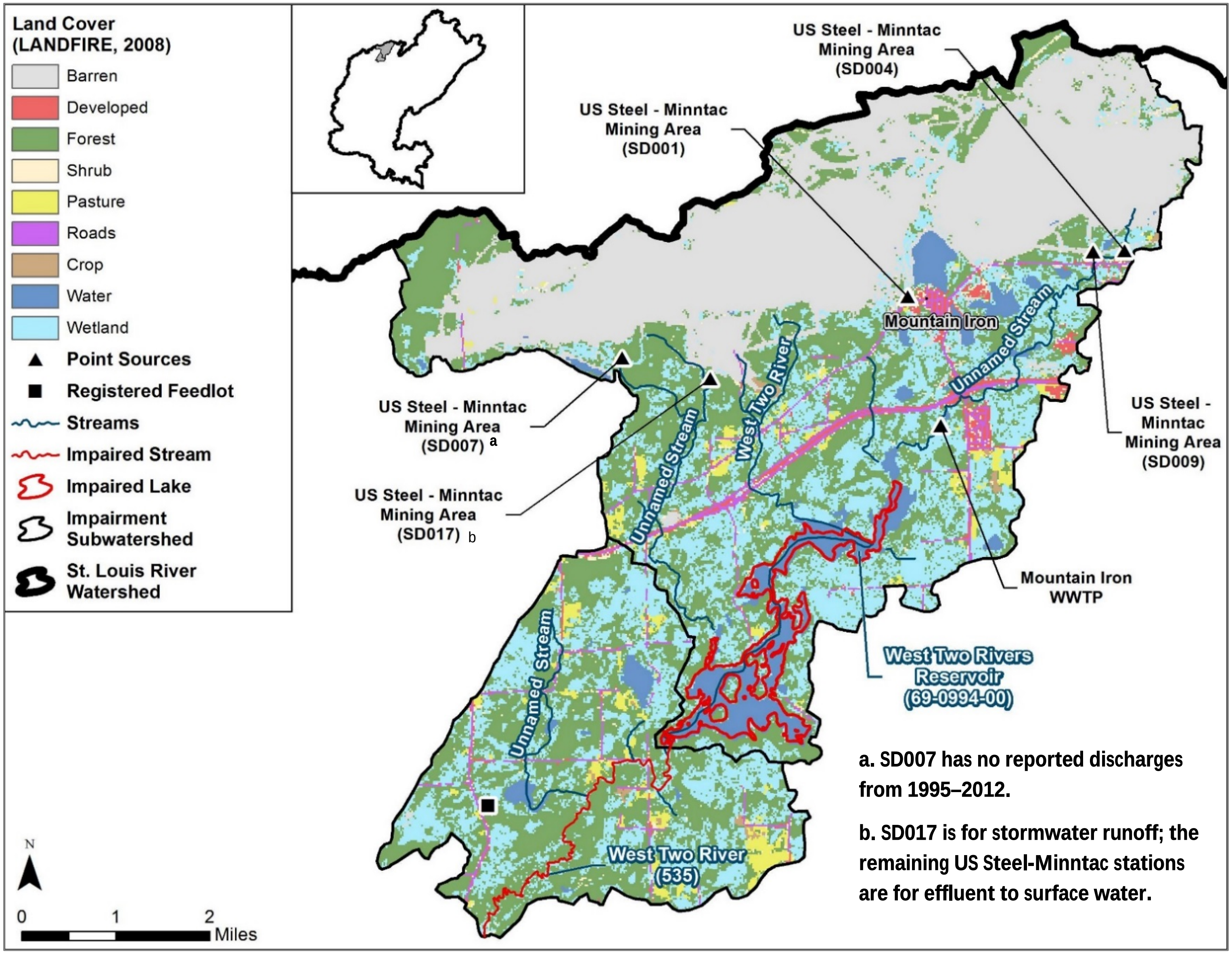


Figure 10. Land cover and point source locations for TSS TMDLs



a. SD007 has no reported discharges from 1995–2012.

b. SD017 is for stormwater runoff; the remaining US Steel-Minntac stations are for effluent to surface water.

Figure 11. Land cover, point source locations, and feedlot locations for West Two River and West Two Rivers Reservoir phosphorus TMDLs

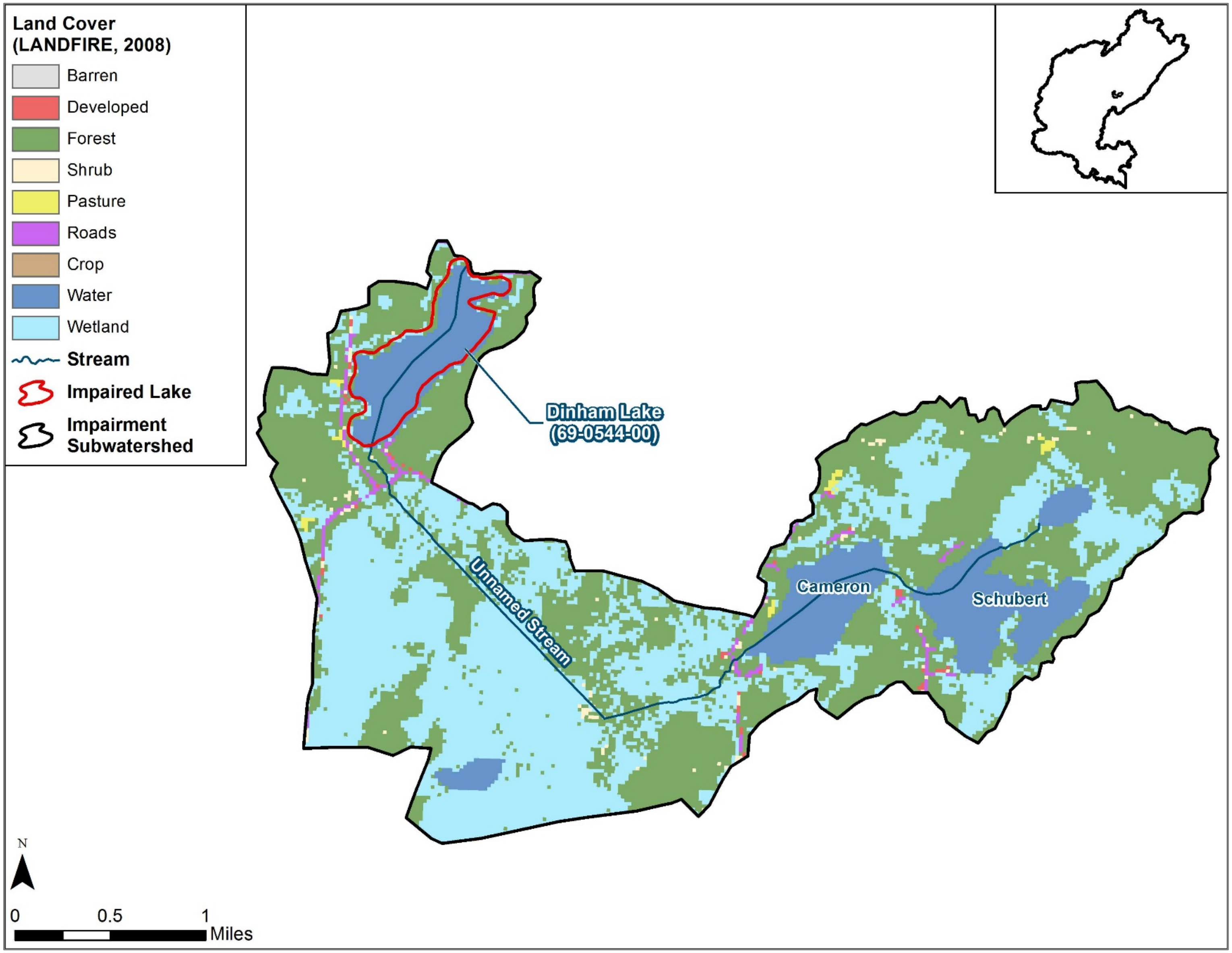


Figure 12. Land cover for Dinham Lake phosphorus TMDL

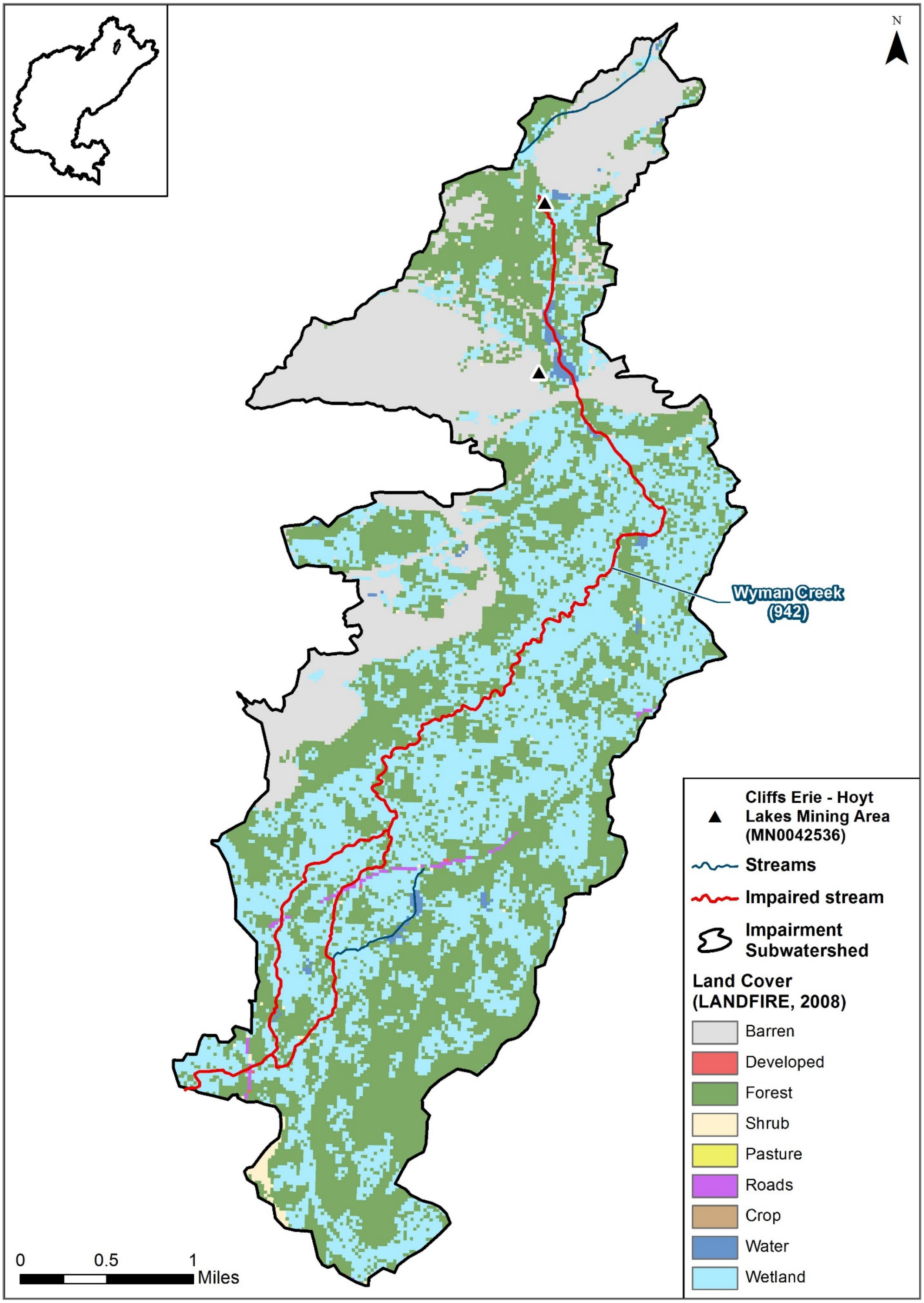


Figure 13. Land cover for Wyman Creek temperature TMDL

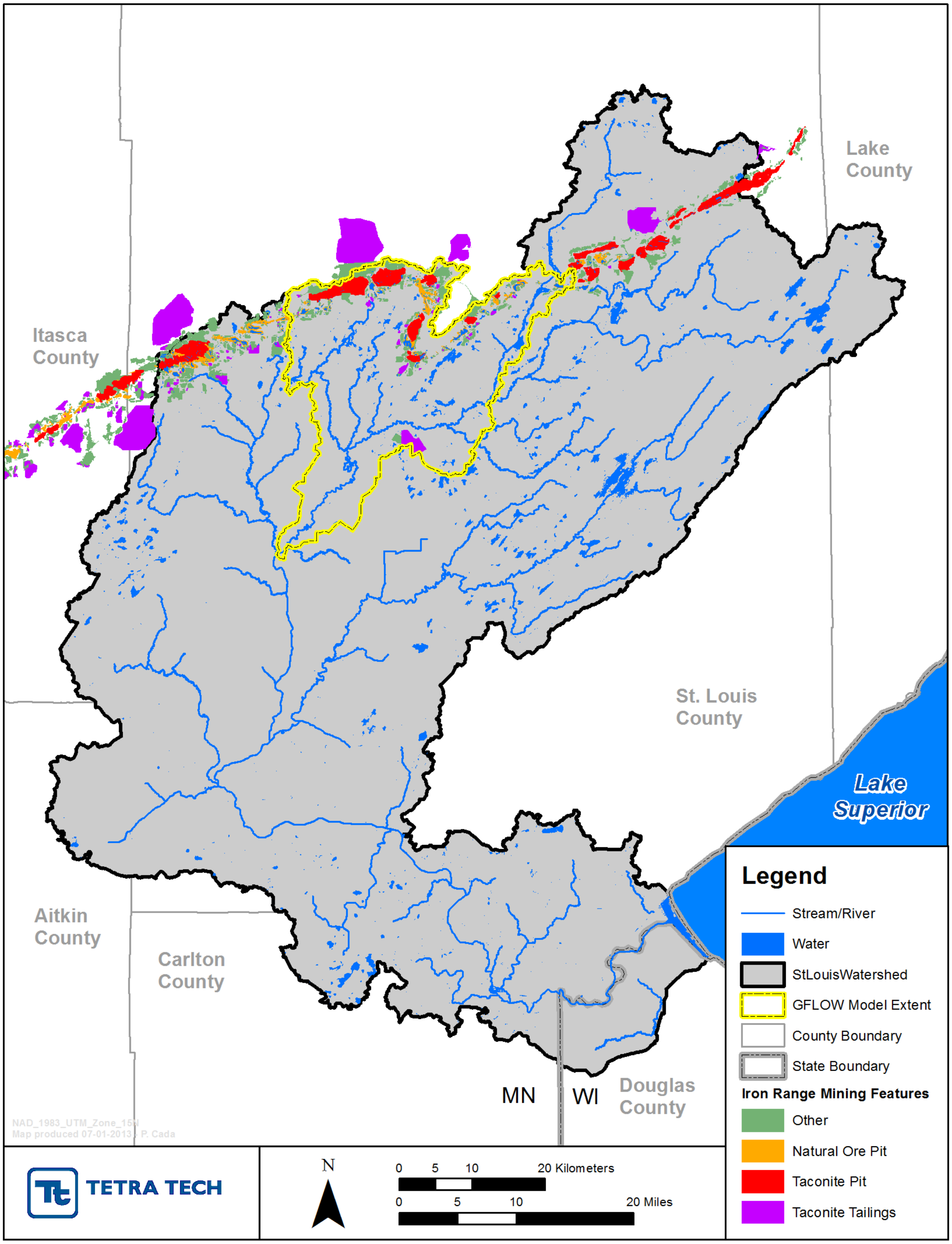


Figure 14. Iron Range mining features

"GFLOW Model Extent" applies to the modeled area described in Tetra Tech (2016c).

3.5 Current/Historic Water Quality

The St. Louis River Watershed Monitoring and Assessment Report (MPCA 2013) contains figures and tables that summarize water quality data on a HUC10 basis and address habitat, channel condition and stability, and water chemistry. The St. Louis River Watershed SID Report (MPCA 2016) includes evaluation of fish, macroinvertebrates, water chemistry, hydrology, and habitat for the streams with biotic impairments.

The analyses in this section use data from the MPCA's Environmental Quality Information System (EQuIS database, received April 30, 2015 from the MPCA staff), from 2003 through 2012. Additional data from the SID data collection were provided by the MPCA staff. Simulated flow for each impaired reach from the MPCA's St. Louis River Watershed HSPF model application was used to supplement the analysis (Tetra Tech 2016a).

Streams. Water quality data from 2003 to 2012 were summarized for the conventional TMDL pollutants (*E. coli*, TSS, and phosphorus); additional data through 2014 were added to supplement the TSS analyses. Data were summarized by year to evaluate trends in long term water quality and by month to evaluate seasonal variation. The summaries of data by year consider data taken only during the time period that the standard is in effect (April through September for TSS and April through October for *E. coli*). Where there are multiple sites along one assessment unit, data from the sites were combined and summarized together. The frequency of exceedances represents the percentage of samples that exceed the water quality standard.

Water quality duration curves are provided for each conventional impairment. Concentration duration curves are a form of water quality duration curves and are used to evaluate the relationships between hydrology and water quality because concentration is often a function of stream flow. For example, sediment concentrations typically increase with rising flows as a result of factors such as channel scour from higher velocities. Other parameters may be more concentrated at low flows and diluted by increased water volumes at higher flows. The concentration duration curve approach provides a visual display of the relationship between stream flow and water quality. Concentration duration curves are provided using water quality monitoring data and simulated daily average stream flow from the St. Louis River Watershed HSPF model application (Tetra Tech 2016a). Simulated flows are drainage area-weighted when the model did not explicitly represent the impaired watershed. Simulated flows from all months (even those outside of the time period that the standard is in effect) are plotted. Because flows are typically lower in the winter months than during the rest of the year, and fewer samples are collected during winter months, there are few samples from very low flow conditions.

The water quality data analysis for Wyman Creek includes data collected for the SID and data collected in 2016 to support TMDL development.

Lakes. The analyses in this section use data from the MPCA's EQuIS database from 2003 through 2012. Water quality data were summarized for TP, chl-*a*, and Secchi transparency. Surface water data were summarized over the entire period and by year to evaluate trends in water quality. The summaries provide monitoring data from the growing season (June through September) because this is the time frame during which the current standard applies. Carlson's Trophic Status Index (TSI) was calculated for each water quality parameter (Carlson and Simpson 1996); the TSI can be interpreted as follows:

- TSI < 30: classic oligotrophy; clear water
- TSI 30–40: hypolimnia in shallow lakes may become anoxic in summer
- TSI 40–50: mesotrophic; water moderately clear
- TSI 50–60: eutrophic; decreased transparency
- TSI 60–70: blue-green algae dominate in summer; algal scums probable
- TSI > 70: hypereutrophic; dense algae

3.5.1 Escherichia coli

Patterns in Stream *E. coli* Concentrations

E. coli concentrations at multiple sites are often correlated with one another, which is likely due to either similar mechanisms that lead to *E. coli* delivery to the stream (e.g., a watershed runoff event) or to hydrologic connections among sites (e.g., high *E. coli* in an upstream site leads to high *E. coli* in a downstream location). *E. coli* concentrations over time were compared among hydrologically connected sites. In this series of figures, if more than one sample was taken on one day, the values were averaged. See Figure 3 and Figure 4 for maps of the impaired reaches.

Concentrations at East Swan Creek's two unnamed tributaries (assessment unit identification (AUIDs) A22 and 542) were often high at the same time (Figure 15). On days when samples were collected at both sites, concentrations at the upstream site (A22) were on average higher than concentrations at the downstream site (542; paired t-test, $p < 0.1$). This pattern suggests that the primary sources of *E. coli* occur in the upstream reach.

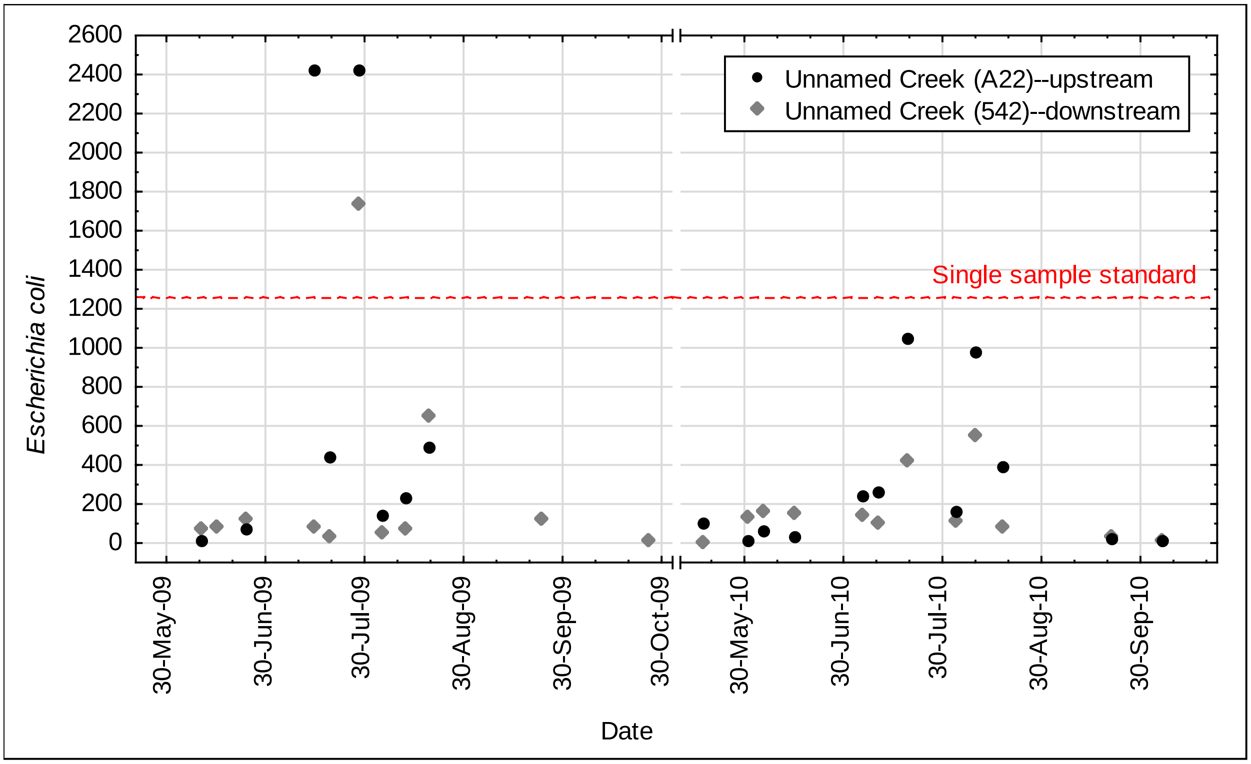


Figure 15. *E. coli* concentrations over time in East Swan Creek's unnamed tributaries

In the Barber/East Swan Creek Subwatersheds (Figure 16), the pattern is different (Figure 17 and Figure 18). Concentrations in the upstream Barber/East Swan reach were only marginally high (the monthly geometric mean standard was exceeded in June and August, but the individual sample maximum was not exceeded). However, downstream of the confluence with Penobscot Creek, the concentrations were much higher. This is likely due to the *E. coli* load from Penobscot Creek, where concentrations were on average the highest observed in the project area.

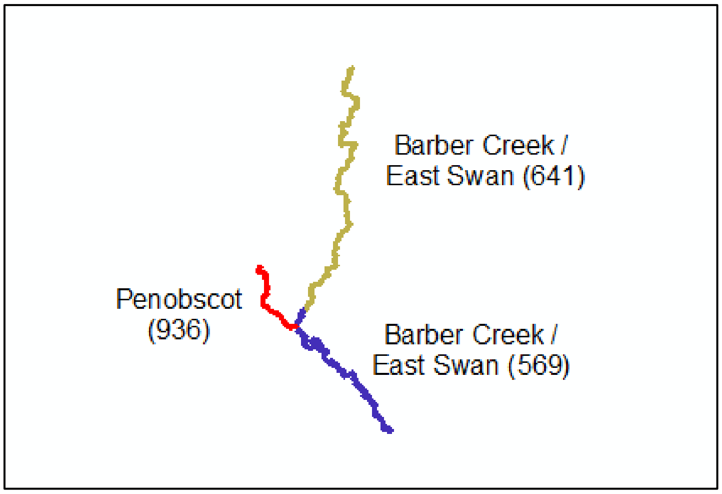


Figure 16. Location of impaired streams adjacent to Penobscot Creek

Stick figure shown to illustrate upstream–downstream relationships of the reaches.

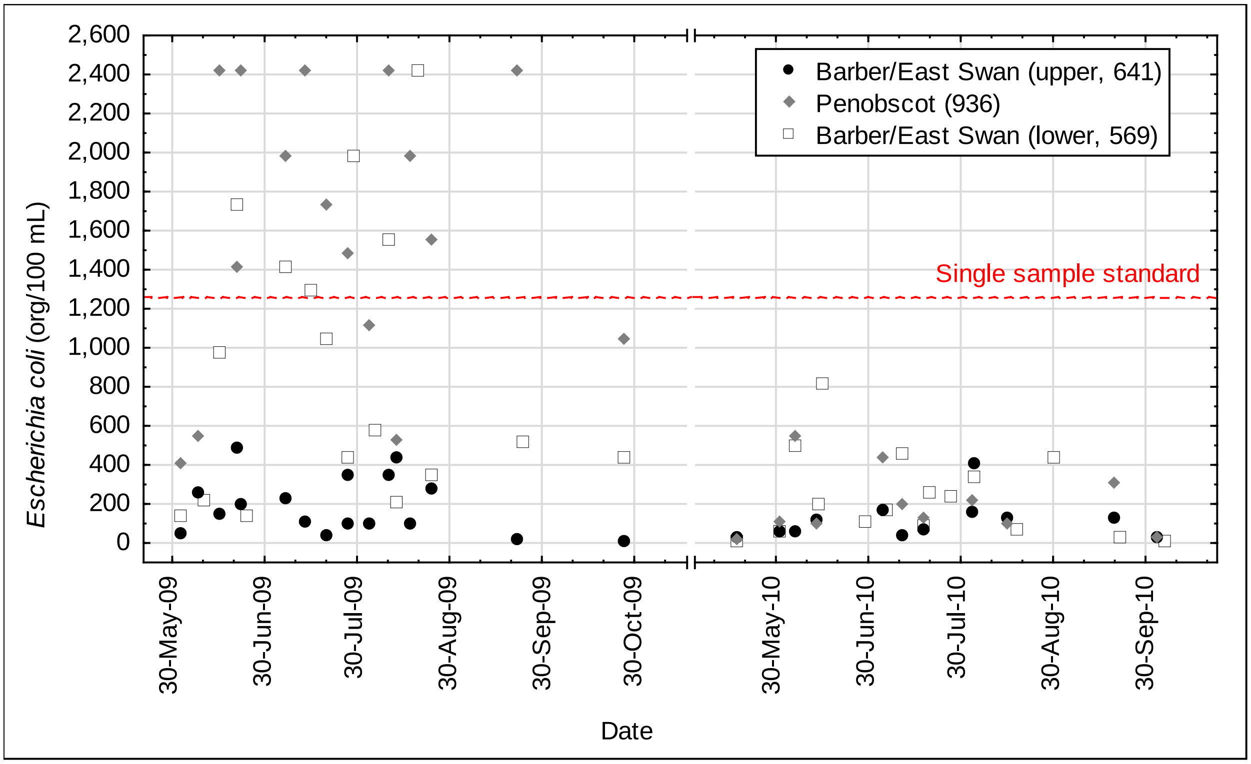


Figure 17. *E. coli* concentrations over time at Barber/East Swan and Penobscot Creeks

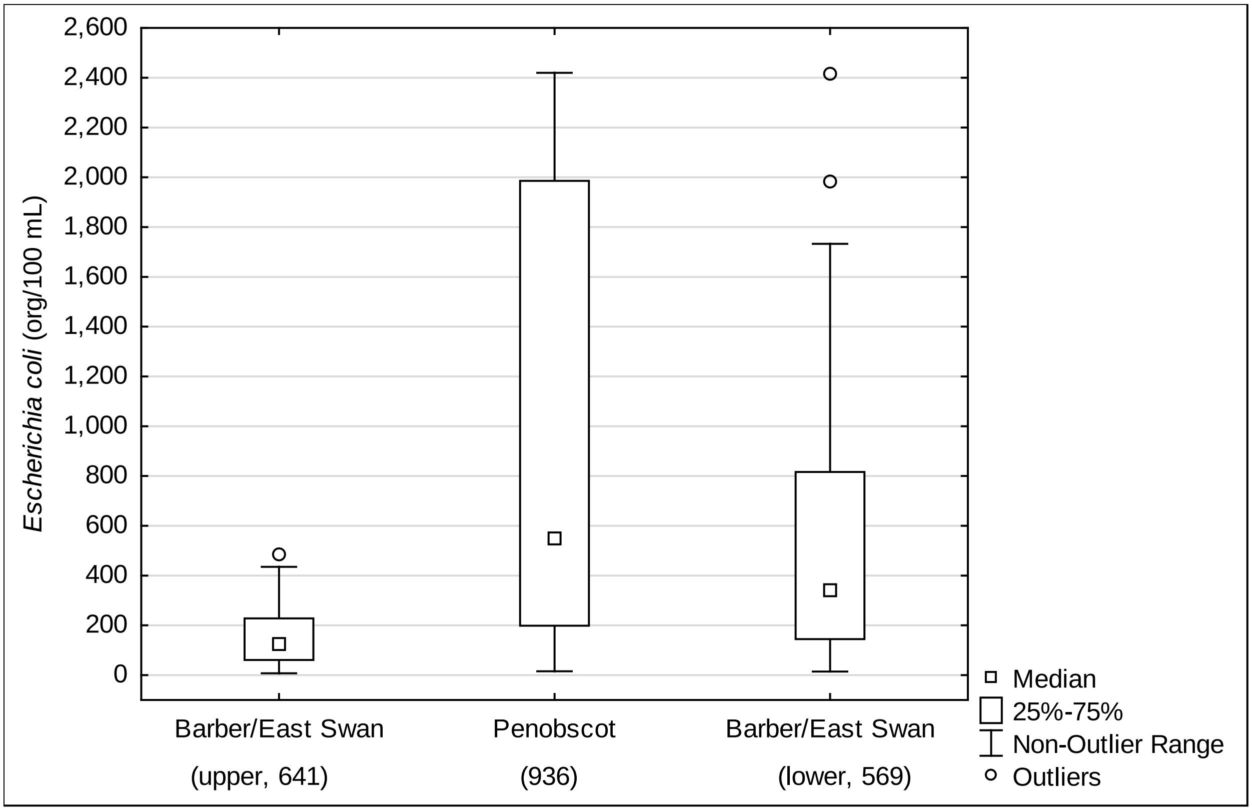


Figure 18. *E. coli* concentrations at Barber / East Swan and Penobscot Creeks

The *E. coli* concentrations in Buhl Creek and Dempsey Creek were relatively similar to one another, but there was not a clear upstream-downstream relationship (Figure 19). Although the two creeks are hydrologically connected, there is a lake in between the two reaches, and the monitoring sites are over seven miles apart (Figure 20).

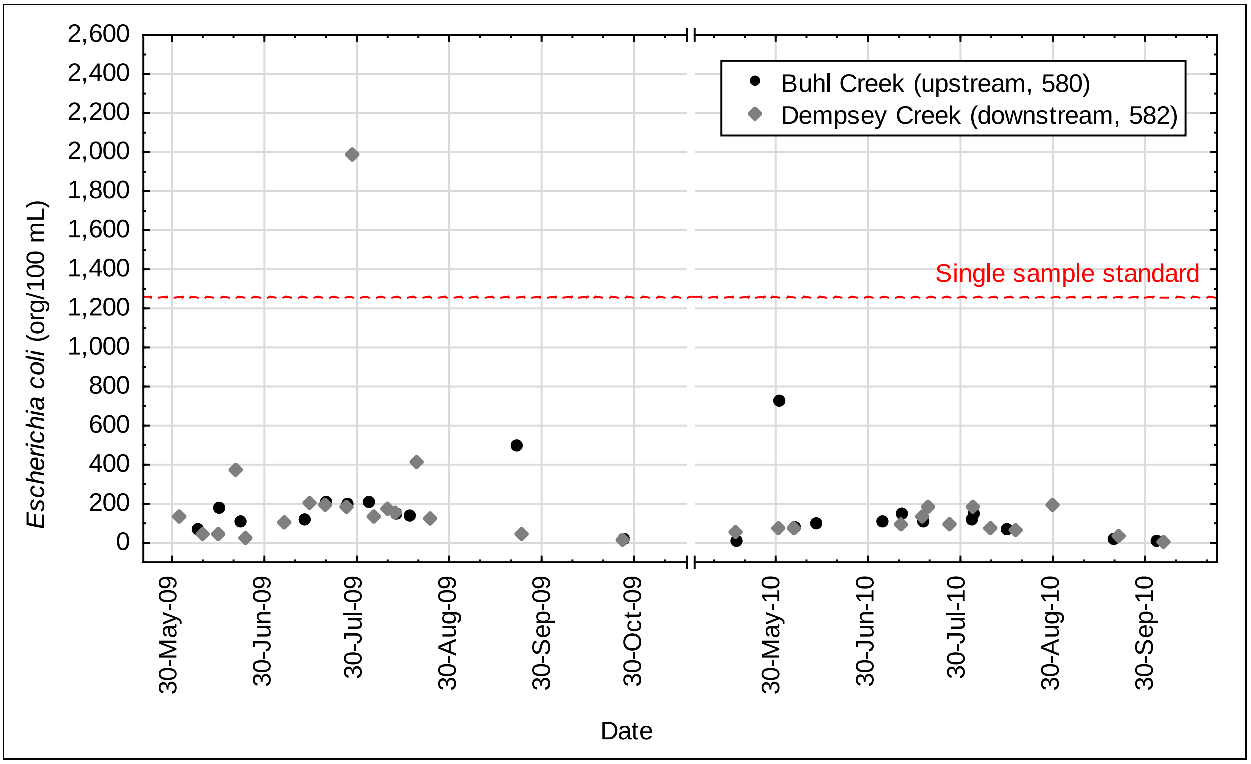


Figure 19. *E. coli* concentrations over time at Buhl Creek and Dempsey Creek

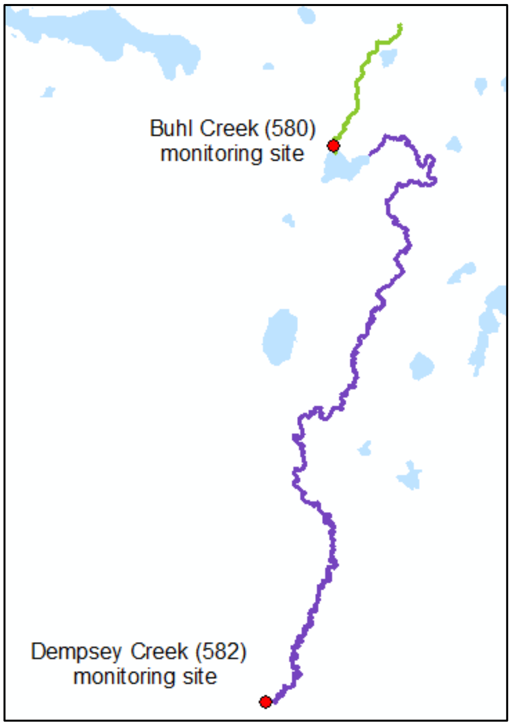


Figure 20. Location of monitoring sites on Buhl Creek and Dempsey Creek

Stick figure shown to illustrate upstream–downstream relationships of the reaches.

The three impaired reaches in the lower portion of the SLRW are not hydrologically connected (see Figure 4); however, they are shown here to illustrate concentrations over time (Figure 21). The measurements above the standard in Hay Creek and Unnamed Creek/West Rocky Run occurred on the same days, suggesting that a similar mechanism (e.g., watershed runoff) influenced the high concentrations. The concentrations in the Pine River were lower than at the other two sites.

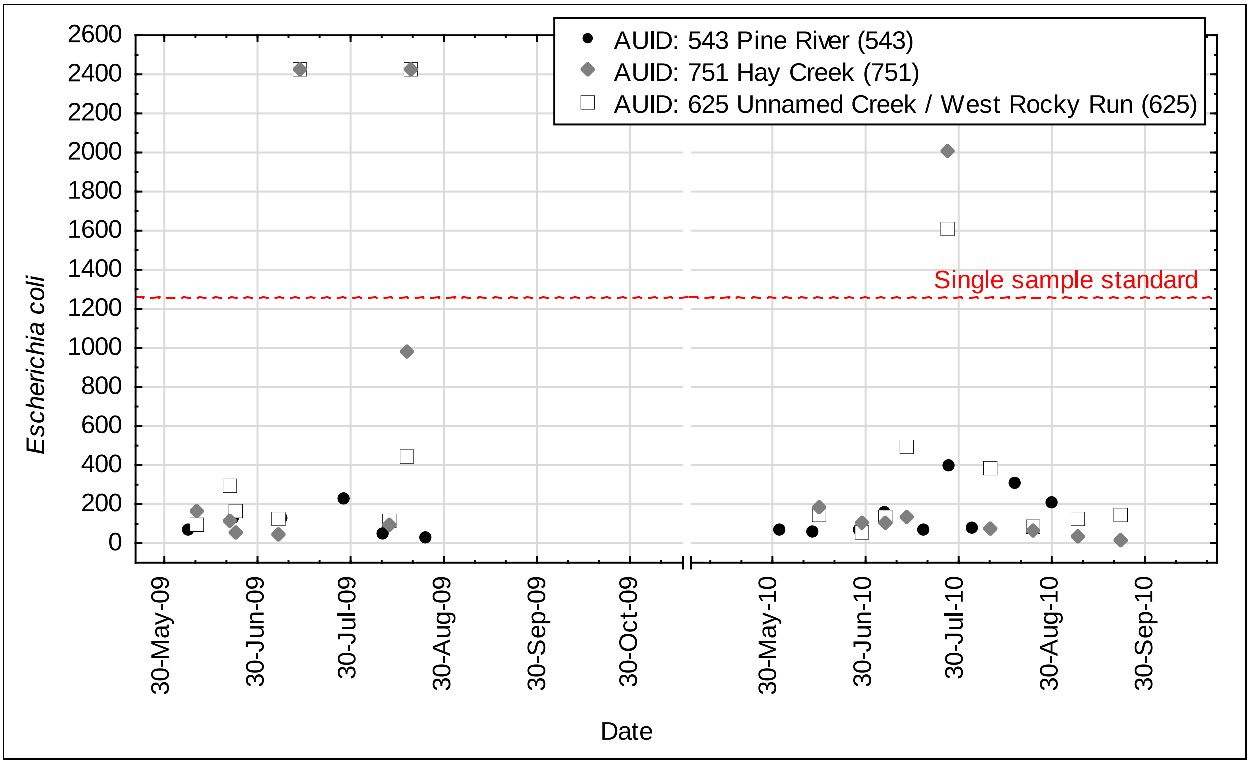


Figure 21. *E. coli* concentrations over time at Pine River, Hay Creek, and Unnamed Creek

Analysis by Reach

The order in which the stream reaches in this section are presented is from upstream to downstream. The impaired reaches in the Swan River Subwatershed (see map in Figure 3) are presented first, followed by the impaired reaches in the lower portion of the watershed (see map in Figure 4). The concentration duration curves (Figure 22 through Figure 32) display *E. coli* data relative to the *E. coli* individual sample standard of 1,260 org/100 mL.

Buhl Creek (04010201-580)

There is one monitoring station on the downstream end of Buhl Creek (Figure 3). The individual sample standard was not exceeded in Buhl Creek in 2009 or 2010 (Table 11), but the monthly geometric mean standard was exceeded in July and August (Table 12). There is no clear relationship between flow and *E. coli* concentration in the available data, and there are no samples from low or very low flows (Figure 22).

Table 11. Annual summary of *E. coli* data at Buhl Creek (AUID 04010201-580, site S005-682, May–Oct)

Year	Sample Count	Annual Geometric Mean (org/100 mL)	Minimum (org/100mL)	Maximum (org/100mL)	Number of Individual Sample Standard Exceedances (> 1,260 org/100 mL)	Percent of Individual Sample Standard Exceedances
2009	12	77	20	613	0	0
2010	13	81	6	727	0	0

Table 12. Monthly summary of *E. coli* data at Buhl Creek (AUID 04010201-542, site S005-682, 2009–2010)

Values in red indicate months in which the monthly geometric mean standard of 126 org/100 mL was exceeded or the individual sample standard of 1,260 org/100 mL was exceeded in greater than 10% of the samples.

Month	Sample Count	Monthly Geometric Mean (org/100 mL)	Minimum (org/100mL)	Maximum (org/100mL)	Number of Individual Sample Standard Exceedances (> 1,260 org/100 mL)	Percent of Individual Sample Standard Exceedances
May	1 [a]	6	6	6	0	0
June	6	70	68	727	0	0
July	6	146	106	214	0	0
August	6	133	70	214	0	0
September	3 [a]	168	20	613	0	0
October	3 [a]	12	8	20	0	0

a. Not enough samples to assess compliance with the monthly geometric mean standard

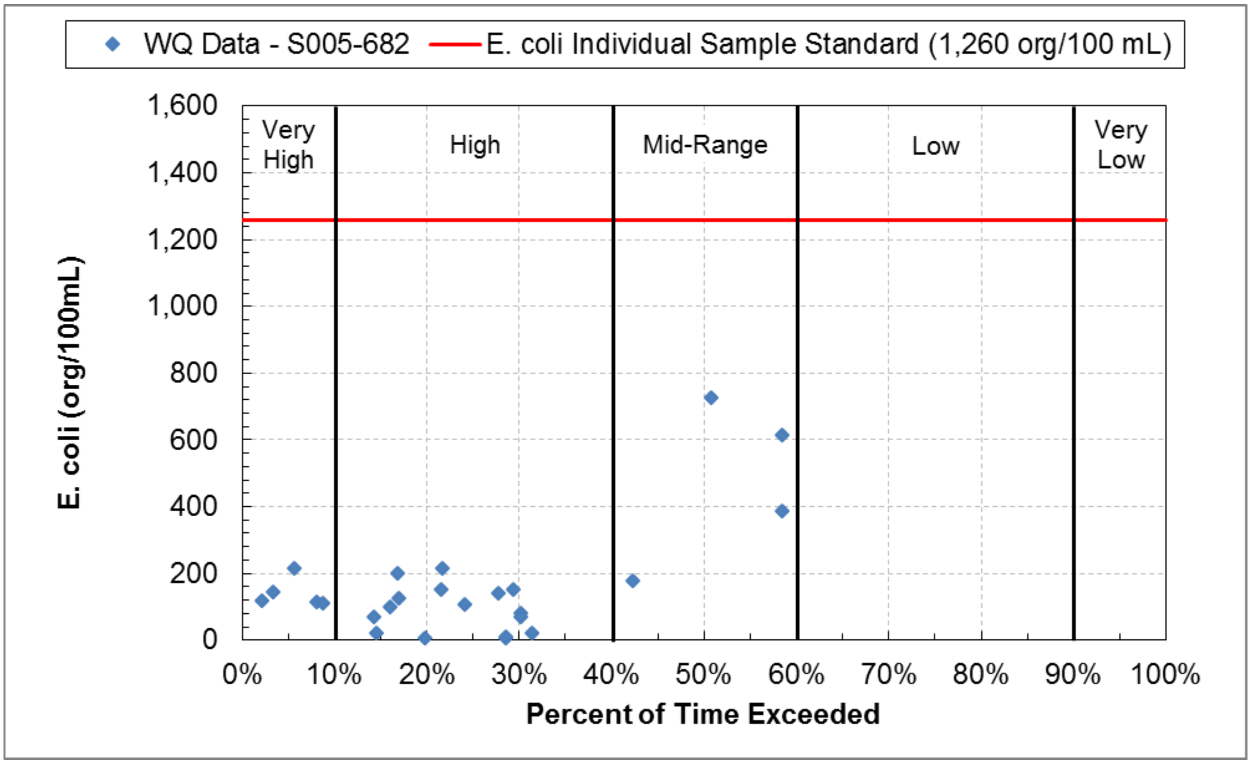


Figure 22. ***E. coli*** **concentration duration plot, Buhl Creek (AUID 04010201-580)**

Dempsey Creek (04010201-582)

There is one monitoring station on the downstream end of Dempsey Creek (Figure 3). The *E. coli* concentration was greater than the individual sample standard in one sample in Dempsey Creek in 2009 (Table 13). The individual sample standard and the monthly geometric mean standard were exceeded in July (Table 14). The individual exceedance occurred under high flow conditions; there are no samples from very low flows and only one from low flows (Figure 23).

Table 13. Annual summary of *E. coli* data at Dempsey Creek (AUID 04010201-582, site S000-597, May–Oct)

Year	Sample Count	Annual Geometric Mean (org/100 mL)	Minimum (org/100mL)	Maximum (org/100mL)	Number of Individual Sample Standard Exceedances (> 1,260 org/100 mL)	Percent of Individual Sample Standard Exceedances
2009	17	106	8	1,986	1	6
2010	18	75	4	190	0	0

Table 14. Monthly summary of *E. coli* data at Dempsey Creek (AUID 04010201-582, site S000-597, 2009–2010)
Values in red indicate months in which the monthly geometric mean standard of 126 org/100 mL was exceeded or the individual sample standard of 1,260 org/100 mL was exceeded in greater than 10% of the samples.

Month	Sample Count	Monthly Geometric Mean (org/100 mL)	Minimum (org/100mL)	Maximum (org/100mL)	Number of Individual Sample Standard Exceedances (> 1,260 org/100 mL)	Percent of Individual Sample Standard Exceedances
May	2 [a]	49	49	50	0	0
June	8	70	25	365	0	0
July	9	183	86	1,986	1	11
August	12	123	50	411	0	0
September	2 [a]	36	31	43	0	0
October	2 [a]	6	4	8	0	0

a. Not enough samples to assess compliance with the monthly geometric mean standard

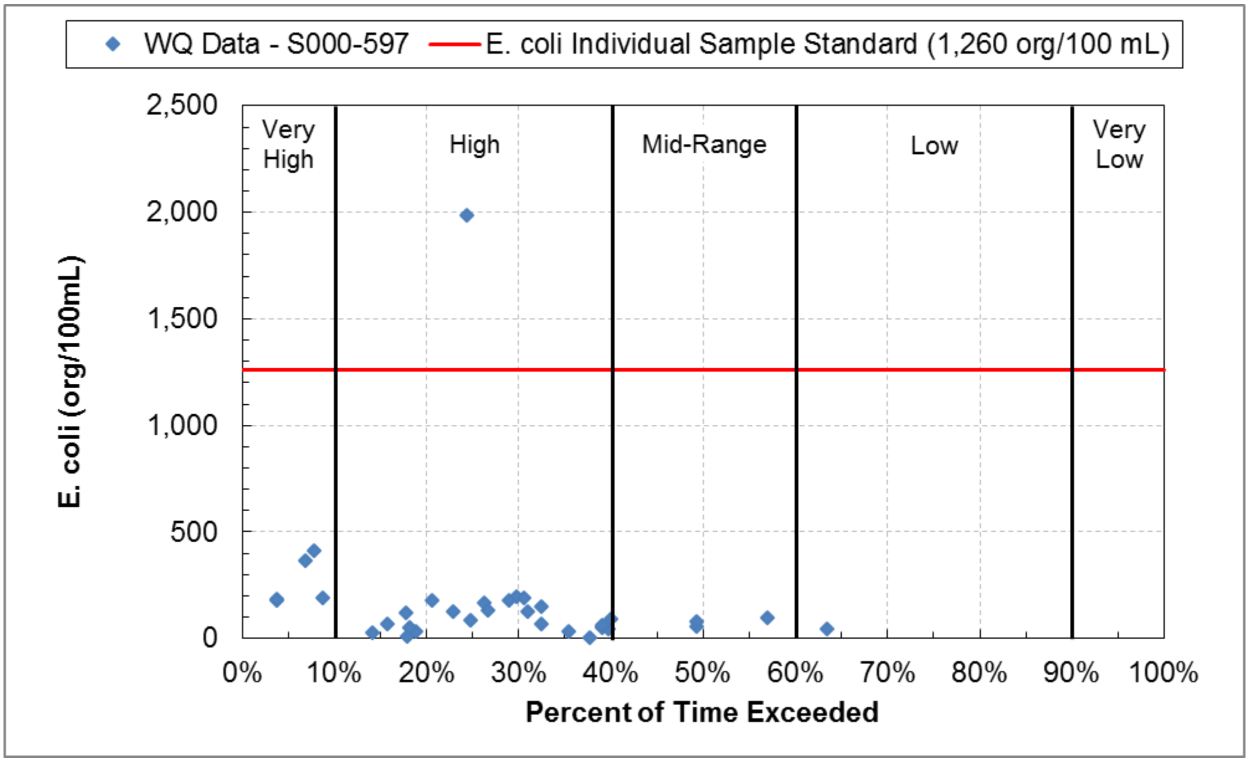


Figure 23. *E. coli* concentration duration plot, Dempsey Creek (AUID 04010201-582)

Barber Creek (East Swan River; 04010201-641)

There are two monitoring stations on this impaired reach of Barber Creek (Figure 3). The individual sample standard was not exceeded in Barber Creek in 2009 or 2010 (Table 15), but the monthly geometric mean standard was exceeded in June and August (Table 16). There is no clear relationship between flow and *E. coli* concentration in the available data, and there are no samples from very low flows (Figure 24).

Table 15. Annual summary of *E. coli* data at Barber Creek (AUID 04010201-641, sites S005-685 and 748, May–Oct)

Year	Sample Count	Annual Geometric Mean (org/100 mL)	Minimum (org/100mL)	Maximum (org/100mL)	Number of Individual Sample Standard Exceedances (> 1,260 org/100 mL)	Percent of Individual Sample Standard Exceedances
2009	18	123	7	488	0	0
2010	13	95	31	411	0	0

Table 16. Monthly summary of *E. coli* data at Barber Creek (AUID 04010201-641, sites S005-685 and 748, 2009–2010)

Values in red indicate months in which the monthly geometric mean standard of 126 org/100 mL was exceeded or the individual sample standard of 1,260 org/100 mL was exceeded in greater than 10% of the samples.

Month	Sample Count	Monthly Geometric Mean (org/100 mL)	Minimum (org/100mL)	Maximum (org/100mL)	Number of Individual Sample Standard Exceedances (> 1,260 org/100 mL)	Percent of Individual Sample Standard Exceedances
May	1 [a]	36	36	36	0	0
June	8	132	51	488	0	0
July	8	106	36	345	0	0
August	10	191	96	435	0	0
September	2 [a]	53	22	130	0	0
October	2 [a]	15	7	31	0	0

a. Not enough samples to assess compliance with the monthly geometric mean standard

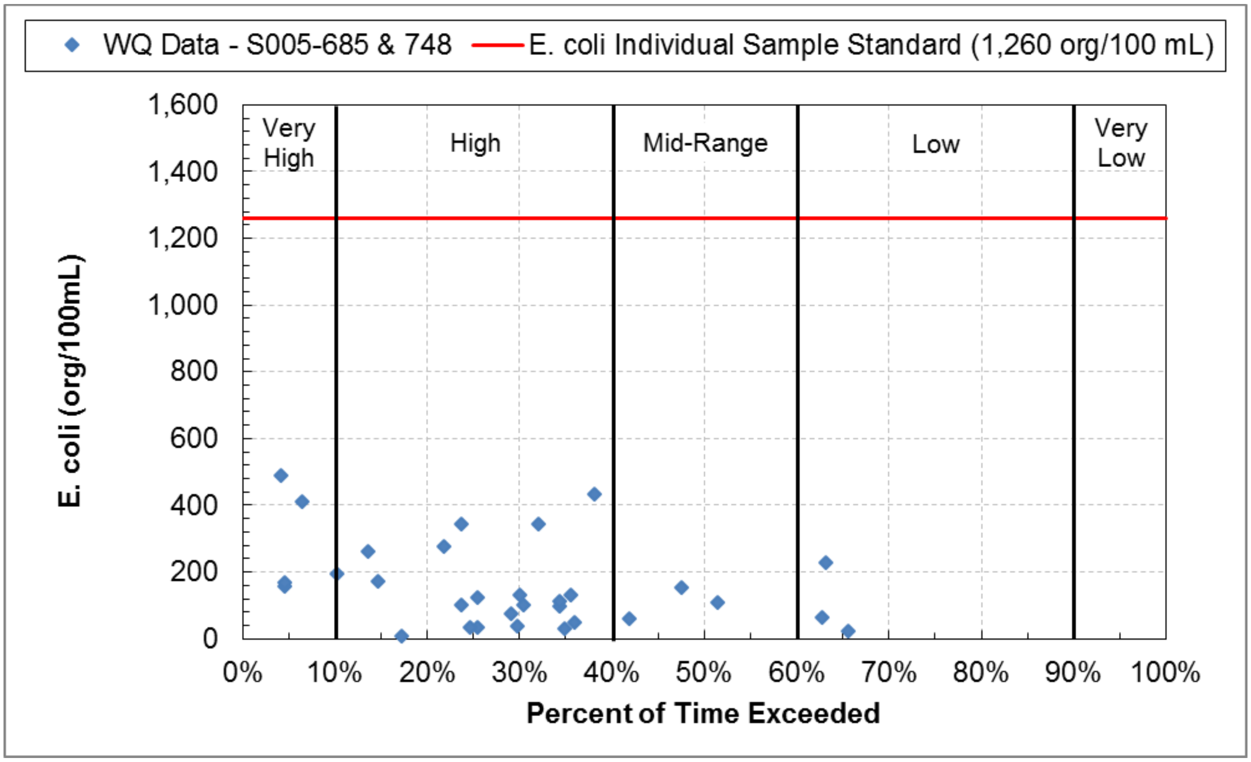


Figure 24. *E. coli* concentration duration plot, Barber Creek (AUID 04010201-641)

Penobscot Creek (04010201-936)

There is one monitoring station on the upstream end of the impaired reach of Penobscot Creek (Figure 3). The *E. coli* concentration was greater than the individual sample standard 12 times in Penobscot Creek in 2009 (Table 17). The individual sample standard was exceeded in July through September, and the monthly geometric mean standard was exceeded in June, July, and August (Table 18). Monthly geometric means were also above the standard in September; however, there were not enough samples to assess compliance with the standard. The individual exceedances occurred from low to very high flow conditions; there are no samples from very low flows (Figure 25).

Table 17. Annual summary of *E. coli* data at Penobscot Creek (AUID 04010201-936, site S000-592, May–Oct)

Year	Sample Count	Annual Geometric Mean (org/100 mL)	Minimum (org/100mL)	Maximum (org/100mL)	Number of Individual Sample Standard Exceedances (> 1,260 org/100 mL)	Percent of Individual Sample Standard Exceedances
2009	18	572	411	≥ 2,420 [a]	12	67
2010	12	493	16	548	0	0

a. 2,420 org/100mL is the method's maximum recordable value

Table 18. Monthly summary of *E. coli* data at Penobscot Creek (AUID 04010201-936, site S000-592, 2009–2010)
Values in red indicate months in which the monthly geometric mean standard of 126 org/100 mL was exceeded or the individual sample standard of 1,260 org/100 mL was exceeded in greater than 10% of the samples.

Month	Sample Count	Monthly Geometric Mean (org/100 mL)	Minimum (org/100mL)	Maximum (org/100mL)	Number of Individual Sample Standard Exceedances (> 1,260 org/100 mL)	Percent of Individual Sample Standard Exceedances
May	1 [a]	16	16	16	0	0
June	8	575	105	≥ 2,420 [b]	3	38
July	8	820	130	≥ 2,420 [b]	5	63
August	9	341	96	≥ 2,420 [b]	3	33
September	2 [a]	870	313	≥ 2,420 [b]	1	50
October	2 [a]	170	28	1,046	0	0

a. Not enough samples to assess compliance with the monthly geometric mean standard
b. 2,420 org/100mL is the method's maximum recordable value

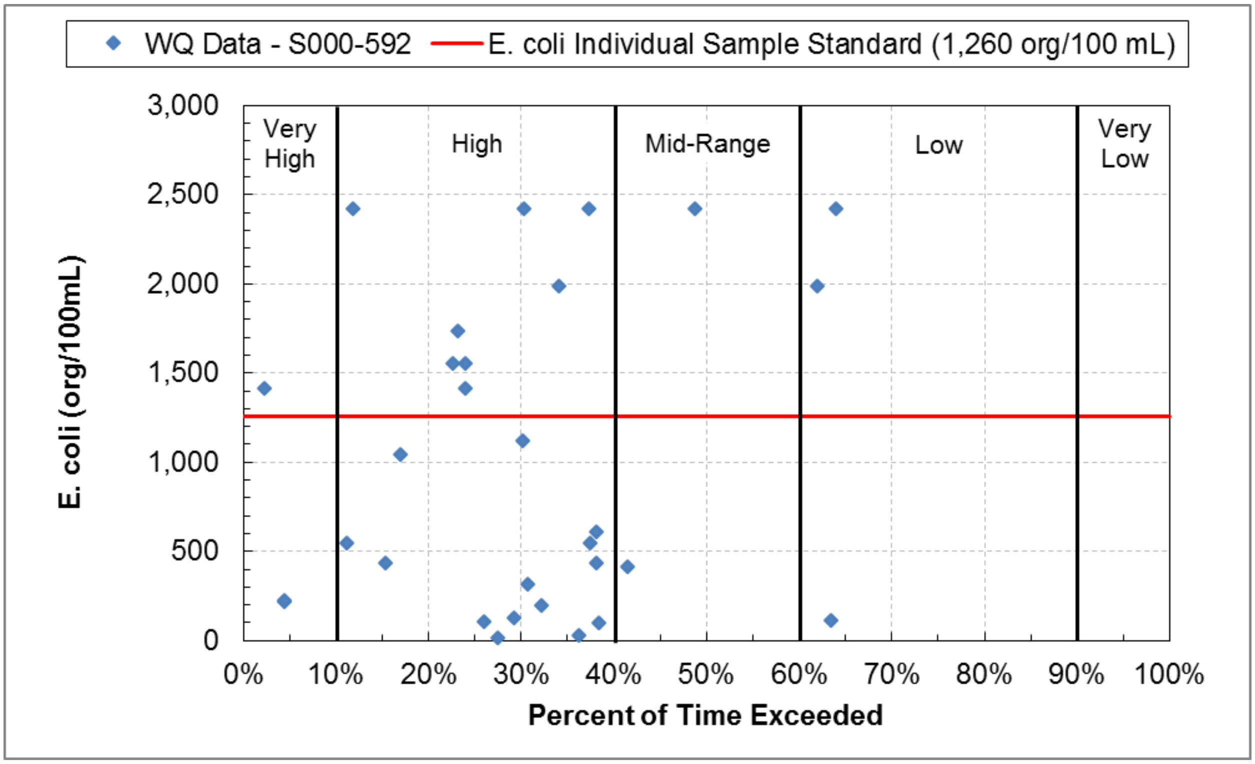


Figure 25. *E. coli* concentration duration plot, Penobscot Creek (AUID 04010201-936)

Barber Creek (East Swan River; 04010201-569)

There is one monitoring station on this impaired reach of Barber Creek (Figure 3). The *E. coli* concentration was greater than the individual sample standard seven times in Barber Creek in 2009 (Table 19). The individual sample standard was exceeded in July and August, and the monthly geometric mean standard was exceeded in June, July, and August (Table 20). The individual exceedances occurred from low to very high flow conditions; there are no samples from very low flows (Figure 26).

Table 19. Annual summary of *E. coli* data at Barber Creek (AUID 04010201-569, site S000-596, May–Oct)

Year	Sample Count	Annual Geometric Mean (org/100 mL)	Minimum (org/100mL)	Maximum (org/100mL)	Number of Individual Sample Standard Exceedances (> 1,260 org/100 mL)	Percent of Individual Sample Standard Exceedances
2009	18	336	137	2,420	7	39
2010	24	251	15	816	0	0

Table 20. Monthly summary of *E. coli* data at Barber Creek (AUID 04010201-569, site S000-596, 2009–2010)

Values in red indicate months in which the monthly geometric mean standard of 126 org/100 mL was exceeded or the individual sample standard of 1,260 org/100 mL was exceeded in greater than 10% of the samples.

Month	Sample Count	Monthly Geometric Mean (org/100 mL)	Minimum (org/100mL)	Maximum (org/100mL)	Number of Individual Sample Standard Exceedances (> 1,260 org/100 mL)	Percent of Individual Sample Standard Exceedances
May	1[a]	15	15	15	0	0
June	12	306	63	1,733	1	8
July	14	292	73	1,986	4	29
August	11	359	74	2,420	2	18
September	2[a]	130	33	517	0	0
October	2[a]	80	15	435	0	0

a. Not enough samples to assess compliance with the monthly geometric mean standard

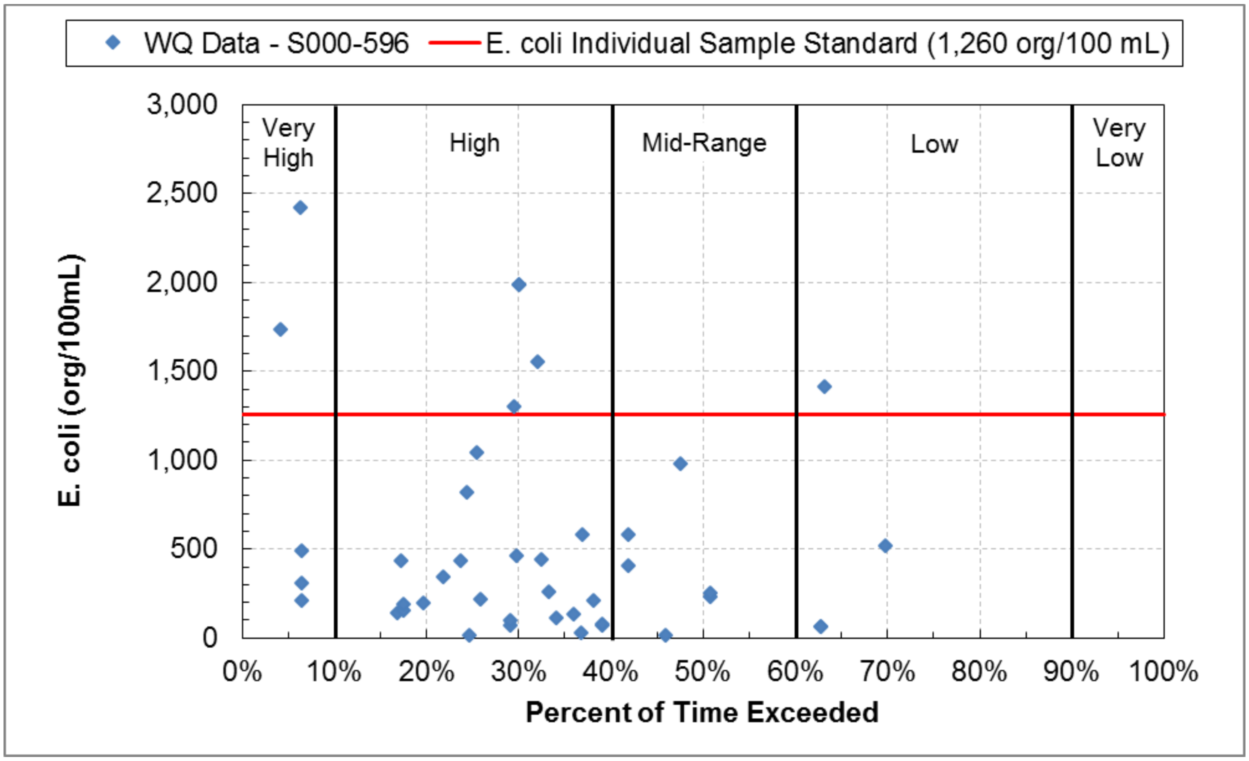


Figure 26. *E. coli* concentration duration plot, Barber Creek (AUID 04010201-569)

Unnamed Creek (04010201-A22)

There is one monitoring station on this impaired reach (Figure 3). The *E. coli* concentration was greater than the individual sample standard twice in Unnamed Creek in 2009 (Table 21). The individual sample standard was exceeded in July, and the monthly geometric mean standard was exceeded in July and August (Table 22). The individual exceedances occurred under high flow conditions; there are no samples from very low flows and only one from low flows (Figure 27).

Table 21. Annual summary of *E. coli* data at Unnamed Creek (AUID 04010201-A22, site S005-680, May–Oct)

Year	Sample Count	Annual Geometric Mean (org/100 mL)	Minimum (org/100mL)	Maximum (org/100mL)	Number of Individual Sample Standard Exceedances (> 1,260 org/100 mL)	Percent of Individual Sample Standard Exceedances
2009	9	68	11	2,420	2	22
2010	13	69	6	1,046	0	0

Table 22. Monthly summary of *E. coli* data at Unnamed Creek (AUID 04010201-A22, site S005-680, 2009–2010)
Values in red indicate months in which the monthly geometric mean standard of 126 org/100 mL was exceeded or the individual sample standard of 1,260 org/100 mL was exceeded in greater than 10% of the samples.

Month	Sample Count	Monthly Geometric Mean (org/100 mL)	Minimum (org/100mL)	Maximum (org/100mL)	Number of Individual Sample Standard Exceedances (> 1,260 org/100 mL)	Percent of Individual Sample Standard Exceedances
May	1 [a]	102	102	102	0	0
June	6	25	6	66	0	0
July	6	741	238	2,420	2	33
August	7	276	116	980	0	0
September	1 [a]	16	16	16	0	0
October	1 [a]	7	7	7	0	0

a. Not enough samples to assess compliance with the monthly geometric mean standard

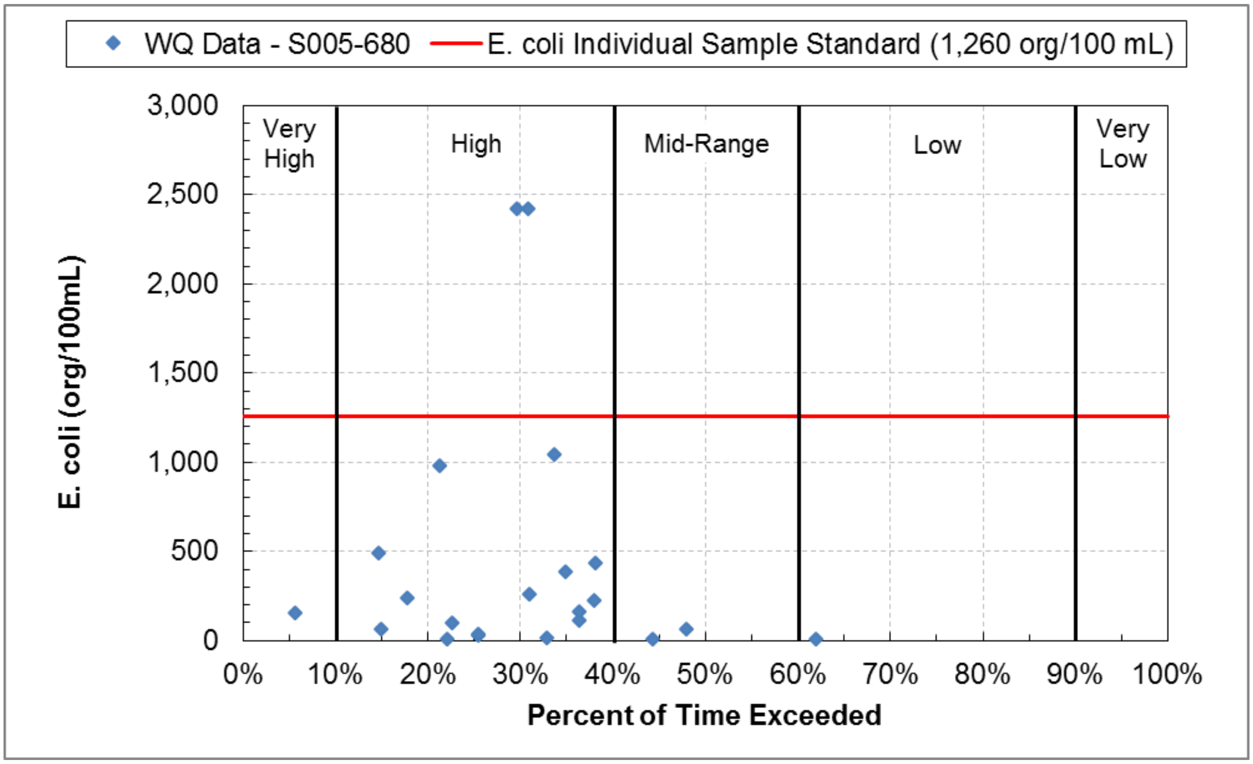


Figure 27. *E. coli* concentration duration plot, Unnamed Creek (AUID 04010201-A22)

Unnamed Creek (04010201-542)

There is one monitoring station on this impaired reach (Figure 3). The *E. coli* concentration was greater than the individual sample standard in one sample in Unnamed Creek in 2009 (Table 23). The individual sample standard was exceeded in July, and the monthly geometric mean standard was exceeded in July and August (Table 24). The one exceedance of the individual sample standard was during high flow conditions (Figure 28). There are no samples during very low flow conditions and only one from low flow conditions.

Table 23. Annual summary of *E. coli* data at Unnamed Creek (AUID 04010201-542, site S000-792, May–Oct)

Year	Sample Count	Annual Geometric Mean (org/100 mL)	Minimum (org/100mL)	Maximum (org/100mL)	Number of Individual Sample Standard Exceedances (> 1,260 org/100 mL)	Percent of Individual Sample Standard Exceedances
2009	12	70	11	1,733	1	8
2010	12	89	5	548	0	0

Table 24. Monthly summary of *E. coli* data at Unnamed Creek (AUID 04010201-542, site S000-792, 2009–2010)
Values in red indicate months in which the monthly geometric mean standard of 126 org/100 mL was exceeded or the individual sample standard of 1,260 org/100 mL was exceeded in greater than 10% of the samples.

Month	Sample Count	Monthly Geometric Mean (org/100 mL)	Minimum (org/100mL)	Maximum (org/100mL)	Number of Individual Sample Standard Exceedances (> 1,260 org/100 mL)	Percent of Individual Sample Standard Exceedances
May	1[a]	5	5	5	0	0
June	7	64	72	162	0	0
July	6	175	35	1,733	1	17
August	6	150	46	648	0	0
September	2[a]	58	27	125	0	0
October	2[a]	12	11	14	0	0

a. Not enough samples to assess compliance with the monthly geometric mean standard

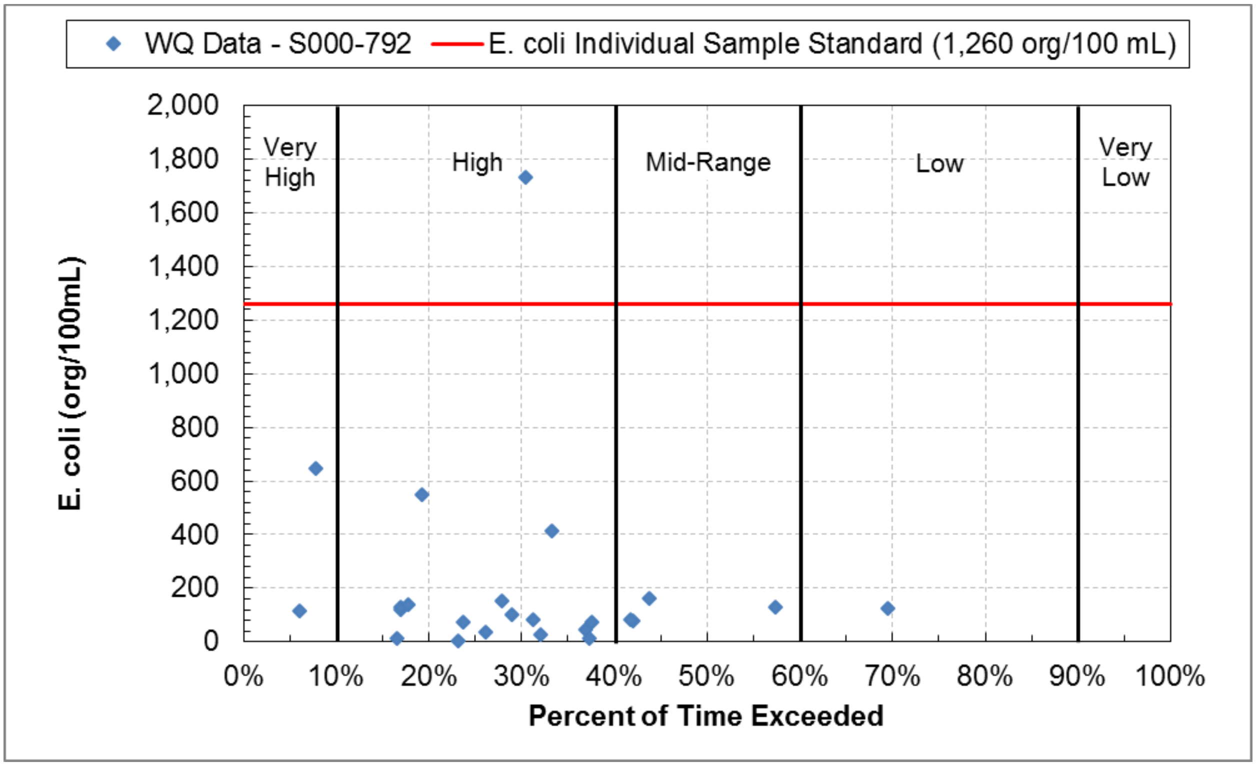


Figure 28. ***E. coli*** **concentration duration plot, Unnamed Creek (AUID 04010201-542)**

Unnamed Creek (East Swan Creek, 04010201-888)

There is one monitoring station on this impaired reach (Figure 3). The *E. coli* concentration was greater than the individual sample standard three times in Unnamed Creek in 2009 (Table 25). The individual sample standard was exceeded in July, and the monthly geometric mean standard was exceeded in July and August (Table 26). The individual exceedances occurred under high flow conditions; there are no samples from very low flows (Figure 29).

Table 25. Annual summary of ***E. coli*** **data at Unnamed Creek (AUID 04010201-888, site S000-589, May–Oct)**

Year	Sample Count	Annual Geometric Mean (org/100 mL)	Minimum (org/100mL)	Maximum (org/100mL)	Number of Individual Sample Standard Exceedances (> 1,260 org/100 mL)	Percent of Individual Sample Standard Exceedances
2009	19	183	19	2,420	3	16
2010	13	188	17	1,120	0	0

Table 26. Monthly summary of *E. coli* data at Unnamed Creek (AUID 04010201-888, site S000-589, 2009–2010)
Values in red indicate months in which the monthly geometric mean standard of 126 org/100 mL was exceeded or the individual sample standard of 1,260 org/100 mL was exceeded in greater than 10% of the samples.

Month	Sample Count	Monthly Geometric Mean (org/100 mL)	Minimum (org/100mL)	Maximum (org/100mL)	Number of Individual Sample Standard Exceedances (> 1,260 org/100 mL)	Percent of Individual Sample Standard Exceedances
May	1 [a]	17	17	17	0	0
June	9	96	36	435	0	0
July	10	494	113	2,420	3	33
August	8	231	96	1,120	0	0
September	2 [a]	219	157	308	0	0
October	2 [a]	29	19	45	0	0

a. Not enough samples to assess compliance with the monthly geometric mean standard

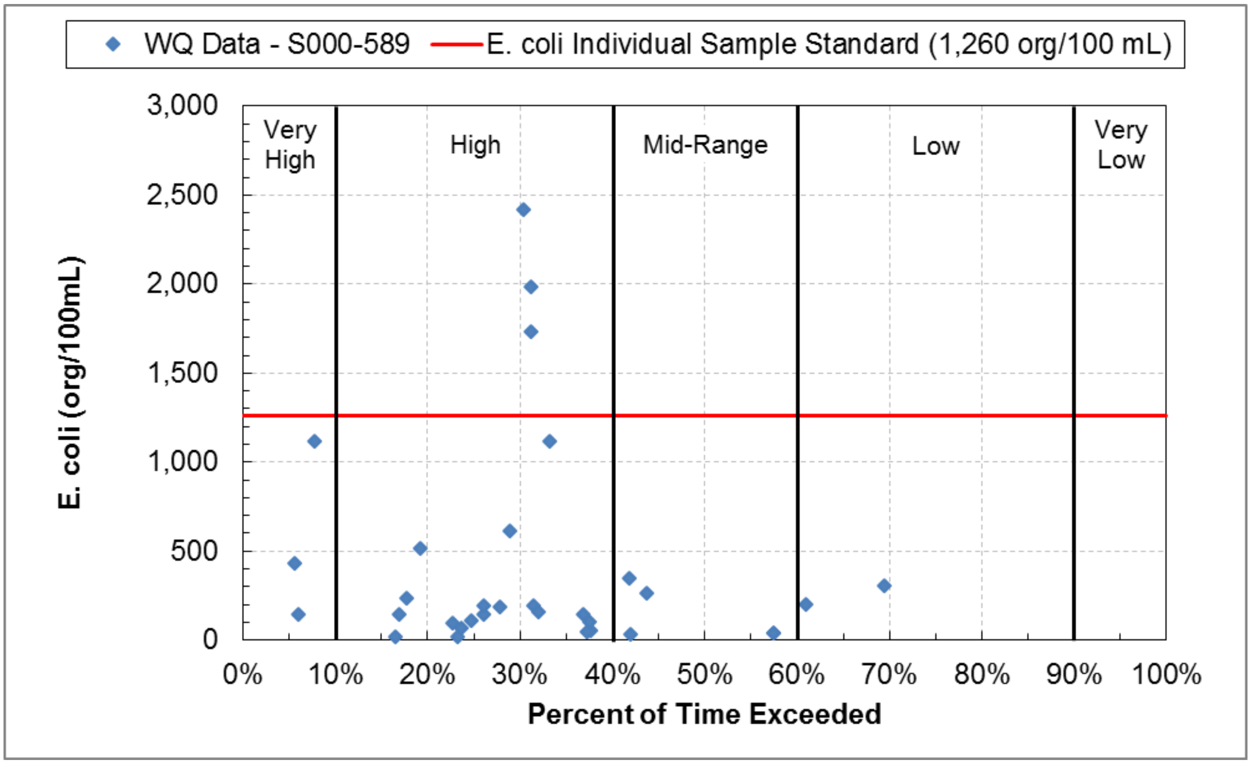


Figure 29. *E. coli* concentration duration plot, Unnamed Creek (AUID 04010201-888)

Pine River (White Pine River, 04010201-543)

There is one monitoring station on the impaired reach of the Pine River (Figure 4). The individual sample standard was not exceeded in the Pine River, and the monthly geometric mean standard was exceeded in July (Table 27 and Table 28). *E. coli* concentrations did not appear to vary substantially by flow (Figure 30); however, there are no samples from very low flows.

Table 27. Annual summary of *E. coli* data at Pine River (AUID 04010201-543, site S005-759, Jun–Aug)

Year	Sample Count	Annual Geometric Mean (org/100 mL)	Minimum (org/100mL)	Maximum (org/100mL)	Number of Individual Sample Standard Exceedances (> 1,260 org/100 mL)	Percent of Individual Sample Standard Exceedances
2009	7	80	31	228	0	0
2010	11	143	55	410	0	0

Table 28. Monthly summary of *E. coli* data at Pine River (AUID 04010201-543, site S005-759, 2009–2010)
Values in red indicate months in which the monthly geometric mean standard of 126 org/100 mL was exceeded or the individual sample standard of 1,260 org/100 mL was exceeded in greater than 10% of the samples.

Month	Sample Count	Monthly Geometric Mean (org/100 mL)	Minimum (org/100mL)	Maximum (org/100mL)	Number of Individual Sample Standard Exceedances (> 1,260 org/100 mL)	Percent of Individual Sample Standard Exceedances
June	6	76	55	131	0	0
July	7	184	74	410	0	0
August	5	95	31	310	0	0

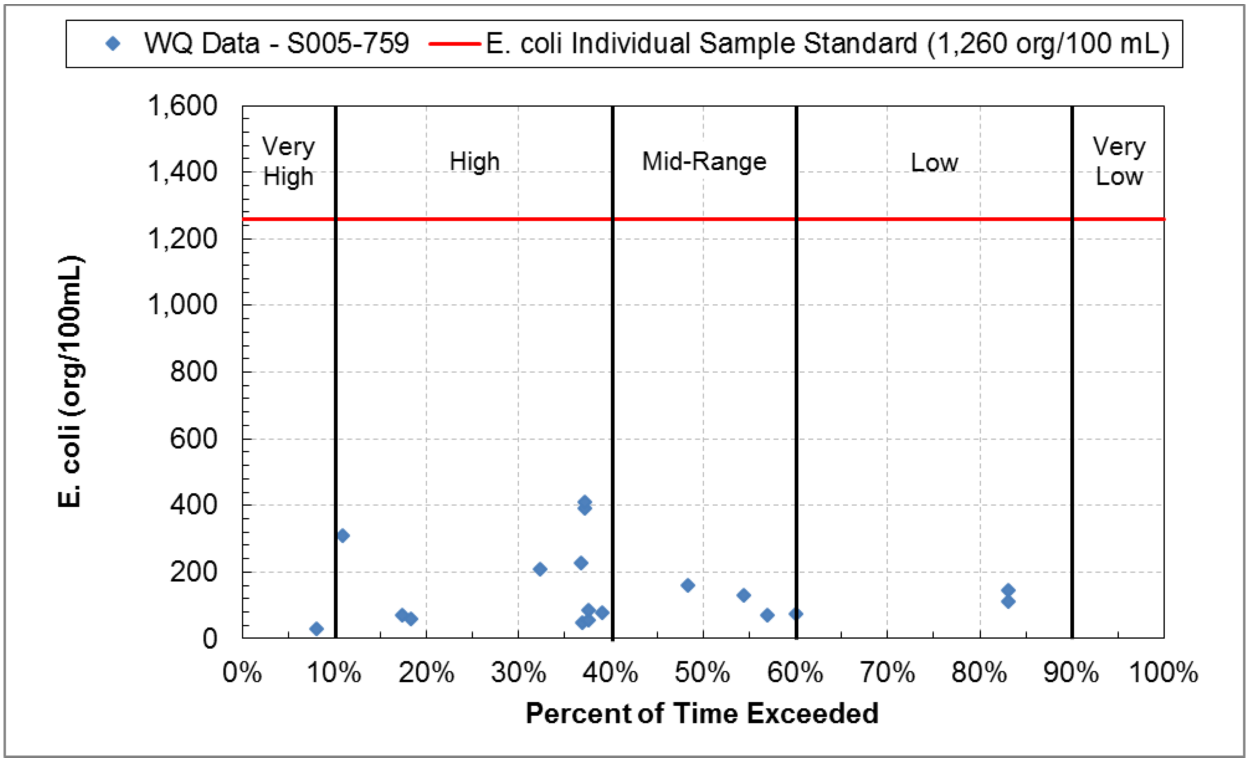


Figure 30. ***E. coli*** **concentration duration plot, Pine River (AUID 04010201-543)**

Hay Creek (04010201-751)

There is one monitoring station on the impaired reach of Hay Creek (Figure 4). The *E. coli* concentration was greater than the individual sample standard three times in Hay Creek (Table 29). The individual sample standard was exceeded in July and August, and the monthly geometric mean standard was exceeded in July and August (Table 30). The individual exceedances occurred from mid-range to very high flow conditions and were more severe during very high flow conditions; there are no samples from very low flows and only one from low flows (Figure 31).

Table 29. Annual summary of ***E. coli*** **data at Hay Creek (AUID 04010201-751, site S005-942, Jun–Sep)**

Year	Sample Count	Annual Geometric Mean (org/100 mL)	Minimum (org/100mL)	Maximum (org/100mL)	Number of Individual Sample Standard Exceedances (> 1,260 org/100 mL)	Percent of Individual Sample Standard Exceedances
2009	8	144	45	2,420	2	25
2010	11	146	15	2,000	1	9

Table 30. Monthly summary of *E. coli* data at Hay Creek (AUID 04010201-751, site S005-942, 2009–2010)
Values in red indicate months in which the monthly geometric mean standard of 126 org/100 mL was exceeded or the individual sample standard of 1,260 org/100 mL was exceeded in greater than 10% of the samples.

Month	Sample Count	Monthly Geometric Mean (org/100 mL)	Minimum (org/100mL)	Maximum (org/100mL)	Number of Individual Sample Standard Exceedances (> 1,260 org/100 mL)	Percent of Individual Sample Standard Exceedances
June	5	109	50	180	0	0
July	6	253	45	2,420	2	33
August	6	197	59	2,420	1	17
September	2[a]	23	15	34	0	0

a. Not enough samples to assess compliance with the monthly geometric mean standard

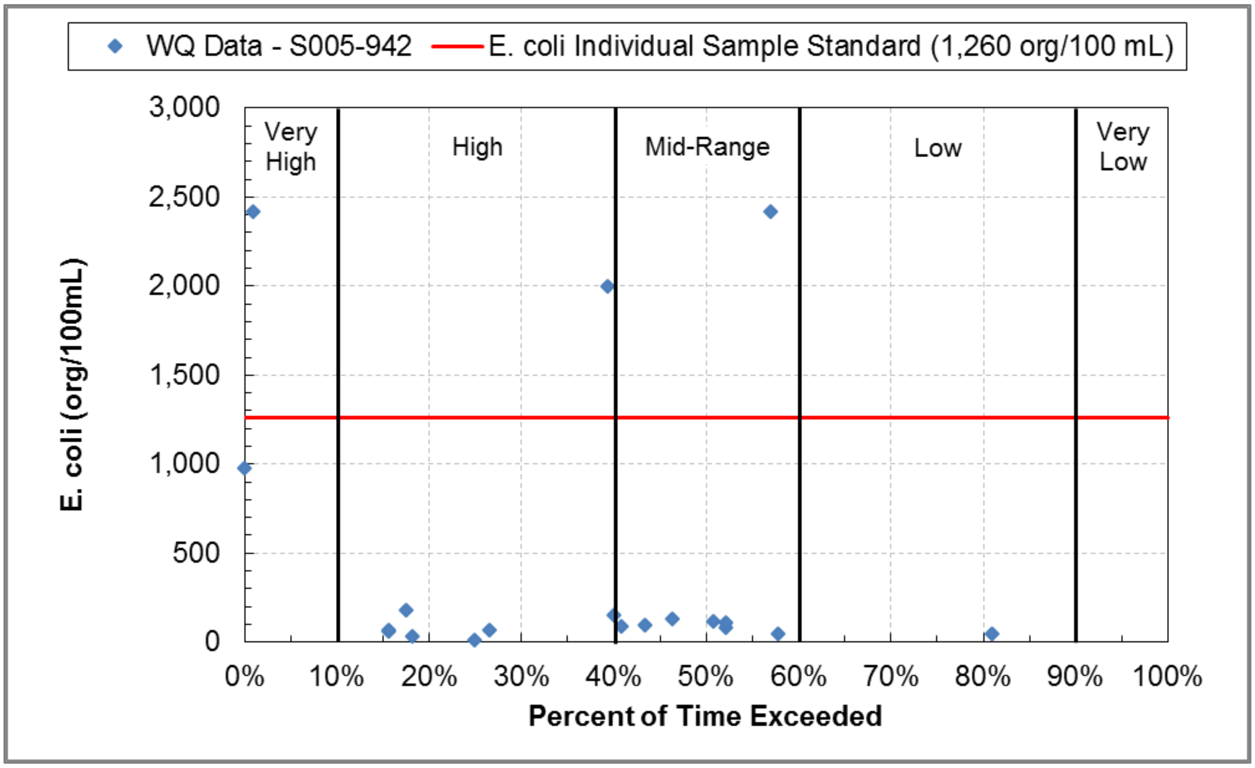


Figure 31. *E. coli* concentration duration plot, Hay Creek (AUID 04010201-751)

Unnamed Creek / West Rocky Run (04010201-625)

There is one monitoring station on this impaired reach (Figure 4).The *E. coli* concentration was greater than the individual sample standard three times in Unnamed Creek/West Rocky Run (Table 31). The individual sample standard was exceeded in July and August, and the monthly geometric mean standard was exceeded in June, July, and August (Table 32). The individual exceedances occurred from low to very high flow conditions; there are no samples from very low flows and only one from low flows (Figure 26).

Table 31. Annual summary of *E. coli* data at Unnamed Creek / West Rocky Run (AUID 04010201-625, site S005-863, Jun–Sep)

Year	Sample Count	Annual Geometric Mean (org/100 mL)	Minimum (org/100mL)	Maximum (org/100mL)	Number of Individual Sample Standard Exceedances (> 1,260 org/100 mL)	Percent of Individual Sample Standard Exceedances
2009	8	184	93	2,420	2	25
2010	12	266	55	1,600	1	8

Table 32. Monthly summary of *E. coli* data at Unnamed Creek / West Rocky Run (AUID 04010201-625, site S005-863, 2009–2010)

Values in red indicate months in which the monthly geometric mean standard of 126 org/100 mL was exceeded or the individual sample standard of 1,260 org/100 mL was exceeded in greater than 10% of the samples.

Month	Sample Count	Monthly Geometric Mean (org/100 mL)	Minimum (org/100mL)	Maximum (org/100mL)	Number of Individual Sample Standard Exceedances (> 1,260 org/100 mL)	Percent of Individual Sample Standard Exceedances
June	5	127	55	291	0	0
July	6	404	125	2,420	2	33
August	5	329	84	2,420	1	20
September	4[a]	132	120	160	0	0

a. Not enough samples to assess compliance with the monthly geometric mean standard

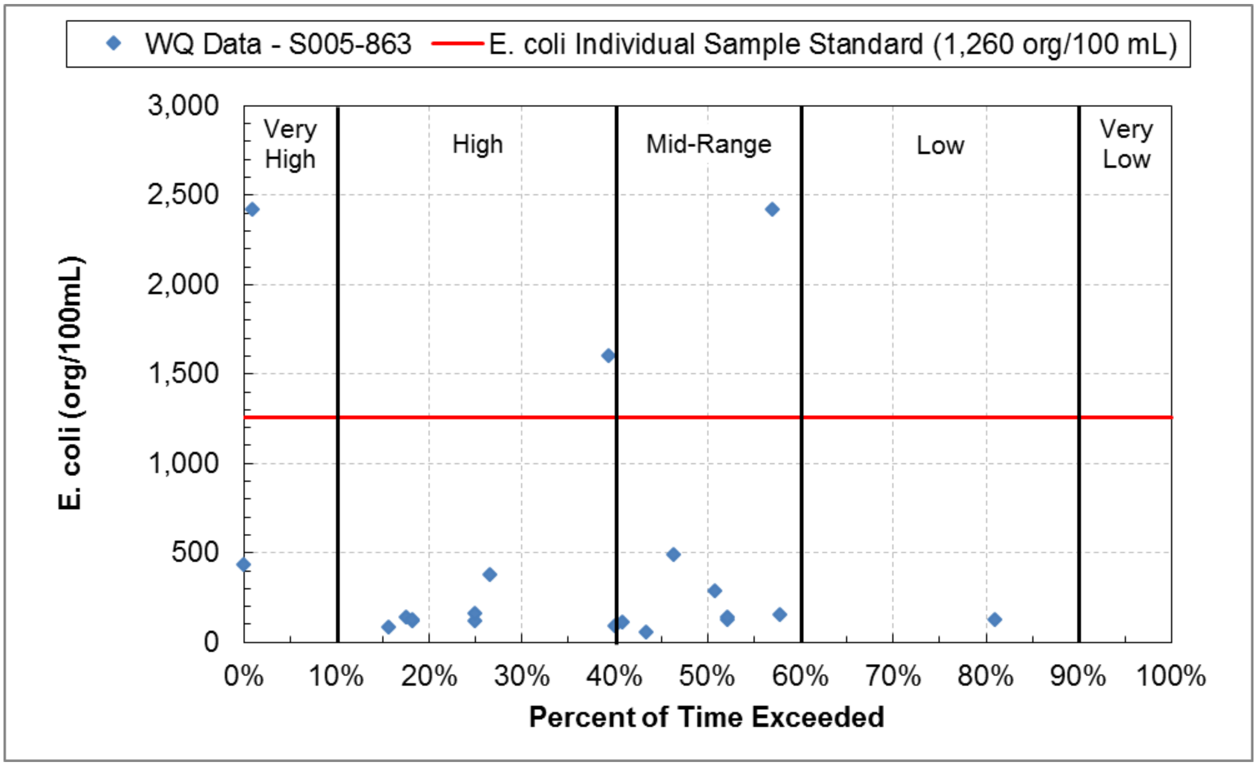


Figure 32. ***E. coli*** **concentration duration plot, Unnamed Creek/West Rocky Run (AUID 04010201-625)**

3.5.2 Total Suspended Solids

East Swan River (04010201-558)

There are four monitoring sites on the impaired reach of the East Swan River (Figure 5). Average annual TSS concentrations in the East Swan River range from 29 to 43 mg/L (Table 33). Greater than 10% of the samples exceeded the 10 mg/L TSS standard in each year that was monitored. Monthly means (during the months in which the standard applies) vary from 10 to 55 mg/L, with exceedances occurring every month (Table 34). The standard was exceeded during mid-range to very high flows, with higher concentrations occurring under very high flows (Figure 33).

Table 33. Annual summary of TSS data for the East Swan River (AUID 04010201-558, sites S000-281, S006-192, S007-157 and S007-158, Apr–Sep)

Values in red indicate years in which the numeric criteria of 10 mg/L was exceeded in greater than 10% of the samples.

Year	Sample Count	Mean (mg/L)	Minimum (mg/L)	Maximum (mg/L)	Number of Exceedances	Frequency of Exceedances
2010	17	36	6	250	14	82%
2012	8	29	6	56	5	63%
2013	8	43	17	84	8	100%

Table 34. Monthly summary of TSS data for the East Swan River (AUID 04010201-558, sites S000-281, S006-192, S007-157 and S007-158; 2010, 2012–2013)

Values in red indicate months in which the numeric criteria of 10 mg/L was exceeded in greater than 10% of the samples.

Month	Sample Count	Mean (mg/L)	Minimum (mg/L)	Maximum (mg/L)	Number of Exceedances	Frequency of Exceedances
April	5	54	6	84	4	80%
May	3	19	9	34	2	67%
June	7	39	17	56	7	100%
July	6	10	6	14	2	33%
August	8	55	17	250	8	100%
September	4	22	11	43	4	100%
October	3	6	5	7	NA	NA

NA: not applicable because the TSS standard does not apply during this month

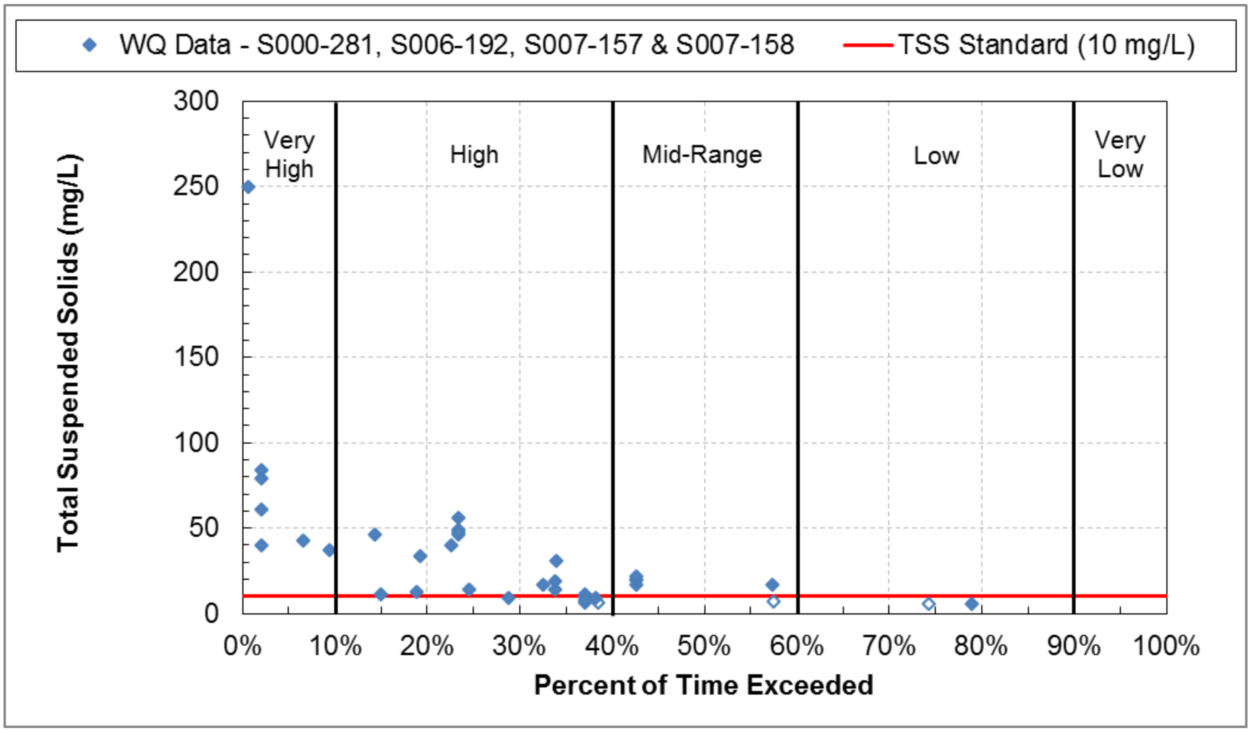


Figure 33. TSS concentration duration plot, East Swan River (AUID 04010201-558), 2010, 2012-2013.

Hollow points indicate samples during months when the standard does not apply.

The East Swan River joins with the West Swan River to form the Swan River (AUID 04010201-557). TSS concentrations in the Swan River are high, with average annual TSS concentrations ranging from 11 to 44 mg/L (Table 35), and monthly means ranging from 8 to 67 mg/L (Table 36). Concentrations are highest under very high flows (Figure 34). The data evaluation in the SID (MPCA 2016) indicates that, after any significant rainfall or snowmelt event, the river remains turbid for long periods of time due to the suspended fine silt and clay particles.

Table 35. Annual summary of TSS data for the Swan River (AUID 04010201-557, sites S000-641 and S005-770, Apr–Sep).

Year	Sample Count	Mean (mg/L)	Minimum (mg/L)	Maximum (mg/L)
2009	10	11	5	28
2012	20	44	5	143
2013	28	44	3	190
2014	19	37	5	89

Table 36. Monthly summary of TSS data for the Swan River (AUID 04010201-557, sites S000-641 and S005-770, 2009, 2012–2014).

Month	Sample Count	Mean (mg/L)	Minimum (mg/L)	Maximum (mg/L)
March	5	13	10	15
April	16	67	8	190
May	19	55	10	143
June	16	34	8	85
July	12	13	5	22
August	8	8	4	15
September	6	8	3	16
October	10	8	2	15

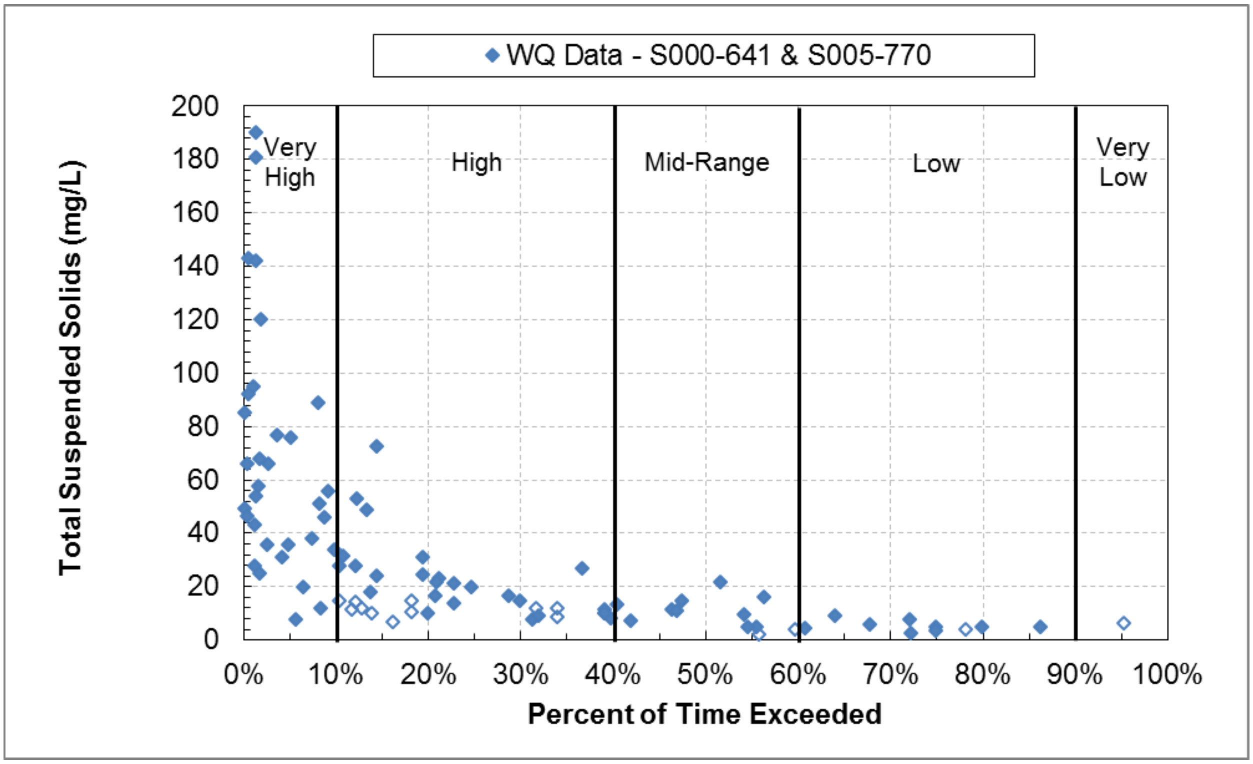


Figure 34. TSS concentration duration plot, Swan River (AUID 04010201-557); 2009, 2012–2014.
Hollow points indicate samples during months when the TSS standard does not apply.

In May and June, transparency is better in the East Swan River compared to the Swan River; transparencies during other months are similar in both reaches (Figure 35). There is not enough TSS data from the two reaches over the same time period to compare concentrations between the two reaches.

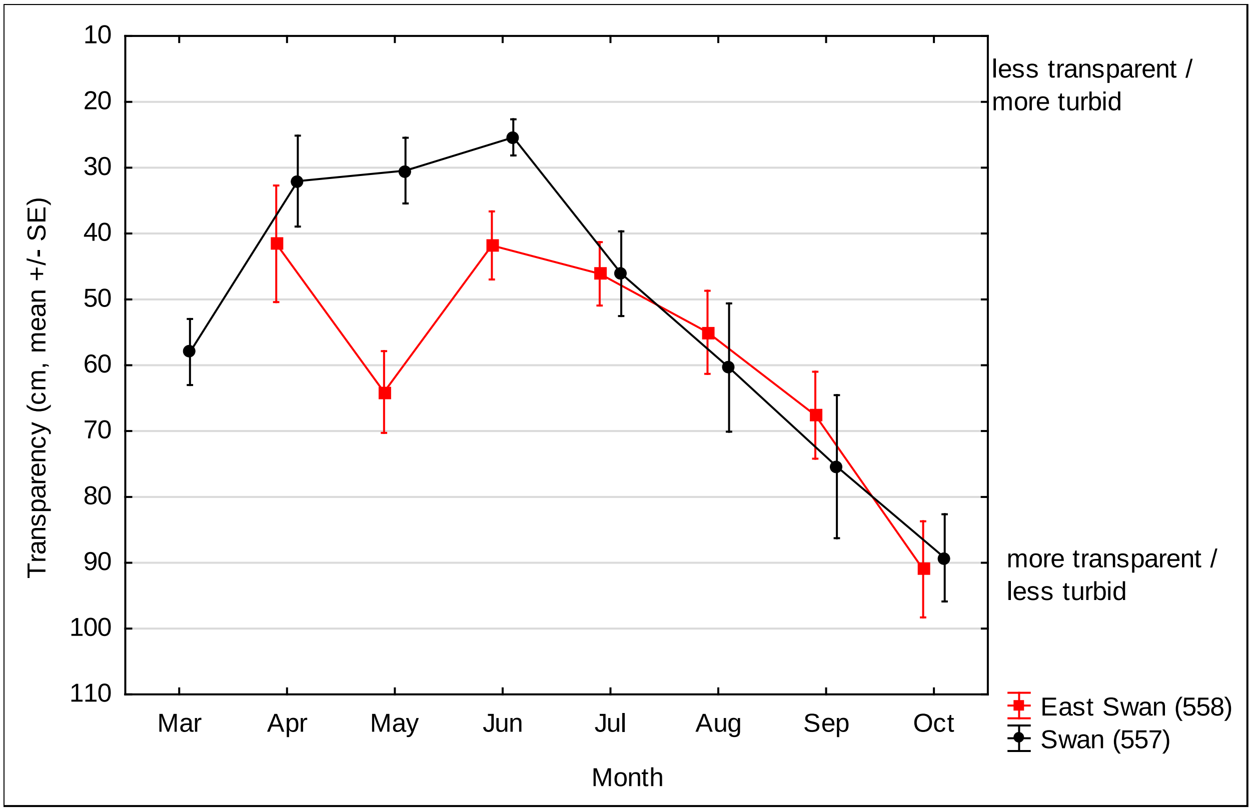


Figure 35. Average monthly transparency, East Swan and Swan River (AUIDs 04010201-558 and -557).
The two data series are offset to avoid overlapping points/bars.

Stony Creek (04010201-963)

The Stony Creek monitoring site is located at the downstream end of the impaired reach (Figure 5). Average annual TSS concentrations in Stony Creek range from 12 to 16 mg/L (Table 37). 2012 and 2013 were the only years during which TSS was measured more than once, and one TSS exceedance was recorded during each of those years. Because of the low sample size, a single exceedance in a year leads to an exceedance of the standard (i.e., greater than 10% of the readings exceed the standard). Monthly means vary from 11 to 20 mg/L (Table 38); the sample size is too low to draw conclusions regarding data trends. The standard was exceeded once during mid-range flows, once during high flows, and once during very high flows (Figure 36).

Table 37. Annual summary of TSS data for Stony Creek (AUID 04010201-963, site S007-052 / 09LS036, Apr–Sep)
Values in red indicate years in which the numeric criteria of 15 mg/L was exceeded in greater than 10% of the samples.

Year	Sample Count	Annual Mean (mg/L)	Minimum (mg/L)	Maximum (mg/L)	Number of Exceedances	Frequency of Exceedances
2009	1	14	14	14	0	0%
2012	4	13	10	20	1	25%
2013	6	12	8	18	1	17%
2014	1	16	16	16	1	100%

Table 38. Monthly summary of TSS data for Stony Creek (AUID 04010201-963, site S007-052 / 09LS036; 2009, 2012–2014)
Values in red indicate months in which the numeric criteria of 15 mg/L was exceeded in greater than 10% of the samples.

Month	Sample Count	Mean (mg/L)	Minimum (mg/L)	Maximum (mg/L)	Number of Exceedances	Frequency of Exceedances
March	1	13	13	13	NA	NA
April	1	11	11	11	0	0%
May	1	20	20	20	1	100%
June	5	12	10	18	1	20%
July	4	11	8	14	0	0%
August	1	16	16	16	1	100%

NA: not applicable because the TSS standard does not apply during this month

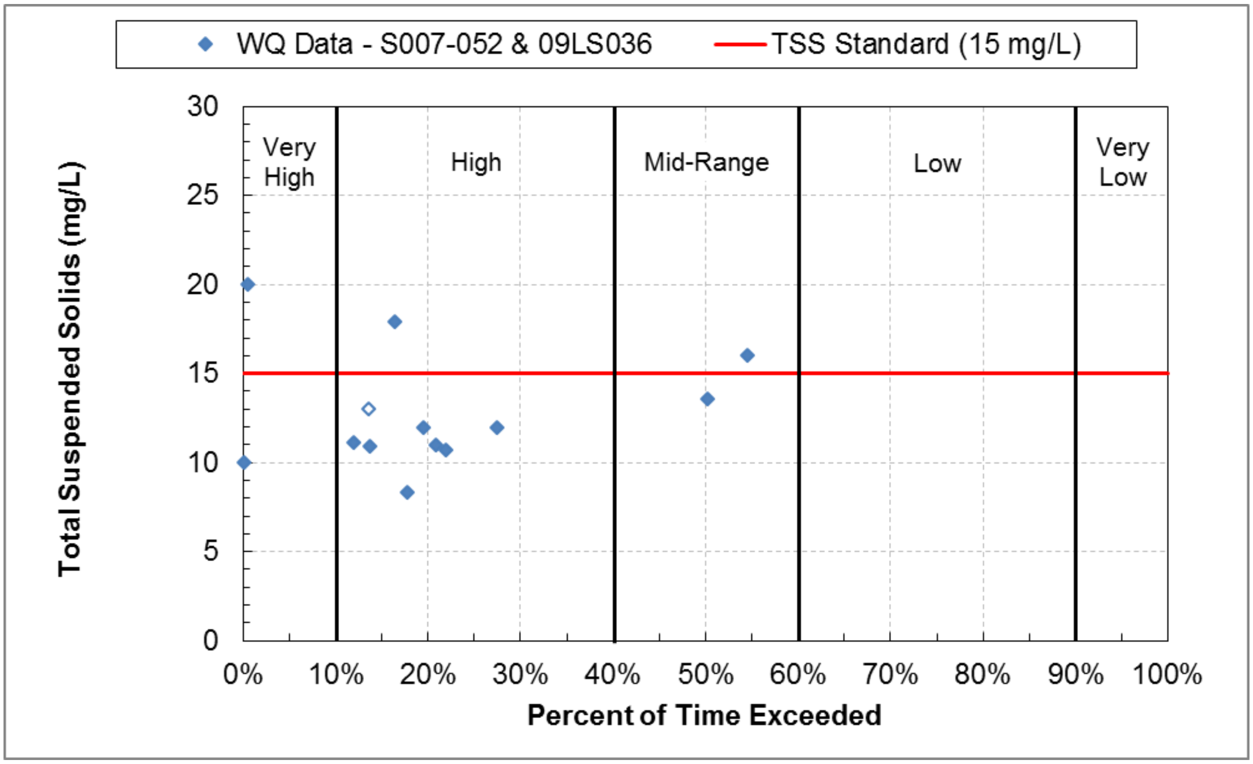


Figure 36. TSS concentration duration plot, Stony Creek (AUID 04010201-963); 2009, 2012–2014.
Hollow points indicate samples during months when the standard does not apply.

3.5.3 Phosphorus

This section presents the phosphorus data assessment for the two impaired lakes (Dinham Lake and West Two Rivers Reservoir) and the stream (West Two River) for which phosphorus TMDLs were developed. A high daily DO range and low DO were identified as primary stressors to the biota in West Two River, to be addressed by a phosphorus TMDL (Table 4).

Dinham Lake (69-0544-00)

There are two monitoring sites on Dinham Lake (Figure 7). All of the data presented here are from site 69-0544-00-102 except for the 2011 Secchi transparency data, which are from site 69-0544-00-103. The average TP concentration in Dinham Lake is 36 µg/L (Table 39), with growing season means from the two years of monitoring at 34 and 39 µg/L (Figure 37). Average growing season phosphorus, chl-*a*, and Secchi transparency means did not meet the water quality standards in any of the years that were monitored (Figure 37). Carlson's TSI ranges from 56 to 60 (Table 39), indicating a eutrophic lake. Water quality fluctuates throughout the growing season (Figure 38). In both years that were monitored, surface phosphorus concentrations were high in September. Chl-*a* steadily increased between the May and August sampling dates, after which it dropped slightly.

The lake stratifies in the summer (Figure 39). In 2010, this stratification led to build-up of phosphorus in the hypolimnion in July; the phosphorus from the bottom waters mixed with the surface water at fall turnover and increased the surface phosphorus concentration (Figure 40). This effect of stratification on surface phosphorus was less pronounced in 2009.

Table 39. Dinham Lake surface water quality data summary (sites 69-0544-00-102 and -103).
Values in red indicate exceedances of the standard.

Parameter	Years of Data	Average of Annual Growing Season Means (Jun–Sep)	Water Quality Standard	Carlson's Trophic Status Index
Total Phosphorus (µg/L)	2009–2010	36	≤ 30	56
Chlorophyll-*a* (µg/L)	2009–2010	20	≤ 9	60
Secchi Transparency (m)	2009–2011	1.3	≥ 2.0	56

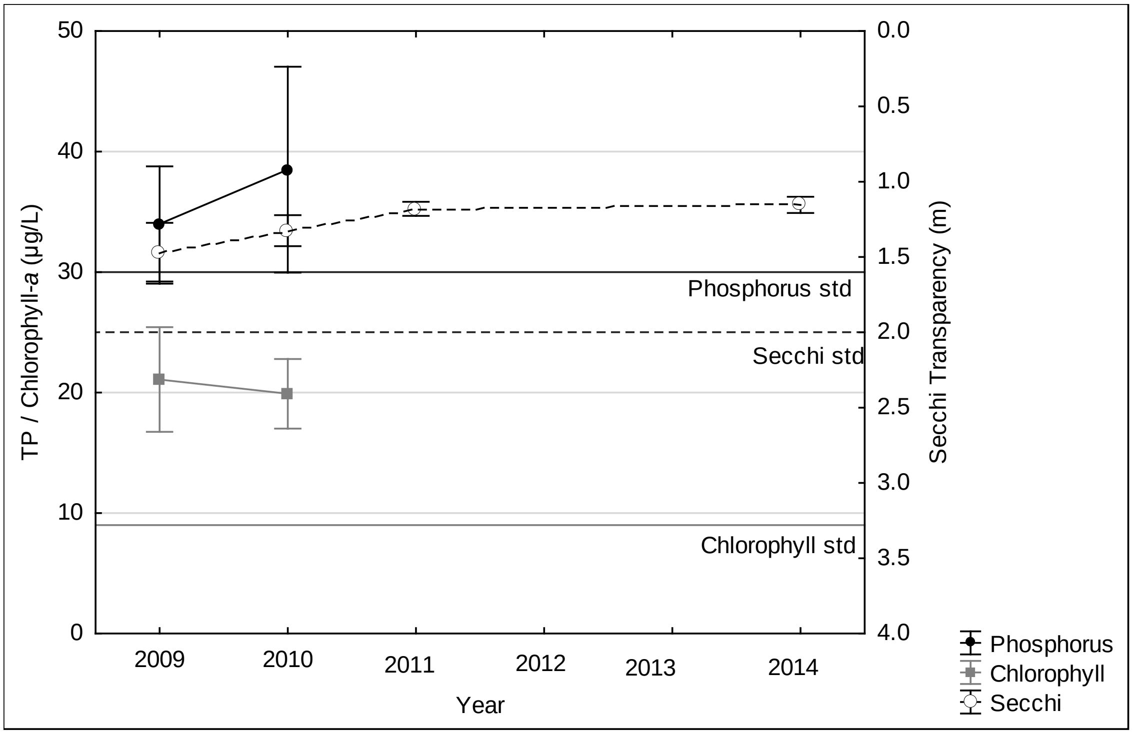


Figure 37. Dinham Lake water quality data, 2009–2014 (growing season means + / - standard error; sites 69-0544-00-102 and -103).

Phosphorus and chlorophyll data are from site 102; Secchi data are from site 102 for 2009, 2010, and 2014 and from site 103 for 2011.

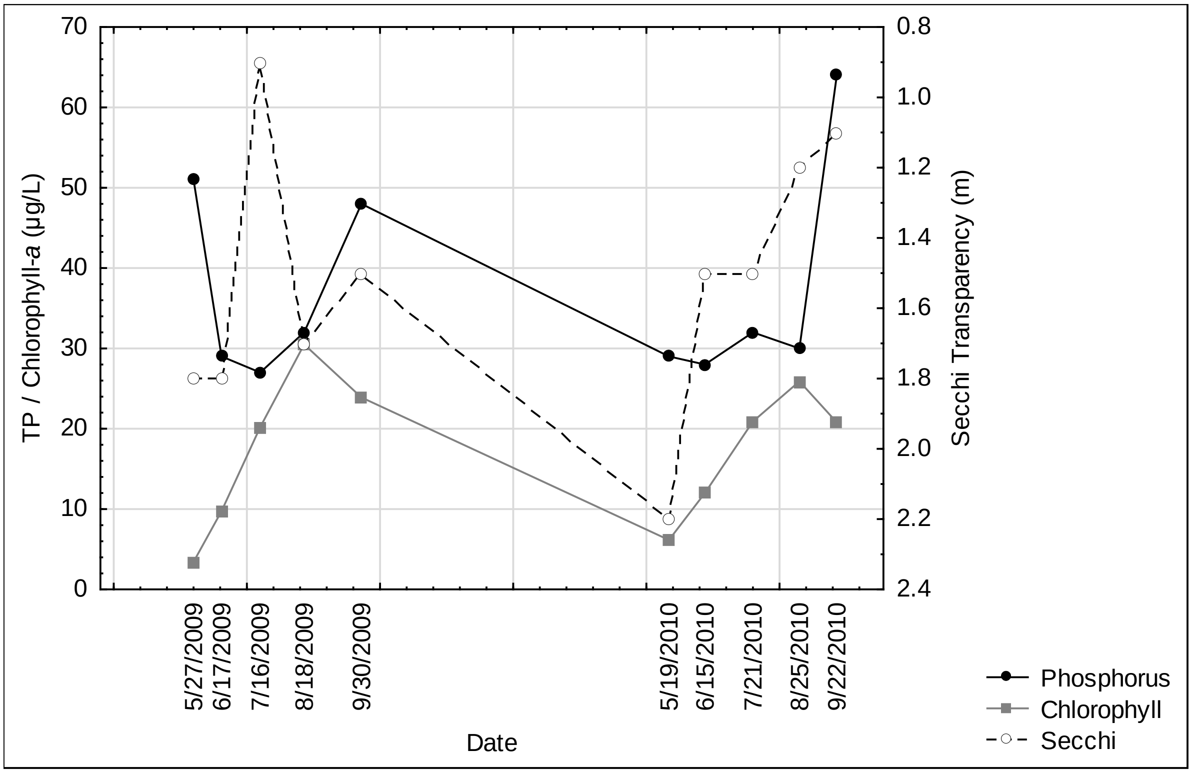


Figure 38. Dinham Lake phosphorus, chlorophyll-*a*, and transparency measurements, 2009 and 2010 (site 69-0544-00-102)

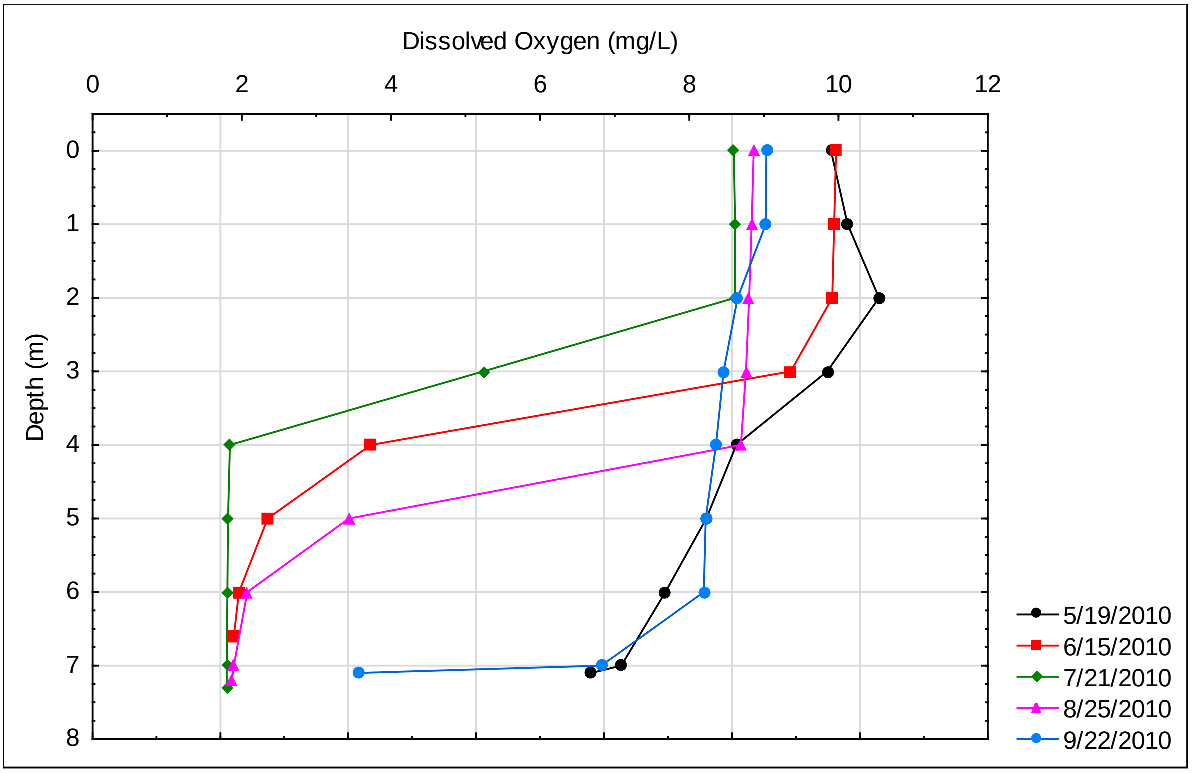


Figure 39. Dinham Lake dissolved oxygen profiles, 2010 (site 69-0544-00-102)

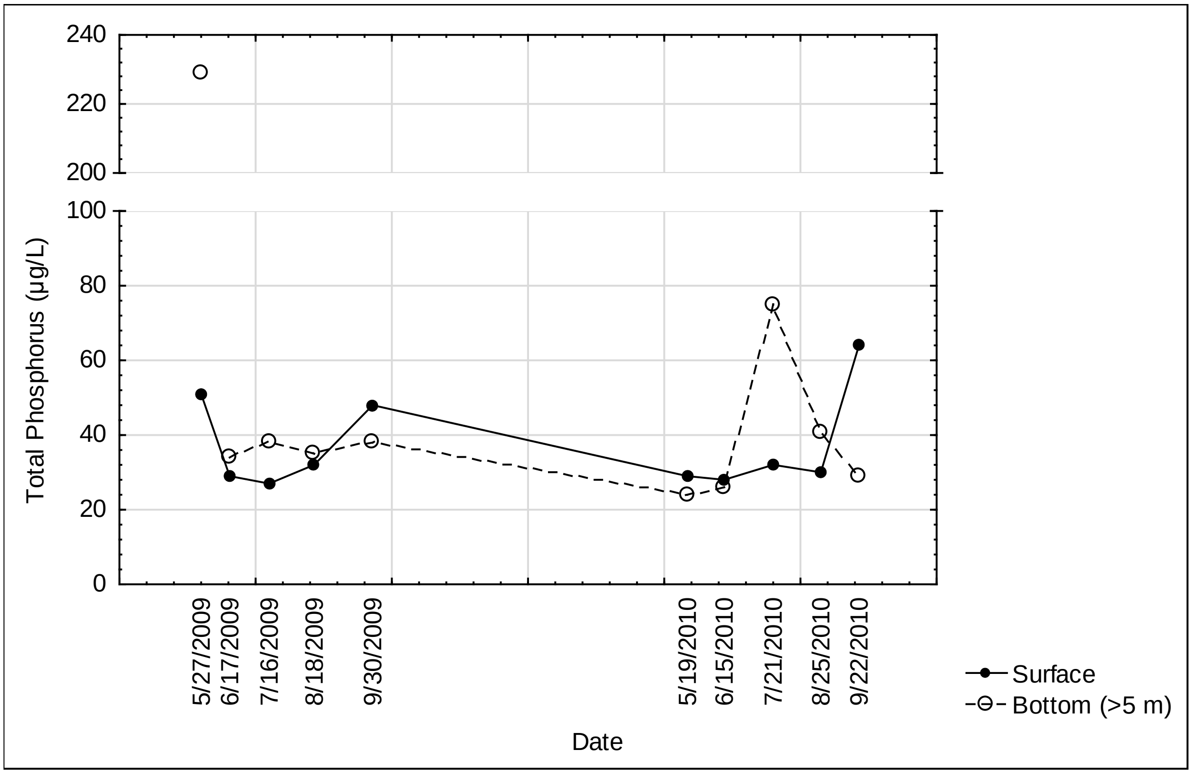


Figure 40. Dinham Lake surface versus bottom phosphorus concentrations, 2009–2010 (site 69-0544-00-102)

The most recent aquatic macrophyte survey on Dinham Lake was completed by the DNR in July of 2012. A list of plants is provided, but estimates of abundance or location are not available. The percent occurrence of *Ceratophyllum echinatum* (soft coontail, spiny hornwort) was recorded in the Natural Heritage Rare Features Database. Information on aquatic vegetation was also collected in 2010 by the DNR at the time of the fisheries assessment. Large-leaf pondweed, flat-stem pondweed, and variable-leaf pondweed were the most frequently found species.

A DNR fisheries population assessment in 2010 found walleye, northern pike, black crappie, bluegill, largemouth bass, yellow perch, brown and yellow bullhead, golden shiner, pumpkinseed sunfish, and white sucker. Walleye, black crappie, and yellow perch abundances were below average compared to other Minnesota lakes of similar type; northern pike and bluegill abundances were average.

West Two Rivers Reservoir (69-0994-00)

There is one monitoring site on West Two Rivers Reservoir (Figure 6). The average TP concentration in West Two Rivers Reservoir is 40 µg/L (Table 40), with growing season means from the two years of monitoring at 39 and 40 µg/L (Figure 41). Average growing season phosphorus, chlorophyll, and Secchi transparency means did not meet the water quality standards in any of the years that were monitored (Figure 41). Carlson's TSI ranges from 52 to 57 (Table 40), indicating a eutrophic lake. Water quality fluctuates throughout the growing season, and chlorophyll is typically high when phosphorus is high (Figure 42).

In the 2009 (Figure 43) and 2010 growing seasons, the lake stratified in the deep area where the monitoring site is located. In 2009, the hypolimnetic phosphorus concentration was slightly higher than the surface concentration in August. The lake mixed between the August and September sampling dates (Figure 43), after which the surface and bottom phosphorus concentrations were equal (Figure 44). In 2010, the hypolimnetic phosphorus concentration was slightly higher than the surface concentration in June and July; the pattern was reversed in August (Figure 44). Because a substantial portion of the lake is less than 15 feet deep (Figure 45), the lake likely stratifies intermittently in the shallow areas. This cycle of intermittent stratification and mixing, known as polymixis, can lead to phosphorus loading from lake sediments throughout the growing season. The lake phosphorus data and the shallow nature of the lake suggest that internal phosphorus loading can affect surface water quality in West Two Rivers Reservoir.

Table 40. West Two Rivers Reservoir surface water quality data summary (site 69-0994-00-100).
Values in red indicate exceedances of the standard.

Parameter	Years of Data	Average of Annual Growing Season Means (Jun–Sep)	Water Quality Standard	Carlson's Trophic Status Index
Total Phosphorus (µg/L)	2009–2010 [a]	40	≤ 30	57
Chlorophyll-a (µg/L)	2009–2010	15	≤ 9	57
Secchi Transparency (m)	2009–2010	1.7	≥ 2.0	52

a. One phosphorus measurement is available in 2005 but was not included in the data summary because of the limited sample size.

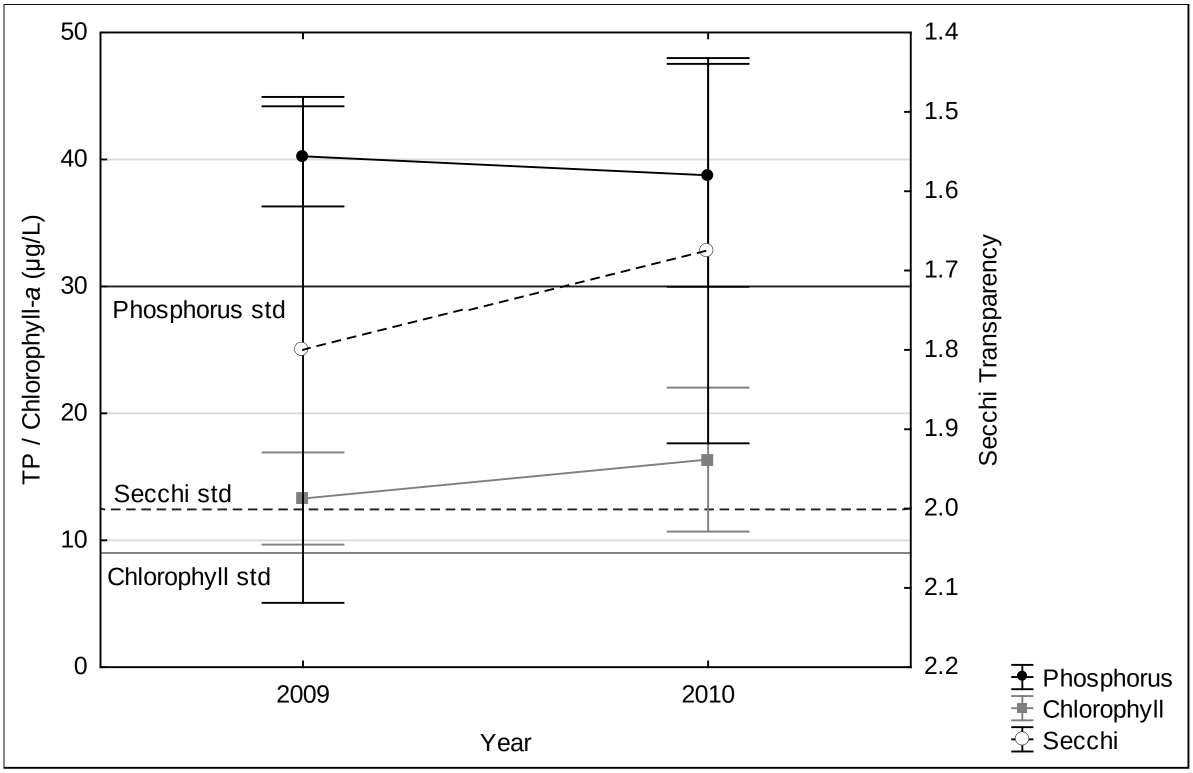


Figure 41. West Two Rivers Reservoir water quality data, 2009–2010 (growing season means + / - standard error; site 69-0994-00-100)

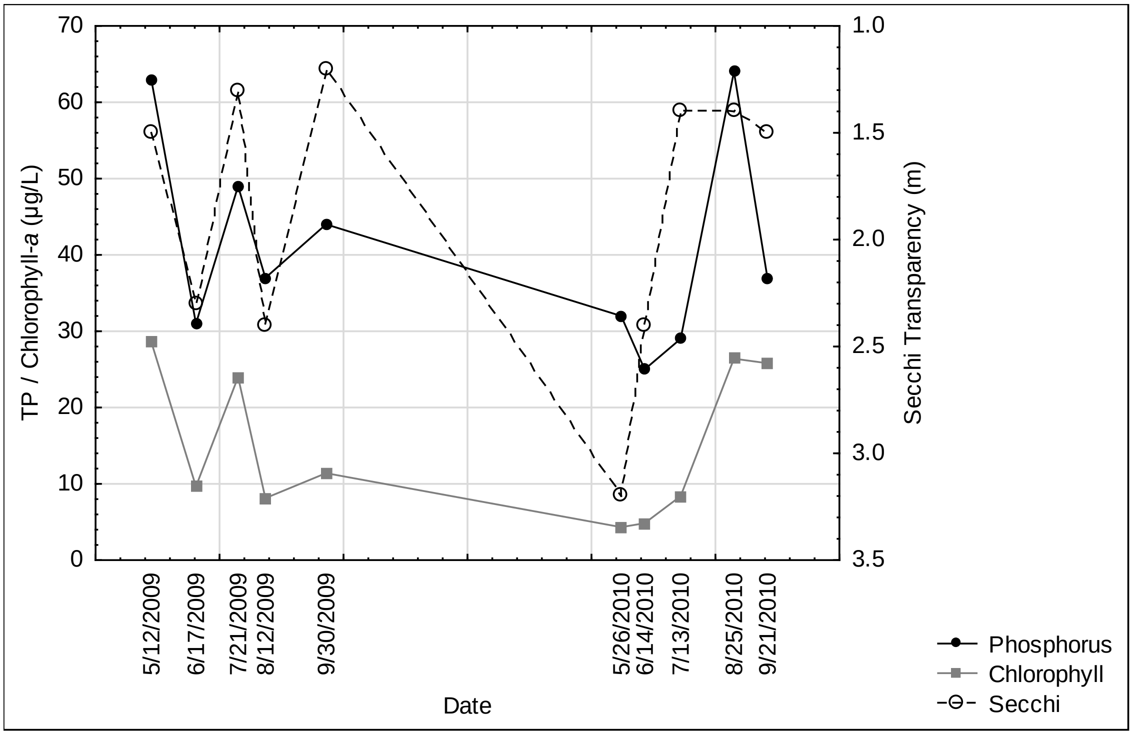


Figure 42. West Two Rivers Reservoir phosphorus, chlorophyll-*a*, and transparency measurements, 2009 and 2010 (site 69-0994-00-100)

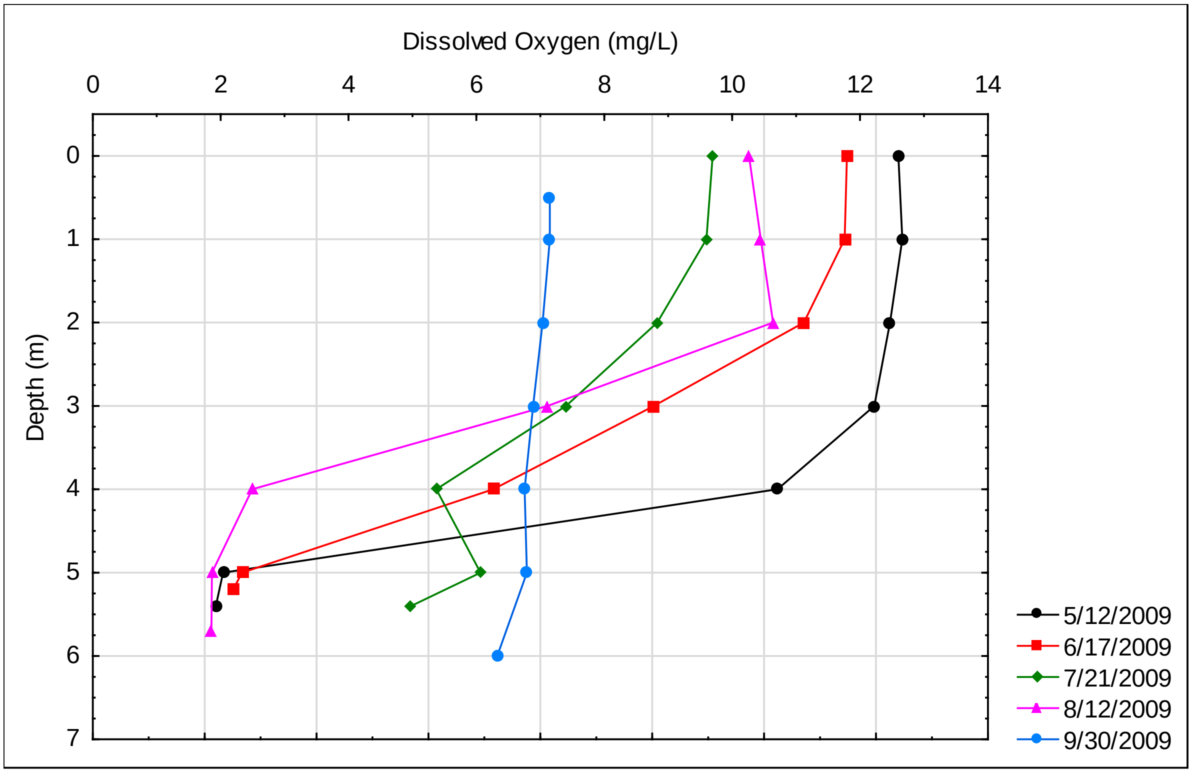


Figure 43. West Two Rivers Reservoir dissolved oxygen profiles, 2009 (site 69-0994-00-100)

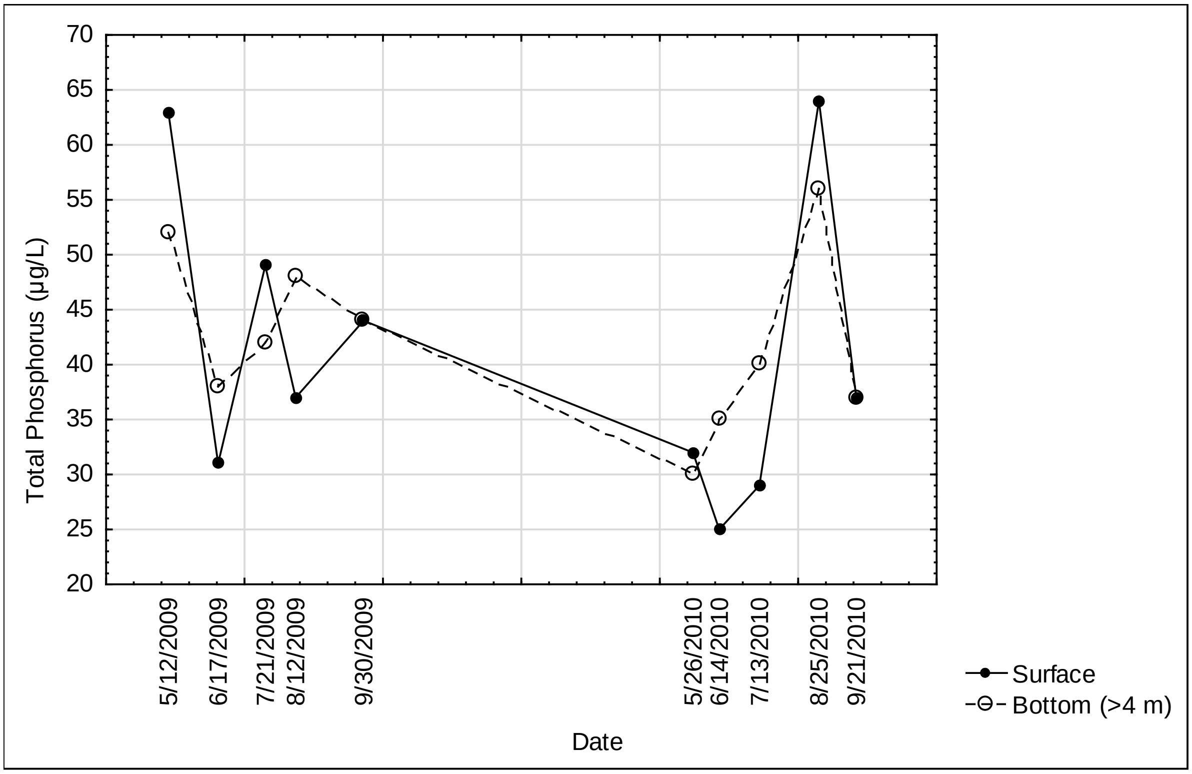


Figure 44. West Two Rivers Reservoir surface versus bottom phosphorus concentrations, 2009–2010 (site 69-0994-00-100)

The most recent aquatic macrophyte survey on West Two Rivers Reservoir was completed by the DNR in July of 2012. A list of plants is provided, but estimates of abundance or location are not available.

A DNR fisheries population assessment in 2013 found northern pike, black crappie, yellow perch, black bullhead, brown bullhead, pumpkinseed sunfish, green sunfish, hybrid sunfish, and golden shiner. Northern pike, black crappie, and black bullhead abundance was above average for a lake such as West Two Rivers Reservoir.

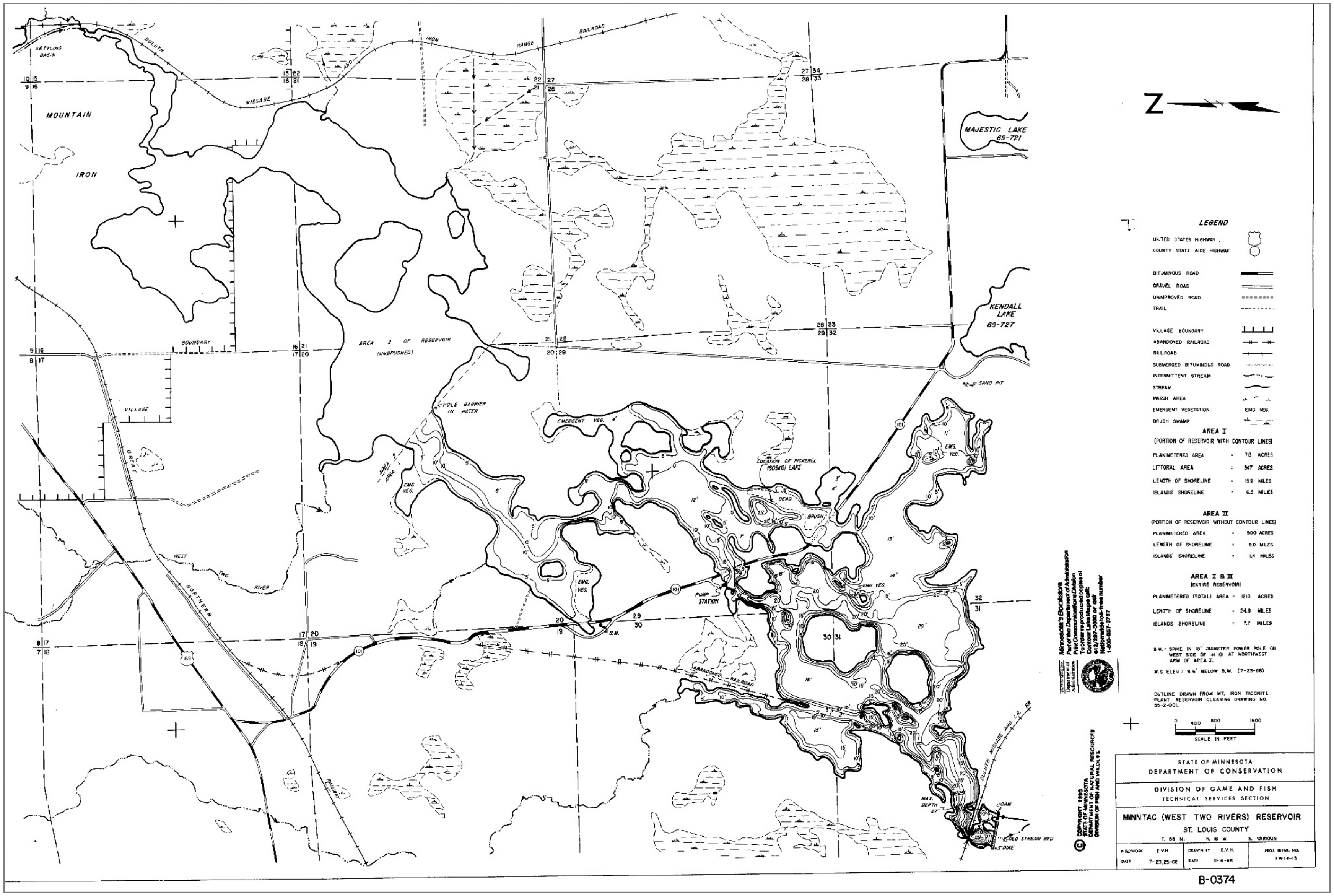


Figure 45. West Two Rivers Reservoir Bathymetry (Source: DNR LakeFinder)

West Two River (04010201-535)

Daily fluctuations in DO just downstream of the West Two Rivers Reservoir dam were high, and DO concentrations were low, during continuous monitoring of low flow conditions in 2012 and 2013. The DO daily range was 7.5 to 11 mg/L (compared to the 3 mg/L standard), and daily minimum DO concentrations were consistently below the 5 mg/L standard. Moving downstream, DO increased and DO flux decreased. The nutrient enrichment in and productivity of West Two Rivers Reservoir is the primary cause of the DO stress in the impaired reach of West Two River (MPCA 2016).

There are two adjacent monitoring sites with phosphorus data on the impaired reach of West Two River, located approximately one mile downstream of the West Two Rivers Reservoir outlet (Figure 6). There are only four phosphorus measurements from West Two River, and all four measurements are below the stream eutrophication standard of 0.05 mg/L (Table 41, Figure 46). The measurements on May 25 and September 12, 2012, were collected as part of the SID study and were provided by the MPCA staff. There are no chlorophyll data on the impaired reach.

Whereas the available phosphorus data from West Two River do not exceed the river eutrophication phosphorus standard, West Two Rivers Reservoir, located immediately upstream of the impaired river reach, has an eutrophication impairment. Phosphorus and chlorophyll concentrations in the reservoir are high (Table 40), and the high levels of algae can create high daily fluctuations in DO not only in the lake but also in the lake’s outlet. The high daily fluctuations in DO in West Two River are likely due to the high algal growth that is generated in the reservoir, and restoration of the reservoir will lead to improvement in the DO concentration and daily fluctuations in the river and subsequent improvement in the aquatic macroinvertebrate assemblage.

Table 41. TP data for West Two River (AUID 04010201-535, sites S007-039 and 09LS075)

Date	Total Phosphorus (mg/L)	Exceeds River Eutrophication Standard (0.05 mg/L)
6/11/2009	0.048	No
3/9/2012	0.031	No
5/25/2012	0.023	No
9/12/2012	0.016	No

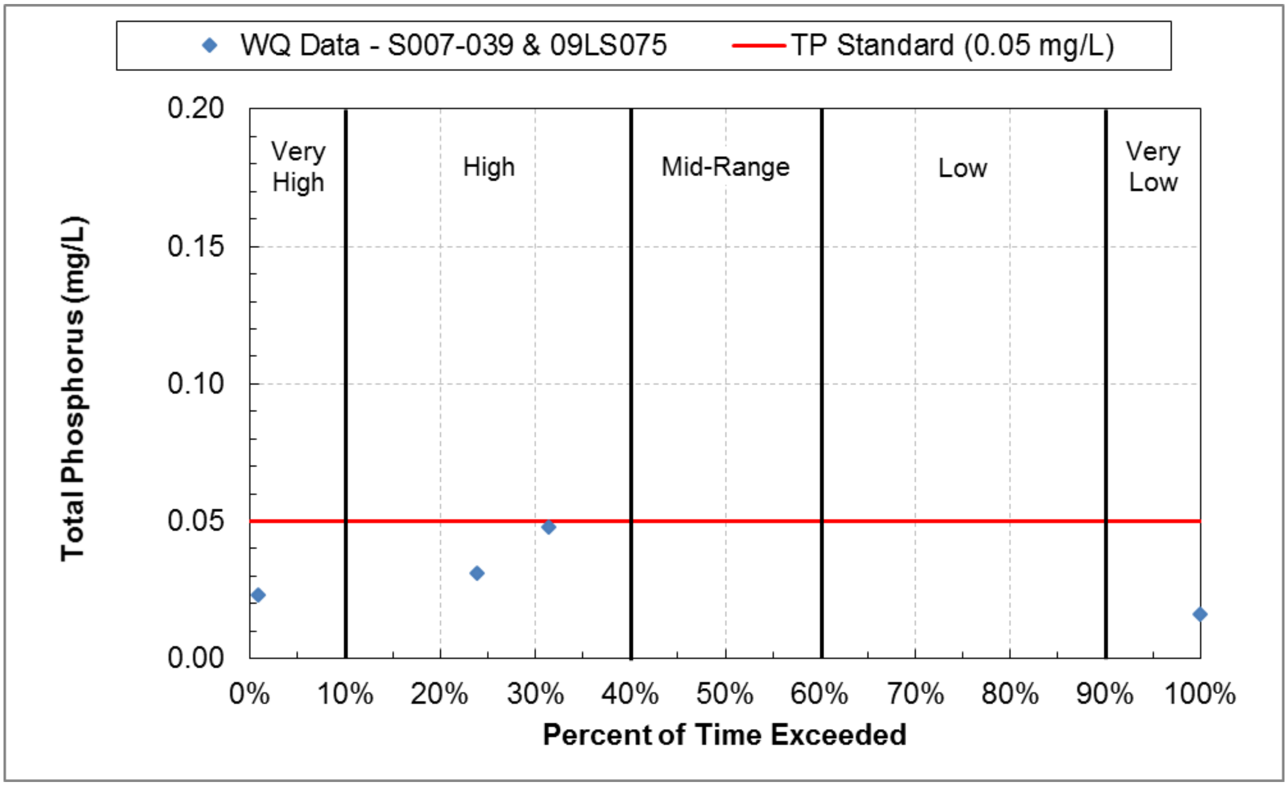


Figure 46. Total phosphorus concentration duration plot, West Two River (AUID 04010201-535); 2009 and 2012

3.5.4 Temperature and Dissolved Oxygen in Wyman Creek (04010201-942)

There have been a number of water quality monitoring efforts in Wyman Creek over the past decade with data collection at multiple sites (Figure 47). The two primary datasets presented here include monitoring conducted as part of watershed SID (MPCA 2016) and a large sampling effort conducted during summer 2016 to support further Wyman Creek analysis and TMDL development (Figure 47).

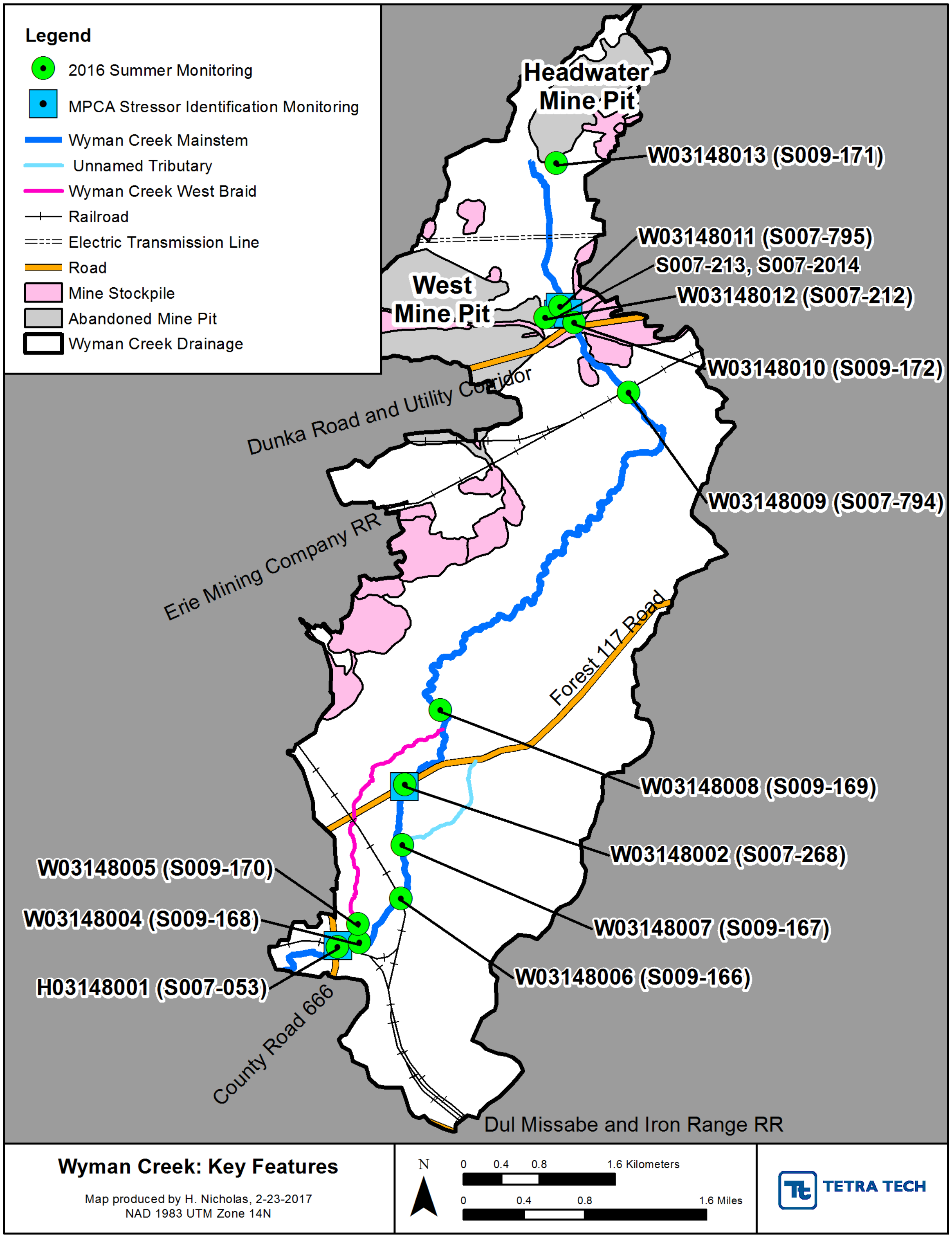


Figure 47. Wyman Creek monitoring sites

The entire Wyman Creek Subwatershed is located within the boundary of the city of Hoyt Lakes.

MPCA Stressor Identification Monitoring

The MPCA conducted water quality sampling in 2009, 2012, and 2013 for the Wyman Creek SID (MPCA 2016). Water temperature, DO, pH, and conductivity were measured with sondes at 15-minute intervals. Monitoring was conducted at two sites along Wyman Creek (Figure 47):

- Wyman Creek near Hoyt Lakes, Superior National Forest Rd 117 (site 12LS006/W03148002, S007-268)
- Wyman Creek at Hoyt Lakes, CR666 (site 81LS008/H03148001, S007-053)

The observed DO at both sampling sites did not meet the numeric water quality standard of 7.0 mg/l at any time (Figure 48, Figure 49). Sondes also monitored 15-minute interval water temperature at three sites to characterize the impacts of the West Mine Pit, which is an abandoned mine pit (Cliffs Erie–Hoyt Lakes Mining Area) that provides a fairly consistent supply of baseflow to the stream:

- Wyman Creek upstream of the West Mine Pit (site S007-213)
- West Mine Pit outfall (site S007-212)
- Wyman Creek downstream of the West Mine Pit (site S007-214)

The relative influence of the abandoned mine pits, beaver dams, and other factors that can increase water temperature changed throughout the summer of 2012, when continuous temperature was monitored at multiple sites on Wyman Creek. At the beginning of July (Figure 50), the water from the West Mine Pit (site S007-212) was cooler than the water in Wyman Creek (site S007-213) and lowered the creek's temperature (S007-214). Towards the downstream end of the impaired reach, the creek's water temperature increased along the braided section of the reach (between sites S007-268 and S007-053), where there are fewer human disturbances. Later in the month, water from the West Mine Pit was warmer than in the creek, leading to higher temperatures in the creek downstream of the West Mine Pit inflow (Figure 51). Water temperatures were cooler downstream, and water temperature decreased along the braided section. Temperature at two sites was monitored in August and September 2013; temperature generally decreased during the monitoring period (Figure 52). DO increased over the same time period (Figure 49). This relationship is expected because cooler water can hold more DO.

Conductivity was relatively stable at both monitored sites during both summers. Average conductivity at the more upstream site (W03148002) was 360 micromhos per centimeter (µmhos/cm, a measure of a material's ability to conduct an electric charge) during summer 2012, and 366 µmhos/cm during summer 2013. Average conductivity at the most downstream site (H03148001) was 297 µmhos/cm during summer 2012, and 315 µmhos/cm during summer 2013.

pH data were relatively stable at both sites during both summers as well, suggesting that plant and algae photosynthesis and respiration were a relatively small part of the DO balance. Average pH at the more upstream site (W03148002) was 7.3 during the monitored summer of 2012. Average pH at the most downstream site (H03148001) was 7.1 and 7.2 for summer 2012 and 2013, respectively.

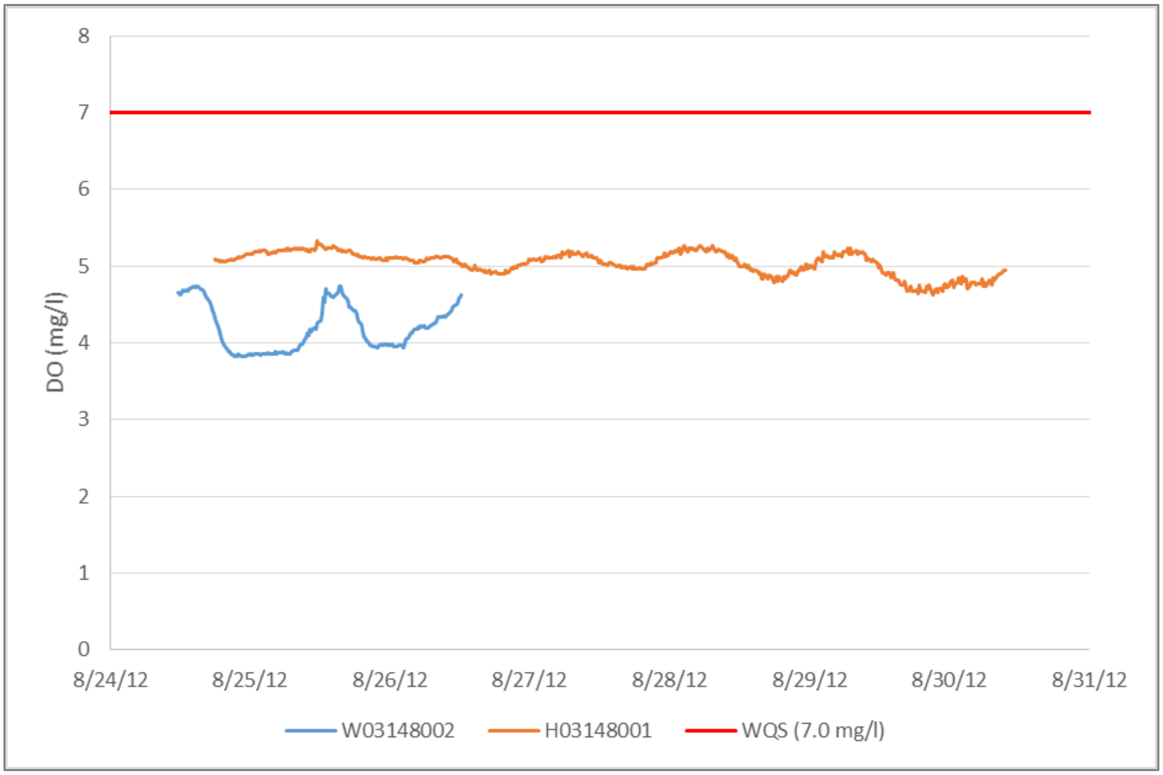


Figure 48. Continuous DO data along Wyman Creek, summer 2012

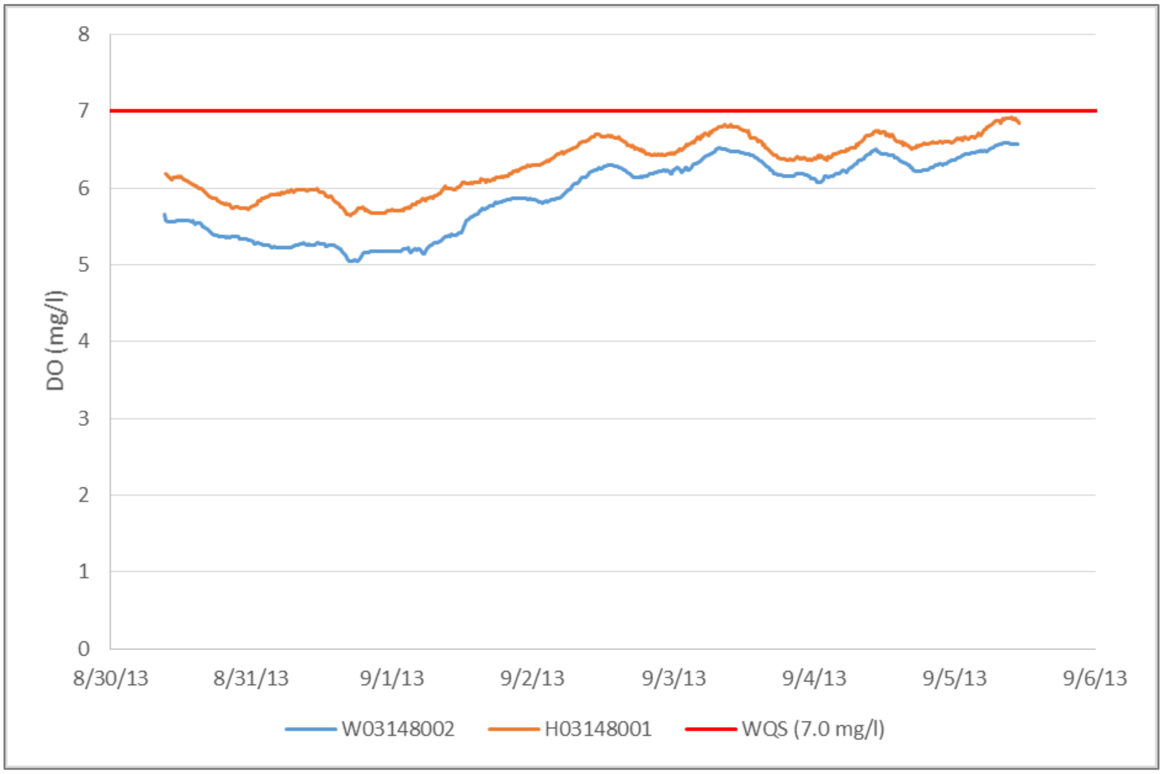


Figure 49. Continuous DO data along Wyman Creek, summer 2013

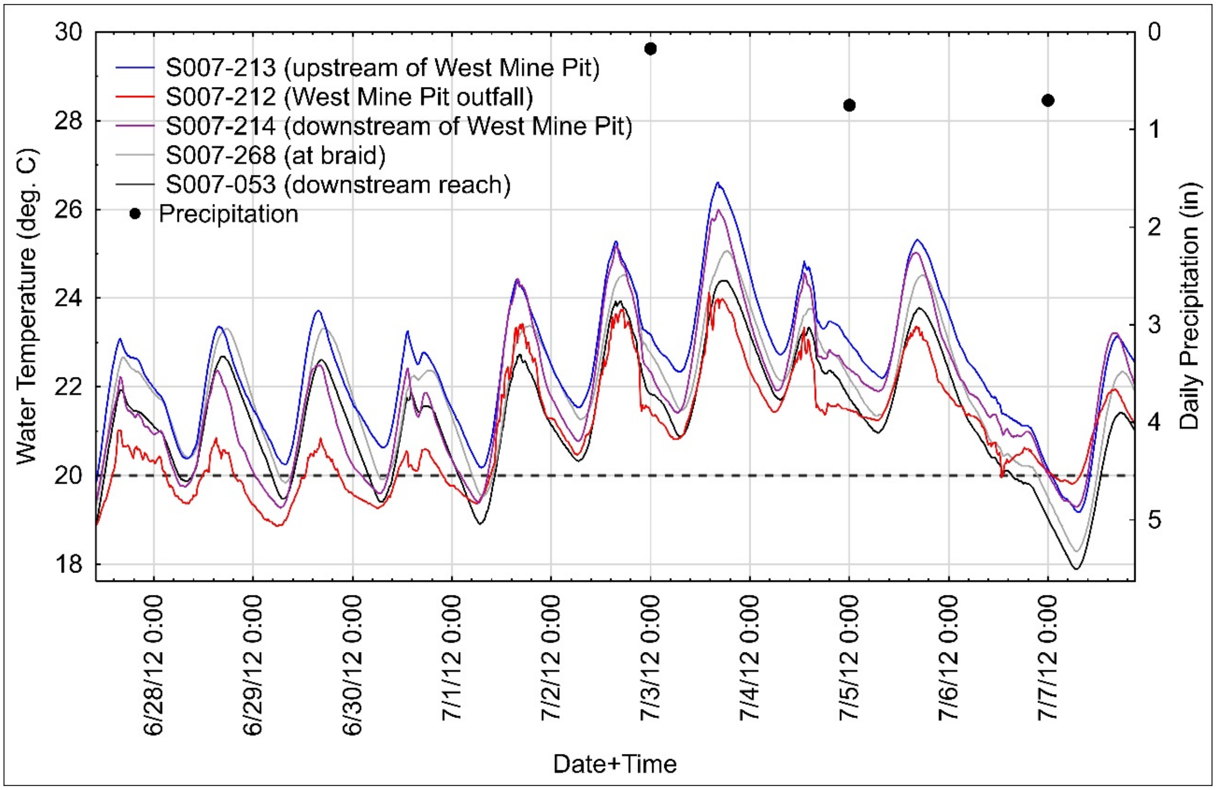


Figure 50. Wyman Creek water temperature, June 28–July 12, 2012

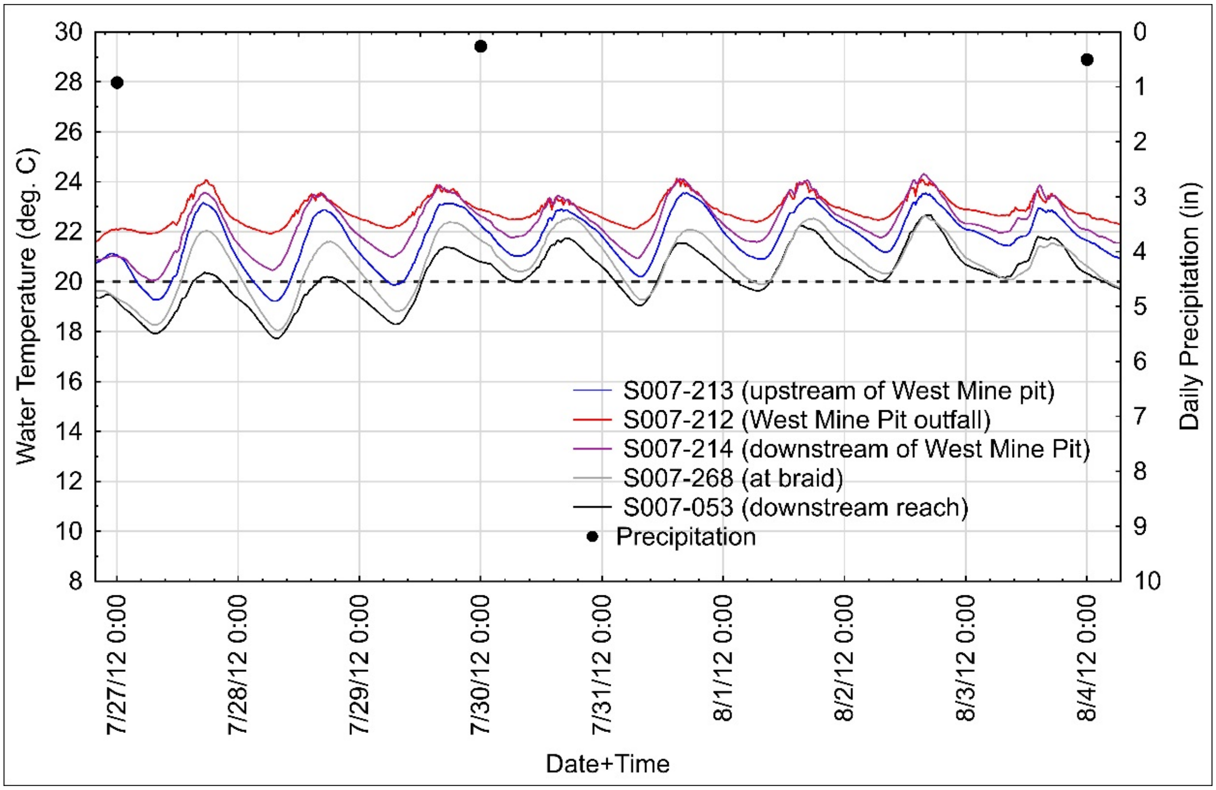


Figure 51. Wyman Creek water temperature, July 27–August 4, 2012

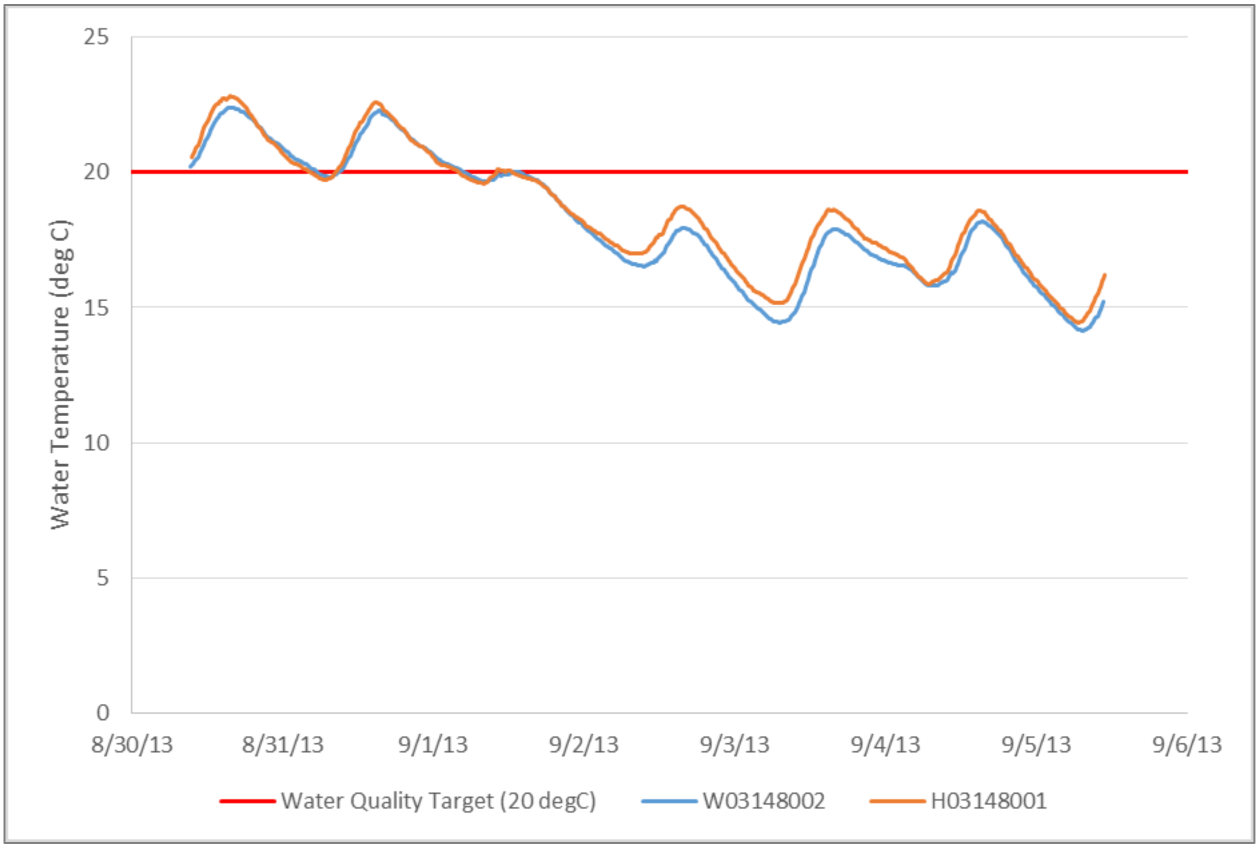


Figure 52. Continuous water temperature data along Wyman Creek, summer 2013

2016 Critical Conditions Monitoring

An extensive sampling effort was undertaken during critical summer conditions in 2016 to support the Wyman Creek TMDL and modeling effort. Between July 28 and August 18, 2016, monitoring and other data collection were completed at twelve sites (Table 42, Figure 47) along Wyman Creek and included the following parameters and constituents: channel geometry, flow, air temperature, water temperature, DO, pH, conductivity, total and dissolved iron, orthophosphate, alkalinity, ammonia, chl-*a*, inorganic nitrogen, Kjeldahl nitrogen, TP, sulfate, TSS, biochemical oxygen demand, total organic carbon in soil, as well as photographs and notes about vegetation and bed sediment.

A detailed data inventory, including reach hydraulics and water quality grab sampling is in the modeling report in Appendix D.

Table 42. Sampling sites along Wyman Creek (2016 monitoring)

Sites are ordered from upstream to downstream

HYDSTRA ID	EQUIS ID	MPCA Site Name	Descriptions Used in Memo
W03148013	S009-171	Wyman Creek near Hoyt Lakes, 1.1 mi upstream of Mining Rd	Mainstem, most upstream reach originating near the Headwater Mine
W03148011	S007-795	Wyman Creek near Hoyt Lakes, 0.1mi upstream of Mining Rd (upstream of West Mine Pit)	Mainstem, above West Mine Pit
W03148012	S007-212	West Mine Pit outflow Tributary near Hoyt Lakes, 0.1mi upstream of Wyman Cr	West Mine pit outflow
W03148010	S009-172	Wyman Creek near Hoyt Lakes, Mining Rd (downstream of West Mine Pit)	Mainstem, below West Mine Pit
W03148009	S007-794	Wyman Creek near Hoyt Lakes, 0.6 mi downstream of Mining Rd	Mainstem, downstream of railroad
W03148008	S009-169	Wyman Creek near Hoyt Lakes, 0.7 mi upstream of FR117	Mainstem, above braid split
W03148002	S007-268	Wyman Creek near Hoyt Lakes, Superior National Forest Rd 117	Mainstem, below braid split
W03148007	S009-167	Unnamed Tributary near Hoyt Lakes, 0.85 mi downstream of FR117	Unnamed Tributary
W03148006	S009-166	Wyman Creek near Hoyt Lakes, 0.8mi downstream of FR117	Mainstem, below unnamed tributary
W03148004	S009-168	Wyman Creek near Hoyt Lakes, 0.25mi upstream of CR666	Mainstem, above braid confluence
W03148005	S009-170	Wyman Creek Braid near Hoyt Lakes, 0.25mi upstream of CR666	West braid, downstream end
H03148001	S007-053	Wyman Creek at Hoyt Lakes, CR666	Mainstem, most downstream

Relationships between water temperature and DO concentration are well documented. Cold water can hold more DO than warm water, and DO can have both daily and seasonal cycles in response to changes in air and water temperature. DO is also influenced by aquatic organisms; for example most organisms use oxygen for cellular respiration (including bacteria and algae), and photosynthetic organisms (plants and algae) produce oxygen when they are photosynthesizing.

The following summary presents a synthesis of the temperature, DO, and shade data to tease apart the importance of the multiple factors controlling temperature and DO in Wyman Creek. Paired observations of average hourly water temperature versus DO at each monitoring site for which both parameters are available are presented in Figure 53. The graphic in the top left of the figure serves as a key: values in the top left quadrant of each inset meet both the water temperature and DO targets; values in the top right quadrant meet the DO target but not the temperature, etc.

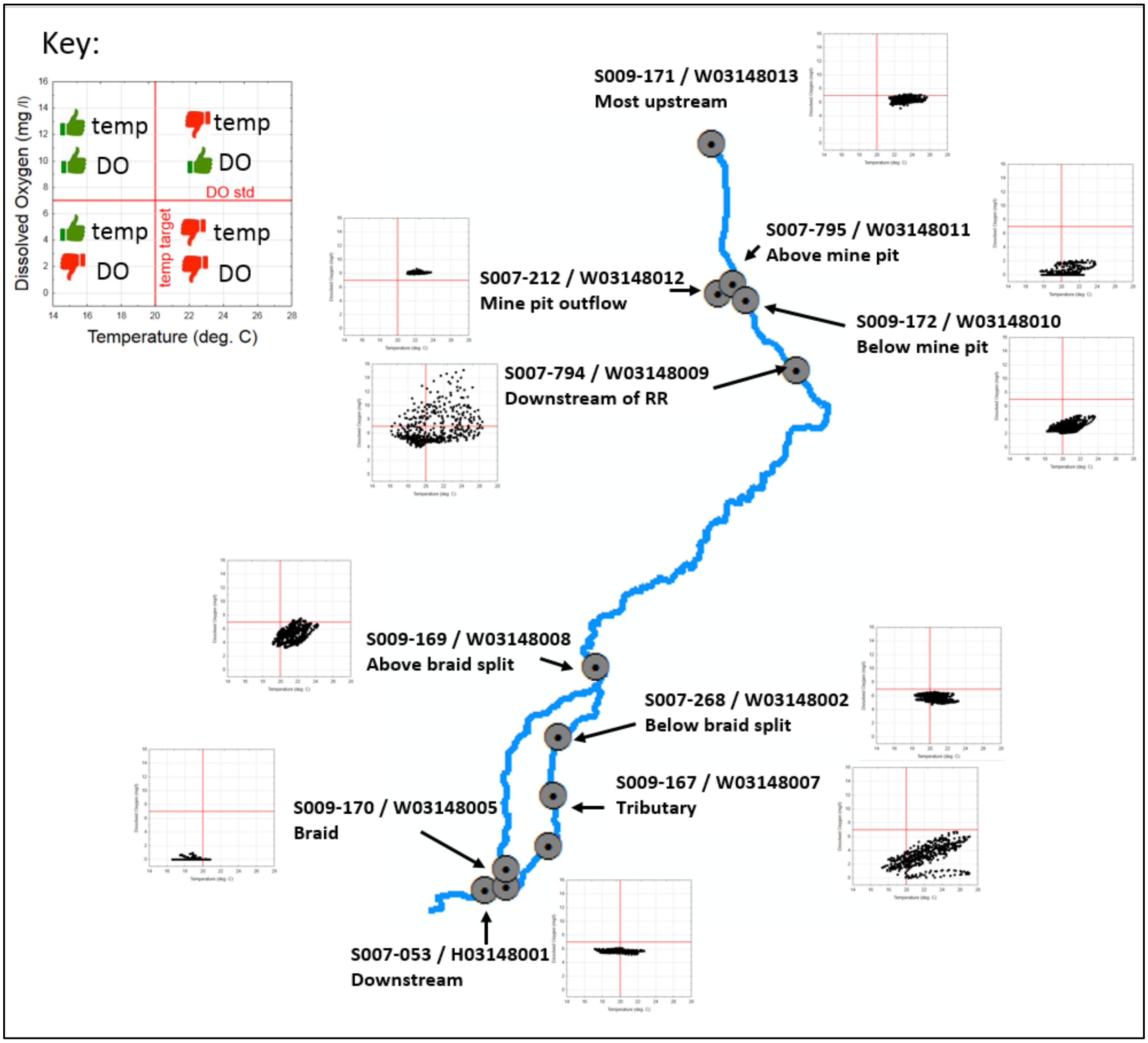


Figure 53. Schematic of DO and temperature along Wyman Creek

Starting at the most upstream monitoring site on Wyman Creek (W03148013), which represents outflow from the Headwater Mine at the northern tip of the watershed, water temperatures were high and DO concentrations moderately high. Moving downstream (W03148011), DO dropped substantially and temperatures decreased. The drop in DO was likely due to low gradient wetlands and the stagnation of water and ponding that occurs immediately in the vicinity of the DO logger, which is downstream of a series of beaver dam debris ponds. The temperature decrease was likely due to the increased shade from riparian vegetation between the two monitoring locations and groundwater inflows.

Moving downstream to the outflow from the West Mine Pit (W03148012), Figure 54 shows the local air temperature, water temperature, and DO for the outflow from August 8 through August 11. DO in the West Mine Pit outflow was greater than 7 mg/l during the entire monitoring period, and the water temperature was higher than the temperature target for the entire monitoring period. As water temperatures rose in the morning, DO typically reached its daily minimum at around 10:00 AM; as water temperatures fell in the evening, DO reached its daily maximum at around 6:00–7:00 PM. The DO fluctuations were minor and are not evident in Figure 54, which has been scaled for comparison. Air temperatures fluctuated daily by approximately 10 degrees Celsius over the course of the day, while water temperatures fluctuated in the West Mine Pit outflow by approximately only 1 or 2 degrees Celsius. This small fluctuation provides insight into the temperature buffering capacity of the mine pit. The outflow of the West Mine Pit (W03148012) had relatively high DO and warm temperatures; the outflow increased DO in Wyman Creek and slightly increased temperature (W03148010) relative to upstream of the West Mine Pit outflow.

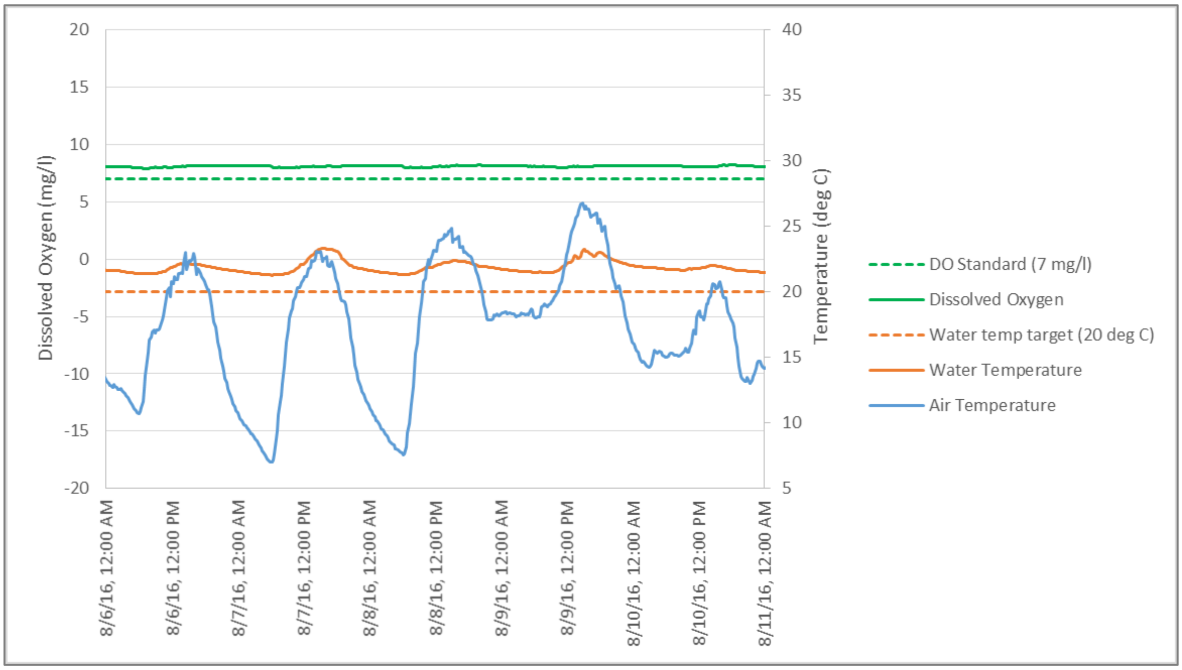


Figure 54. Continuous water, air temperature, and DO at the West Mine Pit outflow (W03148012), August 6–11

The site downstream of the Erie Mining Company Railroad crossing (W03148009) represents outflow from a large, shallow ponded area that is a result of a perched culvert. DO and temperature were highly variable—diurnal fluctuations in DO were likely caused by plant photosynthesis, and diurnal fluctuations in temperature were due to the ponded area, which is shallow with a relatively large and unshaded surface area (Figure 55). The daily maxima are similar to the daily air temperature maxima, which are higher than the instream target. The large diel fluctuations in DO suggest high rates of photosynthesis. Aerial photos suggest that the large pond immediately upstream contains large amounts of macrophytes and is fairly shallow.

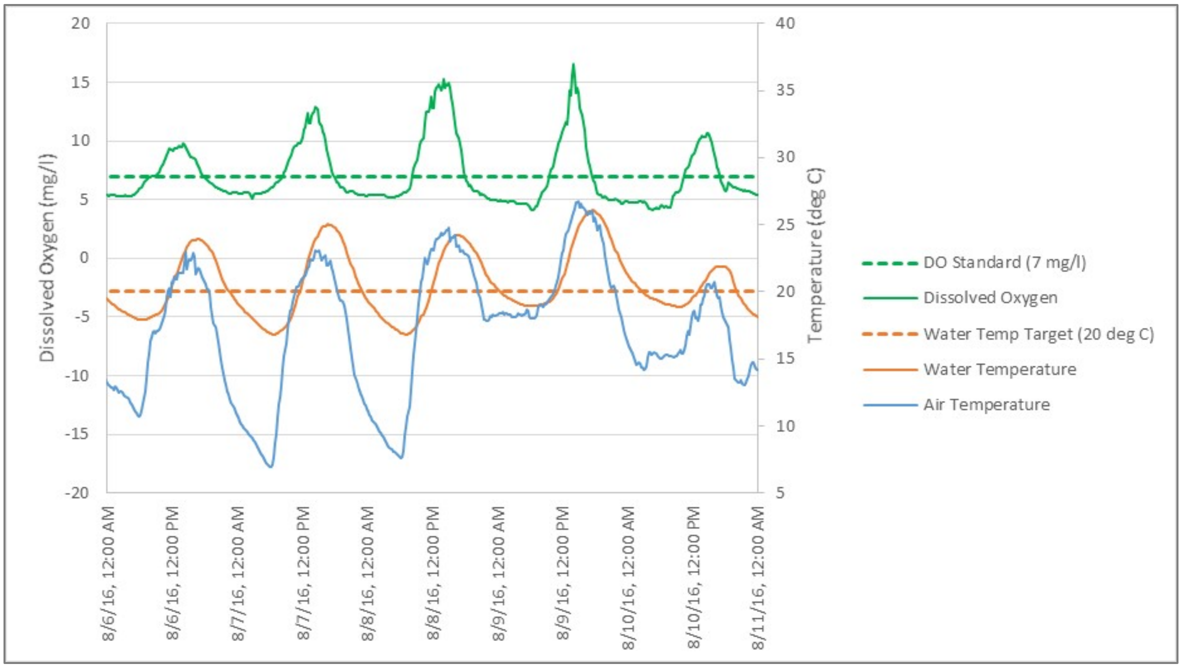


Figure 55. Continuous water and air temperature, and DO downstream of the Erie Mining Company Railroad crossing on Wyman Creek (W03148009)

The next monitoring site is above the braid split (W03148008), where temperatures were high and DO low (Figure 53). This site, which has been historically difficult to monitor due to inaccessibility, is located at the downstream end of a 6-mile stretch of Wyman Creek that flows through wetlands and is punctuated by approximately 12 to 15 beaver dams. The impact of beavers on Wyman Creek can be seen in the character of riparian vegetation as well as the changes in channel width due to debris dam ponds. Beavers will not only remove shade-providing riparian vegetation to construct their dams, but they also create what are known as “beaver meadows” adjacent to their ponds due to subsequent flooding and soil saturation in the preexisting riparian corridor of the channel (Johnston et al. 1995; Wright et al. 2002). This segment also appears to lose water, having less flow at the bottom of the reach. Below the braid split (W03148002), conditions were similar although with slightly cooler temperatures. Baseflows increase over the length of the east side of the braid. The unnamed tributary input (W03148007) had high temperatures and high diel temperature and DO fluctuations due to ponding from beaver dams and relatively high instream plant and/or algae growth. The downstream end of the west side of the braid (W03148005) had extremely low DO and cool water temperatures. This side of the braid is less than two meters wide and has low flows compared to the east side of the braid. The cool water temperatures suggest that the braid is reasonably well shaded, despite the presence of a number of beaver dams and beaver meadow environments along the channel. It is likely that the low DO at this site on the braid is attributed to a combination of water stagnation in the beaver dams (lack of reaeration) and a build-up of organic matter and mucky sediment.

The most downstream site of Wyman Creek (H03148001), after the braid confluence, had moderately low DO and moderate temperatures (Figure 53); water temperature typically exceeds the standard during the warmest part of the day (Figure 56). The diel DO range at this gage is much lower than seen upstream as well, ranging overall by about 0.2 mg/l daily, which reflects that this stream reach is much less dominated by the presence of photosynthetic organisms.

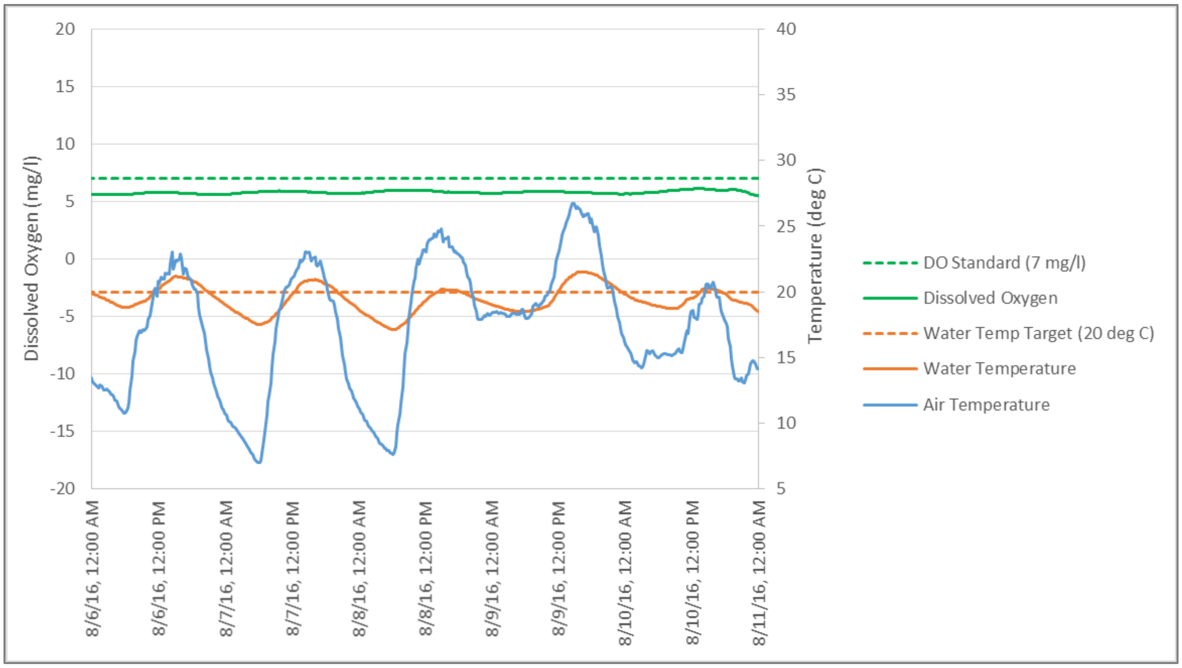


Figure 56. Continuous water and air temperature, and DO near Wyman Creek outlet (H03148001)

In summary, the 2016 summer observations indicate that high water temperatures in Wyman Creek are likely exacerbated by a combination of beaver dams and mine pits, both of which impound water and expose more surface water to warmer ambient air. The creek flows through numerous wetlands, generated by backwater flooding from beaver dams, which provide minimal shade. The relative influence of mine pits, beaver dams, and other factors changes throughout the year as air temperature influences water temperature, especially in locations where unshaded bodies of water are highly exposed due to ponding or in abandoned mine pits (Figure 54 and Figure 55). In waters ponded by natural and human factors, warm, stagnant water and high aquatic plant and/or algae productivity and the presence of mucky oxygen-demanding sediment can influence in-stream DO concentrations. The water drained from mine pits does not have as low observed DO, or as large daily DO fluctuations, as some stream channels with similarly high temperatures due to the depth of these pits and the relative absence of macrophyte growth.

3.6 Pollutant Source Summary

Multiple pollutant source types contribute to the water quality impairments in the SLRW, including wastewater and stormwater, stream channel erosion, watershed runoff, and internal loading. Although mining along the Iron Range has dramatically altered surface and subsurface hydrology in the region, the impairments for which TMDLs are developed in this report are not heavily influenced by pollutant sources related to mining. West Two Rivers Reservoir receives industrial wastewater from the US Steel–Minntac Mining Area. However, the wastewater discharge is low in the relevant pollutant (phosphorus) and thus dilutes the phosphorus concentration in the lake and is not a substantial pollutant source.

3.6.1 E. coli

The *E. coli* source assessment evaluated permitted and non-permitted source loads from humans, livestock, wildlife, and domestic pets. A weight of evidence approach was used to determine the primary sources of *E. coli*, with a focus on the sources that can be effectively reduced with management practices. Appendix A provides supplemental information to the *E. coli* source assessment.

Die-off or instream growth of *E. coli* was not explicitly addressed. However, *E. coli* strains can become naturalized components of the soil microbial community (Ishii et al. 2006) and have been found in ditch sediment in the Seven Mile Creek Subwatershed, Minnesota (Sadowsky et al. n.d., Chandrasekaran et al. 2015). The ultimate origin of the naturalized bacteria is unknown.

Permitted

Permitted sources of *E. coli* in the SLRW include municipal wastewater effluent and stormwater runoff from regulated municipal separate storm sewer systems (MS4s). There are no industrial wastewater sources of *E. coli* or permitted concentrated animal feeding operations (CAFOs) in the watershed.

Municipal Wastewater

Wastewater dischargers that operate under National Pollutant Discharge Elimination System (NPDES) Permits are required to disinfect wastewater to reduce fecal coliform concentrations to 200 organisms/100 mL or less as a monthly geometric mean. Like *E. coli*, fecal coliform are an indicator of fecal contamination. The primary function of a bacterial effluent limit is to assure that the effluent is being adequately treated with a disinfectant to assure a complete or near complete kill of fecal bacteria prior to discharge (MPCA 2007b). Dischargers to Class 2 waters are required to disinfect from April 1 through October 31, and dischargers to Class 7 waters are required to disinfect from May 1 through October 31. These dischargers are a potential source of *E. coli* to surface waters during months when disinfection is not required.

The two municipal wastewater dischargers upstream of *E. coli* impaired streams are required to monitor three times per week, and the monthly geometric means of the monitoring data are used to determine compliance with permits. There are no permitted combined sewer overflows in the impaired watersheds.

There are two municipal wastewater dischargers (Central Iron Range Sanitary Sewer District [CIRSSD] and Hibbing Wastewater Treatment Facility [WWTF] South) with active permits in the impaired watersheds (Figure 8). There are four additional facilities that operated during the TMDL period (2003 through 2012) but do not currently have active permits: Buhl Kinney WWTP and Chisholm WWTP, which ceased operations in 2014 when flow was routed to the CIRSSD WWTP; Hibbing WWTP North Plant, which ceased operations in 2004 when flow was routed to Hibbing WWTP South Plant; and the ISD (Independent School District) 704 discharge, which was terminated in 2000. Even though these four facilities are not current or future dischargers, they were investigated as part of the source assessment because they were in operation during the 10-year TMDL time period.

Of these facilities, the Chisolm WWTP has the only documented permit exceedances for fecal coliform as provided in discharge monitoring reports (DMRs) for the time period between 2003 and 2012. A release of untreated wastewater was recorded in October 2007; the monthly geometric mean exceeded the permit limit during that month. The closest (approximately 2.8 miles) *E. coli* impairment downstream of the discharge is Barber Creek/East Swan River. There are no instream *E. coli* or fecal coliform monitoring data from this reach in 2007 when the release occurred.

In September 2010, the monthly geometric mean of Chisolm WWTP's discharge again exceeded the permit limit. Two stream samples were taken in September 2010 at the closest downstream site (S005-658, approximately 2.8 miles downstream of the facility's discharge), and they were both well below the individual sample standard of 1,260 organisms/100 mL. Because permit exceedances are infrequent and do not coincide with instream exceedances of the water quality standard, discharge from Chisolm WWTP is not considered a significant source of *E. coli*.

Sanitary sewer overflows or releases can contribute to the *E. coli* load in the impaired streams. In the TMDL time period (2003 through 2012), the Hibbing WWTP South Plant, which discharges to East Swan Creek, recorded five releases of wastewater during wet weather conditions (i.e., heavy rains or snowmelt). Most of the overflow wastewater from this WWTP is disinfected. There was one *E. coli* sample from East Swan Creek within a few days of a release in August 2010; the *E. coli* concentration was 146 org/100 mL, which does not exceed the individual sample standard. In August 2009, the collapse of a sewer line led to a release of untreated wastewater to a ditch that flows to Penobscot Creek. The MPCA staff noted that it was unlikely that the discharge reached the creek. There was one *E. coli* sample from Penobscot Creek within a few days before and after the release; the *E. coli* concentration was 1,120 org/100 mL five days before the release and was greater than the method's maximum recordable value of 2,420 org/100 mL two days after.

Unintended releases from municipal wastewater collection systems may lead to exceedances of the *E. coli* standard at times. However, because these releases are infrequent, these discharges are not considered a significant source. Releases from the Hibbing South WWTP collection system are at times disinfected (per documentation provided to MPCA by Hibbing South WWTP). Additional monitoring in the watershed could be used to further evaluate this source.

The sanitary sewer system can also serve as a source of *E. coli* in developed areas via illicit connections of sanitary sewer to the storm sewer system and leaking from aging sanitary sewer systems. Urban stormwater can contribute substantial amounts of fecal bacteria to surface waters even in the absence of combined or sanitary system overflows (Salmore et al. 2006). Average *E. coli* concentrations in samples taken from storm sewers in the Milwaukee metropolitan area were approximately 1,800 organisms/100 mL, and receiving water *E. coli* concentrations increased from below 200 organisms/100 mL to over 20,000 organisms/100 mL following storm events. The study authors suggest that the high *E. coli* loads may be due to leaky sanitary sewers infiltrating into the stormwater system in addition to watershed runoff (Salmore et al. 2006). Sauer et al. (2011) found sewage contamination in all but one of 828 samples at stormwater outfalls in the Milwaukee metropolitan area. Higher *E. coli* loads from human sources have been correlated with residential land uses (Wu et al. 2011). *E. coli* growth in storm sewers can also be a substantial contributor (Jiang et al. 2007). These studies are discussed here to illustrate that both storm sewers and sanitary sewers can be sources of *E. coli* in urban watersheds.

Aging wastewater collection infrastructure has been noted in Hibbing, especially in the older, northern section (City of Hibbing, n.d.). The northern part of the city is in the Penobscot Creek Subwatershed, which on average has the highest percentage of developed land and the highest *E. coli* concentrations of the impaired reaches in the SLRW (Figure 57). Aging infrastructure in other developed areas also likely contributes to the *E. coli* impairments.

Stormwater

Regulated MS4s can be a source of *E. coli* to surface waters through the impact of urban systems on delivery of *E. coli* from humans, pets, and wildlife to surface waters. Impervious areas (such as roads, driveways, and rooftops) can directly connect the location where *E. coli* is deposited on the landscape to points where stormwater runoff carries *E. coli* into surface waters. For example, there is a greater likelihood that uncollected pet waste in an urban area will reach surface waters through stormwater runoff than it would in a rural area with less impervious surfaces. Wildlife, such as birds and raccoons, can be another source of *E. coli* in urban stormwater runoff (Wu et al. 2011, Jiang et al. 2007).

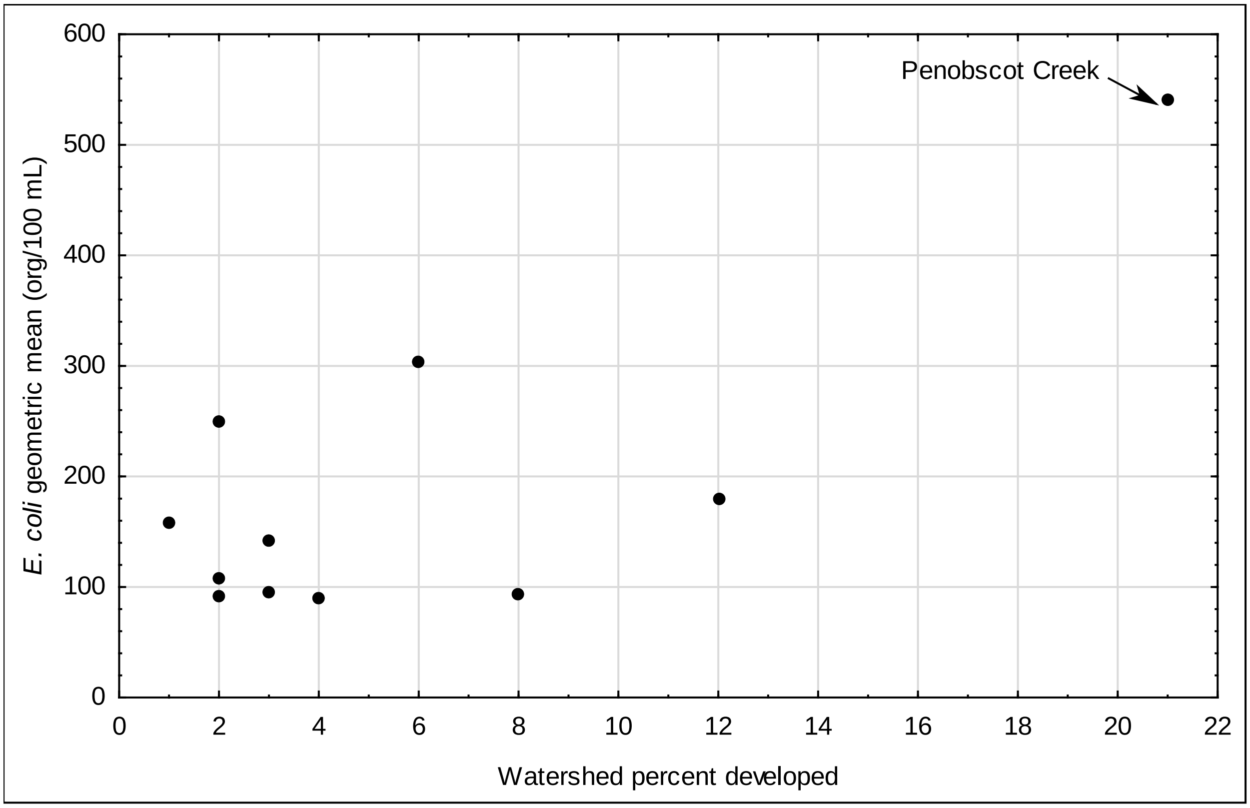


Figure 57. *E. coli* geometric mean (April through October, 2003–2014) by impaired reach versus the percent of the impaired reach's watershed that is developed.
Each point represents one impaired reach.

Straight Pipe Discharges

Straight pipe discharges are illicit point sources of *E. coli*. Straight pipe systems are sewage disposal systems that transport raw or partially settled sewage directly to a lake, stream, drainage system, or the ground surface. Straight pipe systems likely exist in the SLRW, but their number and locations are unknown and were not quantified.

Non-permitted

The non-permitted sources evaluated included humans, livestock, wildlife, and domestic pets. Stormwater runoff is considered a delivery mechanism for non-permitted *E. coli* sources in developed areas that are not regulated through the MS4 Permit and is also discussed in this section.

Human

Septic systems that function properly do not contribute *E. coli* to surface waters. Septic systems that discharge untreated sewage to the land surface are considered an imminent public health threat (IPHT) and can contribute *E. coli* to surface waters. In the MPCA's *Recommendations and Planning for Statewide Inventories, Inspections of Subsurface Sewage Treatment Systems* (SSTS) (Sabel et al. 2011), St. Louis County reports that 3% of their SSTS are IPHTs, and Carlton County reports 4%. If these IPHTs were distributed evenly across the county, the number of IPHTs per impairment watershed would range from zero in one of the unnamed creek's watershed to seven in the Pine River and Barber Creek Subwatersheds (Table 43).

Table 43. Estimated number of imminent public health threat (IPHT) systems in each *E. coli* impaired watershed

***E. coli* Impaired Reach**	**Estimated Number of IPHT Systems** [a]
Unnamed Creek (542)	1
Pine River (543)	7
Barber Creek (569)	7
Buhl Creek (580)	1
Dempsey Creek (582)	5
West Rocky Run (625)	1
Barber Creek (641)	5
Hay Creek (751)	3
East Swan Creek (888)	2
Penobscot Creek (936)	1
Unnamed Creek (A22)	0

a. Assumes that the IPHTs are distributed evenly across the counties in which the watersheds are located (St. Louis County and Carlton County).

Other human sources of *E. coli* in the watershed include earthen pit outhouses and land application of septage. Earthen pit outhouses likely exist in the SLRW, but their number and locations are unknown and were not quantified.

Application of biosolids from WWTFs could also be a potential source of *E. coli* in the watershed. Application is regulated under Minn. R. ch. 7401 and includes pathogen removal in biosolids prior to spreading on agricultural fields or other areas. Within the watersheds with *E. coli* impairments, there are 23 active biosolids application sites. Application should not result in violations of the *E. coli* water quality standard.

Livestock

Animal waste from animal feeding operations (AFOs) can be delivered to surface waters from failure of manure containment, runoff from the AFO itself, or runoff from nearby fields where the manure is applied. In Minnesota, feedlots with greater than 50 animal units, or greater than 10 animal units in shoreland areas, are required to register with the state. Facilities with fewer animal units are not required to register with the state. Feedlots with greater than 1,000 animal units also require coverage under an NPDES/State Disposal System (SDS) Permit from the MPCA; however, there are no permitted feedlots (i.e., CAFOs) in the SLRW.

The MPCA Data Desk provided the feedlot locations and numbers and types of animals in registered feedlots. This estimate includes the maximum number of animals at each registered feedlot; therefore, the actual number of livestock in registered facilities is likely lower. There are four registered feedlots in the *E. coli* impaired watersheds, with a total registration of 635 bovines. Livestock in non-registered, smaller operations (e.g., hobby farms) likely contribute *E. coli* to surface waters through watershed runoff from fields and direct deposition in surface waters. St. Louis County provided additional spatial information on non-registered livestock operations within the county. The number of non-registered feedlots in each impaired watershed (Table 44) was taken into account in the source summaries.

Table 44. Livestock inventory

Impairment Watershed	Number of Registered Bovines	Number of Non-Registered Feedlots [a]
Unnamed Creek (542)	370	0
Pine River (543)	150	4
Barber Creek (569)	0	0
Buhl Creek (580)	0	1
Dempsey Creek (582)	0	0
Unnamed Creek / West Rocky Run (625)	98	2
Barber Creek (641)	0	1
Hay Creek (751)	17	2
Unnamed Creek / East Swan Creek (888)	370	1
Penobscot Creek (936)	0	0
Unnamed Creek (A22)	370	1

a. Data provided by St. Louis County Planning Department

Wildlife

The primary wildlife types of concern are deer, beavers, and waterfowl. Deer densities were derived from deer population densities in *Monitoring Populations Trends of White-Tailed Deer in Minnesota's Farmland/Transition Zone—2006* (Grund 2006) and *Monitoring Population Trends of White-Tailed Deer in Minnesota—2012* (Grund and Walberg 2012); beaver densities were derived from the DNR (DNR 2015), and goose densities were derived from *Minnesota Spring Canada Goose Survey* (Rave 2014); Table 45). Goose densities were doubled to account for ducks and other waterfowl.

Table 45. Wildlife inventory

Impairment Watershed	Numbers of Animals		
	Deer	Waterfowl	Beaver
Unnamed Creek (542)	157	2	39
Pine River (543)	1,023	100	160
Barber Creek (569)	728	144	160
Buhl Creek (580)	101	38	13
Dempsey Creek (582)	608	170	105
Unnamed Creek / West Rocky Run (625)	216	2	42
Barber Creek (641)	524	144	92
Hay Creek (751)	288	2	63
Unnamed Creek / East Swan Creek (888)	320	4	80
Penobscot Creek (936)	79	0	30
Unnamed Creek (A22)	72	0	11

Domestic Pets

When pet waste is not disposed of properly, it can be picked up by runoff and washed into nearby water bodies. Dogs are considered the primary source of *E. coli* from domestic pets. Because cats bury their waste, *E. coli* from cats typically does not reach surface water bodies through runoff. The number of dogs in the impaired watersheds was estimated as the product of the number of housing units in the watershed (2010 U.S. Census data), the percentage of households that own dogs in Minnesota (American Veterinary Medical Association 2007), and the average number of dogs per Minnesota household (American Veterinary Medical Association 2007) (Table 46).

Table 46. Domestic pet animal inventory

Impairment Watershed	Estimated Number of Dogs in Watershed
Unnamed Creek (542)	187
Pine River (543)	694
Barber Creek (569)	1,237
Buhl Creek (580)	189
Dempsey Creek (582)	328
Unnamed Creek / West Rocky Run (625)	127
Barber Creek (641)	708
Hay Creek (751)	143
Unnamed Creek / East Swan Creek (888)	908
Penobscot Creek (936)	481
Unnamed Creek (A22)	76

Stormwater Runoff

Whereas stormwater runoff is not an actual source of *E. coli* to surface waters, it acts as an important delivery mechanism of multiple *E. coli* sources including humans, wildlife, and domestic pets. Stormwater runoff from developed land covers in non-permitted areas has the same source types and mechanisms of delivery as stormwater runoff from regulated MS4 communities, discussed under permitted sources. The developed areas in the impairment watersheds that are not regulated through an MS4 Permit can be a source of *E. coli* loads to surface waters.

Summary of Results

Sources in the entire drainage area to each impaired water body were considered. The summary of *E. coli* sources (Table 47) identifies which source types exist in each impaired watershed and which of the source types should be a source of concern, based on the following:

- Waste from livestock is a source of concern when feedlots are numerous and/or are located close to surface water bodies.
- Waste from wildlife is not a priority source for management.
- Waste from pets is a source of concern in watersheds with a higher density of developed area. Compared to rural areas, developed areas have higher densities of pets and a higher delivery of waste to surface waters due to connected impervious surfaces.
- There is not enough information on locations of IPHT septic systems to determine which watersheds have high IPHT loads. Additionally, there is not enough *E. coli* monitoring data from low flow conditions to determine if a direct source such as IPHT systems are of concern.
- Effluent from WWTPs is typically below the *E. coli* standard and is not considered a source of concern.
- Aging wastewater collection infrastructure has the potential to be a primary source of *E. coli* to surface waters in developed areas. Aging infrastructure has been noted in Hibbing, but the extent of aging infrastructure in the other developed areas is not known. The impact of aging infrastructure on *E. coli* concentrations in surface waters should be investigated and addressed in the developed areas of impaired watersheds.
- Stormwater runoff has the potential to be a primary source of *E. coli* in developed areas. Proximity of developed areas (based on land cover data) to the impairment and extent of developed areas in the impaired watershed informed the identification of stormwater runoff sources of concern.

The sources of concern can be considered a higher priority for targeting by local watershed planners. The monitoring data and source assessment suggest that the impairments are due to a mix of sources that occur during all flow regimes (Table 47). In the watersheds with developed areas, aging infrastructure and stormwater runoff have the potential to be primary sources. Livestock is the primary source of concern in the three impaired watersheds in the southern portion of the SLRW (Pine River, Unnamed Creek/West Rocky Run, and Hay Creek).

Table 47. Summary of *E. coli* sources in impaired watersheds

Impaired Reach	Livestock	Wildlife	Domestic Pets	Humans			Stormwater Runoff [a]
				IPHT	WWTP	Aging Infrastructure	
Unnamed Creek (542)	●	○	●	○	-	●	●
Pine River (543)	●	○	○	○	-	-	-
Barber Creek (569)	-	○	○	○	○	●	●
Buhl Creek (580)	●	○	●	○	-	●	●
Dempsey Creek (582)	-	○	○	○	-	●	●
Unnamed Creek / West Rocky Run (625)	●	○	○	○	-	-	-
Barber Creek (641)	●	○	●	○	○	●	●
Hay Creek (751)	●	○	○	○	-	-	-
Unnamed Creek / East Swan Creek (888)	●	○	●	○	○	●	●
Penobscot Creek (936)	-	○	●	○	-	●	●
Unnamed Creek (A22)	●	○	○	○	-	-	-

● *E. coli* source that is a higher priority for targeting ○ *E. coli* source that is a lower priority for targeting

- Not an *E. coli* source

a. Stormwater runoff refers to runoff from developed land covers from either regulated MS4 communities or unregulated areas.

3.6.2 Total Suspended Solids

TSS sources in the East Swan River and Stony Creek Subwatersheds were assessed. The source assessment evaluated permitted and non-permitted source loads from watershed loading, channel erosion, and municipal wastewater. Where applicable, average annual (2003 through 2012) TSS source loads were estimated with the St. Louis River Watershed HSPF model (Tetra Tech 2016a and 2016b).

Permitted

TSS sources regulated through NPDES Permits include municipal wastewater and regulated stormwater runoff. There are no permitted industrial wastewater discharges in the TSS impaired watersheds. Industrial wastewater from the mining area in the East Swan River and Swan River Subwatersheds discharges outside of the watersheds.

Municipal Wastewater

Municipal wastewater effluent can be a source of suspended solids. Effluent from mechanical treatment plants typically is approximately 81% organic matter and 19% inorganic particles (MPCA 2015). The organic matter decomposes relatively rapidly and likely does not contribute to the impairment in the East Swan River. There is no municipal wastewater effluent in the Stony Creek Subwatershed.

Average annual (2003 through 2012) TSS loads from the following WWTPs in the East Swan River Subwatershed were estimated with the St. Louis River Watershed HSPF model (Tetra Tech 2016a and 2016b): Hibbing South, Chisolm, Buhl Kinney, and Hibbing North (discontinued November 24, 2004) WWTPs. The effluent discharge volumes and TSS concentrations in the model were determined from discharge monitoring records provided by the MPCA. The Chisolm and Buhl Kinney WWTPs ceased operations when flow was routed to the CIRSSD WWTP, which became operational in 2014.

Municipal Separate Storm Sewer Systems

MS4s are defined by the MPCA as conveyance systems owned or operated by an entity such as a state, city, township, county, district, or other public body having jurisdiction over disposal of stormwater or other wastes. The municipal stormwater permit holds permittees responsible for stormwater discharging from the conveyance system they own and/or operate. The conveyance system includes ditches, roads, storm sewers, stormwater ponds, etc. Stormwater runoff that falls under these permits is regulated as a point source and therefore must be included in the WLA portion of a TMDL (EPA 2014; see 40 C.F.R. § 130.2(h)). EPA recommends that WLAs be broken down as much as possible in the TMDL, as information allows. This facilitates implementation planning and load reduction goals for the MS4 entities.

The city of Hibbing is the only regulated MS4 in the impaired TSS watersheds. Stormwater runoff from the city of Hibbing's regulated MS4 was estimated together with watershed runoff from non-permitted areas, discussed under non-permitted sources.

Industrial Stormwater

Industrial stormwater is regulated through an NPDES Permit when stormwater discharges have the potential to come into contact with materials and activities associated with the industrial activity. Loading from industrial stormwater is inherently incorporated in the watershed runoff estimates, discussed under non-permitted sources.

Construction Stormwater

Untreated stormwater that runs off a construction site often carries sediment and other pollutants to surface water bodies. An NPDES Permit is needed for construction activity that disturbs one acre or more of soil or for smaller sites if the activity is part of a larger development. A permit may also be needed if the MPCA determines that the activity poses a risk to water resources. Coverage under the construction stormwater general permit requires sediment and erosion control measures that reduce stormwater pollution during and after construction activities.

On average, approximately 0.02% of the watershed area is permitted under the construction stormwater permit in any given year (average of 2003 through 2014). Construction stormwater loading is not quantified and is not considered a significant source.

Non-Permitted

TSS sources that are not regulated through NPDES Permits include watershed runoff and channel erosion.

Watershed Runoff

TSS loads in watershed runoff were estimated by land cover in the St. Louis River Watershed HSPF model (Tetra Tech 2016a and 2016b). Average loading rates over the SLRW range from 0.003 tons per acre per year for wetlands to 0.492 tons per acre per year for barren land (Table 48).

Table 48. Average upland TSS loading rates in the St. Louis River Watershed (Tetra Tech 2016a)

Land Cover	Upland TSS Loading Rates (tons/acre/year)
Forest	0.016
Shrub	0.194
Pasture	0.075
Crop	0.274
Barren	0.492
Developed	0.200
Roads	0.104
Wetland	0.003
Water	0.000

The East Swan River Subwatershed is 12% barren land (Table 10), which is associated with mining operations. The loading estimates from the HSPF model assume that only a part of the barren land drains directly to mine pits and that the rest drains to other surface waters. Additional information provided by the MPCA suggests that all but 50 acres of the barren land in the East Swan River Subwatershed flows either to low elevation pit lakes with no surface outflow or to mining pits whose outflow is accounted for in a permitted effluent discharge from the mining area. In the East Swan River Subwatershed TSS source assessment (Table 49), the HSPF loading estimates from barren land were reduced to account for the drainage of barren land.

Channel Erosion

The high TSS in the East Swan River is likely caused by bank and bluff erosion, as detailed in the East Swan River Watershed Geomorphic Study (SWCD Technical Services Area #3 2011). Channel instability in Barber Creek, Dempsey Creek, and the East Swan River (see Figure 2 for a map of streams) contributes to the high TSS concentrations observed in the East Swan River under high flows. Stream channels in the upper region of the East Swan River Subwatershed generally are connected to their floodplain. However, some streams in the upper reaches have altered channel geometry that could be leading to instabilities; these reaches were not studied in the East Swan River Watershed Geomorphic Study.

High TSS in Stony Creek is likely caused by channel straightening that leads to channel incision and bed and bank erosion; the majority of the tributaries to Stony Creek have been channelized (MPCA 2016). The SID states, “the primary source of TSS and bedded sediment in this stream appears to be bank erosion caused by channel incision, widening, and bank scour in areas where large debris jams are impeding flow and re-directing currents towards vulnerable banks” (MPCA 2016).

Load estimates for channel erosion are not provided; however, based on the analyses in the East Swan River Watershed Geomorphic Study (SWCD Technical Services Area #3 2011) and the SID (MPCA 2016), it is assumed that loads from channel erosion in East Swan River and Stony Creek are substantial.

Summary of Results

East Swan River

Upland sediment loads in the East Swan River Subwatershed are dominated by stormwater runoff from developed areas (Table 49). Although not quantified, bank and bluff erosion contributes to the high TSS in the East Swan River, as detailed in the East Swan River Watershed Geomorphic Study (SWCD Technical Services Area #3 2011). See Figure 10 for the map of land cover and point source locations.

Table 49. Summary of TSS loads by source to the East Swan River

Source	TSS Load	
	ton/yr	percent
Barren	13	1%
Developed, unregulated	254	18%
Developed, regulated MS4	726	50%
Forest	106	7%
Pasture and crop	141	10%
Shrub	148	10%
Wetland and water	2	< 1%
Point sources	58	4%
Channel erosion	--[a]	--[a]
Total	1,448	100%

a. Loads from channel erosion were not quantified but are assumed to be substantial.

Stony Creek

Sediment loads in the Stony Creek Watershed are dominated by channel erosion and stormwater runoff from forested and developed areas (Table 50). The developed areas in the watershed primarily consist of roads. Indications of channel instability were observed during the SID study, including debris jams (MPCA 2016). Channel instabilities might be a result of increased peak flows from the channelized streams in the watershed or due to a “local base level drop in the St. Louis River that caused a headcut to migrate up through the Stony Creek Watershed” (MPCA 2016). See Figure 10 for the map of land cover.

Table 50. Summary of TSS loads by source to Stony Creek

Source	TSS Load	
	ton/yr	percent
Barren	< 1	< 1%
Developed	14	22%
Forest	35	54%
Pasture and crop	9	14%
Shrub	4	6%
Wetland and water	3	5%
Channel erosion [a]	--[a]	--[a]
Total	65	100%

a. Loads from channel erosion were not quantified but are assumed to be substantial.

3.6.3 Phosphorus

Phosphorus loads to the following water bodies were evaluated:

- Dinham Lake
- West Two Rivers Reservoir
- West Two River

Phosphorus loads to the five impaired shallow lakes for which TMDLs are being deferred were also evaluated and are presented in Appendix A.

Watershed and municipal and industrial wastewater phosphorus loads were primarily quantified by the watershed HSPF model (Tetra Tech 2016a and 2016b). In addition to the modeled loads, non-permitted source loads from septic systems, internal loading, and atmospheric deposition, and permitted sources from construction and industrial stormwater were estimated, where applicable.

Permitted
Permitted sources of phosphorus include municipal wastewater, industrial wastewater, and construction and industrial stormwater. There are no regulated MS4s or CAFOs in the phosphorus-impaired watersheds.

Municipal Wastewater

The average annual phosphorus load from the Mountain Iron WWTP in the West Two Rivers Reservoir Watershed was estimated with the St. Louis River Watershed HSPF model (Tetra Tech 2016a and 2016b). The effluent discharge volumes and phosphorus concentrations in the model were determined from discharge monitoring records provided by the MPCA. The average wet weather design flow (AWWDF) of Mountain Iron WWTP is 0.55 million gallons per day (MGD), and the facility has phosphorus effluent limits of 1.0 mg/L and 2.08 kg/day as calendar monthly averages.

Industrial Wastewater

The average annual phosphorus load from US Steel–Minntac Mining Area in the West Two Rivers Reservoir Subwatershed was estimated with the St. Louis River Watershed HSPF model (Tetra Tech 2016a and 2016b) and monitoring data. Surface discharge stations 001, 004, 007, and 009 are located in the West Two Rivers Reservoir Subwatershed (Figure 11). The effluent discharge volumes in the model were determined from discharge monitoring records provided by the MPCA. Surface discharge station 007 has no reported discharges from 1995 through 2012. The discharge volumes were multiplied by a TP concentration of 0.005 mg/L, based on monitoring of US Steel–Minntac mine pit dewatering discharge from the #3 sump (surface discharge station 001) and the Prindle Sump (surface discharge station 004) in the West Two Rivers Reservoir Subwatershed from the spring of 2016 (personal communication, Erik Smith, MPCA).

Industrial Stormwater

Industrial stormwater is regulated through an NPDES Permit when stormwater discharges have the potential to come into contact with materials and activities associated with industrial activities. Loading from industrial stormwater is inherently incorporated in the watershed runoff estimates, discussed under non-permitted sources.

Industrial stormwater runoff in the West Two Rivers Reservoir Subwatershed is from a portion of the US Steel–Minntac mining area, from a sand and gravel mining entity, and from sites permitted through the multi-sector general permit for industrial activity. The majority of the runoff from the mining area flows to either a low elevation pit lake with no surface outflow or to a mine pit, in which case it is discharged as industrial wastewater effluent.

Construction Stormwater

Construction stormwater is regulated through an NPDES Permit. Stormwater that runs off construction sites often carries sediment and other pollutants to surface water bodies. Because phosphorus travels adsorbed to sediment, construction sites can be a source of phosphorus to surface waters. An NPDES Permit is needed for a construction activity that disturbs one acre or more of soil; a permit is needed for smaller sites if the activity is either part of a larger development or if the MPCA determines that the activity poses a risk to water resources. Coverage under the construction stormwater general permit requires sediment and erosion control measures that reduce stormwater pollution during and after construction activities.

Loading from construction stormwater is inherently incorporated in the watershed runoff estimates, discussed under non-permitted sources. On average, based on county-wide data, approximately 0.02% of the lakes' watershed areas is permitted under the construction stormwater permit in any given year (average of 2003 through 2014). Construction stormwater is not considered a significant phosphorus source.

Non-permitted

Watershed Runoff

Watershed loading of phosphorus is quantified in the HSPF model (Tetra Tech 2016a and 2016b) and summarized by land cover type (Table 51). Land cover loading rates vary among watersheds because of differences in soils, slope, and weather patterns. Land cover in the model is characterized by satellite data (LANDFIRE 2008). The data differentiate among most of the major land cover types; however, low densities of development in forested areas are not recognized in the satellite data as developed. Therefore, estimates of loading from shoreland development might be underestimated in the model. A survey of shoreland development around Dinham Lake could be used to determine if loading from shoreland development affects lake water quality. Characteristics that can increase phosphorus loading from shoreland areas include shoreline erosion, lawns adjacent to the lake and management of lawns (e.g., fertilizer), and impervious surfaces.

There is one registered feedlot in the West Two River Subwatershed (downstream of the reservoir, see Figure 11). The watershed loading rates take into account sources of phosphorus in the watershed that are not explicitly modeled, including feedlots. The net effect of these sources is included in the watershed load estimates to the extent that the loading rates are calibrated.

Table 51. Average upland phosphorus unit area loading rates to impaired lakes (2003–2012)

Land Cover	Dinham Lake		West Two Rivers Reservoir	
	Area (acres)	P Loading Rate (lb/ac-yr)	Area (acres)	P Loading Rate (lb/ac-yr)
Forest	1,976	0.12	4,448	0.10
Wetland	1,845	0.20	3,921	0.16
Shrub	25	0.05	204	0.07
Pasture	13	0.19	275	0.21
Developed	35	0.18	568	0.19
Water	615	0.28	1,010	0.23
Crop	0	--	43	0.28
Barren	0	--	1,664 [a]	0.19

a. The HSPF model assumes runoff from 1,664 acres of barren land. Subsequent information provided by MPCA suggests that the majority of the barren land in the West Two Rivers Reservoir Subwatershed flows to either low elevation pit lakes with no surface outflow or to mining pits, in which case it is discharged as industrial wastewater effluent. The HSPF loading estimates from barren land were reduced proportional to area.

Septic Systems

Septic systems can be sources of phosphorus to surface waters. Systems that are functioning properly (conforming) contribute less phosphorus than failing systems or systems that are considered an IPHT. Failing systems do not protect groundwater from contamination, and IPHT systems discharge partially treated sewage to the surface. For septic systems located in close proximity to surface waters, both failing and conforming systems contribute phosphorus to surface waters; a conforming system contributes on average 20% of the phosphorus that is found in the system, while a failing or IPHT system contributes on average 43% (Barr Engineering 2004). Phosphorus loads from septic systems to the impaired lakes were evaluated.

Phosphorus loads attributed to SSTS adjacent to Dinham Lake were calculated using data provided by St. Louis County Environmental Services Department and the MPCA's *Detailed Assessment of Phosphorus Sources to Minnesota Watersheds* (Barr Engineering 2004). Total loading is based on the number of shoreline residences, whether the house is used as a permanent or seasonal residence, if the SSTS is conforming or non-conforming, the number of people using the system, and an average value for phosphorus production per person per year (MPCA 2014). The St. Louis County Environmental Services Department provided information on the septic systems located within 1,000 feet of the Lake Dinham shoreline, including whether the septic system is a seasonal or permanent residence and the year of the last inspection on record. To estimate the number of conforming and non-conforming septic systems, it was assumed that any system that was inspected within the last 20 years is conforming. The year 1992 (20 years before the end of the TMDL period, which is 2003 through 2012) was used as the cutoff year. If the system does not have an inspection on record after 1992, or if the permit is expired, it was assumed that the system is non-conforming. Fifty-eight septic systems are within the shoreland of Dinham Lake; approximately one-third of the systems are conforming and two-thirds are non-conforming (Table 52).

For West Two Rivers Reservoir, aerial imagery provided information on the number of residences along the lake shoreline. Because of the low number of septic systems close to the lake (fewer than two), it was assumed that loading from septic systems is insignificant relative to loading from watershed runoff, and loading from septic systems was not quantified.

Table 52. Septic system inventory

Impaired Lake	Number of Conforming SSTS		Number of Non-Conforming SSTS	
	Permanent	Seasonal	Permanent	Seasonal
Dinham	7	12	10	29

Internal Loading

Internal phosphorus loading from lake bottom sediments can be a substantial component of the phosphorus budget in lakes. The sediment phosphorus originates as an external phosphorus load that settles out of the water column to the lake bottom. There are multiple mechanisms by which phosphorus can be released back into the water column as internal loading.

- Low oxygen concentrations (also called anoxia) in the water overlying the sediment can lead to phosphorus release. In a shallow lake or shallow regions of a lake that undergo intermittent mixing of the water column throughout the growing season, the released phosphorus can mix with surface waters throughout the summer and become available for algal growth. In deeper lakes with a more stable summer stratification period, the released phosphorus will remain in the bottom water layer until the time of fall mixing, when it will mix with surface waters. Levels of iron and sulfur in lakes can influence phosphorus cycling and internal loading rates.
- Bottom-feeding fish such as carp and bullhead forage in lake sediments. This physical disturbance can release phosphorus into the water column.
- Wind energy in shallow depths can mix the water column and disturb bottom sediments, which leads to phosphorus release.
- Other sources of physical disturbance, such as motorized boating in shallow areas, can disturb bottom sediments and lead to phosphorus release.

Internal phosphorus loading was estimated based on the existing conditions lake response models (see Section 4.3.1) as follows:

- For West Two Rivers Reservoir, an additional phosphorus load was added to the phosphorus budget to calibrate the lake response model; this load was attributed to internal loading. The phosphorus and DO monitoring data suggest that internal loading can be a substantial source of phosphorus to the reservoir (see Section 3.5.3). However, a portion of the load that was attributed to internal loading could be from watershed loads that were not quantified with the available data.
- For Dinham Lake, an additional phosphorus load was not needed to calibrate the lake response model. The lake response model implicitly includes internal loading, and it is assumed that internal loading exists in Dinham Lake. To explicitly quantify the internal load, an average phosphorus release rate of 4 mg P / m2-day -1 was used, which is typical of mesotrophic lakes (Nürnberg 1988). The internal load was then estimated as the product of the release rate, the predicted anoxic factor (Nürnberg 2005), and the lake surface area.

Upstream Lakes

The impaired reach of West Two River is located immediately downstream of the outlet from West Two Rivers Reservoir (Figure 11). The phosphorus load from West Two Rivers Reservoir to West Two River was estimated in the BATHTUB lake response model (see "total outflow" load in West Two Rivers Reservoir benchmark model in Appendix B).

Atmospheric Deposition

Phosphorus is bound to atmospheric particles, which settle out of the atmosphere and are deposited directly onto a surface water. Atmospheric deposition to the impaired lakes was estimated using the average for the Lake Superior basin in Minnesota (0.200 kg/ha-year, Barr Engineering 2007).

Summary of Results

Phosphorus source assessment results are presented below for each impaired water body.

Dinham Lake

The primary sources of phosphorus to Dinham Lake are from watershed runoff and internal loading (Table 53). Loading from shoreland development is not quantified but likely impacts lake water quality. Shoreland loading can be from impervious surfaces, lawns adjacent to the lake, and/or shoreline erosion. Internal loading in Dinham Lake can be a substantial source in some years (see "Analysis by Water Body" in Section 3.5.3). See Figure 12 for the watershed land cover distribution.

Table 53. Summary of phosphorus sources to Dinham Lake, 2003–2012

Source		TP Load (lb/yr)	Percent TP Load (%)
Watershed loading	Forest	233	21%
	Shrub	1	< 1%
	Pasture and crop	2	< 1%
	Wetland and water	492	43%
	Developed	6 [a]	1% [a]
Septic		86	8%
Atmospheric deposition		36	3%
Internal loading		267	24%
Total		*1,123*	*100%*

a. Estimates of loading from shoreland development might be underestimated because low densities of development in forested areas are not recognized in the land cover data.

Two lakes are located in the upstream portion of the Dinham Lake Watershed —Cameron/West Bass Lake and Schubert/East Bass Lake (Figure 7). Phosphorus and chlorophyll data are not available for these two lakes, but Secchi transparency data suggest that the lakes have relatively good water quality (Figure 58). The growing season mean transparency in the most upstream lake, Schubert Lake, has met the transparency standard since 2001. Cameron Lake, located just downstream of Schubert Lake, has slightly poorer water quality, with fluctuating growing season mean transparencies and a long term average of 2.1 meters. Because of the general good water quality of these lakes, Cameron Lake and Schubert Lake likely have minimal effect on the water quality of Dinham Lake.

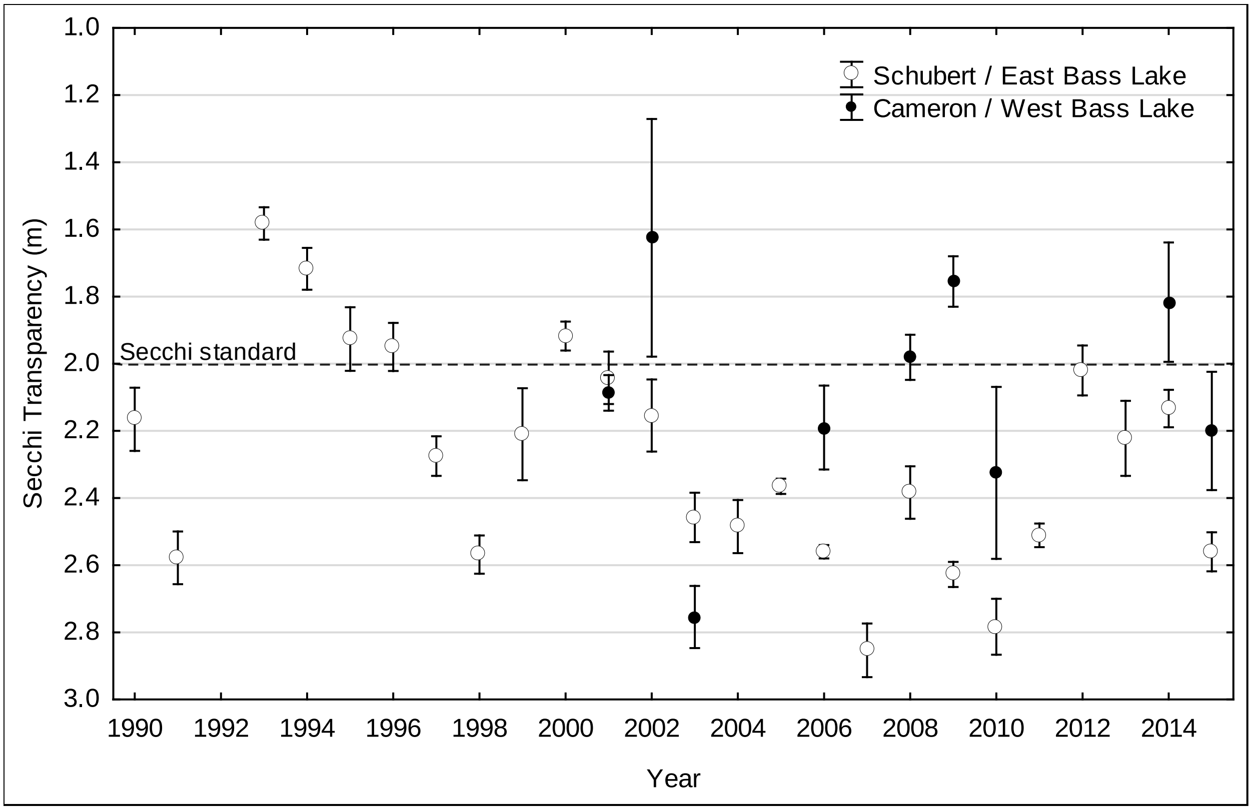


Figure 58. Cameron / West Bass Lake and Schubert / East Bass Lake transparency (growing season means +/- standard error; sites 69-0545-00-201 and 69-0546-00-201)

West Two Rivers Reservoir

The primary sources of phosphorus to West Two Rivers Reservoir are from watershed runoff, point sources, and internal loading (Table 54). Internal loading can be a substantial source in some years (see "Analysis by Water Body" in Section 3.5.3). See Figure 11 for land cover and point source locations.

Table 54. Summary of phosphorus sources to West Two Rivers Reservoir, 2003–2012

Source		**TP Load (lb/yr)**	**Percent TP Load (%)**
Watershed loading	Forest	464	14
	Shrub	15	0
	Pasture and crop	70	2
	Wetland and water	712	21
	Developed	107	3
	Barren	19	1
Point sources	Mountain Iron WWTP (MN0040835)	673	20
	US Steel–Minntac Mining Area (MN0052493)	94	3
Atmospheric deposition		130	4
Internal loading		1,105	32
Total		*3,389*	*100*

West Two River

The impaired reach of West Two River is located immediately downstream from West Two Rivers Reservoir (Figure 11). Approximately half of the phosphorus load to West Two River is from the reservoir outlet, and the other half of the load is from watershed runoff (Table 55).

Table 55. Summary of phosphorus sources to West Two River, 2003–2012

Source		TP Load (lb/yr)	Percent TP Load (%)
Watershed loading	Barren	1	< 1
	Developed	48	1
	Forest	732	22
	Pasture and crop	118	4
	Shrub	12	< 1
	Wetland and water	749	23
West Two Rivers Reservoir outflow		1,625	49
Total		*3,285*	*100*

3.6.4 Temperature and Dissolved Oxygen in Wyman Creek (04010201-942)

Sources of thermal loading and DO were evaluated as part of a comprehensive monitoring and modeling effort (see Section 3.5.4 and Appendix D). Based on the data collected, high water temperatures and low DO conditions in Wyman Creek appear to be caused by a combination of natural and human factors. Natural factors include the low gradient system, natural wetlands, peaty soils that have naturally low DO in baseflow discharge, organic material in the stream that exerts sediment oxygen demand, ponded water from beaver dams, and oxygen demand caused by the presence of iron reducing bacteria. Potential anthropogenic factors include mine pits and ponded water, altered hydrology, and lack of riparian shade.

Modeling simulated the interactions of temperature and DO, and determined that in the case of Wyman Creek, reductions in temperature would improve low DO conditions enough to meet water quality standards. Therefore, the source assessment only addresses sources of thermal loading.

Permitted

There is one permitted point source discharge in the Wyman Creek Watershed: Cliffs Erie–Hoyt Lakes Mining Area (MN0042536, SD012 and SD030). There are two separate mine pits that are regulated under this permit. Temperature inputs from these two mine pit outflows to Wyman Creek were evaluated with the 2016 monitoring data and determined to have little to no effect on the temperature or DO in the lower Wyman Creek reaches (scenario 4 in Appendix D).

Non-permitted

Non-permitted causes of high temperatures in Wyman Creek include the low gradient system, wetlands, lack of riparian shade, ponded waters and altered hydrology (e.g., from beaver dams). The data evaluation in Section 3.5.4 and the complete modeling report (Appendix D) provide additional details.

4. TMDL Development

A TMDL is the total amount of a pollutant that a receiving water body can assimilate while still achieving water quality standards. TMDLs can be expressed in terms of mass per time or by other appropriate measures. TMDLs are composed of the sum of individual wasteload allocations (WLAs) for point sources and load allocations (LAs) for nonpoint sources and natural background levels. In addition, the TMDL includes a MOS, either implicit or explicit, that accounts for the uncertainty in the relationship between pollutant loads and the quality of the receiving water body. Conceptually, this is defined by the equation:

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

A summary of the allowable loads for all parameters in the St. Louis River Watershed is presented in this section. The allocations for each of the various sources and parameters are shown in the tables throughout this section.

<u>Streams:</u> Allowable pollutant loads in streams are determined through the use of load duration curves for *E. coli* and TSS. A load duration curve is similar to a concentration duration curve (Section 3.5) except that loads rather than concentrations are plotted on the vertical axis. Discussions of load duration curves are presented in *An Approach for Using Load Duration Curves in the Development of TMDLs* (EPA 2007). The approach involves calculating the allowable loadings over the range of flow conditions expected to occur in the impaired stream by taking the following steps:

1. A flow duration curve for the stream is developed by generating a flow frequency table and plotting the data points to form a curve. The data reflect a range of natural occurrences from extremely high flows to extremely low flows. The flow data are year-round simulated daily average flows (2003 through 2012) from the SLRW HSPF model application. For reaches for which flow was not simulated explicitly in the HSPF model, flows from nearby model reaches were area-weighted to estimate flows in the impaired reach. The model report (Tetra Tech 2016a) describes the framework and the data that were used to develop the model, and includes information on the calibration.
2. The flow duration curve is translated into a load duration curve by multiplying each flow value by the water quality standard/target for a contaminant (as a concentration), then multiplying by conversion factors to yield results in the proper unit. The resulting points are plotted to create a load duration curve.
3. Each water quality sample is converted to a load by multiplying the water quality sample concentration by the average daily flow on the day the sample was collected. Then, the individual loads are plotted as points on the load duration curve graph and can be compared to the water quality standard/target, or load duration curve.
4. Points plotting above the curve represent deviations from the water quality standard/target and the daily allowable load. Those plotting below the curve represent compliance with standards and the daily allowable load.
5. The area beneath the TMDL curve is interpreted as the loading capacity of the stream. The difference between this area and the area representing the current loading conditions is the load that must be reduced to meet water quality standards/targets.

The resulting load duration curve can provide insight into pollutant sources. The exceedances at the right side of the graph occur during low flow conditions, and may be derived from sources such as IPHT septic systems. Exceedances on the left side of the graph occur during higher flow events, and may be derived from sources such as runoff. The load duration curve approach helps select implementation practices that are most effective for reducing loads on the basis of flow regime. If loads are considerable during wet-weather events (including snowmelt), implementation efforts can target those best management practices (BMPs) that will most effectively reduce stormwater runoff.

The stream flows displayed on load duration curves may be grouped into various flow regimes to aid with interpretation of the load duration curves. The flow regimes are typically divided into 10 groups, which can be further categorized into the following five hydrologic zones (EPA 2007):

- Very high flow zone: stream flows that plot in the 0 to 10 percentile range, related to flood flows
- High zone: flows in the 10 to 40 percentile range, related to wet weather conditions
- Mid-range zone: flows in the 40 to 50 percentile range, median stream flow conditions
- Low zone: flows in the 60 to 90 percentile range, related to dry weather flows
- Very low flow zone: flows in the 90 to 100 percentile range, related to drought conditions

The duration curve approach helps to identify the issues surrounding the impairment and to roughly differentiate among sources. Table 56 summarizes the general relationship among the five hydrologic zones and potentially contributing source areas (the table is not specific to an individual pollutant). For example, the table indicates that impacts from point sources are usually most pronounced during low and very low flow zones because there is less water in the stream to dilute their loads. In contrast, impacts from channel bank erosion is most pronounced during high flow zones because these are the periods during which stream velocities are high enough to cause erosion to occur.

Table 56. Relationship between duration curve zones and contributing sources

Source	Duration Curve Zone				
	Very High	High	Mid-range	Low	Very Low
Point sources				M	H
Livestock access to streams				M	H
Septic systems	M	M-H	H	H	H
Riparian areas		H	H	M	
Stormwater	H	H	M		
Bank erosion	H	M			

Note: Potential relative importance of source to contribute loads under given hydrologic condition (H: High; M: Medium; L: Low).

The load duration curve method was used to develop the stream TMDLs. The approach is based on an analysis that encompasses the cumulative frequency of historic flow data over a specified period. Because this method uses a long-term record of daily flow volumes, virtually the full spectrum of allowable loading capacities is represented by the resulting curve. In the TMDL equation tables, only five points on the entire loading capacity curve are depicted—the midpoints of the designated flow zones (e.g., for the high flow zone [0th to 10th percentile], the TMDL was calculated at the 5th percentile). However, the entire curve represents the TMDL and is what is ultimately approved by the EPA.

The temperature and DO TMDLs for Wyman Creek were developed using an in-stream response model, QUAL2K. The full model report is provided in Appendix D.

Lakes: Allowable pollutant loads in lakes are determined using the lake response model BATHTUB. BATHTUB is a steady state model that predicts eutrophication response in lakes based on empirical formulas developed for nutrient balance calculations and algal response (Walker 1987). The model was developed and is maintained by the U.S. Army Corps of Engineers and has been used extensively in Minnesota and across the Midwest for lake nutrient TMDLs. The BATHTUB model requires nutrient loading inputs from the upstream watershed and atmospheric deposition, morphometric data for the lake, and estimates of mixing depth and non-algal turbidity. Watershed loads (see Section 3.6.3, under "Watershed Runoff") were derived from the HSPF model (Tetra Tech 2016a and 2016b).

Additional details on the approaches used to develop the TMDL components are provided in the following sections.

4.1 E. coli

4.1.1 Approach

Loading Capacity and Percent Reductions

The loading capacity for *E. coli* is based on the monthly geometric mean standard (126 org/100 mL). It is assumed that practices that are implemented to meet the geometric mean standard will also address the individual sample standard (1,260 org/100 mL) and that the individual sample standard will also be met. The loading capacity is calculated as flow multiplied by the *E. coli* geometric mean standard (126 org/100 mL).

The existing loads were calculated as the geometric mean of the observed loads in each flow zone from the months in which the standard applies (April through October); the monitoring data concentrations were multiplied by estimated flow, and then multiplied by a unit conversion factor. The percent reductions needed to meet the TMDL were calculated as the TMDL minus the existing load divided by the existing load; this calculation generates the portion of the existing load that must be reduced to achieve the TMDL. If the existing load is lower than the TMDL for a flow regime, the percent reduction needed to meet the TMDL is reported as zero. If there are no monitoring data for a flow regime, the existing load and the load reduction are not reported. A second percent reduction that addresses only watershed runoff was also calculated for each impairment. The watershed runoff loading goal was calculated as the TMDL minus the MOS minus WLAs for WWTFs, and applies to both regulated and non-regulated watershed runoff. The simulated flow data and the *E. coli* monitoring data used to calculate the loading capacity and the percent reductions needed to meet the TMDL are from 2003 through 2012. 2012 is thus the baseline year against which future reductions will be compared.

The Clean Water Act requires that TMDLs take into account critical conditions for stream flow, loading, and water quality parameters as part of the analysis of loading capacity. Through the load duration curve approach it has been determined that load reductions are needed for specific flow conditions; however, the critical conditions (the periods when the greatest reductions are required) vary by location and are inherently addressed by specifying different levels of reduction according to flow.

Load Allocation Methodology

The LA represents the portion of the loading capacity that is allocated to pollutant loads that are not regulated through an NPDES Permit and is calculated as the loading capacity minus the sum of the WLAs and the MOS. The LA covers watershed runoff that is generated in areas that are not regulated through the MS4 Permit, along with other nonpoint sources such as septic systems.

Wasteload Allocation Methodology

WLAs are provided for municipal WWTFs and for regulated MS4 communities. There are no permitted CAFOs in the watershed. Permitted industrial stormwater sources are not expected to be sources of *E. coli* and are not provided WLAs. The MPCA's Industrial Stormwater Permit does not regulate discharges of *E. coli*. The permit does not contain *E. coli* benchmarks; industrial stormwater permittees are required to sample their stormwater for parameters that more closely match the potential contribution of pollutants for their industry sector or subsector. For example, recycling facilities and auto salvage yards are required to sample for TSS, metals, and other pollutants likely present at these types of facilities.

Municipal Wastewater

The two existing municipal WWTFs in the *E. coli*-impaired watersheds are the CIRSSD and Hibbing WWTP South. Hibbing South discharges to East Swan Creek, which is a Class 2B water. Hibbing South's fecal coliform effluent limit applies from April 1 through October 31 (the aquatic recreation season), which is the same time frame as the receiving water body's *E. coli* standard and the WLA. The WLA is based on the *E. coli* geometric mean standard of 126 organisms per 100 mL and the facility's AWWDF (Table 57). It is assumed that if a facility meets the fecal coliform limit of 200 organisms per 100 mL, it is also meeting the *E. coli* WLA. On March 17, 2008, Minn. R ch. 7050 water quality standards for bacteria were changed from fecal coliform concentration to *E. coli* concentration supported by an EPA guidance document on bacteriological criteria (EPA 1986). In conjunction with the change of indicator organisms for bacterial water quality, a decision was made to retain existing fecal coliform effluent limits for WWTFs. This decision is extensively documented in the regulation's Statement of Need and Reasonableness, Book III, Section VII.G.

CIRSSD discharges to Barber Creek, which is a Class 7 (limited resource value) water. The fecal coliform effluent limit in the existing permit applies from May 1 through October 31, which is one month shorter than the time frame of the *E. coli* standard of the downstream impaired reach of Barber Creek (April 1 through October 31). The WLA is based on the *E. coli* geometric mean standard of 126 organisms per 100 mL and the facility's AWWDF (Table 57). The TMDL table for Barber Creek (Table 63) and associated discussion provides details on CIRSSD's *E. coli* WLA.

Table 57. Permitted wastewater treatment facilities for *E. coli* TMDLs

Wastewater Treatment Facility (NPDES Permit #)	Average Wet Weather Design Flow (million gallons per day) [a]	*E. coli* WLA (billion organisms per day), April through October	Impairments
Central Iron Range Sanitary Sewer District (MN0020117)	2.5	11.9 [b]	Barber Creek / East Swan River: 04010201-569 and -641
Hibbing WWTP South Plant (MN0030643)	4.5	21.5	Unnamed Creek / East Swan Creek: 04010201-888

a. Determination of a facility's AWWDF is described in MPCA (2002).

b. To comply with the CIRSSD's WLA, the MPCA has future permit discretion to: 1) expand the fecal coliform effluent limit effective period to include April, or 2) require the permittee to conduct a stream monitoring program to determine whether Barber Creek is impaired for *E. coli* in April and implement an expanded disinfection period only if the impairment occurs in April. Further reductions in *E. coli* load, beyond the extension of the disinfection months, are not needed.

Municipal Separate Storm Sewer Systems

There are six regulated MS4s in the *E. coli* impairment watersheds, and there are three MS4s that are expected to come under permit coverage in the next permit cycle (Table 58; see Figure 3 and Figure 4 for city and township boundaries). The regulated MS4s consist of cities, townships, and road authorities. For cities and townships, the area regulated through the MS4 Permit was approximated by the developed land cover classes. For the regulated road authorities (St. Louis County and the Minnesota Department of Transportation [MnDOT]), the applicable roads are those within the urbanized areas defined by the U.S. Census Bureau. The regulated road area was approximated by multiplying the road length by the average right of way width determined by measuring representative rights of way in GIS (180 feet for state roads and 70 feet for county roads).

Each MS4's WLA was calculated by multiplying the percentage of MS4 area by the load that is allocated to watershed runoff. The load allocated to watershed runoff equals the loading capacity minus the MOS, minus the WLAs for WWTFs. In cases where stormwater runoff from the regulated MS4 does not contribute to the impairment (Table 47), reductions in loading from regulated MS4s are not needed. Where watershed runoff from regulated MS4s is a likely source, the watershed percent reductions needed to meet the TMDL apply to the MS4 WLAs.

Table 58. Permitted MS4s for *E. coli* TMDLs

MS4 Name (NPDES Permit #)	Impairment AUIDs	Regulated Area (Approximated) in Impairment Watersheds (acres)	Reductions to Meet WLA
Hibbing City (MS400270)	542, 569, 580, 582, 641, 888, 936 & A22	5,424	0–93% [b]
Hermantown City (MS400093)	543, 625	117	0%
Midway Township (MS400146)	625	9	0%
Cloquet City (MS400267)	543	895	0%
St. Louis County (MS400158)	543	38	0%
MnDOT Outstate District (MS400180)	543	44	0%
Grand Lake Township [a]	543	262	0%
Canosia Township [a]	543	143	0%
Thomson Township [a]	543, 751	126	0%

a. Not currently regulated but expected to come under permit coverage in the next permit cycle.

b. Range of the maximum percent reduction of the five flow regimes in each relevant TMDL table (Table 59 through Table 66).

Margin of Safety

An explicit 10% MOS was calculated for the *E. coli* TMDLs. The explicit MOS accounts for environmental variability in pollutant loading and variability in water quality monitoring data. The simulated flow data are based on a calibrated and validated HSPF model application that was used to simulate daily average flow between 1995 and 2012 (Tetra Tech 2016a). The MOS accounts for uncertainty in the calibration data, errors in the model's hydrologic calibration, and conservative assumptions made during the modeling efforts. The model was calibrated and validated using nine stream flow gaging stations. Five gaging stations have over 10 years of continuous flow records, and four have shorter term flow records. Calibration results indicate that the HSPF model is a valid representation of hydrologic conditions in the watershed. To estimate flow in reaches that were not explicitly modeled in HSPF, simulated flow data from nearby reaches were area-weighted; this adds to uncertainty in the flow estimates.

Die-off and instream growth of *E. coli* were not explicitly addressed. The MOS helps to account for variability in *E. coli* concentrations associated with growth and die-off.

Seasonal Variation

Seasonal variations are addressed in this TMDL by assessing conditions only during the season when the water quality standard applies (April 1 through October 31). The load duration approach also accounts for seasonality by evaluating allowable loads on a daily basis over the entire range of observed flows and by presenting daily allowable loads that vary by flow.

4.1.2 TMDL Summaries

Figure 59 through Figure 68 present the *E. coli* load duration curves, and Table 59 through Table 68 summarize the TMDLs, allocations, existing loads, and load reductions for the *E. coli* impairments. The figures show the individual *E. coli* data measurements, the geometric mean by flow regime of the individual data points, and the load duration curves developed using the monthly geometric mean standard (126 org/100 mL). Loads are rounded to three significant digits, except in the case of values greater than 1,000, which are rounded to the nearest whole number. Percent reductions are rounded to the nearest whole number.

In this section, the stream reaches are presented from upstream to downstream. The impaired reaches in the Swan River Subwatershed (see map in Figure 3) are presented first, followed by the impaired reaches in the lower portion of the watershed (see map in Figure 4).

Buhl Creek (04010201-580)

Load reductions in Buhl Creek are needed under very high and mid-range flow conditions (Figure 59, Table 59). The *E. coli* standard was violated in July and August (Table 12), and the high priority sources are livestock, pets, aging wastewater infrastructure, and stormwater runoff from unregulated areas (Table 47). The regulated MS4 (City of Hibbing, Figure 8) does not contribute to the impairment and is not required to reduce *E. coli* loading.

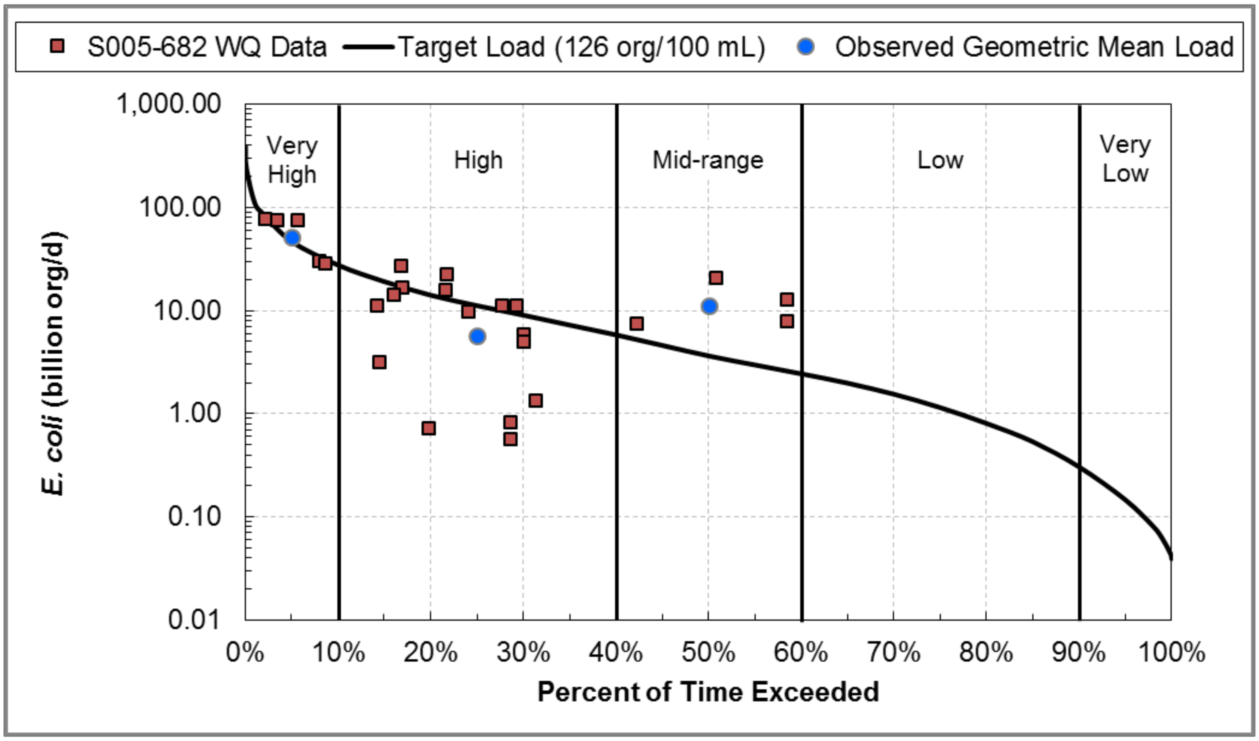


Figure 59. *E. coli* load duration curve, Buhl Creek (04010201-580)

Table 59. *E. coli* TMDL summary, Buhl Creek (04010201-580)

TMDL Parameter (Permit #)	Flow Regime				
	Very High	**High**	**Mid-Range**	**Low**	**Very Low**
	***E. coli* Load (billion org/day)**				
Wasteload Allocation: Hibbing City MS4 (MS400270)	0.201	0.0481	0.0156	0.00494	0.000631
Load Allocation	41.9	10.0	3.26	1.03	0.132
MOS	4.68	1.12	0.364	0.115	0.0147
Loading Capacity [a]	46.8	11.2	3.64	1.15	0.147
Existing Load	51.7	5.71	11.1	–	–
Percent Load Reduction	9%	0%	67%	–	–
Percent Load Reduction for Regulated MS4 [b]	0%	0%	0%	0%	0%
Percent Load Reduction for Unregulated Sources	19%	0%	71%	–	–

a. Loading capacities are rounded to three significant digits.

b. Runoff from the regulated MS4 does not contribute to the impairment, and MS4 load reductions are not required.

Dempsey Creek (04010201-582)

Load reductions in Dempsey Creek are needed only under very high flow conditions (Figure 60, Table 60). The *E. coli* standard was violated in July (Table 14), and the high priority sources are livestock, pets, aging wastewater infrastructure, and stormwater runoff from unregulated areas (Table 47). These sources are in the upstream portion of the Dempsey Creek Subwatershed (in the Buhl Creek Subwatershed); primary sources of *E. coli* in the Dempsey Creek direct watershed are unknown. The regulated MS4 (City of Hibbing, Figure 8) does not contribute to the impairment and is not required to reduce *E. coli* loading.

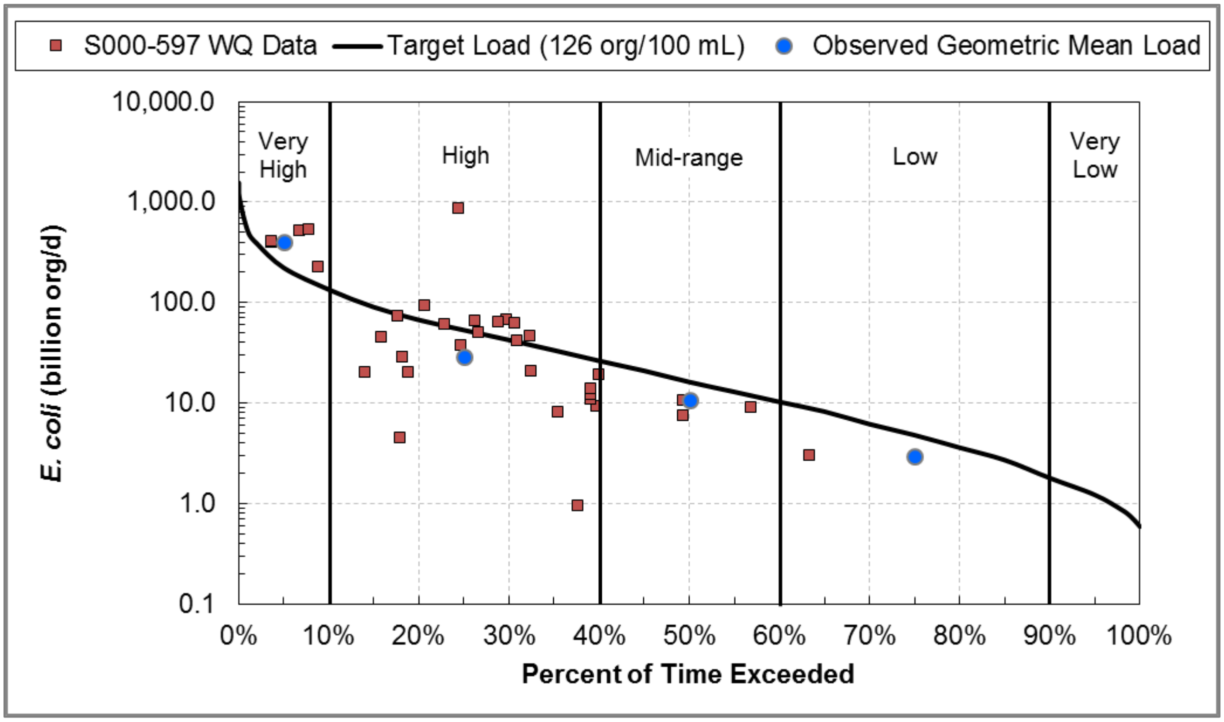


Figure 60. *E. coli* load duration curve, Dempsey Creek (04010201-582)

Table 60. *E. coli* TMDL summary, Dempsey Creek (04010201-582)

TMDL Parameter (Permit #)	Flow Regime				
	Very High	High	Mid-Range	Low	Very Low
	E. coli Load (billion org/day)				
Wasteload Allocation: Hibbing City MS4 (MS400270)	4.11	0.984	0.301	0.0892	0.0221
Load Allocation	196	46.9	14.3	4.22	1.08
MOS	22.2	5.32	1.62	0.479	0.122
Loading Capacity [a]	222	53.2	16.2	4.79	1.22
Existing Load	398	29.0	10.7	2.98	–
Percent Load Reduction	44%	0%	0%	0%	–
Percent Load Reduction for Regulated MS4 [b]	0%	0%	0%	0%	0%
Percent Load Reduction for Unregulated Sources	50%	0%	0%	0%	–

a. Loading capacities are rounded to three significant digits.

b. Runoff from the regulated MS4 does not contribute to the impairment, and MS4 load reductions are not required.

Barber Creek (East Swan River, 04010201-641)

Load reductions in Barber Creek are needed only under very high flow conditions (Figure 61, Table 61). The *E. coli* standard was violated in June and August (Table 16), and the high priority sources are livestock, pets, aging wastewater infrastructure, and stormwater runoff from regulated (City of Hibbing, Figure 8) and unregulated (City of Chisolm) areas (Table 47).

CIRSSD's fecal coliform permit limit applies from May 1 through October 31; however, the *E. coli* standard of the impaired reach of Barber Creek also applies in April. Because of a lack of April *E. coli* data in Barber Creek, it is not known if an impairment exists in April and if CIRSSD has the potential to contribute to the impairment. To implement CIRSSD's WLA, the MPCA has future permit discretion to[2]:

- Expand the fecal coliform effluent limit effective period to include April or require the permittee to conduct a stream monitoring program to determine whether Barber Creek is impaired for *E. coli* in April.
- Implement an expanded disinfection period only if the impairment occurs in April.

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[2] 40 CFR 122.44(d)(vii)(B) states that "effluent limits developed to protect a narrative water quality criterion, a numeric water quality criterion, or both, are consistent with the assumptions and requirements of any available wasteload allocation for the discharge prepared by the State and approved by EPA."

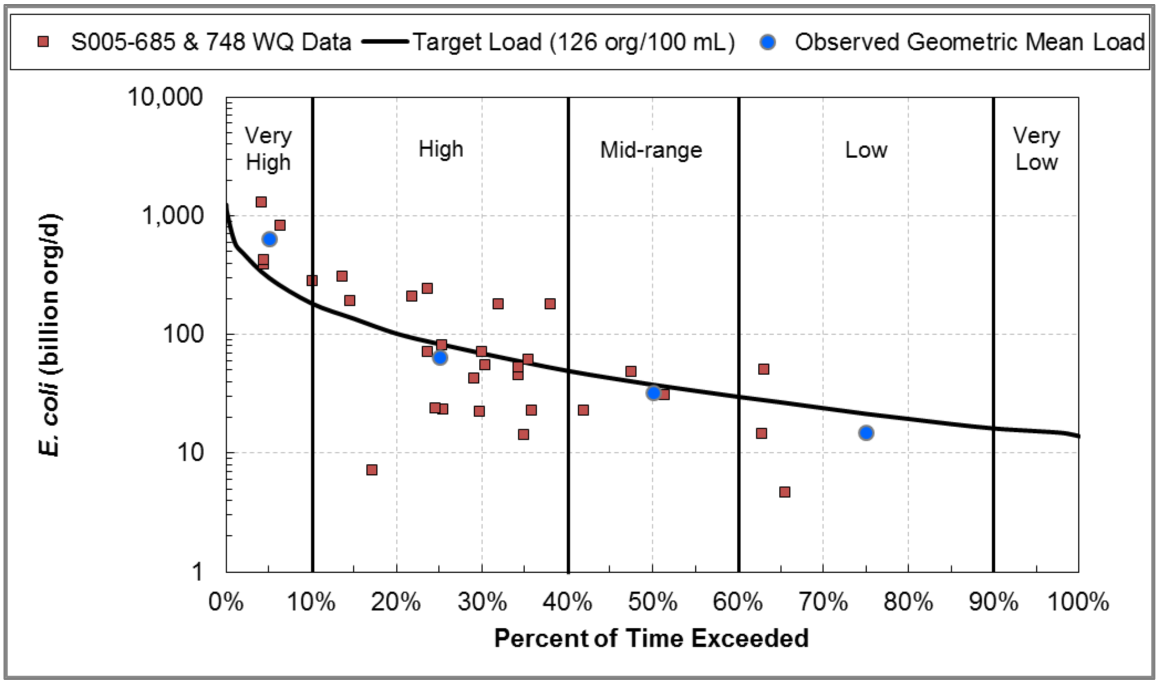

Figure 61. ***E. coli*** **load duration curve, Barber Creek (04010201-641)**

Table 61. ***E. coli*** **TMDL summary, Barber Creek (04010201-641)**

TMDL Parameter (Permit #)		**Flow Regime**				
		Very High	**High**	**Mid-Range**	**Low**	**Very Low**
		E. coli **Load (billion org/day)**				
Wasteload Allocation	Hibbing City MS4 (MS400270)	6.97	1.69	0.593	0.198	0.0503
	Central Iron Range Sanitary Sewer District (MN0020117) [a]	11.9	11.9	11.9	11.9	11.9
Load Allocation		252	61.2	21.4	7.16	1.82
MOS		30.1	8.31	3.77	2.14	1.53
Loading Capacity [b]		301	83.1	37.7	21.4	15.3
Existing Load		646	64.6	32.5	15.0	–
Percent Load Reduction		53%	0%	0%	0%	–
Watershed Percent Load Reduction [c]		59%	0%	0%	0%	–

a. To implement CIRSSD's WLA, the MPCA has future permit discretion to: 1) expand the fecal coliform effluent limit effective period to include April, or 2) require the permittee to conduct a stream monitoring program to determine whether Barber Creek is impaired for *E. coli* in April and implement an expanded disinfection period only if the impairment occurs in April. Further reductions in *E. coli* load, beyond the extension of the disinfection months, are not needed.

b. Loading capacities are rounded to three significant digits.

c. The watershed percent reductions apply to the regulated MS4s and the unregulated watershed runoff in the LA.

Penobscot Creek (04010201-936)

Load reductions in Penobscot Creek are needed under all flow conditions for which there are monitoring data (Figure 62, Table 62). The *E. coli* standard was violated in June, July, August, and September (Table 18), and the high priority sources are pets, aging wastewater infrastructure, and stormwater runoff from regulated areas (City of Hibbing; Table 47, Figure 8).

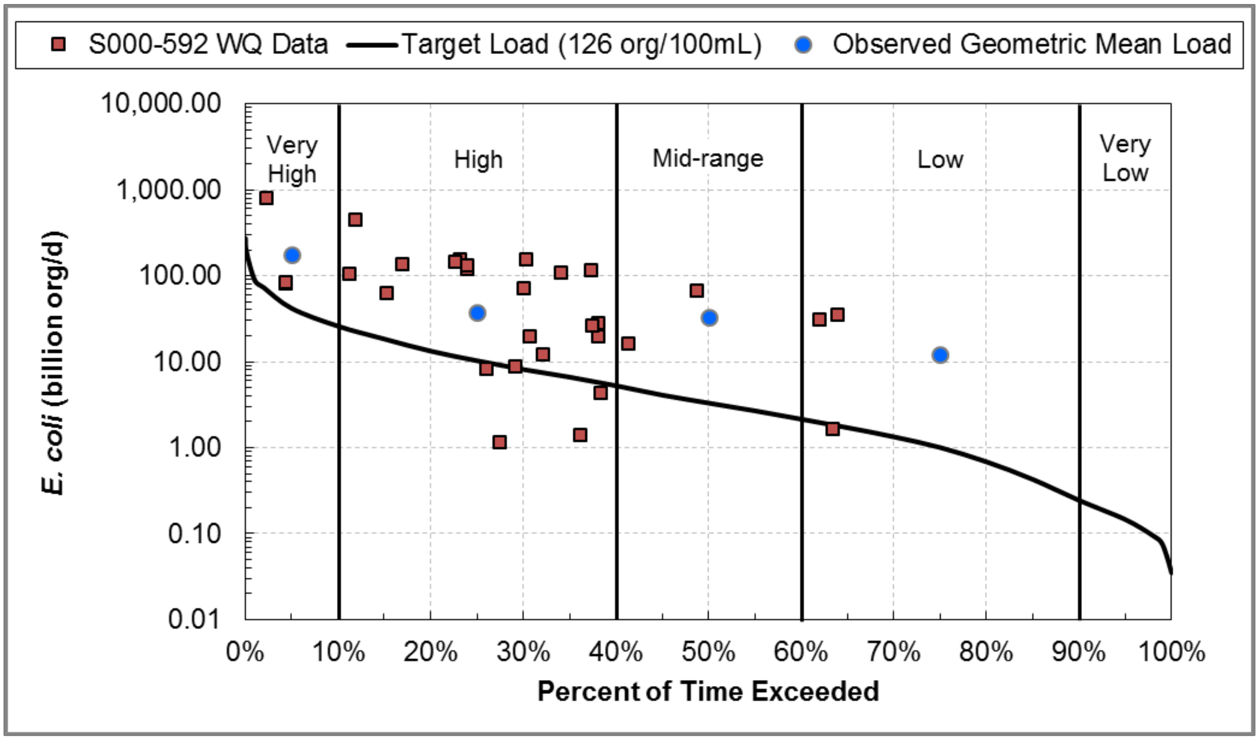

Figure 62. *E. coli* load duration curve, Penobscot Creek (04010201-936)

Table 62. *E. coli* TMDL summary, Penobscot Creek (04010201-936)

TMDL Parameter (Permit #)	**Flow Regime**				
	Very High	**High**	**Mid-Range**	**Low**	**Very Low**
	***E. coli* Load (billion org/day)**				
Wasteload Allocation: Hibbing City MS4 (MS400270)	12.6	3.12	1.00	0.306	0.0443
Load Allocation	24.9	6.15	1.98	0.603	0.0871
MOS	4.17	1.03	0.331	0.101	0.0146
Loading Capacity [a]	41.7	10.3	3.31	1.01	0.146
Existing Load	177	37.1	32.8	12.1	–
Percent Load Reduction	76%	72%	90%	92%	–
Watershed Percent Load Reduction [b]	79%	75%	91%	93%	–

a. Loading capacities are rounded to three significant digits.

b. The watershed percent reductions apply to the regulated MS4s and the unregulated watershed runoff in the LA.

Barber Creek (East Swan River, 04010201-569)

Load reductions in Barber Creek are needed under all flow conditions for which there are monitoring data (Figure 63, Table 63). The *E. coli* standard was violated in June, July, and August (Table 20), and the high priority sources are aging wastewater infrastructure and stormwater runoff from regulated areas (City of Hibbing, Table 47, Figure 8).

CIRSSD’s fecal coliform permit limit applies from May 1 through October 31; however, the *E. coli* standard of the impaired reach of Barber Creek also applies in April. Because of a lack of April *E. coli* data in Barber Creek, it is not known if an impairment exists in April and if CIRSSD has the potential to contribute to the impairment. To implement CIRSSD’s WLA, the MPCA has future permit discretion to:

- Expand the fecal coliform effluent limit effective period to include April or require the permittee to conduct a stream monitoring program to determine whether Barber Creek is impaired for *E. coli* in April.
- Implement an expanded disinfection period only if the impairment occurs in April.

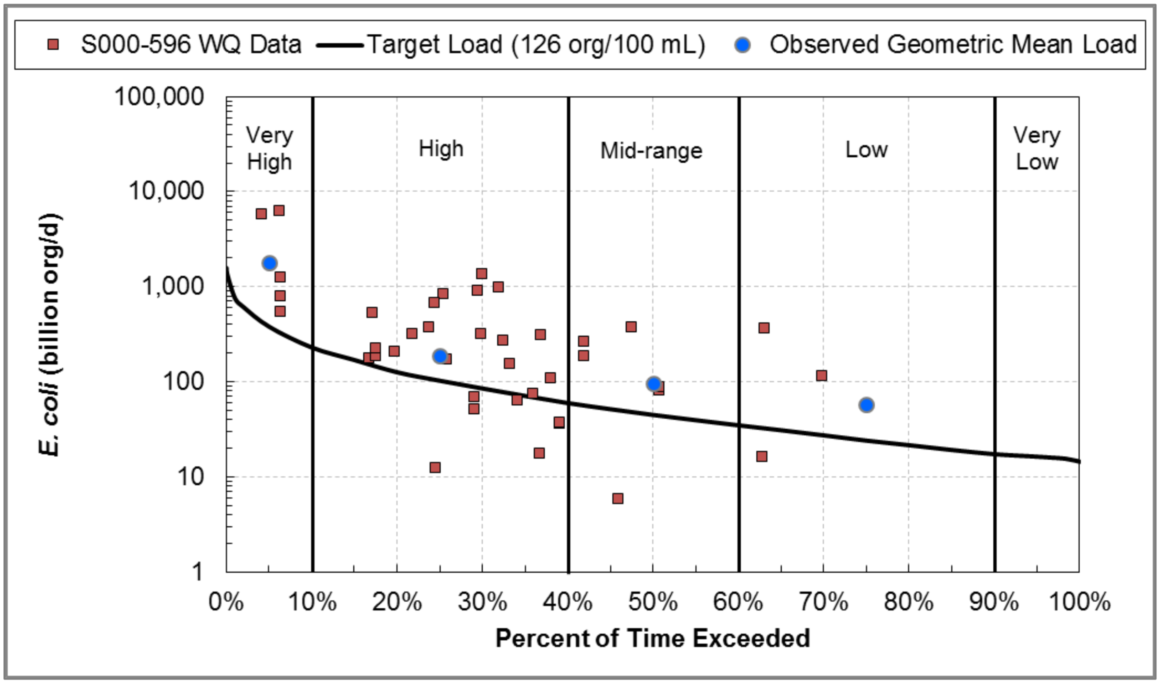

Figure 63. *E. coli* load duration curve, Barber Creek (04010201-569)

Table 63. *E. coli* TMDL summary, Barber Creek (04010201-569)

TMDL Parameter (Permit #)		**Flow Regime**				
		Very High	**High**	**Mid-Range**	**Low**	**Very Low**
		***E. coli* Load (billion org/day)**				
Wasteload Allocation	Hibbing City MS4 (MS400270)	21.3	5.23	1.74	0.555	0.110
	Central Iron Range Sanitary Sewer District (MN0020117) [a]	11.9	11.9	11.9	11.9	11.9
Load Allocation		309	75.6	26.7	9.14	2.66
MOS		38.0	10.3	4.48	2.40	1.63
Loading Capacity [b]		380	103	44.8	24.0	16.3
Existing Load		1,810	189	94.9	57.4	–
Percent Load Reduction		79%	46%	53%	58%	–
Watershed Percent Load Reduction [c]		82%	54%	66%	79%	–

a. To implement CIRSSD's WLA, the MPCA has future permit discretion to: 1) expand the fecal coliform effluent limit effective period to include April, or 2) require the permittee to conduct a stream monitoring program to determine whether Barber Creek is impaired for *E. coli* in April and implement an expanded disinfection period only if the impairment occurs in April. Further reductions in *E. coli* load, beyond the extension of the disinfection months, are not needed.

b. Loading capacities are rounded to three significant digits.

c. The watershed percent reductions apply to the regulated MS4s and the unregulated watershed runoff in the LA.

Unnamed Creek (04010201-A22)

Load reductions in Unnamed Creek are needed under the very high and high flow zones (Figure 64, Table 64). The *E. coli* standard was violated in June, July, August, and September (Table 22), and the high priority source is livestock (Table 47); reductions should come primarily from *E. coli* loading from livestock. The only developed areas in the watershed are roads. Because these developed areas are limited, the regulated MS4 does not contribute to the impairment (Table 47, Figure 8) and is not required to reduce *E. coli* loading.

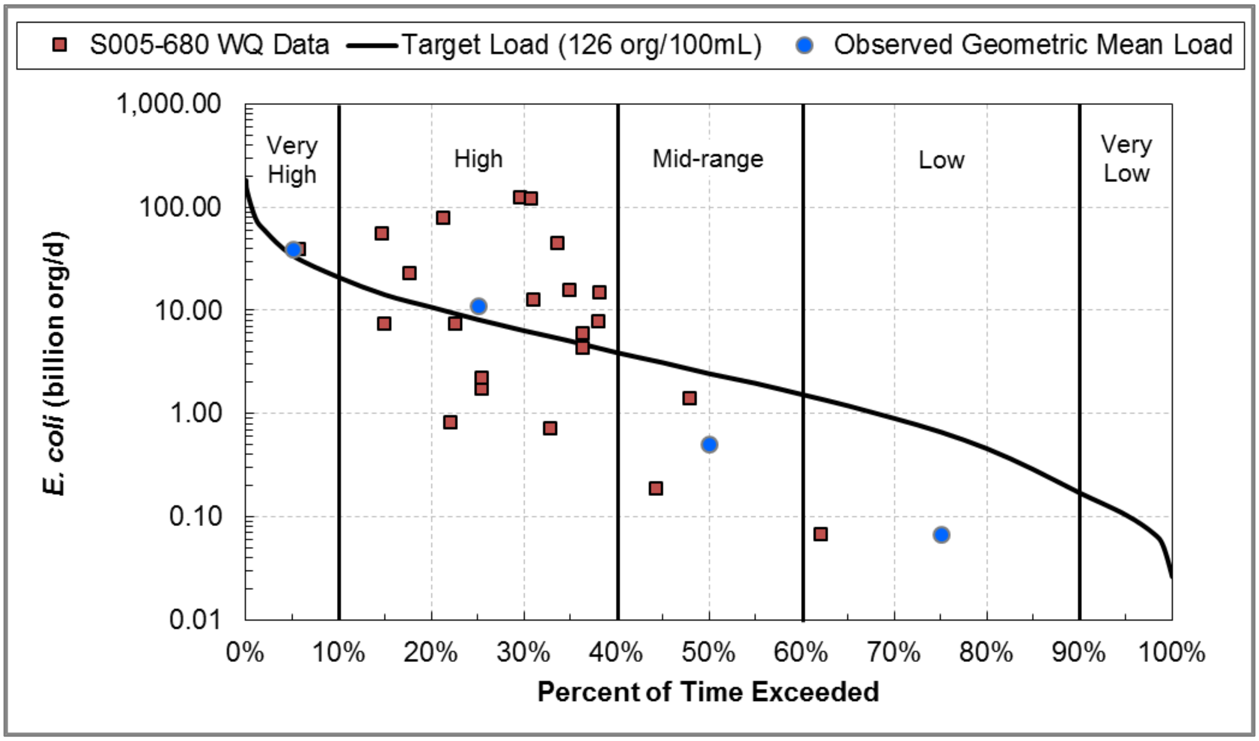

Figure 64. *E. coli* load duration curve, Unnamed Creek (04010201-A22)

Table 64. *E. coli* TMDL summary, Unnamed Creek (04010201-A22)

TMDL Parameter (Permit #)	Flow Regime				
	Very High	High	Mid-Range	Low	Very Low
	E. coli Load (billion org/day)				
Wasteload Allocation: Hibbing City MS4 (MS400270)	2.51	0.599	0.179	0.049	0.00762
Load Allocation	28.3	6.75	2.02	0.548	0.0860
MOS	3.42	0.817	0.244	0.0663	0.0104
Loading Capacity [a]	34.2	8.17	2.44	0.663	0.104
Existing Load	39.6	11.0	0.511	0.0681	–
Percent Load Reduction	14%	26%	0%	0%	–
Percent Load Reduction for Regulated MS4 [b]	0%	0%	0%	0%	0%
Percent Load Reduction for Unregulated Sources	22%	33%	0%	0%	–

a. Loading capacities are rounded to three significant digits.

b. Runoff from the regulated MS4 does not contribute to the impairment, and MS4 load reductions are not required.

Unnamed Creek (04010201-542)

Load reductions in Unnamed Creek are needed only under very high flow conditions (Figure 65, Table 65). The *E. coli* standard was violated in July and August (Table 24), and the high priority sources are livestock, pets, aging infrastructure, and stormwater runoff from regulated areas (City of Hibbing; Table 47). All of the stormwater runoff (i.e., from developed land covers) in this watershed is within the city of Hibbing (Figure 8).

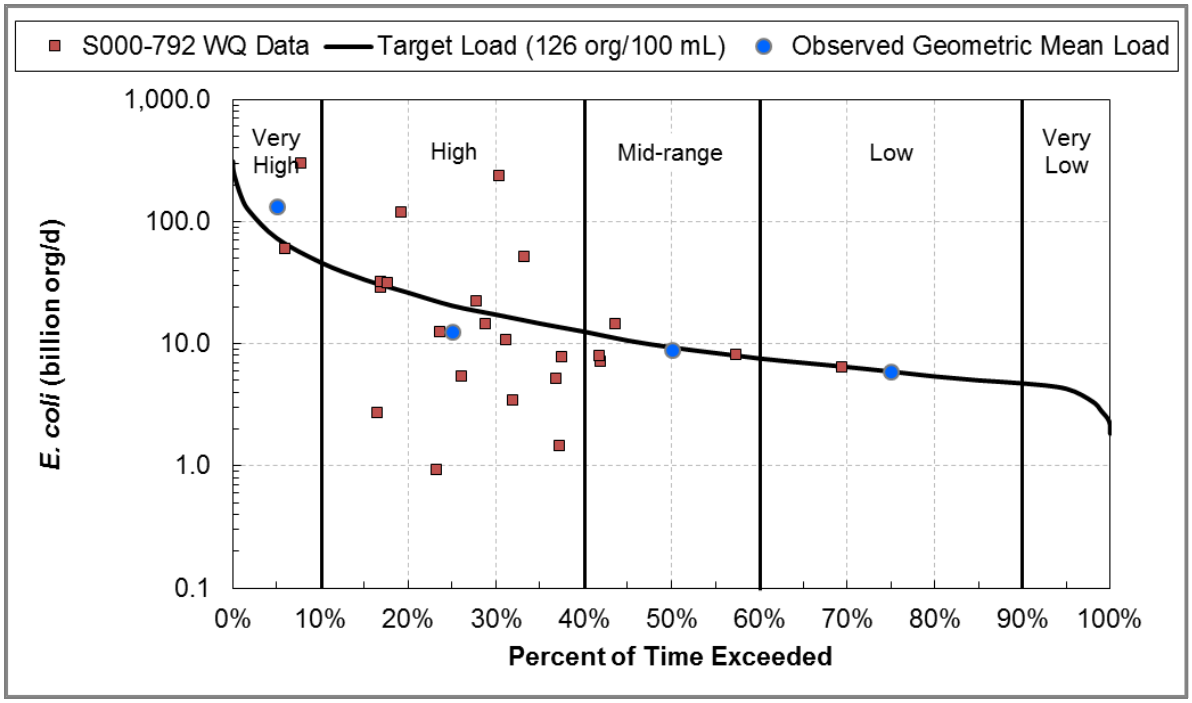

Figure 65. *E. coli* load duration curve, unnamed creek (04010201-542)

Table 65. *E. coli* TMDL summary, unnamed creek (04010201-542)

TMDL Parameter (Permit #)	**Flow Regime**				
	Very High	**High**	**Mid-Range**	**Low**	**Very Low**
	***E. coli* Load (billion org/day)**				
Wasteload Allocation: Hibbing City MS4 (MS400270)	9.19	2.48	1.05	0.606	0.414
Load Allocation	56.7	16.0	7.36	4.72	3.44
MOS	7.32	2.05	0.934	0.592	0.428
Loading Capacity [a]	73.2	20.5	9.34	5.92	4.28
Existing Load	133	12.5	8.98	5.88	–
Percent Load Reduction	45%	0%	0%	0%	–
Watershed Percent Load Reduction [b]	51%	0%	0%	0%	–

a. Loading capacities are rounded to three significant digits.

b. The watershed percent reductions apply to the regulated MS4s and the unregulated watershed runoff in the LA.

Unnamed Creek (East Swan Creek, 04010201-888)

Load reductions in Unnamed Creek are needed under very high, high, and low flow conditions (Figure 66, Table 66). The *E. coli* standard was violated in July and August (Table 26), and the high priority sources are livestock, pets, aging infrastructure, and stormwater runoff from regulated areas (City of Hibbing, Table 47, Figure 8).

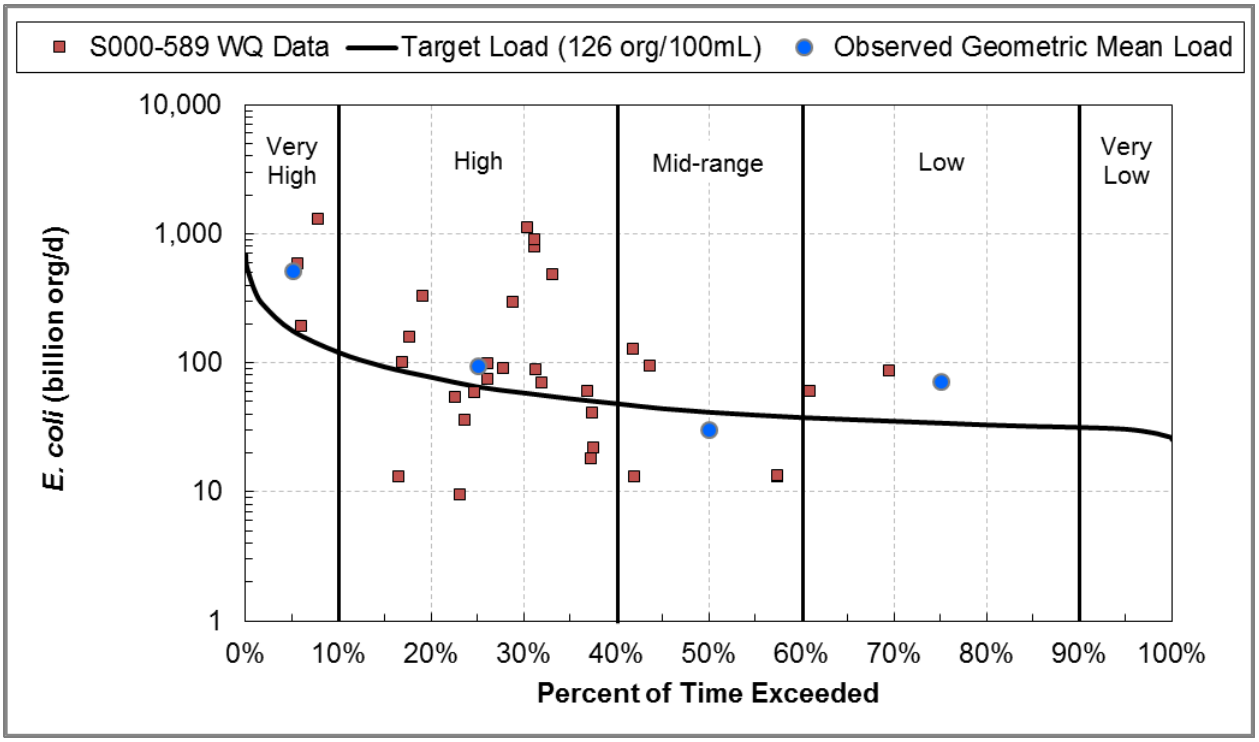

Figure 66. *E. coli* load duration curve, Unnamed Creek (04010201-888)

Table 66. *E. coli* TMDL summary, Unnamed Creek (04010201-888)

TMDL Parameter (Permit #)		**Flow Regime**				
		Very High	**High**	**Mid-Range**	**Low**	**Very Low**
		***E. coli* Load (billion org/day)**				
Wasteload Allocation	Hibbing City MS4 (MS400270)	27.4	7.37	3.12	1.82	1.21
	Hibbing WWTP South (MN0030643) [a]	21.5	21.5	21.5	21.5	21.5
Load Allocation		111	29.8	12.6	7.37	4.83
MOS		17.8	6.52	4.14	3.41	3.06
Loading Capacity [b]		178	65.2	41.4	34.1	30.6
Existing Load		522	94.5	30.7	71.7	–
Percent Load Reduction		66%	31%	0%	52%	–
Watershed Percent Load Reduction [c]		72%	49%	0%	82%	–

a. Reductions in *E. coli* load from Hibbing WWTP South are not needed to meet the WLA.

b. Loading capacities are rounded to three significant digits.

c. The watershed percent reductions apply to the regulated MS4s and the unregulated watershed runoff in the LA.

Pine River (White Pine River, 04010201-543)

The Pine River evaluation of *E. coli* data by flow regime suggests that load reductions are not needed to meet the standard (Figure 67, Table 67). However, compliance with the standard is evaluated on a monthly basis, and the monthly geometric mean was violated based on July data (Table 28). Using the July *E. coli* geometric mean of 184 organisms per 100 mL, a 32% reduction is needed for the Pine River to meet water quality standards in July. Reductions should come primarily from *E. coli* loading from livestock; the primary known source of *E. coli* to the Pine River is livestock (Table 47). Because there are no developed areas in close proximity to the impairment (Figure 9), regulated MS4s do not contribute to the impairment and are not required to reduce *E. coli* loading.

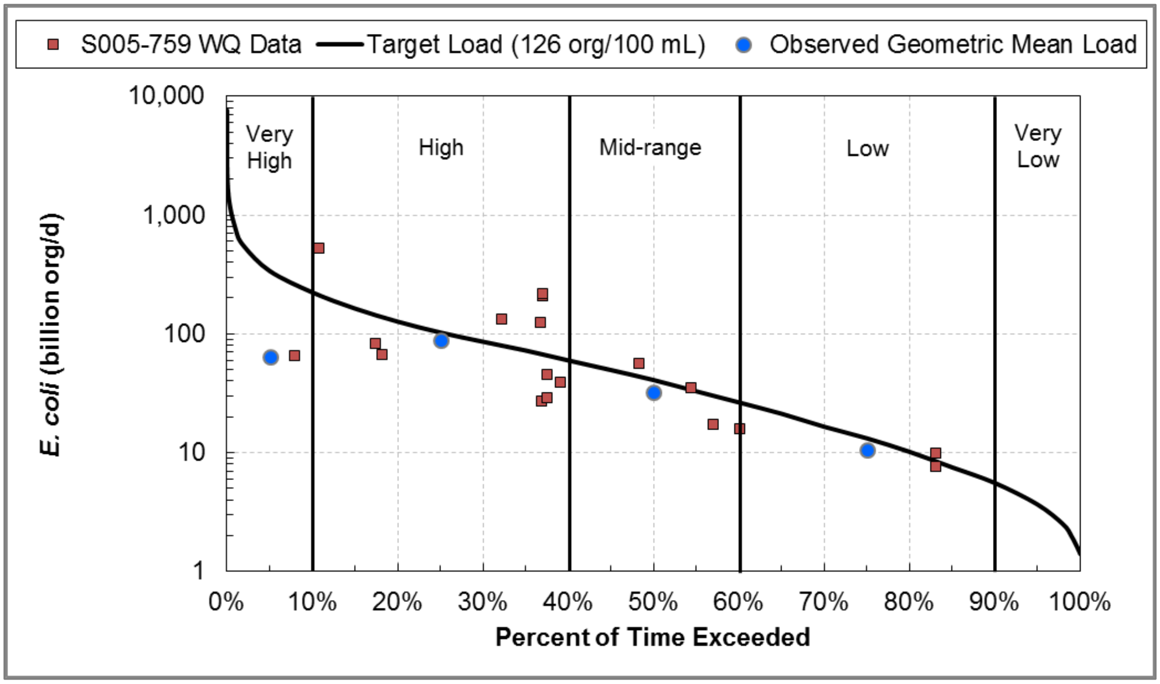

Figure 67. *E. coli* load duration curve, Pine River (04010201-543)

Table 67. *E. coli* TMDL summary, Pine River (04010201-543)

TMDL Parameter (Permit #)		**Flow Regime**				
		Very High	**High**	**Mid-Range**	**Low**	**Very Low**
		***E. coli* Load (billion org/day)**				
Wasteload Allocation	Hermantown City MS4 (MS400093)	0.273	0.0833	0.0330	0.0107	0.00295
	Cloquet City MS4 (MS400267)	0.119	0.0362	0.0143	0.00464	0.00128
	Canosia Township MS4 [a]	1.46	0.445	0.176	0.0570	0.0158
	Grand Lake Township MS4 [a]	2.68	0.816	0.323	0.105	0.0289
	MnDOT Outstate District MS4 (MS400180)	0.448	0.136	0.0540	0.0175	0.00483
	St. Louis County MS4 (MS400158)	0.383	0.117	0.0463	0.0150	0.00414
Load Allocation		299	91.1	36.1	11.7	3.23
MOS		33.8	10.3	4.08	1.32	0.365
Loading Capacity [b]		338	103	40.8	13.2	3.65
Existing Load		64.1	88.7	32.1	10.5	–
Percent Load Reduction [c]		0%	0%	0%	0%	–
Percent Load Reduction for Regulated MS4s [d]		0%	0%	0%	0%	0%
Percent Load Reduction for Unregulated Sources [c]		32%				

a. Not currently regulated but expected to come under permit coverage in the next permit cycle.

b. Loading capacities are rounded to three significant digits.

c. When comparing the geometric mean *E. coli* concentration of each flow regime to the geometric mean standard, the Pine River does not require a load reduction (Figure 67). However, the monthly geometric mean standard was violated based on July data. Using the July *E. coli* geometric mean of 184 organisms per 100 mL, a 32% reduction is needed for the Pine River to meet water quality standards in July, and should come primarily from reduction in *E. coli* loading from livestock; the primary known source of *E. coli* to the Pine River is livestock (Table 47).

d. Regulated MS4s do not contribute to the impairment and are not required to reduce *E. coli* loading.

Unnamed Creek / West Rocky Run (04010201-625)

Load reductions in Unnamed Creek / West Rocky Run are needed under very high, high, and mid-range flow conditions (Figure 68, Table 68). The *E. coli* standard was violated in June, July, and August (Table 32), and the high priority source is livestock (Table 47); reductions should come primarily from E. *coli* loading from livestock. Because there are limited developed areas in close proximity to the impairment (Figure 9), regulated MS4s do not contribute to the impairment and are not required to reduce *E. coli* loading.

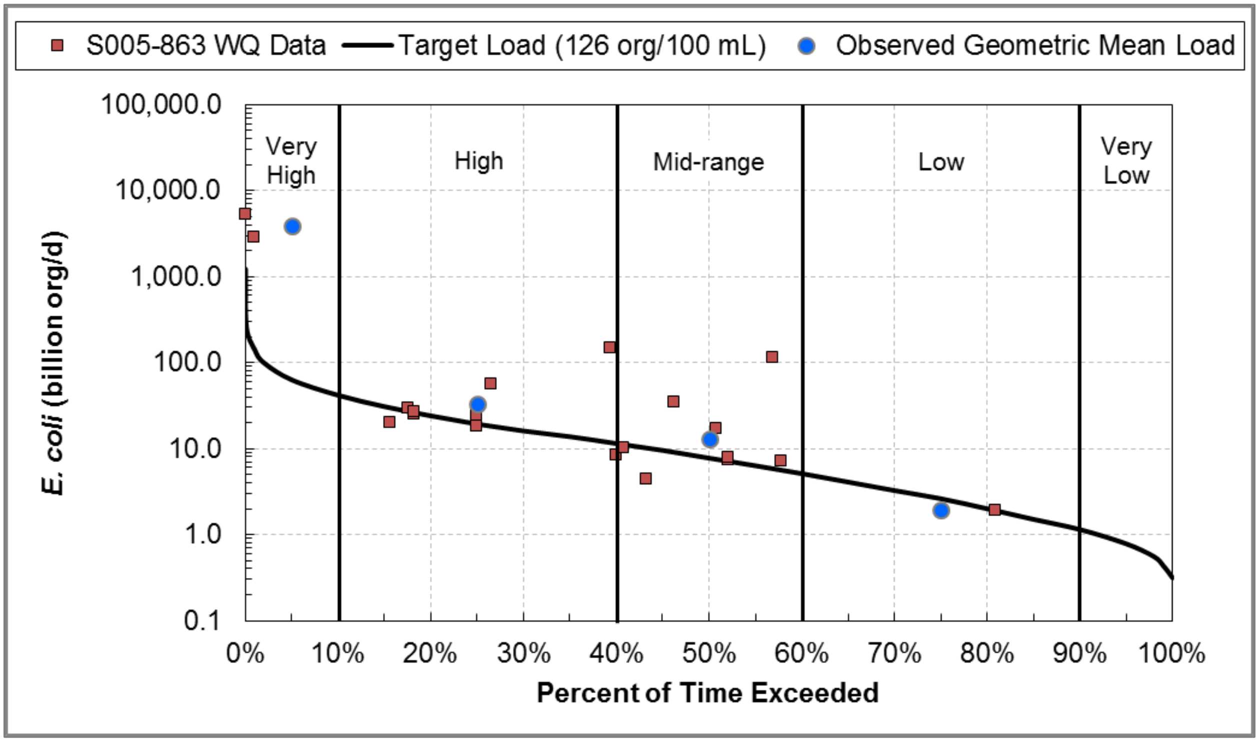

Figure 68. *E. coli* load duration curve, Unnamed Creek / West Rocky Run (04010201-625)

Table 68. *E. coli* TMDL summary, Unnamed Creek / West Rocky Run (04010201-625)

TMDL Parameter (Permit #)		Very High	High	Mid-Range	Low	Very Low
		Flow Regime				
		E. coli Load (billion org/day)				
Wasteload Allocation	Hermantown City MS4 (MS400093)	0.885	0.271	0.109	0.0368	0.0110
	Midway City MS4 (MS400146)	0.0834	0.0255	0.0103	0.00347	0.00103
Load Allocation		55.7	17.1	6.86	2.32	0.692
MOS		6.30	1.93	0.775	0.262	0.0782
Loading Capacity [a]		63.0	19.3	7.75	2.62	0.782
Existing Load		3,840	33.3	13.0	1.91	–
Percent Load Reduction		98%	42%	40%	0%	–
Percent Load Reduction for Regulated MS4 [b]		0%	0%	0%	0%	0%
Percent Load Reduction for Unregulated Sources		99%	48%	46%	0%	–

a. Loading capacities are rounded to three significant digits.

b. Runoff from the regulated MS4s does not contribute to the impairment, and MS4 load reductions are not required.

Hay Creek (04010201-751)

Load reductions in Hay Creek are needed under very high and mid-range flow conditions (Figure 69, Table 69). The *E. coli* standard was violated in July and August (Table 30), and the high priority source is livestock (Table 47); reductions should come primarily from *E. coli* loading from livestock. The regulated MS4 does not contribute to the impairment and is not required to reduce *E. coli* loading (Figure 9).

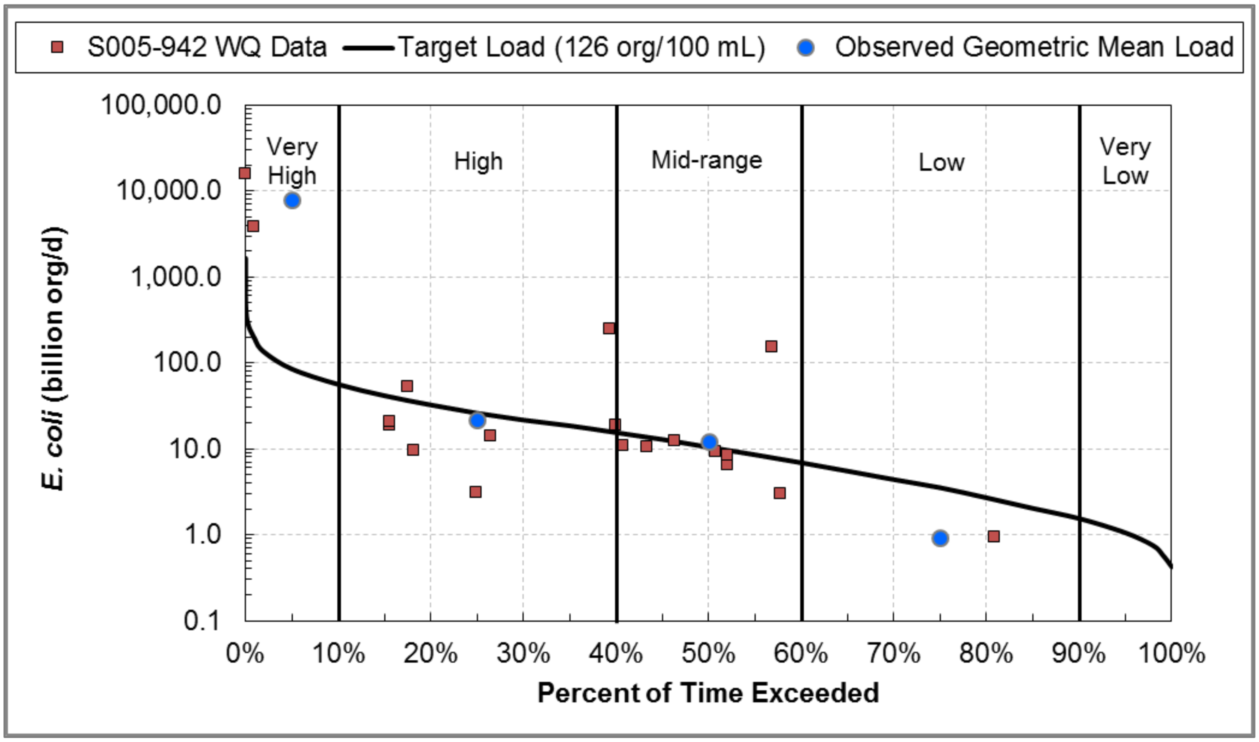

Figure 69. *E. coli* load duration curve, Hay Creek (04010201-751)

Table 69. ***E. coli*** **TMDL summary, Hay Creek (04010201-751)**

TMDL Parameter	Flow Regime				
	Very High	High	Mid-Range	Low	Very Low
	E. coli Load (billion org/day)				
Wasteload Allocation: Thomson Township MS4 [a]	1.23	0.376	0.151	0.0511	0.0152
Load Allocation	75.1	23.0	9.21	3.13	0.930
MOS	8.48	2.60	1.04	0.353	0.105
Loading Capacity [b]	84.8	26.0	10.4	3.53	1.05
Existing Load	7,770	21.5	12.2	0.925	–
Percent Load Reduction	99%	0%	15%	0%	–
Percent Load Reduction for Regulated MS4 [c]	0%	0%	0%	0%	0%
Percent Load Reduction for Unregulated Sources	99%	0%	23%	0%	–

a. Not currently regulated but expected to come under permit coverage in the next permit cycle.

b. Loading capacities are rounded to three significant digits.

c. Runoff from the regulated MS4 does not contribute to the impairment, and MS4 load reductions are not required.

4.2 Total Suspended Solids

4.2.1 Approach

Loading Capacity and Load Reduction

The loading capacity is calculated as flow multiplied by the applicable TSS standard (10 or 15 mg/L). The existing loads are calculated as the 90th percentile of observed TSS loads in each flow zone from the months that the standard applies (April through September); the monitoring data concentrations are multiplied by estimated flow, and then multiplied by a unit conversion factor. The percent reductions needed to meet the TMDL are calculated as the TMDL minus the existing load divided by the existing load; this calculation generates the portion of the existing load that must be reduced to achieve the TMDL. If the existing load is lower than the TMDL for a flow regime, the percent reduction needed to meet the TMDL is reported as zero. If there are no monitoring data for a flow regime, the existing load and the load reduction are not reported. The simulated flow data and the TSS monitoring data used to calculate the loading capacity and the percent reductions needed to meet the TMDL are from 2003 through 2012; 2012 is the baseline year against which future reductions will be compared.

The Clean Water Act requires that TMDLs take into account critical conditions for stream flow, loading, and water quality parameters as part of the analysis of loading capacity. Through the load duration curve approach it has been determined that load reductions are needed for specific flow conditions; however, the critical conditions (the periods when the greatest reductions are required) vary by location and are inherently addressed by specifying different levels of reduction according to flow.

Load Allocation

The LA represents the portion of the loading capacity that is allocated to pollutant loads from watershed runoff that is not regulated through an NPDES Permit and channel erosion. The allocation for all watershed loading (from permitted and non-permitted sources) and channel erosion is calculated as the loading capacity minus the MOS minus the WWTP WLAs. The allocation is then divided among all watershed and channel sources based on the percent area of the source type. For example, if regulated stormwater runoff is generated in 95% of an impaired water body's watershed area, the LA would be 95% of the watershed and channel erosion loading allocation.

Wasteload Allocation

The WLAs represent the portion of the loading capacity that is allocated to pollutant loads that are regulated through an NPDES Permit.

Municipal Wastewater

Hibbing South WWTP and CIRSSD are both located in the East Swan River Subwatershed. These WWTPs are mechanical facilities with TSS technology based effluent limits of 30 mg/L TSS as a calendar month average and 45 mg/L as a maximum calendar week average. The concentration limits are higher than the stream water quality standard, which is 10 mg/L TSS in the East Swan River, however; both WWTPs are tertiary treatment facilities with effluent filters, which result in very low effluent TSS concentrations. Effluent filtration, which is necessary in order to maintain compliance with the permits' extremely restrictive mercury limits, ensures that these WWTPs will not contribute to TSS water quality standard violations in the East Swan River. WLAs for the two WWTFs are expressed in terms of TSS. The WLAs for the two WWTFs apply from April 1 through September 30, and were calculated as the East Swan River's TSS standard of 10 mg/L TSS multiplied by each facility's AWWDF (Table 70).

Table 70. Permitted wastewater treatment facilities for TSS TMDLs

Wastewater Treatment Facility (NPDES Permit #)	Average Wet Weather Design Flow (million gallons per day)	TSS WLA (tons per day), April through September [a]	Impairments
Central Iron Range Sanitary Sewer District (MN0020117)	2.5	0.10	East Swan River 04010201-558
Hibbing WWTP South Plant (MN0030643)	4.5	0.19	East Swan River 04010201-558

a. WLAs for the two WWTPs apply from April 1 through September 30 and are based on the AWWDF and 10 mg/L TSS. It is assumed that each facility's restrictive mercury effluent limit are sufficient to ensure that effluent TSS concentrations will not exceed the 10 mg/L inorganic TSS concentration, which is the basis for the water quality standard.

Municipal Separate Storm Sewer Systems

The regulated area of the city of Hibbing MS4 within the impaired watersheds was approximated by the developed land cover classes within the jurisdictional boundary of the city or township (see Figure 10 for the developed land cover classes). The MS4 WLA was calculated as the regulated area multiplied by a target export rate of 0.05 tons of TSS per acre per year for the mid-range flow zone. This target rate is within the expected range of loading rates that are achievable by cities in Minnesota using primarily wet ponds to treat stormwater runoff. WLAs for the high and very high flow zones were scaled proportional to flow. WLAs are not provided for the low and very low flow zones because stormwater runoff is not expected to occur under these low flow conditions.

Table 71. Permitted MS4s for TSS TMDLs

MS4 Name (NPDES Permit #)	Impairments (AUID)	Regulated Area (Approximated) in Impairment Watersheds (acres)
Hibbing City (MS400270)	East Swan River (558)	4,643

Construction Stormwater

A single categorical WLA for construction stormwater (Construction Stormwater General Permit MNR100001) is provided for each impaired water. The MPCA provided the total areas of projects regulated by construction stormwater permits by county. The average annual (2003 through 2014) percent area of St. Louis County that is regulated through the Construction Stormwater Permit was calculated as 0.02%. Recent permits (from 2013 and 2014) were included in the calculation to better represent the future extent of permitted construction projects. The construction stormwater WLA was calculated as the loading capacity (or TMDL) minus the MOS and the WLAs for WWTPs multiplied by the percent area:

construction stormwater WLA = (TMDL – MOS – WWTP WLAs) x 0.02%

Industrial Stormwater

Industrial stormwater WLAs were developed for stormwater runoff from the following permits:

- General Permit MNR050000 for Industrial Stormwater Multi-Sector and General Permit MNG490000 for Nonmetallic Mining and Associated Activities
- Hibbing Taconite Company (Permit #MN0001465)
  The following Surface Discharge Stations are located within the St. Louis River Watershed: SD-001, SD-002, SD-006 and SD-007.

  SD-001, SD-006 and SD-007 are stormwater, non-specific runoff stations within the mining area and are associated with the Scranton Pit, Carmi Pit and Albany Pit, respectively. These pits are former hematite-mining operations located on the southern extent of the Mining Area and are at the lowest elevation within the operation. To support mining activities within the areas covered under SD-001 and SD-007, dewatering of the mining area involves transferring water from the Albany Pit to the Susquehanna Pit to the Scranton Pit, with final discharge into the Penobscot Creek. Dewatering of the area covered under SD-006 is managed through appropriations from the Carmi Pit to either the Morton Pit or to the Snowshoe/Kelly Lake system. A TSS TMDL boundary condition is established at the outlet of the Mahoning Hull-Rust Complex (WID 69-1427-00). The mine pit's long hydraulic residence time and low TSS concentration ensure that outflow from this headwater reservoir does not contribute to the downstream Swan River TSS impairment.

  SD-002 is a stormwater, non-specific runoff station located within the HTC northeastern Group 1 stockpile area. Runoff from this area reports to a wetland/ditch complex that ultimately flows off-site into ponded areas. The Army Corps of Engineers determined in 2013 (2013-00763-DWW), that this area of the facility is not navigationally connected to Waters of the US, including the East Swan River. However, since the wetland complex may be hydrologically connected to the East Swan River watershed a wasteload allocation for this station has been applied.

The following Surface Discharge Stations are located within the Upper Mississippi Watershed and are therefore not included in the St. Louis River Watershed TMDL and WRAP: SD-003, SD-004, and SD-005.

A single categorical WLA for regulated industrial stormwater is provided for each impaired water body. Permitted industrial activities make up a small portion of the watershed areas, and the industrial stormwater WLA for each water body was set equal to the construction stormwater WLA. Because permittees are required to 1) prevent pollutants from interacting and becoming associated with stormwater runoff, and 2) control or manage stormwater runoff and drainage, it is assumed that loads from permitted industrial stormwater sites that operate in compliance with the permits are meeting the WLA.

Margin of Safety

An explicit 10% MOS was calculated for the TSS TMDLs. The explicit MOS accounts for environmental variability in pollutant loading and variability in water quality monitoring data. The simulated flow data are based on a calibrated and validated HSPF model application that was used to simulate daily average flow between 1995 and 2012 (Tetra Tech 2016a). The MOS accounts for uncertainty in the calibration data, errors in the model's hydrologic calibration, and conservative assumptions made during the modeling efforts. The model was calibrated and validated using nine stream flow gaging stations. Five gaging stations have over ten years of continuous flow records, and four have shorter term flow records. Seven in-stream water quality stations were used for the sediment calibration (Tetra Tech 2016b). Calibration results indicate that the HSPF model is a valid representation of hydrologic and water quality conditions in the watershed. To estimate flow in reaches that were not explicitly modeled in HSPF, simulated flow data from nearby reaches were area-weighted; this adds to uncertainty in the flow estimates.

Seasonal Variation

TSS concentrations and loads vary seasonally. Seasonal variation is partially addressed by the TSS water quality standard's application during the period when the highest TSS concentrations are expected via snowmelt and storm event runoff. The load duration approach accounts for seasonal variation by evaluating allowable loads on a daily basis over the entire range of observed flows and by presenting daily allowable loads that vary by flow.

4.2.2 TMDL Summaries

Figure 71 and Figure 72 show the load duration curves, and Table 72 and Table 74 summarize the TMDLs, allocations, existing loads, and load reductions for the TSS TMDLs. Loads are rounded to two significant digits, except in the case of values greater than 100, which are rounded to the nearest whole number. Percent reductions are rounded to the nearest whole number.

East Swan River (04010201-558)

To meet the East Swan River TSS TMDL, load reductions range from 0% under low flows to 97% under very high flows; data are not available under very low flows (Figure 70 and Table 72).

Because there is limited information available to estimate the existing load contribution from each of the sources presented in Table 72, the percent load reductions are not intended to be applied uniformly across the sources. Per the source summary in section 3.6.2, much of the reduction will need to come from near-channel sources (e.g., streambank erosion). However, these near-channel sources are often largely affected or driven by stormwater discharge rates and volume. Improvements in stormwater management should help to reduce sediment contributions from the near-channel sources.

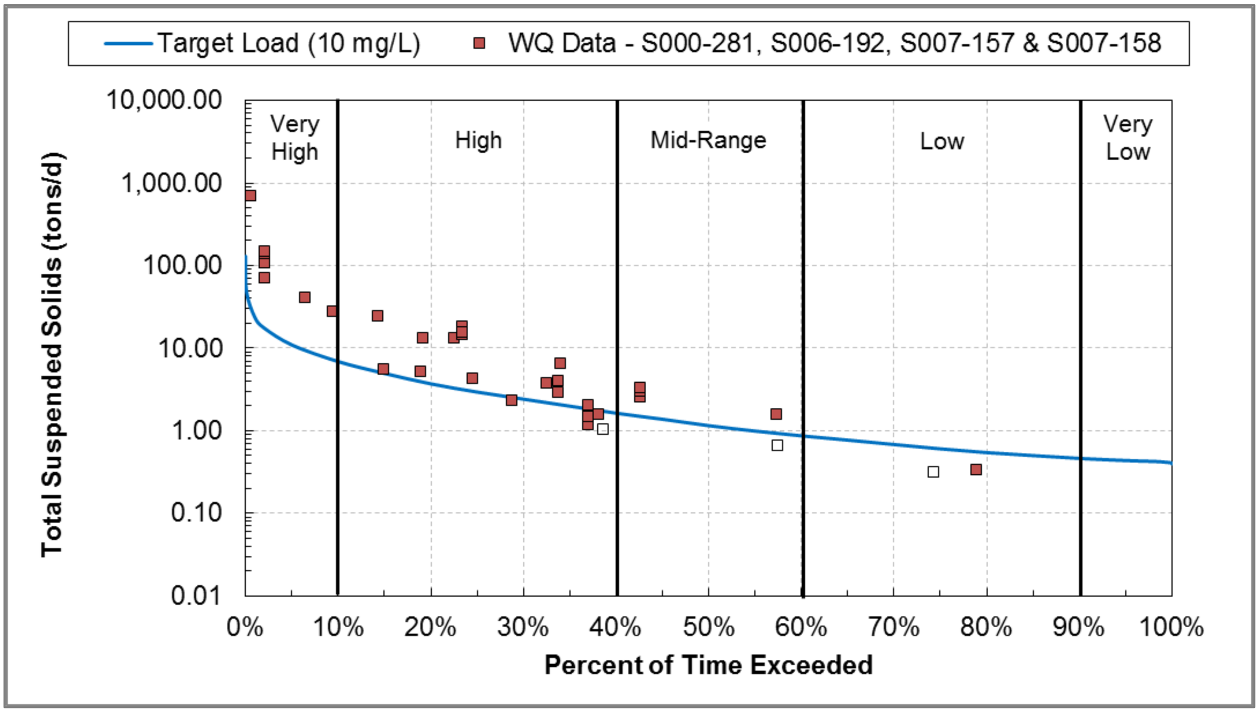

Figure 70. TSS load duration curve, East Swan River (04010201-558).

Hollow points indicate samples during months when the standard does not apply.

Table 72. TSS TMDL summary, East Swan River (04010201-558)

TMDL Parameter (NPDES permit number, where applicable)			Flow Regime				
			Very High	High	Mid-Range	Low	Very Low
			TSS Load (ton/day)				
Wasteload Allocation	Construction Stormwater (MNR100001) [a]		0.0018	0.00044	0.00014	0.000047	0.000019
	Industrial Stormwater	Industrial Stormwater General Permits (MNR050000	0.0018	0.00044	0.00014	0.000047	0.000019
	Hibbing City MS4 (MS400270)		6.0	1.6	0.64	– [c]	– [c]
	Hibbing South WWTP [d] (MN0030643)		0.19	0.19	0.19	0.19	0.19
	Central Iron Range Sanitary Sewer District [d] (MN0020117)		0.10	0.10	0.10	0.10	0.10
Load Allocation [e]			3.6	0.81	0.15	0.26	0.11
MOS			1.1	0.30	0.12	0.061	0.044
Loading Capacity [f]			11	3.0	1.2	0.61	0.44
Existing Load			361	16	3.2	0.34	–
Percent Load Reduction			97%	81%	63%	0%	–

a. It is assumed that loads from permitted construction and industrial stormwater sites that operate in compliance with the permits are meeting the WLA.

b. General Permit MNR050000 for Industrial Stormwater Multi-Sector and General Permit MNG490000 for Nonmetallic Mining and Associated Activities.

c. WLAs for the two WWTPs apply from April 1 through September 30 and are based on the AWWDF and 10 mg/L TSS. d. Applies to channel erosion and unregulated watershed runoff.

e. Loading capacities are rounded to two significant digits, except in the case of values greater than 100, which are rounded to the nearest whole number.

High TSS concentrations have also been found in the Swan River (04010201-557), which is located where the East Swan and the West Swan Rivers join. The Swan River is not currently listed as impaired, but the following analysis is included because the reach may be listed in the future due to the high TSS concentrations. Similar to the East Swan River, the highest TSS concentrations in the Swan River are under very high flows (Figure 71).

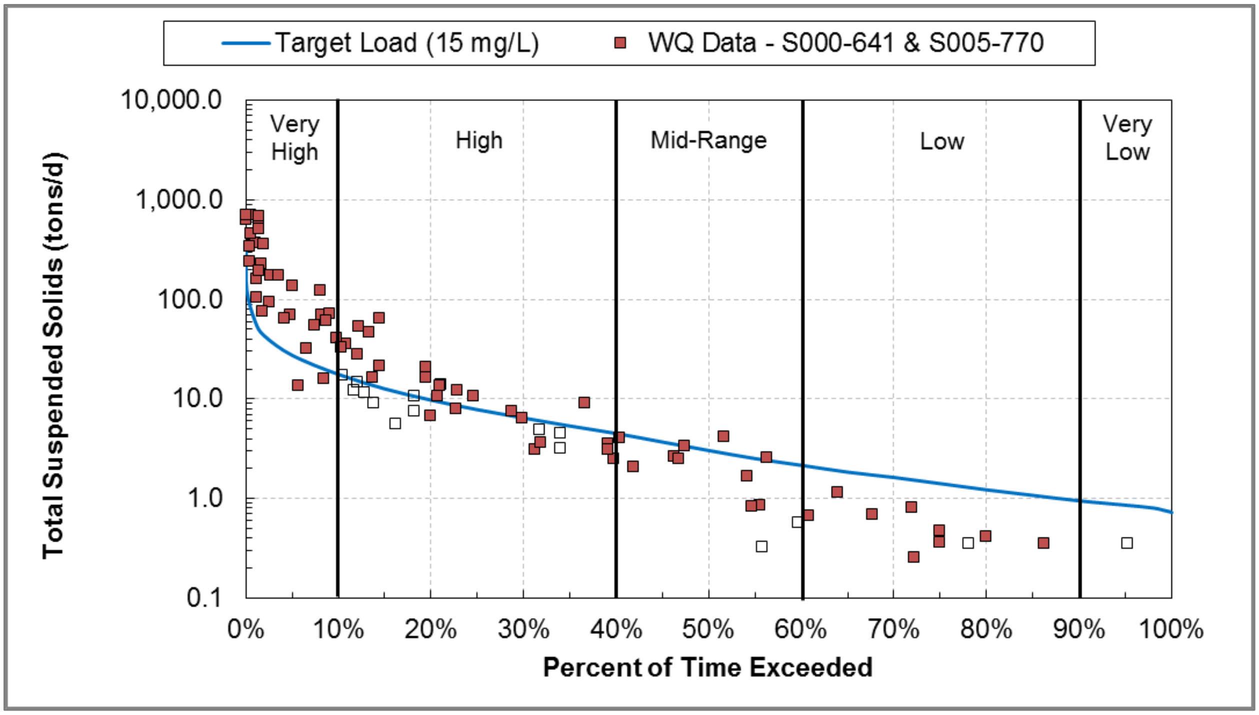

Figure 71. TSS load duration curve, Swan River (04010201-557).
Hollow points indicate samples from October–March.

Assuming a target concentration of 15 mg/L TSS in the Swan River[3], loads under very high flows need to be reduced by 96%. Approximately half of the load reduction needed for the Swan River to reach the target under very high flow conditions will be achieved through the load reductions needed for the East Swan River TMDL (Table 73).

Table 73. Comparison of load reductions needed for the East Swan River and the Swan River

Impaired Stream	Load reductions needed (ton/day)				
	Very High	High	Mid-Range	Low	Very Low [a]
East Swan River	350	13	2	0	–
Swan River	623	33	1	0	–
Percent of the Swan River's needed reduction that is addressed in East Swan TMDL	56%	39%	100%	100%	–

a. Data not available under very low flows.

Stony Creek (04010201-963)

To meet the Stony Creek TSS TMDL, load reductions range from 0% under mid-range flows to 69% under very high flows; data are not available under low or very low flows (Figure 72 and Table 74).

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[3] The Swan River is in process of a use class change. Under the proposed use class change, the Swan River would be classified as Class 2B, with a 15 mg/L TSS standard.

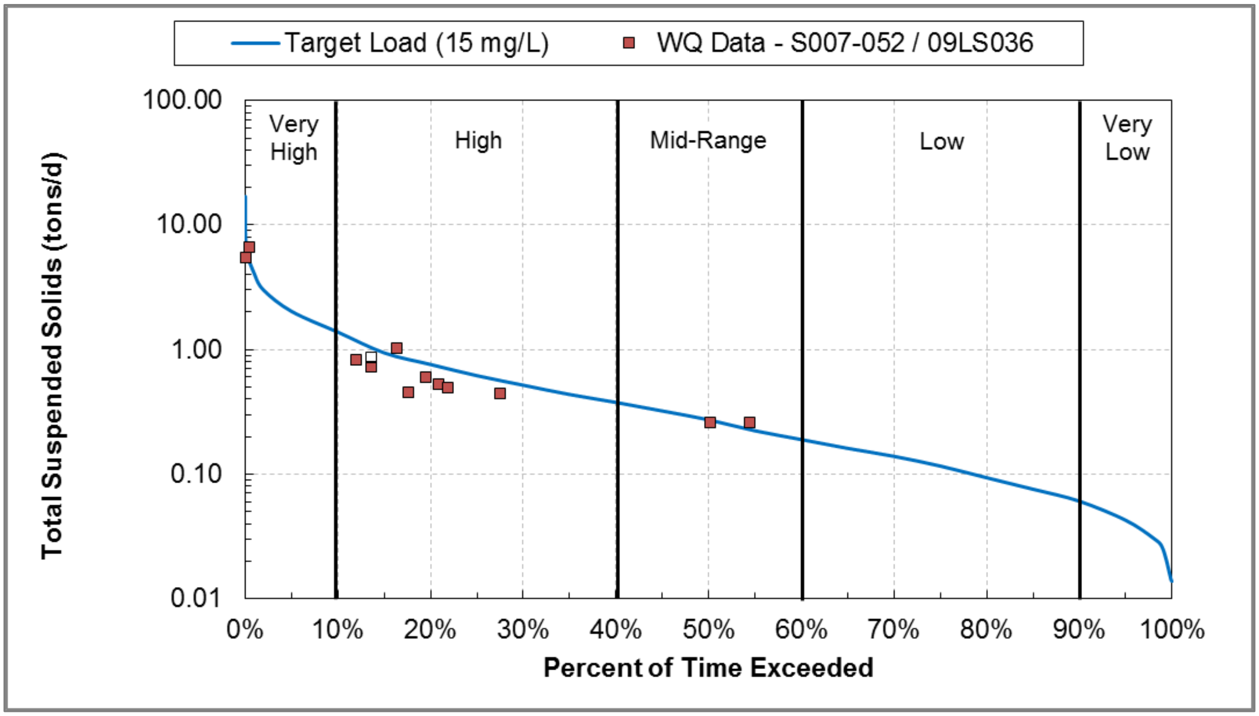

Figure 72. TSS load duration curve, Stony Creek (04010201-963).

Hollow points indicate samples during months when the standard does not apply.

Table 74. TSS TMDL summary, Stony Creek (04010201-963)

TMDL Parameter		Flow Regime				
		Very High	High	Mid-Range	Low	Very Low
		TSS Load (tons/d)				
Wasteload Allocation	Construction Stormwater General Permit (MNR100001) [a]	0.00034	0.00010	0.000046	0.000020	0.0000072
	Industrial Stormwater General Permit (MNR050000) [a]	0.00034	0.00010	0.000046	0.000020	0.0000072
Load Allocation		1.8	0.56	0.25	0.10	0.038
MOS		0.20	0.062	0.027	0.012	0.0043
Loading Capacity [b]		2.0	0.62	0.28	0.11	0.042
Existing Load		6.4	0.88	0.26	–	–
Percent Load Reduction		69%	30%	0%	–	–

a. It is assumed that loads from permitted construction and industrial stormwater sites that operate in compliance with the permits are meeting the WLA.

b. Loading capacities are rounded to two significant digits.

4.3 Phosphorus (Lakes)

4.3.1 Approach

Loading Capacity and Load Reduction

Lake response models were developed using the model BATHTUB (Walker 1987). Inputs included lake morphometry (Table 8), estimated mixed depth, and phosphorus loads (Table 53 and Table 54), and the models were calibrated to lake water quality data (Table 40 and Table 41) through selection of the most appropriate phosphorus sedimentation model and/or adjustment of internal loading rates. Complete model inputs and outputs are presented in Appendix C. The calibrated models were used to estimate each lake's phosphorus loading capacity through development of TMDL model scenarios. The load reductions needed to meet the TMDL represent the difference between the existing phosphorus loads and the loading capacity. The monitoring data used to calculate the loading capacity and the percent reductions needed to meet the TMDL are from 2003 through 2012. Year 2012 is thus the baseline year against which future reductions will be compared.

The models within BATHTUB inherently include an internal load that is typical of lakes in the model development data set. For West Two Rivers Reservoir, the data suggest that internal loading is greater than the average rate inherent in BATHTUB, and an additional internal load was added during model calibration. The West Two Rivers Reservoir Subwatershed is predominantly forested and wetlands, therefore a natural background conditions scenario was simulated using BATHTUB to determine what, if any, additional reduction is needed when point sources are not included. The simulation results indicated that, under natural background conditions, an additional 39% reduction is needed to meet the TMDL. This additional reduction can be attributed to reductions needed for existing internal loading. A TMDL scenario was then used to estimate the additional load reductions needed by the point sources to meet the TMDL.

For Dinham Lake, the independent internal load estimate from the phosphorus source assessment (Section 3.6.3) was not added as an explicit internal load in the BATHTUB model. After the model was calibrated, a TMDL scenario was developed by reducing phosphorus load inputs until the lake TP standard was met. The load reduction needed to meet the standard was then subtracted from the total load in the phosphorus source assessment (Table 53) to determine the loading capacity.

The Clean Water Act requires that TMDLs take into account critical conditions for stream flow, loading, and water quality parameters as part of the analysis of loading capacity. Critical conditions for the lake eutrophication impairments are during the growing season months, which in Minnesota is when phosphorus concentrations peak and clarity is at its worst. Lake goals focus on summer mean TP concentration, chl-*a* concentration, and Secchi transparency. The lake response models are focused on the growing season (June through September) as the critical condition. The load reductions are designed so that the lake will meet the water quality standards over the course of the growing season.

Load Allocation

The LA represents the portion of the loading capacity that is allocated to pollutant loads that are not regulated through an NPDES Permit (i.e., unregulated watershed runoff, septic systems, internal loading, and atmospheric deposition). For the Dinham Lake TMDL, the LA was calculated as the loading capacity minus the MOS minus the WLAs. The West Two Rivers Reservoir LA is based on the natural background conditions scenario, which determined that a reduction of 39% (1,015 lb/yr) is needed relative to the existing watershed, internal, and atmospheric deposition load (2,622 lb/yr; Table 54), for a LA of 1,607 lb/yr. The reductions will need to come primarily from internal loading.

Wasteload Allocation

The WLA represents the portion of the loading capacity that is allocated to pollutant loads that are regulated through an NPDES Permit.

Municipal Wastewater (Mountain Iron WWTP)

Mountain Iron WWTP is located in the West Two Rivers Reservoir Subwatershed. The facility's current effluent limits for phosphorus are 2.08 kg/day and 1.0 mg/L of TP as a calendar monthly average. The facility is required to monitor TP in its effluent once per week. The WLA is based on the TP concentration of 0.23 mg/L and the facility's AWWDF (Table 75). The WLA was determined based on the West Two Rivers Reservoir TMDL model scenario in which the watershed, internal, and atmospheric loads are reduced to natural background conditions, and US Steel–Minntac discharges at their existing observed volume and load. The Mountain Iron WWTP WLA receives the remaining load once the other WLAs and LA are assigned.

Table 75. Permitted municipal wastewater treatment facility for TP TMDLs

Wastewater Treatment Facility (NPDES Permit #)	Average Wet Weather Design Flow (million gallons per day)	TP WLA (lb per year)	Impairment
Mountain Iron (MN0040835)	0.55	385	West Two Rivers Reservoir 69-0994-00

Industrial Wastewater (US Steel–Minntac Mining Area)

Industrial wastewater from the US Steel–Minntac Mining Area (MN0052493) is discharged in the West Two Rivers Reservoir Subwatershed (see phosphorus source assessment in Section 3.6.3 and Figure 11). The permitted discharge volumes (permitted average daily volume—12.8 MGD; permitted maximum daily volume—49.2 MGD) are substantially higher than the observed discharge volume (6.2 MGD from surface discharge stations 001 and 004, based on a 2003–2012 average). Lake model scenarios predict that, if US Steel–Minntac were to discharge at their permitted discharge volumes, the lake would meet the phosphorus eutrophication standard. The increased volumes at low phosphorus concentrations would decrease the hydrologic residence time and reduce the lake phosphorus concentration. Because US Steel–Minntac rarely, if ever, discharges at the permitted maximum flow, the WLA was developed based on existing flows and loads to take into account critical conditions. The WLA is based on the West Two Rivers Reservoir TMDL scenario in which the discharge from US Steel–Minntac remains at the existing load, calculated as the product of the average effluent discharge volume and the observed phosphorus concentration in the effluent (Table 76).

Table 76. Permitted industrial wastewater discharge for TP TMDLs

Industrial Wastewater Source (NPDES Permit #)	Observed Daily Average (2003–2012) Flow (million gallons per day)	Observed Average TP (mg/L) [a]	TP WLA (lb per year	Impairment
US Steel–Minntac Mining Area (MN0052493)	6.2	0.005	94 [b]	West Two Rivers Reservoir 69-0994-00

a. Based on effluent samples collected in spring 2015; see source assessment in Section 3.6.3.

b. The load from US Steel–Minntac Mining Area is allowed to exceed the WLA if the increase is due to higher discharge volumes at the phosphorus concentration on which the WLA is based (0.005 mg/L TP).

Construction Stormwater

A single categorical WLA for construction stormwater (Construction Stormwater General Permit MNR100001) is provided for each impaired water body. The MPCA provided the total areas of projects regulated by construction stormwater permits per county. The average annual (2003 through 2014) percent area of St. Louis County that is regulated through the construction stormwater permit was calculated as 0.02%. Recent permits (from 2013 and 2014) were included in the calculation to better represent the future extent of permitted construction projects. The construction stormwater WLA was calculated as the percent area multiplied by the existing watershed load.

Industrial Stormwater

Industrial stormwater WLAs were developed for stormwater runoff from the following permits:

- General Permit MNR050000 for Industrial Stormwater Multi-Sector and General Permit MNG490000 for Nonmetallic Mining and Associated Activities
- US Steel–Minntac Mining Area (permit #MN0052493, surface discharge 17). The majority of the runoff from this site flows to mine pits, after which it is discharged as industrial wastewater effluent and is accounted for in the TMDL under the permit's WLA for industrial *wastewater*. The WLA for industrial *stormwater* is covered under the categorical WLA for industrial stormwater.

A single categorical WLA for regulated industrial stormwater is provided for each impaired water body. Permitted industrial activities make up a small portion of the watershed areas, and the industrial stormwater WLA for each lake was set equal to the construction stormwater WLA. It is assumed that loads from permitted industrial stormwater sites that operate in compliance with the permits are meeting the WLA.

Margin of Safety

An explicit 10% MOS was calculated for the phosphorus TMDLs to account for variability in the water quality data and uncertainty in the watershed and lake water quality models. Watershed loads were estimated with a calibrated and validated HSPF model application that was used to simulate phosphorus loads between 1995 and 2012 (Tetra Tech 2016a and b). The MOS will account for uncertainty in the calibration data and errors in the model's hydrologic calibration. The model was calibrated and validated using nine stream flow gaging stations. Five gaging stations have over 10 years of continuous flow records, and four have shorter term flow records. Seven in-stream stations were used for the water quality calibration (Tetra Tech 2016b). Calibration results indicate that the HSPF model is a valid representation of hydrologic and water quality conditions in the watershed. The lake response models show a good agreement between the observed and predicted lake water quality data.

Seasonal Variation

Seasonal variations are addressed in this TMDL by assessing conditions during the summer growing season, which is when the water quality standard applies (June 1 through September 30). The frequency and severity of nuisance algal growth in Minnesota lakes is typically highest during the growing season. The nutrient standards set by the MPCA, which are a growing season concentration average, rather than an individual sample (i.e., daily) concentration value—were set with this concept in mind. Additionally, by setting the TMDL to meet targets established for the most critical period (summer), the TMDL will inherently be protective of water quality during all other seasons.

4.3.2 TMDL Summaries

Table 77 and Table 79 summarize the phosphorus TMDLs, allocations, existing loads, and load reductions for the impaired lakes. Loads are rounded to two significant digits, except in the case of values greater than 100, which are rounded to the nearest whole number. Percent reductions are rounded to the nearest whole number.

West Two Rivers Reservoir

A 32% load reduction overall is needed to meet the West Two Rivers Reservoir TMDL (Table 77). Reductions in loading from US Steel–Minntac Mining Area and regulated construction and industrial stormwater are not needed; reductions in loading from Mountain Iron WWTP (43%) and from unregulated sources (39%) are needed (Table 78).

Table 77. Total phosphorus TMDL summary, West Two Rivers Reservoir (69-0994-00)

TMDL Parameter			TP TMDL Load (lbs/yr)	TP TMDL Load (lbs/day)
WLA	Mountain Iron WWTP (MN0040835) [a]		385	1.1
	US Steel–Minntac Mining Area (MN0052493) wastewater [b]		94	0.26
	Construction stormwater (MNR100001) [c]		0.26	0.00071
	Industrial Stormwater	US Steel–Minntac Mining Area (MN0052493) stormwater [c]	0.26	0.00071
		Industrial Stormwater General Permits (MNR050000 and MNG490000) [c,d]		
Load Allocation [e]			1,607	4.4
MOS			232	0.64
Loading Capacity [f]			**2,319**	**6.4**
Existing Load			3,389	9.3
Load Reduction			1,070	2.9
Percent Load Reduction			32%	

a. The WLA for Mountain Iron WWTP is based on the TP concentration of 0.23 mg/L and the facility's AWWDF (Table 75). The WLA was determined based on the TMDL model scenario in which the nonpoint sources are reduced to natural background conditions and US Steel–Minntac discharges at their existing observed volume and load.

b. The WLA for US Steel–Minntac Mining Area is equal to their existing load, calculated as the product of the average effluent discharge volume and the observed phosphorus concentration in the effluent (Table 76). The load from US Steel–Minntac Mining Area is allowed to exceed the WLA if the increase is due to higher discharge volumes at the phosphorus concentration on which the WLA is based (0.005 mg/L TP).

c. It is assumed that loads from permitted construction and industrial stormwater sites that operate in compliance with the permits are meeting the WLA.

d. General Permit MNR050000 for Industrial Stormwater Multi-Sector and General Permit MNG490000 for Nonmetallic Mining and Associated Activities.

e. The load allocation is based on the natural background conditions model scenario, which determined a need for a reduction of 39% (1,015 lb/yr) from nonpoint sources. The reductions will need to come primarily from internal loading. See Table 54 in the Pollutant Source Summary for existing loads.

f. Loading capacities are rounded to whole numbers (annual load) or one decimal place (daily load).

Table 78. Percent Reductions by Source to Meet West Two Rivers Reservoir TMDL

Phosphorus Source	TP Load Reductions to Meet TMDL (Percent)
Mountain Iron WWTP (MN0040835)	43%
US Steel–Minntac Mining Area (MN0052493) wastewater	0%
Unregulated sources (watershed runoff and internal loading)	39%

If the US Steel–Minntac Mining Area discharge volumes were to decrease, the loading capacity of West Two Rivers Reservoir would also decrease, and loading from Mountain Iron WWTP would have to decrease as well in order to meet lake water quality standards. If US Steel–Minntac Mining Area were to cease discharge in the West Two Rivers Reservoir, Mountain Iron WWTP's WLA would be based on the AWWDF of 0.55 MGD and 0.065 mg/L phosphorus.

Dinham Lake

A 19% load reduction overall is needed to meet the Dinham Lake TMDL (Table 79). The only permitted sources of phosphorus (i.e., those in the WLA) are regulated construction and industrial stormwater; reductions are not needed from these sources or from atmospheric deposition, an unregulated source. If all septic systems were conforming, the loading from septic systems would be reduced by 36 lb/yr, from 86 to 50 lb/yr. Additional load reductions are needed from watershed runoff and internal load, both unregulated sources.

Table 79. Total phosphorus TMDL summary, Dinham Lake (69-0544-00)

TMDL Parameter	TP Load (lbs/yr)	TP Load (lbs/day)
WLA: Construction stormwater (MNR100001) [a]	0.14	0.00038
WLA: Industrial Stormwater (MNR050000) [a]	0.14	0.00038
Load Allocation	816	2.2
MOS	91	0.25
Loading Capacity [b]	**907**	**2.5**
Existing Load	1,123	3.1
Load Reduction	216	0.6
Percent Load Reduction	19%	

a. It is assumed that loads from permitted construction and industrial stormwater sites that operate in compliance with the permits are meeting the WLA.

b. Loading capacities are rounded to whole numbers (annual load) or one decimal place (daily load).

4.4 Phosphorus (Streams)—West Two River

Low DO concentrations and a high daily range in DO concentrations were identified as the primary stressors to the biota in West Two River and are due to the eutrophic conditions in West Two Rivers Reservoir (MPCA 2016), located immediately upstream of the impaired reach (Figure 11). The low DO and high daily range in DO concentrations in West Two River are limited to the monitoring station immediately downstream of the reservoir, and moderate levels of suspended algae have been observed in the river just below the reservoir's impoundment (MPCA 2016). This suspended algae can lead to a high daily range in DO concentrations in the river, and decay of the algae can exert an oxygen demand. Restoration of the reservoir will lead to improvement in the DO concentration and decrease daily fluctuations in the river, and subsequent improvement in the aquatic macroinvertebrate assemblage (MPCA 2016). The phosphorus TMDL for West Two Rivers Reservoir (Table 77) applies to West Two River. The only phosphorus reductions needed to restore the biota in West Two River are the reductions needed to restore West Two Rivers Reservoir (Table 77 and Table 78).

4.5 Temperature and Dissolved Oxygen—Wyman Creek

4.5.1 Approach

Loading Capacity and Load Reduction

An in-stream response model was developed using the QUAL2K model. Appendix D includes the full model report. QUAL2K is a steady state (but diurnally variable), one-dimensional model that can simulate in-stream water temperatures and DO concentrations on an hourly time step (Chapra et al. 2012). Most of the factors that affect in-stream temperature and DO concentrations are represented in

QUAL2K, including solar inputs, stream shading, air temperature, sediment oxygen demand, channel reaeration, oxidation of suspended and dissolved organic matter, plankton growth and respiration, and bottom algae (which can be used to approximate impacts of macrophyte growth). The relative magnitude of these factors can be determined through model application, and scenarios can be developed to evaluate if management actions can improve in-stream conditions.

QUAL2K represents streams as a series of segments, each of which has approximately constant characteristics (e.g., slope, shading, and bottom width). Each segment is further divided into a series of equally spaced model computational elements, which are assumed fully mixed. Wyman Creek was divided into 10 model segments (Figure 73).

Based on the summer 2016 sampling effort conducted by the MPCA, the QUAL2K model for Wyman Creek was set up for calibration and validation on two dates in August: August 17 and August 8, respectively. These dates are assumed to represent low flow, critical conditions. A series of scenarios were run to determine the effect of various implementation activities. The model indicated that activities upstream of Reach 6 do not have an impact on the lower reaches (see scenario 4).

A TMDL scenario was developed to achieve the water quality standards in the lower reaches of the stream (reaches 7–10). These reaches have historically supported brook trout populations and have public access for fishing and recreation. The water quality targets at the downstream end of each model reach in lower Wyman Creek are:

1. Maximum daily water temperature does not exceed 20 degrees Celsius, which is the upper limit for brook trout favorable growth conditions (MPCA 2016).
2. Minimum daily DO does not go below 7.0 mg/l, which is the aquatic life standard for cold water streams.

The TMDL scenario involved the following modifications:

1. Removal of the west braid (Reach 9): this reach was removed from the system so there are no associated abstraction and re-entry points from the mainstem. The final downstream flow is the same as when the west braid was present.
2. Increased shade along Reaches 7, 8, and 10: hourly shade inputs were made identical to those of Reach 1, which is much more shaded (average daytime shade of 57%).
3. Water temperature improvements to Reach 6: hourly shade inputs were made identical to those of Reach 1 (average daytime shade of 57%) or equivalent implementation to reduce in-stream temperatures entering Reach 7 to 19.7 degrees Celsius.

The TMDL scenario results in water quality standards being met at the downstream ends of Reaches 7, 8, and 10 (Table 80).

Table 80. Water quality results at the downstream end of Reaches 7, 8, and 10: TMDL Scenario

Reach	Maximum Daily Water Temperature (°C)	Minimum Daily DO (mg/L)
7	18.25	7.93
8	18.84	7.30
10	18.54	8.01

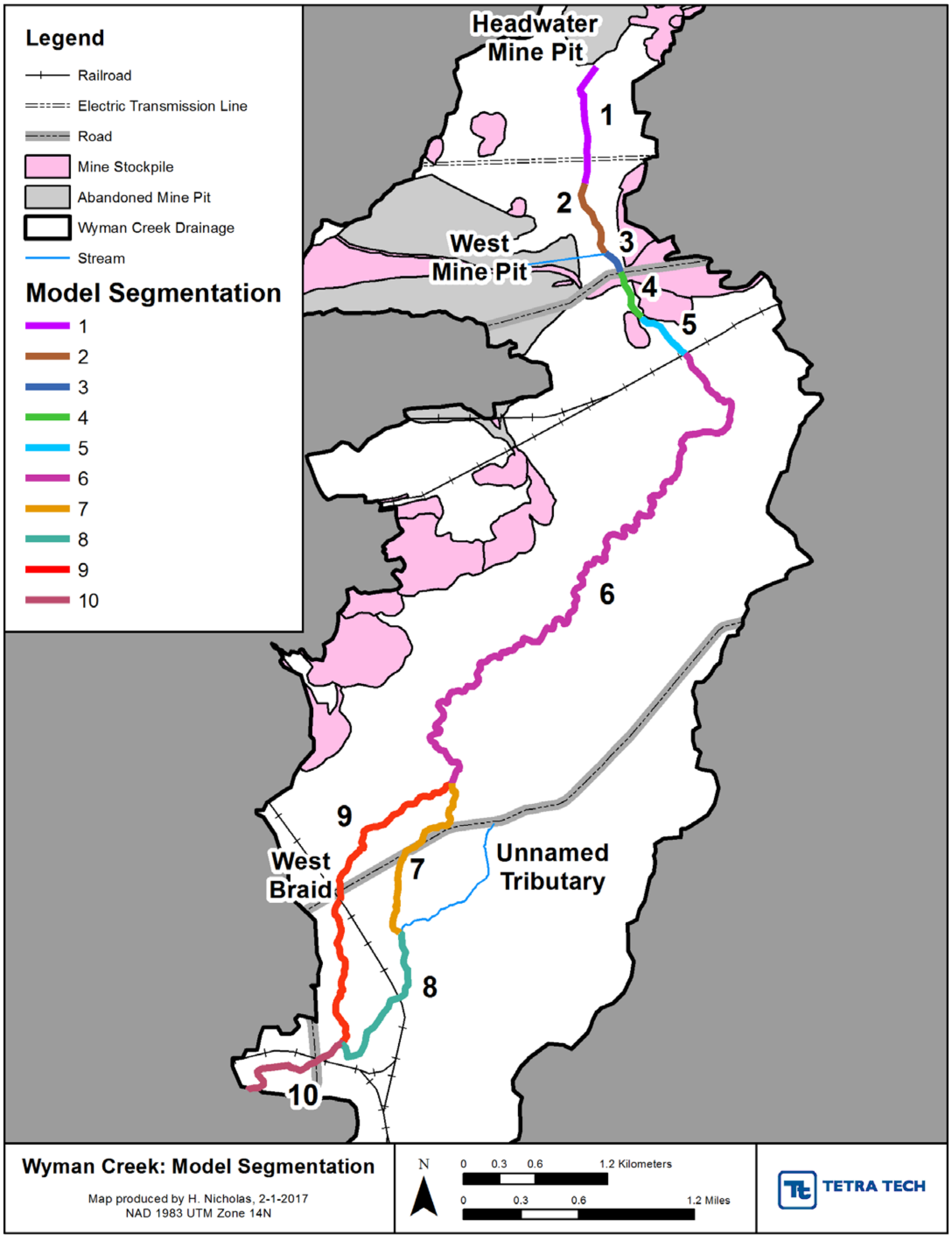

Figure 73. Wyman Creek model segmentation

Thermal loading at the Wyman Creek outlet can be calculated to determine the total allowable thermal load at the water quality target of 20 degrees C and the existing thermal load. In the model simulation, when the stream meets the temperature target, the DO standard is also met because colder water can physically hold more DO.

Thermal loads in kilocalories[4] per day (kcal/d) are calculated based on water temperature, the volumetric flow rate, and a conversion factor:

$$Thermal\ Load\left[\frac{Kcal}{d}\right] = Water\ Temperature\ [°C]\ x\ Flow\ [m^3/s]\ x\ (86.4x10^6)[conversion\ factor]$$

The thermal loads at the Wyman Creek outlet were calculated based on the calibrated model results and water quality standards:

$$Existing\ Thermal\ Load\left[\frac{Kcal}{d}\right] = 22.26\ [°C]\ x\ 0.088\ [m^3/s]\ x\ (86.4x10^6) = 169.2\ million\ \frac{Kcal}{d}$$

$$Allowable\ Thermal\ Load\left[\frac{Kcal}{d}\right] = 20\ [°C]\ x\ 0.088\ [m^3/s]\ x\ (86.4x10^6) = 152.1\ million\ \frac{Kcal}{d}$$

Load Allocation

The LA represents the portion of the loading capacity that is allocated to pollutant loads that are not regulated through an NPDES Permit. Because the MOS is implicit and there are no WLAs, the LA is equal to the loading capacity.

Wasteload Allocation

WLAs represent the portion of the loading capacity that is allocated to pollutant loads that are regulated through an NPDES Permit. There is one permitted point source in the watershed, Cliffs Erie–Hoyt Lakes Mining Area (MN0042536). This permitted facility is in the headwaters of Wyman Creek and has been shown to not have reasonable potential to cause or contribute to impairment on the reaches of interest (sceanario 4 in Appendix D); therefore, the facility can continue to discharge at existing conditions. Reductions from this point source are not needed to meet the temperature TMDL in the lower reaches 7–10.

A WLA of 0.1% of the loading capacity is provided for industrial stormwater permitted through the multi-sector general permit (MNR050000). It is assumed that loads from permitted industrial stormwater sites that operate in compliance with the permit are meeting the WLA.

A WLA of 0.1% of the loading capacity is provided for construction stormwater permitted through the general permit (MNR100001). It is assumed that loads from permitted construction stormwater sites that operate in compliance with the permit are meeting the WLA. The construction stormwater general

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[4] A calorie is the approximate amount of energy needed to raise the temperature of one gram of water by one degree Celsius.

permit does require permittees to take steps to protect impaired waters, and temperature controls for trout streams are explicitly listed in Appendix A of the permit.

Margin of Safety

An implicit MOS is used to account for uncertainty. Due to the comprehensive 2016 stream monitoring, the uncertainty in the stream model and TMDL is fairly low. However, in order to achieve both the temperature and DO standards, the TMDL scenario and associated implementation targets were developed to over-achieve the target and standard (Table 81). This implicit MOS ranges from 4.2% to 8.75%, depending on the reach being evaluated.

Table 81. Margin of safety included in TMDL scenario

Reach	Difference in Maximum Daily Water Temperature (°C)	Difference in Minimum Daily DO (mg/L)
7	-1.75	+0.93
8	-1.16	+0.30
10	-1.46	+1.01

Seasonal Variation

Seasonal variation is addressed in this TMDL by assessing conditions during the critical conditions. Critical conditions for stream temperature and low DO occur during warm, low flow time periods. By setting the TMDL to meet the most critical condition, the TMDL will inherently be protective of water quality during all other seasons.

4.5.2 TMDL Summary

Table 82 summarizes the temperature TMDL for Wyman Creek, which was developed for low flow, critical conditions (3.1 cubic feet per second) at the downstream end of the creek. In addition to allocations, associated implementation targets are also provided. These implementation targets can be used to achieve the thermal load reductions needed to meet the TMDL. A 10% reduction in thermal loading is needed to meet the temperature target and DO standard.

Table 82. Wyman Creek temperature TMDL

Temperature TMDL	Load (million Kcal/day)	Implementation Targets
Wasteload Allocation: Industrial Stormwater General Permit (MNR050000) [a]	0.1	– [a]
Wasteload Allocation: Construction Stormwater General Permit (MNR100001) [a]	0.1	– [a]
Wasteload Allocation: Cliffs Erie–Hoyt Lakes Mining Area (MN0042536)	– [b]	No reductions needed
Load Allocation	151.9	· Removal of the west braid and re-routing of all flow to Reaches 7, 8, and 10 · Average daylight hours shade of 57% along Reaches 7, 8, and 10 · Average daylight hours shade of 57% along Reach 6 or equivalent implementation to reduce in-stream temperatures entering Reach 7 to 19.7 °C
MOS	*Implicit*	
Loading Capacity	152.1	
Existing Load	169.2	
Percent Load Reduction	10%	

a. It is assumed that loads from permitted industrial and construction stormwater sites that operate in compliance with the permit are meeting the WLA.

b. The WLA for Cliffs Erie–Hoyt Lakes Mining Area (MN0042536) is set to existing conditions. Scenario 4 (Appendix D) evaluated the effect of Cliffs Erie–Hoyt Lakes Mining Area discharges, and determined that the point source does not have reasonable potential to cause or contribute to impairment on the reaches of interest (reaches 7–10 in Appendix D); therefore the facility can continue to discharge at existing conditions. Reductions from point sources are not needed to meet the TMDL in the lower reaches 7–10.

5. Future Growth Considerations

5.1 New or Expanding Permitted MS4 WLA Transfer Process

Future transfer of watershed runoff loads in this TMDL may be necessary if any of the following scenarios occur within the project watershed boundaries:

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

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

5.2 New or Expanding Wastewater

For TSS and *E. coli* TMDLs, the MPCA, in coordination with the U.S. EPA Region 5, has developed a streamlined process for setting or revising WLAs for new or expanding wastewater discharges to water bodies with an EPA approved TMDL (described in Section 3.7.1 New and Expanding Discharges in MPCA 2012). This procedure will be used to update WLAs in approved TMDLs for new or expanding wastewater dischargers whose permitted effluent limits are at or below the instream target and will ensure that the effluent concentrations will not exceed applicable water quality standards or surrogate measures. The process for modifying all WLAs will be handled by the MPCA, with input and involvement by the EPA, once a permit request or reissuance is submitted. The overall process will use the permitting public notice process to allow for the public and EPA to comment on the permit changes based on the proposed WLA modification(s). Once any comments or concerns are addressed, and the MPCA determines that the new or expanded wastewater discharge is consistent with the applicable water quality standards, the permit will be issued and any updates to the TMDL WLA(s) will be made.

The above policy also applies to phosphorus limits in industrial wastewater, because the concentration of phosphorus in industrial wastewater is expected to be lower than the lake and stream phosphorus standards. Additional reserve capacity was not added for phosphorus in municipal wastewater. There are no existing municipalities within the phosphorus impaired watersheds that are not already covered by a WLA for municipal wastewater. For more information on the overall process, visit the MPCA's TMDL Policy and Guidance webpage.

6. Reasonable Assurance

The EPA requires reasonable assurance that TMDLs will be achieved and water quality standards will be met. For point source dischargers (including MS4s) in the SLRW, the MPCA will assure implementation of TMDLs through its NPDES and stormwater programs. For nonpoint source control, the St. Louis River WRAPS Report (MPCA 2017a) outlines implementation opportunities and proposed BMPs that will lead to water quality improvements and TMDL achievement. These activities are summarized in the implementation section (Section 8, Table 84 through Table 87). The following sections provide key aspects of reasonable assurance, including previous, current, and planned water quality improvement actions and the technical and financial resources available to conduct them.

Restoration of the SLRW will occur as part of local, regional, state, and federal efforts and will be led by St. Louis County, South Saint Louis Soil and Water Conservation District (SWCD), North St. Louis SWCD, Itasca County, Itasca SWCD, Carlton County, Carlton SWCD, Lake County, Lake SWCD, Aitkin County, Aitkin SWCD, Fond du Lac Band of Lake Superior Chippewa, state agencies, local communities, and residents. These partners will work together to complete planning activities, secure funding, and implement projects in the watershed.

Potential funding sources for implementation activities in the St. Louis River Watershed include:

- Clean Water Fund, part of the Clean Water, Land, and Legacy Amendment
- Local government cost-share and loan programs
- Federal grants and technical assistance programs, including:
    - Conservation Reserve Program and USDA Natural Resources Conservation Service (NRCS) cost-share programs
    - Federal Section 319 program for watershed improvements
    - Great Lakes Restoration Initiative

Agencies, organizations, and landowners in the SLRW have been implementing water quality projects and programs in an effort to reduce pollutant loading in the watershed, and are expected to continue these efforts into the future:

- South St. Louis SWCD implements watershed projects such as large-scale stream restorations in impaired watersheds. The SWCD also offers technical and financial assistance for conservation efforts in the watershed. Potential cost share projects include bank stabilization, riparian buffers, stormwater projects, and animal waste management systems. A streambank connectivity analysis of impaired streams in the SLRW (South St. Louis SWCD 2016) and *The Swan River Channel Stability and Geomorphic Assessment* (South St. Louis SWCD 2013), which addresses TSS impairments in the Swan River Subwatershed, will be used for implementation planning.
- North St. Louis SWCD also implements projects to preserve, protect, and enhance water quality and other natural resources. For example, the SWCD completed the Orr Trout Stream restoration to increase hydrologic connectivity and improve brook trout survival and

reproduction. The SWCD is also active in water quality sampling and aquatic invasive species prevention in the watershed.

- The city of Hibbing has an ordinance that requires dog waste to be immediately removed from public property. They have also adopted a shoreline land protection ordinance for septic systems in addition to maintaining compliance with Minn. R. ch. 7080.
- The Fond du Lac Band of Lake Superior Chippewa has federal Clean Water Act jurisdiction for waters of the reservation, which is located in the downstream portion of the SLRW, adjacent to the Wisconsin border, and is active in watershed management and water quality restoration in the area. The Fond du Lac Band has established water quality standards for its waters and implements a water quality monitoring, assessment, protection, and restoration program on the reservation. In 2017, they developed an integrated resource management plan that identifies shoreline development pressures, surface water runoff, and aquatic invasive species as threats to water quality (Fond du Lac Resource Management Division 2017).
- The Saint Louis County Health Department regulates private wastewater through ordinances, point of sale inspections, and permitting. For example, Ordinance 61 requires that property owners provide full disclosure of the existence and status of on-site wastewater treatment systems to any potential buyers. The county also provides funds through their IPHT Grant Program, which assists low-income homeowners to repair or replace failing systems that are classified as IPHTs or non-compliant systems. Several educational brochures on septic system maintenance and the importance of treating wastewater are also available on their website in addition to a series of videos.

Additionally, the Swan River Subwatershed is identified in the WRAPS report (MPCA 2017a) as a priority for restoration activities. St. Louis County is beginning the process of updating their comprehensive water management plan, which will provide additional detail and focus on prioritizing areas, targeting BMPs, and measuring outcomes.

7. Monitoring Plan

Monitoring is important for several reasons including:

- Evaluating water bodies to determine if they are meeting water quality standards and tracking trends
- Assessing potential sources of pollutants
- Determining the effectiveness of implementation activities in the watershed
- De-listing of waters that are no longer impaired

Monitoring is also a critical component of an adaptive management approach and can be used to help determine when a change in management is needed.

The SLRW is scheduled for intensive monitoring again in 2019 as part of the state's Watershed Approach. The MPCA's intensive watershed monitoring (IWM) approach uses a *pour point* method, in which sampling near the mouth of subwatersheds, from a coarse to a fine scale, is used to characterize the watershed's condition in an unbiased manner (chemical, biological, and physical). IWM allows the evaluation of the overall health of the state's water resources, assessment of the state's streams for aquatic life, recreation, and consumption use support on a rotating 10-year cycle, and identification of waters in need of protection efforts to prevent impairment.

Monitoring of flow and water quality are needed throughout the SLRW to refine modeling and source assessments. Data gaps have been identified as part of the TMDL and associated modeling work. This section describes recommended monitoring activities in the watershed, contingent upon funding and staffing resources. In addition, more data and research are needed in the SLRW regarding the effects of specific conductivity, sulfate, and total dissolved solids on aquatic life.

7.1 E. coli

E. coli samples are needed throughout the impaired watersheds to further assess potential sources and focus implementation activities. *E. coli* sampling under different flow conditions, with an emphasis on low flow conditions, will help refine the source assessments and determine if direct sources are of concern. *E. coli* sampling along longitudinal profiles will also further focus future source assessment work and identify hot spots of *E. coli* loading.

The *E. coli* sources in the impaired reaches in the Swan River Subwatershed generally differ from the sources in the lower impaired watersheds. Monitoring unique to each impairment group is recommended to further refine the source assessment and target implementation:

- Swan River impaired subwatersheds (see Figure 3 for a location map)
    - Monitor stream *E. coli* during low flow conditions to determine if a direct source such as aging wastewater infrastructure is of concern.
    - Assess the effect of aging wastewater collection infrastructure on *E. coli* loads to surface waters through monitoring of storm sewer discharge under low flow conditions.

    Monitor stormwater runoff independently to help tease apart the effects of stormwater runoff and aging wastewater collection infrastructure on *E. coli* loads.

    - Complete a livestock survey to further refine the source assessment and provide detailed information for use by county staff.

- Lower impaired watersheds (see Figure 4 for a location map)
    - Monitor *E. coli* during low flow conditions to determine if a direct source such as IPHT systems are of concern.
    - Complete a livestock survey to further refine the source assessment and provide detailed information for use by county staff.

7.2 Total Suspended Solids

TSS samples are needed throughout the East Swan River and Stony Creek subwatersheds to further assess potential sources and focus implementation activities.

- East Swan River Subwatershed
    - Monitoring of bank erosion can be conducted using a combination of field evaluation, geomorphic assessment, and landscape-level modeling. This information is valuable to determine priority areas for implementation. Recommendations from the East Swan River Watershed Geomorphic Study include:
        - Core and date the sediments in the meander cut offs that are located in the system. This may indicate the date at which the stream cut off the meanders and may be an indication of the rate of change that it will take for the system to recover in these reaches.
        - Conduct more detailed topographic surveys and cross sections at more points to further identify the degree of channel confinement in the lower reaches and to identify where grade control may be installed to improve the channel's connection to its floodplain.
    - Evaluate the effect of mine dewatering on peak flow hydrology in the East Swan River.
- Stony Creek Subwatershed
    - Further monitoring is needed to identify areas of channel incision, bank erosion, channel widening, and debris jams that alter the natural course of the stream channel.

7.3 Phosphorus

The following monitoring recommendations apply to Dinham Lake and West Two Rivers Reservoir in addition to the five shallow lakes for which TMDLs are being deferred (Table 2):

- Continued monitoring of TP, chl-*a*, and Secchi disk transparency is needed to understand trends in lake water quality.

- Monitoring of flow and nutrients in the lake inlets is needed. A better understanding of external loads to each lake would help determine or refine the balance between external and internal phosphorus loading to the lake.
- Field inventory of potential sources including wetlands, forests, roads, and near-shore developed areas could be used to further understand sources of phosphorus to each lake and help focus implementation activities. Evaluate the shoreland and identify areas of disturbance, such as altered vegetation, bare soil, and shoreland erosion.
- Investigate sources of internal loading, such as resuspension of sediment from bottom waters.
- Monitoring to identify septic system sources of phosphorus to the lakes is needed to verify source assessment findings.

The following monitoring recommendations are specific to individual water bodies:

- For Mud Hen Lake, evaluate the effect of pasture and cropland on phosphorus concentrations in runoff.
- For West Two Rivers Reservoir, McQuade Lake, and Lake Manganika, additional data on the phosphorus concentration in the industrial wastewater discharge from the mining sites is needed to confirm the load estimates. The US Steel Minntac Mining Area discharges in the West Two Rivers Reservoir and McQuade Lake Watersheds, and United Taconite LLC Thunderbird Mine discharges in the Lake Manganika Watershed.
- In the three lakes near the mining areas (Lake Manganika, McQuade Lake, and West Two Rivers Reservoir), the drivers of internal loading may involve iron, sulfur, sediment phosphorus content, and DO. These factors should be evaluated to gain a better understanding of nutrient dynamics within the lakes and the options available to reduce internal loading.
- To confirm that low DO and a high daily range in DO in West Two River is caused by eutrophication, monitoring of phosphorus, chl-*a*, and DO in West Two River downstream of the reservoir is recommended.

7.4 Temperature and Dissolved Oxygen (Wyman Creek)

Monitoring as part of adaptive management is recommended for Wyman Creek as implementation activities are conducted. Additional continuous temperature, DO and flow data could be used to further refine the QUAL2K model. In addition, further investigation into the role that iron and iron precipitates play in the overall balance of DO in the Creek would allow further refinement of the QUAL2K model.

8. Implementation Strategy Summary

This section provides a high-level overview of implementation strategies for the impaired water bodies. Additional information can be found in the WRAPS report (MPCA 2017a), and further development and refinement of implementation will occur in local plans and studies. Implementation to achieve compliance with the TMDLs will require cooperation and coordination among state and local agencies and stakeholders. The governmental units with primary implementation responsibility include MPCA, DNR, Board of Water and Soil Resources (BWSR), St. Louis County, Carlton County, South St. Louis SWCD, North St. Louis SWCD, and municipalities. Other entities such as mining and forestry interests, non-profits, universities, and business owners are also anticipated to participate with implementation. Government agencies with secondary responsibilities include the Minnesota Department of Agriculture, Minnesota Department of Health, USDA NRCS, USDA Forest Service, and Fish and Wildlife Service. These agencies will work with private landowners and other agencies and project partners to support implementation.

General implementation strategies are presented for permitted sources and non-permitted sources. Menus of BMPs are included that target the *E. coli*, TSS, phosphorus, and temperature sources to each impaired water body.

Strategies for understanding and addressing mercury and other toxic elements in the St. Louis River system are being addressed through other efforts at MPCA. The SLRW also has waters listed for toxic impairments such as PCBs (in water column and fish tissue), dieldrin, DDT (dichlorodiphenyltrichloroethane), dioxin (including 2, 3, 7, 8-TCDD), and toxaphene. Data collection and research on these toxic impairments is in progress and should be completed in the near future. For more information on mercury, please see https://www.pca.state.mn.us/quick-links/minnesotas-plan-reducing-mercury-contamination-fish.

8.1 Permitted Sources

8.1.1 MS4

There are six regulated MS4s in the impaired watersheds: Hibbing City, Hermantown City, Midway Township, Cloquet City, St. Louis County, and MnDOT. Additionally, there are three MS4s that are expected to come under permit coverage in the next permit cycle: Grand Lake Township, Canosia Township, and Thomson Township. The only regulated MS4 that is required to reduce pollutant (i.e., *E. coli* and TSS) loads to meet the WLAs presented in this TMDL report is the city of Hibbing; the remaining regulated MS4s are not required to reduce their loads but also must not increase pollutant loading.

Implementation strategies that the city of Hibbing can use to meet their WLAs include bacteria source tracking to help identify sources of *E. coli* loading, upgrading leaky wastewater infrastructure, stormwater BMPs to reduce TSS and *E. coli* loading, pet waste management, and disconnecting impervious areas[5] (Table 84 and Table 85). MS4 permittees are required to document compliance with WLA(s) over time as part of their MS4 Stormwater Pollution Prevention program (SWPPP). MS4s must determine if they are currently meeting their WLA(s) and if not must provide a narrative strategy and compliance schedule to meet the WLA(s).

8.1.2 Wastewater

Municipal Wastewater

Three WWTFs receive WLAs from this TMDL report. The conditions of the WLAs are presented in Table 83, and implementation strategies are included in Table 84 through Table 86.

Table 83. Summary of WWTP WLAs

Municipal Wastewater Treatment Facility	*E. coli*	TSS	P
Hibbing South WWTP	Reductions in E. coli load are not needed to meet the WLA.	WLAs for the two WWTPs apply from April 1 through September 30. It is assumed that the facilities' restricitve mercury effluent limit are sufficient to ensure that effluent TSS concentrations will not exceed the 10 mg/L inorganic TSS concentration, which is the basis for the water quality standard.	–
Central Iron Range Sanitary Sewer District	The MPCA has future permit discretion to 1) expand the fecal coliform effluent limit effective period to include April, or 2) require the permittee to conduct a stream monitoring program to determine whether Barber Creek is impaired for *E. coli* in April and implement an expanded disinfection period only if the impairment occurs in April. Further reductions in *E. coli* load, beyond the extension of the disinfection months, are not needed.		
Mountain Iron WWTP	–	–	Phosphorus load reductions (43%) are needed. The WLA for Mountain Iron WWTP is based on the TP concentration of 0.23 mg/L and the facility's average wet weather design flow.

– Facility does not receive a WLA for this parameter.

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[5] Impervious surface disconnection spreads runoff generated from parking lots, driveways, rooftops, sidewalks and other impervious surfaces onto adjacent pervious areas where it can be infiltrated.

Industrial Wastewater
US Steel–Minntac Mining Area receives a WLA for phosphorus loading from industrial wastewater to West Two Rivers Reservoir; however, load reductions are not needed (Table 77).

8.1.3 Construction Stormwater

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

8.1.4 Industrial Stormwater

The WLA for stormwater discharges from sites where there is industrial activity reflects the number of sites in the watershed for which NPDES Industrial Stormwater Permit coverage is required, and the BMPs and other stormwater control measures that should be implemented at the sites to limit the discharge of pollutants of concern. The BMPs and other stormwater control measures that should be implemented at the industrial sites are defined in the state's NPDES/SDS Industrial Stormwater Multi-Sector General Permit (MNR050000), NPDES/SDS General Permit for Construction Sand & Gravel, Rock Quarrying and Hot Mix Asphalt Production facilities (MNG490000), US Steel–Minntac Mining Area (MN0052493), and Hibbing Taconite Company (MN0001465). If a facility owner/operator obtains stormwater coverage under the appropriate NPDES/SDS Permit and properly selects, installs, and maintains all BMPs required under the permit, the stormwater discharges would be expected to be consistent with the WLA in this TMDL. All local stormwater management requirements must also be met.

8.2 Non-Permitted Sources

Non-permitted sources include septic systems, agricultural runoff, shoreland runoff, stormwater runoff, stream bed and bank erosion, lake internal loading, lack of riparian shade, altered hydrology, and beaver activity. BMPs to address these sources are described in Section 8.3.

8.3 Implementation Strategies

Table 84 through Table 87 include implementation strategies for *E. coli*, TSS, phosphorus, and temperature, for both permitted and non-permitted sources. Strategies are presented for each of the impaired water bodies. Additional information on the strategies, such as 10-year milestones, ultimate implementation goals, governmental unit with primary responsibility, and estimated year to achieve water quality targets, can be found in the St. Louis River WRAPS Report (MPCA 2017a).

Table 84. Implementation strategies to reduce *E. coli* loading

Implementation Strategy	Proposed Strategy Types	Buhl Creek (580)	Dempsey Creek (582)	Barber Creek/East Swan River (641)	Penobscot Creek (936)	Barber Creek/East Swan River (569)	Unnamed Creek (542)	Unnamed Creek/East Swan Creek (888)	Unnamed A22	Pine River/White Pine River (543)	Unnamed Creek (625)	Hay Creek (751)
Reduce urban loading from stormwater and pets	Pet waste management programs (in developed areas).	ü		ü	ü		ü	ü				
	BMPs to reduce pollutant loading – see MPCA Stormwater Manual.	ü	ü	ü	ü	ü	ü	ü				
	Disconnected imperviousness.	ü	ü	ü	ü	ü	ü	ü				
Reduce industrial/municipal wastewater discharges	Bacteria source tracking. Address inflow/infiltration. Upgrade leaky wastewater infrastructure in urban areas.	ü	ü	ü	ü	ü	ü	ü				
	Expand Central Iron Range Sanitary Sewer District's (MN0020117) disinfection period to include April, or monitor and expand disinfection period only if April impairment is found.			ü								
	Investigate presence of untreated wastewater in stream and correct upstream problems.							ü				
Address private wastewater systems (e.g., septic systems)	Inventory and assess the potential for septic systems/private wastewater systems to be sources of *E. coli* in impaired streams. Replace all systems deemed IPHT (e.g., straight pipes, surface seepage).	ü	ü	ü	ü	ü	ü	ü	ü	ü	ü	ü
Feedlot, pasture, and livestock management	Updated feedlot inventory. Open lot runoff management to meet 7020 rules. Manure storage in ways that prevent runoff. Animal agriculture producers and animal hobby farm owners outreach.	ü	ü	ü	ü	ü	ü	ü	ü	ü	ü	ü

Implementation Strategy	Proposed Strategy Types	Buhl Creek (580)	Dempsey Creek (582)	Barber Creek/East Swan River (641)	Penobscot Creek (936)	Barber Creek/East Swan River (569)	Unnamed Creek (542)	Unnamed Creek/East Swan Creek (888)	Unnamed A22	Pine River/White Pine River (543)	Unnamed Creek (625)	Hay Creek (751)
	Riparian corridor survey for livestock exclusion, increase livestock exclusion. Rotational grazing.											
Monitoring and source assessment	Conduct longitudinal survey of *E. coli* concentrations to identify sources and target implementation activities.	ü	ü	ü	ü	ü	ü	ü	ü	ü	ü	ü

ü: Implementation strategy recommended for this water body.

Table 85. Implementation strategies to reduce TSS loading

Implementation Strategy	East Swan River	Stony Creek
Monitoring and further evaluate	Monitor total suspended solids discharging from Hibbing South and Central Iron Range Sanitary Sewer District WWTPs for compliance with TMDL; adjust treatment level if needed.	Continue to monitor and evaluate the effect of natural background conditions on impairment (e.g., low gradient).
Increased stormwater management	Water quality ponding and other BMPs to reduce pollutant loading. Stormwater ponding or other rate reduction practices to reduce peak flows and volumes. Disconnected imperviousness.	Not applicable.
Implement recommendations from the St. Louis Connectivity Analysis	Repair or upgrade improperly sized culverts at road crossings including Hibbing M337.	Repair or upgrade improperly sized culverts at road crossings including St. Louis County CSAH 83.
Stream restoration and improved ditch management and altered watercourse improvements	Implementation of the recommendations provided in Swan River Channel Stability and Geomorphic Analysis (SSLSWCD 2013).	Research historic landscape alteration and effect on St. Louis River and channel incision in Stony Creek. Geomorphic assessment and feasibility study to determine restoration opportunities.

Implementation Strategy	East Swan River	Stony Creek
		Address debris jams.
	Restoration of channelized streams and ditches (re-meander, connect to floodplains). Restore natural meander and complexity. Address road crossings (direct erosion) and floodplain cut-offs. Address channel incision (e.g., grade control) and entrenchment. Restore riffle substrate where appropriate. Address erosion in near-shore areas (bank armoring, bioengineering, etc.).	
Wetland restoration	Use of ditch blocks and vegetation to restore ditched wetland and peatland areas.	
Feedlot, pasture, and livestock management	Open lot runoff management to meet 7020 rules. Manure storage in ways that prevent runoff. Animal agriculture producers and animal hobby farm owners outreach. Riparian corridor survey for livestock exclusion, increase livestock exclusion. Rotational grazing.	

Table 86. Implementation strategies to reduce phosphorus loading

Implementation Strategy	Dinham Lake	West Two Rivers Reservoir and West Two River [a]
Education and outreach	Education and outreach on best shoreland management practices.	Provide focused education and outreach to lake users on harmful algal blooms and lake water quality concerns.
Reduce internal release of phosphorus	Investigate sources of internal loading, such as resuspension of sediment from bottom waters. Consider in-lake treatment once external sources of phosphorus have been controlled.	Evaluate the potential drivers of internal loading in West Two Rivers Reservoir (e.g., iron, sulfur, sediment phosphorus content, DO conditions, resuspension of sediment from bottom waters). Evaluate potential options for internal load reduction following reductions in WWTP phosphorus loading and long-term monitoring of inflows to lake.
Protect and stabilize nearshore areas (lakeshores)	Shoreland survey—evaluate the shoreland and identify areas of disturbance such as altered vegetation (e.g., lawns), bare soil, and shoreland erosion.	Not applicable.

Implementation Strategy	Dinham Lake	West Two Rivers Reservoir and West Two River [a]
	Lakeshore revegetation and buffers.	
Address private wastewater systems (e.g., septic systems)	Inventory and assess the potential for septic systems / private wastewater systems to be sources of phosphorus. Replace all systems deemed an imminent public health threat (e.g., straight pipes, surface seepage). Sewering around lakes; identify opportunities for cluster systems and work with landowners to implement. Landowner focused education and outreach on septic system maintenance and compliance. Support increased compliance inspections (in addition to current point of sale inspections). Additional setbacks in sensitive areas (e.g., lakeshore).	Not applicable.
Reduce municipal wastewater phosphorus	Not applicable	Reductions in phosphorus loading from Mountain Iron WWTP (MN0040835) as prescribed in the TMDL. Consider regionalized wastewater treatment solutions.

a. Additional BMPs for West Two River are included in the WRAPS report (MPCA 2017a) to protect and improve conditions in the stream. The additional BMPs are not needed to achieve the TMDL.

Table 87. Implementation strategies to reduce temperature

Implementation Strategy	Wyman Creek
Increased forest cover in riparian areas	Riparian vegetative buffers. Tree planting to increase shading. Consider beaver removal and forest management to eliminate aspen within stream corridor (to limit beavers).
Increase stream flow/reduce ponded water	Beaver dam removal; long-term beaver removal/management.
Beaver dam removal at headwater of braided stream	Removal of beaver dam creating braided stream in lower reaches (downstream end of reach 6).

8.4 Cost

TMDLs are required to include an overall approximation of implementation costs (Minn. Stat. 2007, § 114D.25). The costs to implement the activities outlined in the strategy are approximately $15 to $25 million dollars over the next 25 years. This includes the cost of increasing local capacity to oversee implementation in the watershed, as well as planning and capital costs. Easements and the cost to address nutrient discharges (e.g., replace plant, regional wastewater solution) from the Mountain Iron WWTP are not included in the cost estimate. This range reflects the level of uncertainty in the source assessment.

8.5 Adaptive Management

The implementation strategy above and the more detailed WRAPS report (MPCA 2017a) rely on adaptive management (Figure 74) to ensure management decisions are based on the most recent knowledge. An adaptive management approach allows for changes in the management strategy if environmental indicators suggest that the strategy is inadequate or ineffective. Continued monitoring and “course corrections” responding to monitoring results are the most appropriate strategy for attaining the water quality goals established in this TMDL.

Natural resource management involves a temporal sequence of decisions (or implementation actions), in which the best action at each decision point depends on the state of the managed system (Williams 2009). As a structured iterative implementation process, adaptive management offers the flexibility for responsible parties to monitor implementation actions, determine the success of such actions, and ultimately base management decisions upon the measured results of completed implementation actions and the current state of the system. This process enhances the understanding and estimation of predicted outcomes and ensures refinement of necessary activities to better guarantee desirable results. In this way, understanding of the resource can be enhanced over time, and management can be improved (Williams 2009).

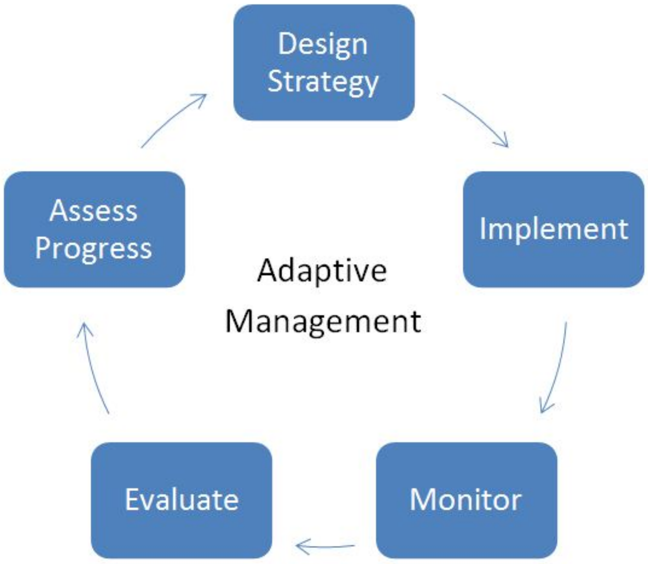


Figure 74. Adaptive management process

9. Public Participation

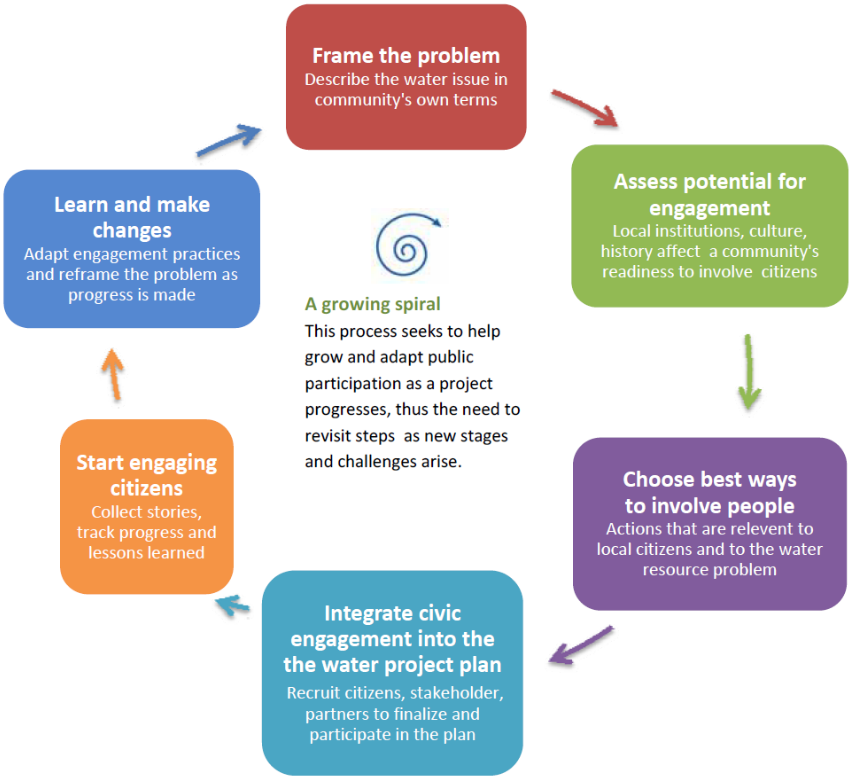
A key prerequisite for successful strategy development and on-the-ground implementation projects for restoring and protecting water quality is meaningful civic engagement. With approximately half of the land in the SLRW in private hands, the water quality in this watershed is ultimately dependent on how private landowners manage their land.

Civic engagement is distinguished from the broader term ‘public participation’ in that civic engagement encompasses a higher, more interactive level of involvement. The University of Minnesota Extension’s definition of civic engagement is “Making ‘resourceFULL’ decisions and taking collective action on public issues through processes that involve public discussion, reflection, and collaboration.” Many local resource professionals in the SLRW, including MPCA and SWCD staff, were formally trained by the University of Minnesota’s Center for Community Vitality in this method of civic engagement in 2013 and 2014; therefore this strategy informed much of the civic engagement efforts that took place in the SLRW for this first WRAPS cycle. More information on the University of Minnesota’s civic engagement philosophy and methods are available at http://www1.extension.umn.edu/community/civic-engagement/.

The St. Louis River WRAPS Civic Engagement team identified three goals for the civic engagement process in the watershed:

1. Introduce the public to the MPCA’s new Watershed Approach to water quality assessment, the 10-year cycle, and the St. Louis River Watershed
2. Start building a network of interested stakeholders within the watershed
3. Convey the importance of having the public engaged and actively participating in the restoration and protection of the SLRW

There are several levels of civic engagement identified by the International Association of Public Participation and used by the University of Minnesota in their civic engagement instruction modules: inform, consult, involve, collaborate, and empower. Each level provides for a deeper level of involvement from the public. Because this was the first 10-year cycle in this watershed, and because the WRAPS is a new process for the MPCA, civic engagement efforts were conducted on an informational and consulting level. During the second 10-year cycle, which begins in 2019, the MPCA expects to solicit a deeper level of involvement from the public in the hopes that they are familiar with the MPCA’s watershed assessment process and their expected role in it. Coordination of civic engagement efforts throughout the whole cycle of the watershed approach, especially local water planning efforts, among all partners is a further goal of the second cycle.



There were three audiences for civic engagement efforts in the SLRW: citizens and landowners (the public), natural resources professionals making up a "Core Team," and NPDES Permit holders.

A summary of the civic engagement activities and events that have been conducted thus far in the watershed and those planned in the near future (in italics) for the SLRW are provided in Table 88 and Table 89. These events were led by the South St. Louis SWCD under contract with the MPCA. Staff from the MPCA and from the North St. Louis SWCD assisted.

The civic engagement process for the public was divided into three phases. These phases coincided with the three major documents that come out of the WRAPS process:

1. Monitoring and assessment report
2. Biotic SID report
3. Final WRAPS document with TMDL calculations

A series of six public meetings, also called community conversations, were held across the watershed for each phase (Table 88).

Table 88. WRAPS public meeting dates and locations

WRAPS Phase	Meeting Date	Meeting Location
Phase 1—Monitoring and Assessment Report	June, 2014	Giants Ridge, Biwabik
	June 4, 2014	Iron Range Resources and Rehabilitation Board Office, Virginia
	June 5, 2014	Inn on Lake Superior, Duluth
	June 5, 2014	Morgan Park Community Center, West Duluth
	June 7, 2014	MN Discovery Center, Chisholm
	June 10, 2014	Floodwood Elementary School, Floodwood
Phase 2—Biotic Stressor Identification Report	January 25, 2016	Duluth Heights Community Center, Duluth, in Cooperation with MN Sea Grant.
	June 25, 2016	Cloquet Forestry Center, Cloquet
	June 26, 2016	Canosia Town Hall, Pike Lake
	June 27, 2016	Mesabi Range College, Virginia
	June 28, 2016	Floodwood Elementary School, Floodwood
	June 30, 2016	Hoyt Lakes Community Center, Hoyt Lakes
Phase 3—WRAPS Report	October 3, 2017	Hoyt Lakes Community Center, Hoyt Lakes
	October 4, 2017	Range Regional Airport, Hibbing
	October 5, 2017	Hermantown Police Training Center, Hermantown

TMDLs were discussed at the public meetings listed above, and there were four meetings held for permit holders and lakeshore owners to address the TMDLs specifically (Table 89).

Table 89. TMDL public meeting dates, locations, and topics

Date	Location	Topic/Audience
November 16, 2016	Iron Range Resources and Rehabilitation Board Office, Virginia	Draft TMDLs in the St. Louis River Watershed/Representatives from NPDES Permit-holders in the watershed.
July 21, 2016	Miners Memorial Building, Virginia	Lakes TMDLs–Impaired Lakes/ Lakeshore property owners and other interested parties.
July 21, 2016	Loon Lake Community Center	Lakes TMDLs–Impaired Lakes/Lakeshore property owners and other interested parties.

The South St. Louis SWCD also provided updates and information about the St. Louis River WRAPS process in its outreach materials including its ENews (seasonal) and Conservation News (annual) publications as noted below (see South St. Louis SWCD website for full texts):

- ENews, August 2013: “Hiking (and floating) rivers for the state”
- ENews, November 2013: “Field data collection keeps staff hoppin'”
- Conservation News 2014: “For the good of the ‘hood: watershed awareness begins with you”
- ENews, April 2014: “Watershed meetings set for June”
- ENews, August 2014: “June Watershed meetings well attended”
- Conservation News 2016: “SWCD continues to assist MPCA with investigating the health of area rivers and streams”
- ENews, June 2016: “St. Louis River Watershed 2016 Meeting Series”
- Conservation News 2017: “Duluth WRAPS”

In 2010, the start of the St. Louis River Watershed WRAPS work, the concept and role of the Core Team was still in its infancy. The Core Team initially consisted of the MPCA staff and local partner South St. Louis SWCD and mainly focused on the administration of contractual services. After 2012, it was determined that, in order to be successful in this complex effort with many stakeholders and partners, we needed to expand and broaden the concept of a Core Team of natural resource professionals who could collectively develop high level strategies for protection and restoration of the watershed. To that end, invitations were sent to the following organizations to participate. Please note that attendance of these organizations has been variable over the life of this project.

- EPA
- Fond du Lac Band of Lake Superior Chippewa
- Itasca County SWCD
- Itasca County
- Lake County SWCD
- Lake County
- Minnesota Department of Agriculture
- Minnesota Department of Health
- Minnesota DNR
- Minnesota BWSR
- MPCA
- North St. Louis SWCD
- NRCS
- South St. Louis SWCD
- St. Louis County
- United States Forest Service
- University of Minnesota-Duluth Natural Resources Institute
- University of Minnesota-Duluth

- United States Geological Service
- Vermilion Community College

This group met 15 times between October 2012 and October 2017, with several additional, smaller focus meetings, to discuss the activities and decisions coming out of the WRAPS process. Meetings occurred on the following dates: 10/1/2012, 12/17/2012, 3/11/2013, 11/21/2013, 3/5/2014, 10/1/2014, 3/5/2015, 10/28/2015, 11/19/2015, 1/12/2016, 3/31/2016, 8/23/2016, 10/18/2016, 1/12/2017, and 2/7/2017.

9.1 Public Notice for Comments

An opportunity for public comment on the draft WRAPS report was provided via a public notice in the State Register from February 20, 2018 to March 22, 2018.

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Appendices

Appendix A. Shallow Lakes Review and Phosphorus Source Assessment

TETRA TECH

MEMO

To:	Mike Kennedy, Minnesota Pollution Control Agency
From:	Andrea Plevan and Jennifer Olson
Date:	June 30, 2016
Subject:	Shallow lakes review and phosphorus source assessment in the St. Louis River watershed

Five of the seven lakes in the St. Louis River watershed with aquatic recreation impairments that are due to eutrophication are classified by the Minnesota Pollution Control Agency (MPCA) as shallow. The MPCA intends to develop eutrophication standards for shallow lakes in the Northern Lakes and Forests ecoregion, but the new standards will not be developed within the time frame of the current total maximum daily load (TMDL) study. The TMDLs for the impaired shallow lakes in the St. Louis River watershed are being deferred until development of the shallow lake standards.

The purpose of this memo is to provide water quality data analysis and an assessment of phosphorus sources to the impaired shallow lakes in the St. Louis River watershed (Table 1).

Table 1. Shallow lakes with aquatic recreation impairments due to nutrient/eutrophication biological indicators

Lake Name	Lake Identification	Year Added to List
Long	69-0495-00	2012
Manganika	69-0726-00	2008
McQuade	69-0775-00	2012
Mud Hen	69-0494-00	2012
Strand	69-0529-00	2012

1.0 WATERSHED AND WATER BODY CHARACTERIZATION

The impaired lakes are all located in St. Louis County, and they range in size from 158 acres (Mud Hen Lake) to 373 acres (Long Lake, Table 2). The mean depths range from 1.8 meters in Mud Hen Lake to 4.8 meters in Strand Lake. Strand Lake has a small watershed area relative to the lake surface area, while Long Lake and McQuade Lake's watersheds are much larger relative to the lake area, suggesting that the watershed has more impact on the water quality of Long Lake and McQuade Lake than the lakes with smaller watershed to lake area ratios.

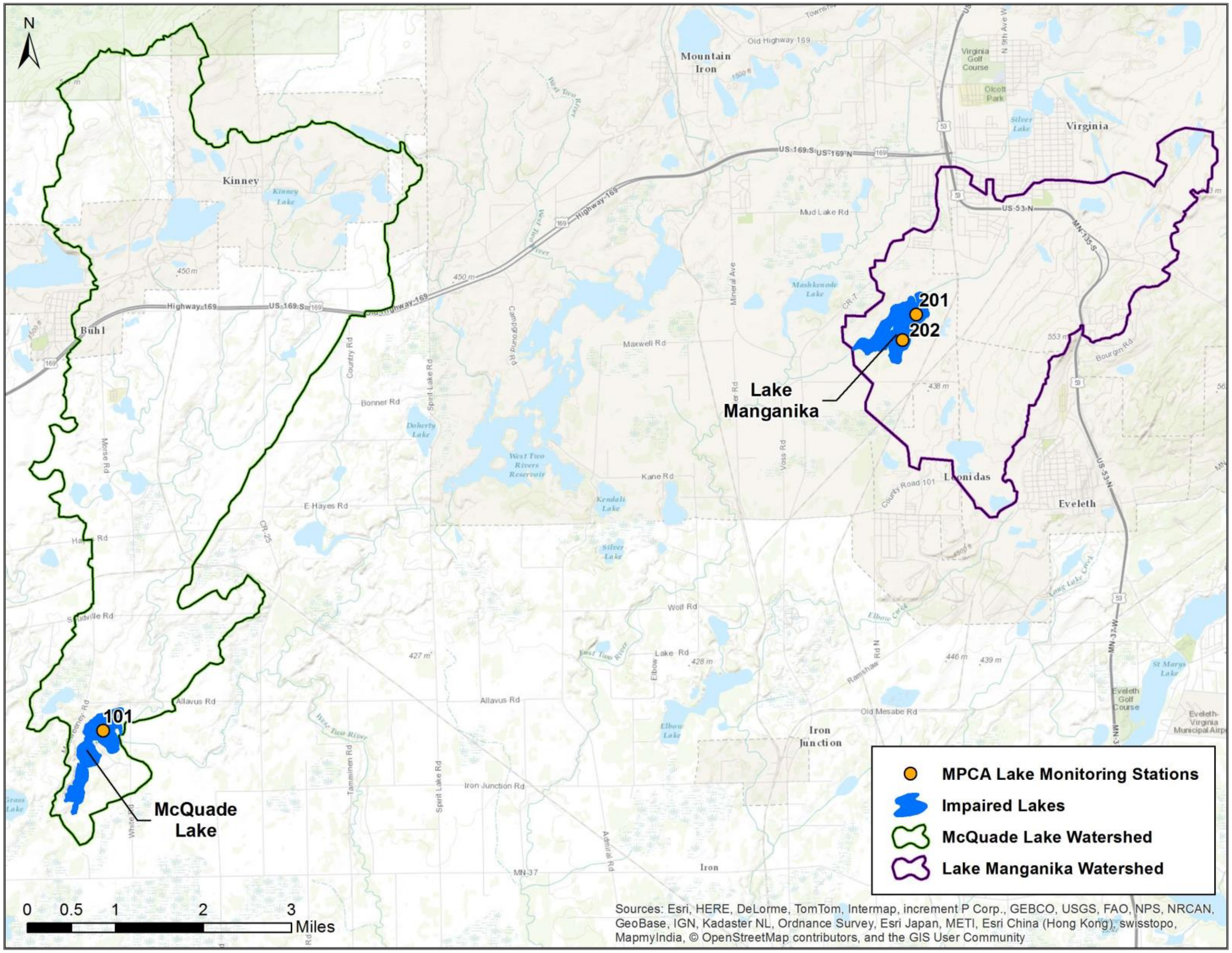
Table 2. Lake morphometry and watershed area

Lake Name	Assessment Unit ID	Surface Area (ac)	Mean Depth (m)	Max Depth (m)	Watershed Area (incl. lake surface area; ac)	Watershed Area : Surface Area	Littoral Area (% total area less than 15 feet deep)
Mud Hen	69-0494-00	158	1.8	2.4	3,683	22:1	100
Long	69-0495-00	373	2.1	4.2	31,535	84:1	100
Strand	69-0529-00	330	1.7	4.6	2,910	8:1	99
Manganika	69-0726-00	175	3	7.2	5,571	31:1	88
McQuade	69-0775-00	173	4.6	6.3	12,493	71:1	96

Surface area, mean depth, maximum depth, and littoral area from the *St. Louis River Watershed Monitoring and Assessment Report* (MPCA 2013a), with the exception of Strand Lake. The data for Strand Lake are from the DNR's statewide Lake Basin Morphology dataset. Watershed areas were derived as described in Section 1.1.

1.1 WATERSHED BOUNDARIES

The watershed boundaries of the impaired water bodies (Figure 1 through Figure 3) were developed using multiple data sources, including watershed delineations from the HSPF model application of the St. Louis River watershed (Tetra Tech 2016a), which are based on HUC12 watershed boundaries and modified as needed to accommodate calibration sites and water bodies of interest; DNR Level 8 and Level 9 watershed boundaries; and a 10-meter digital elevation model.



Sources: Esri, HERE, DeLorme, TomTom, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), swisstopo, MapmyIndia, © OpenStreetMap contributors, and the GIS User Community

Figure 1. McQuade Lake and Lake Manganika watershed boundaries and lake monitoring sites

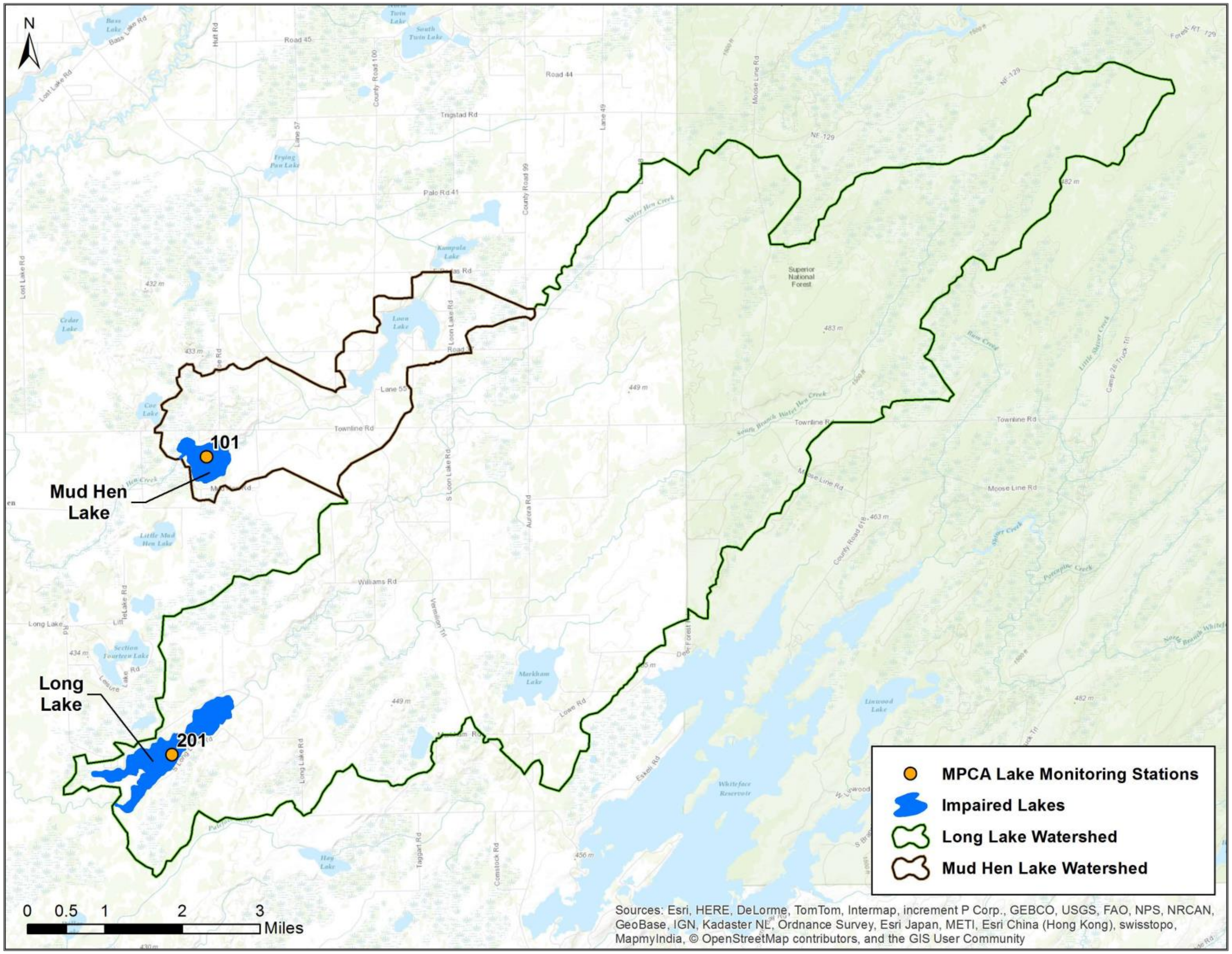


Figure 2. Mud Hen Lake and Long Lake watershed boundaries and lake monitoring sites

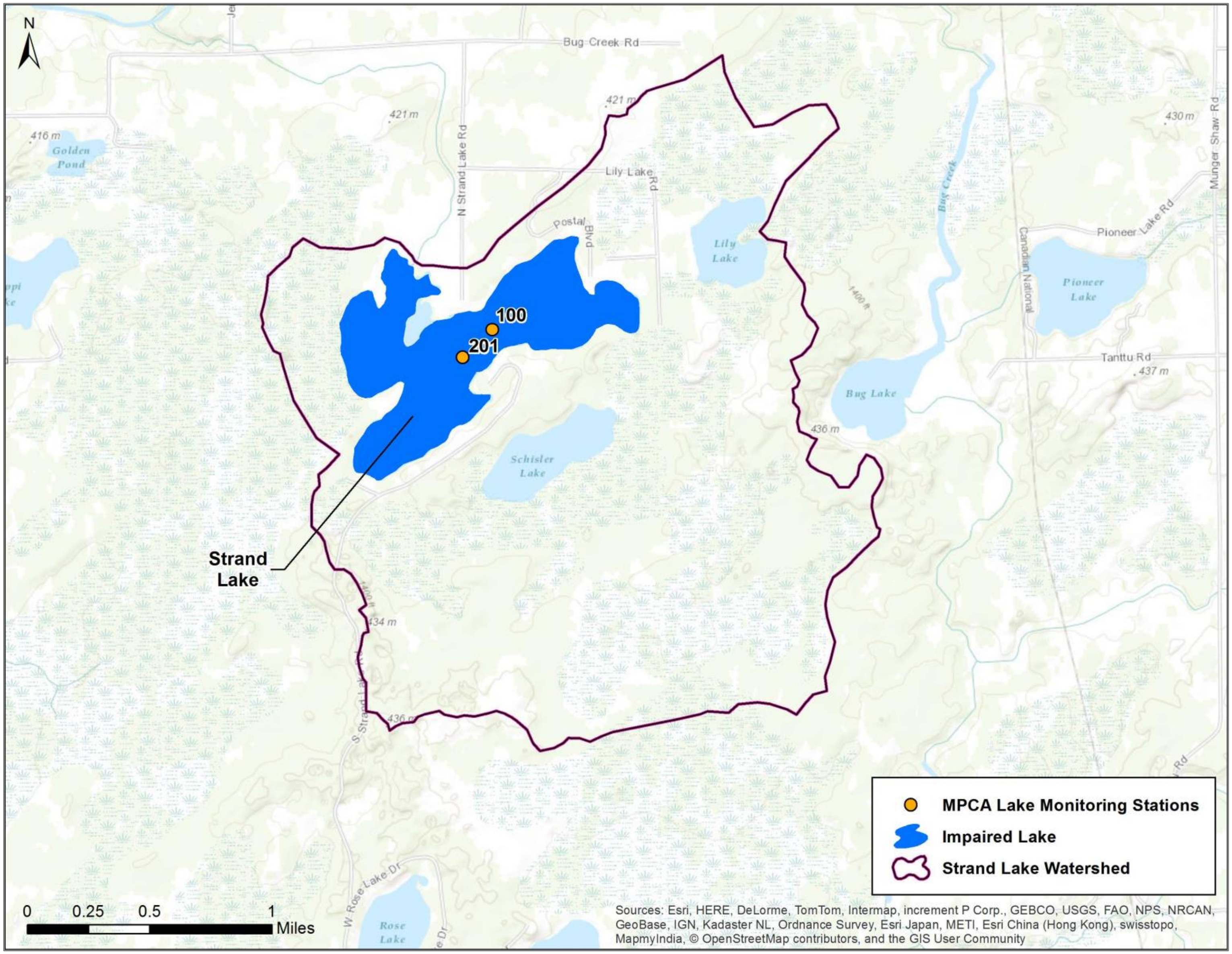


Figure 3. Strand Lake watershed boundary and lake monitoring sites

1.2 LAND COVER

Land cover is represented in the watershed model (Tetra Tech 2016a) with LANDFIRE 2008 data. Areas that are internally drained to mine pits were removed from the watershed land cover calculations. The dominant land covers in the impaired watersheds are wetlands and forest (Table 3).

Table 3. Land cover (Tetra Tech 2016a). Values rounded to nearest whole number.

Water Body Name (AUID)	Percent of Watershed (%)									Watershed Area (square miles)
	Forest	Shrub	Pasture	Crop	Barren	Developed	Roads	Wetland	Water	
Mud Hen (69-0494-00)	25	2	10	3	0	2	3	44	11	6
Long (69-0495-00)	42	1	4	0	0	1	1	49	2	49
Strand (69-0529-00)	37	0	1	0	0	0	0	47	15	5
Manganika (69-0726-00)	20	3	0	0	24	13	10	29	1	5
McQuade (69-0775-00)	55	2	3	1	1	2	2	29	5	19

1.3 CURRENT/HISTORIC WATER QUALITY

The analyses in this section use data from the MPCA's Environmental Quality Information System (EQuIS database, received April 30, 2015 from MPCA staff), from 2003 through 2014. Water quality data were summarized for total phosphorus, chlorophyll-*a*, and Secchi transparency. Surface water data were summarized over the entire period and by year to evaluate trends in water quality. The summaries provide monitoring data from the growing season (June through September) because this is the timeframe during which the current standard applies. Carlson's Trophic Status Index (TSI) was calculated for each water quality parameter (Carlson and Simpson 1996); the TSI can be interpreted as follows:

- TSI < 30: classic oligotrophy; clear water
- TSI 30–40: hypolimnia in shallow lakes may become anoxic in summer
- TSI 40–50: mesotrophic; water moderately clear
- TSI 50–60: eutrophic; decreased transparency
- TSI 60–70: blue-green algae dominate in summer; algal scums probable
- TSI > 70: hypereutrophic; dense algae

1.3.1 Long Lake

The average total phosphorus concentration in Long Lake is 51 µg/L (Table 4), with growing season means ranging from 42 to 61 µg/L (Figure 4). Carlson's TSI ranges from 61 to 71 (Table 4), indicating a eutrophic lake. Phosphorus, chlorophyll-*a*, and transparency are correlated with one another (Figure 5), suggesting that reductions in phosphorus loading to the lake will improve water quality. In 2010, total phosphorus concentrations increased throughout the growing season, suggesting that internal loading could have been a factor in poor water quality that year. The lake did not stratify in 2009 or 2010.

Table 4. Long Lake surface water quality data summary (site 69-0495-00-201)

Parameter	Years of Data	Average of Growing Season Means (Jun–Sep)	Carlson's Trophic Status Index
Total Phosphorus (µg/L)	2009–2010	51	61
Chlorophyll-a (µg/L)	2009–2010	16	71
Secchi Transparency (m)	2009–2010	0.9	62

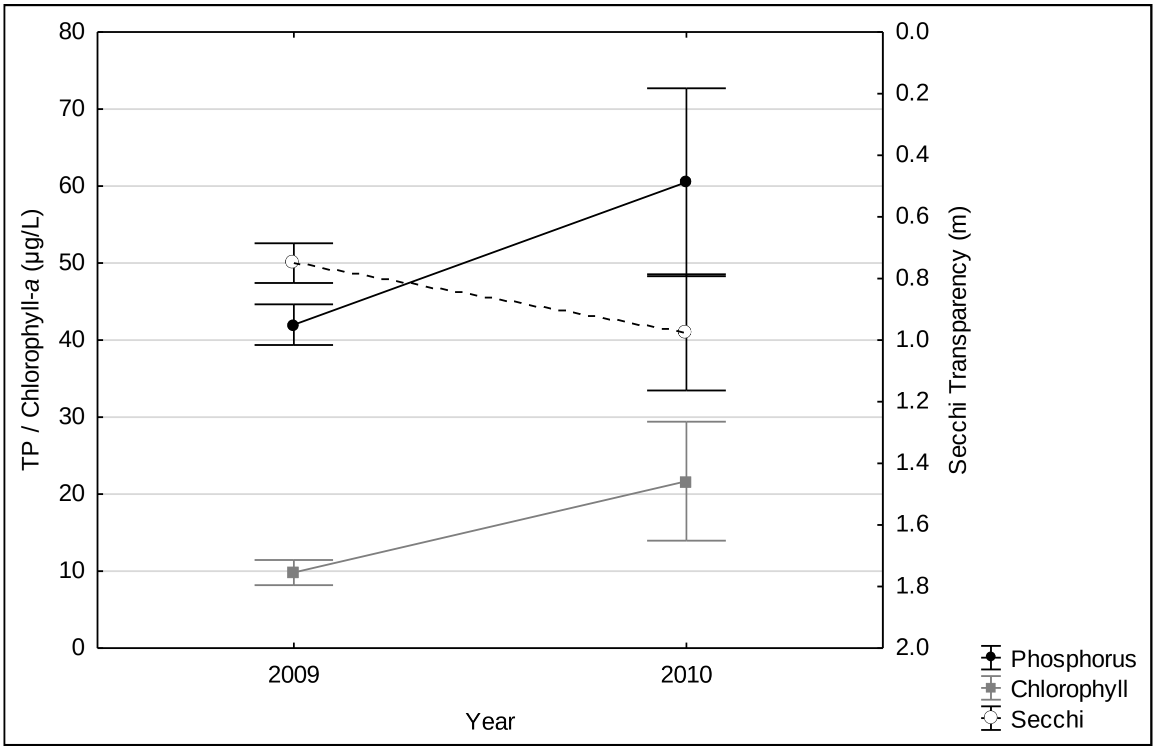


Figure 4. Long Lake water quality data, 2009–2010 (growing season means + / - standard error; site 69-0495-00-201)

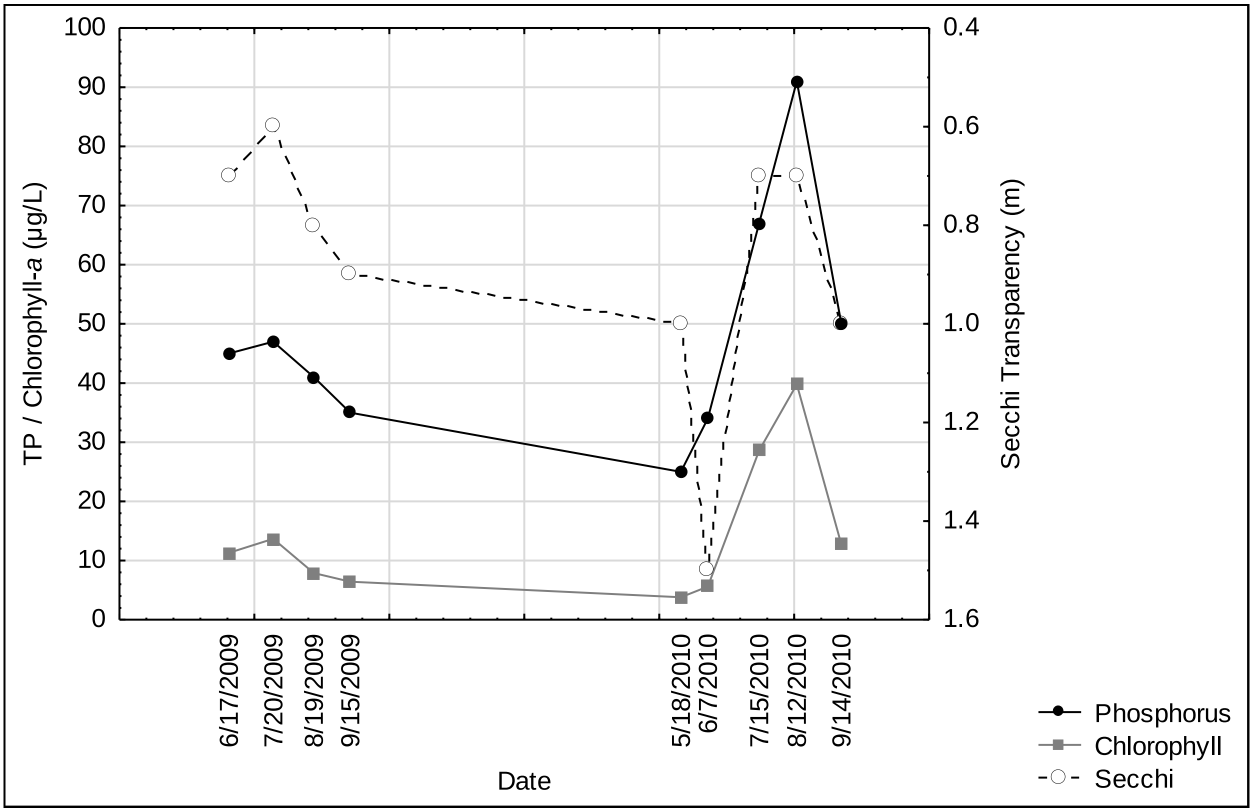


Figure 5. Long Lake phosphorus, chlorophyll-*a*, and transparency measurements, 2009 and 2010 (site 69-0495-00-201)

The most recent aquatic macrophyte survey on Long Lake was completed by the DNR in July of 2013. A list of plants is provided, but estimates of abundance or location are not available. The percent occurrence of *Ceratophyllum echinatum* (soft coontail, spiny hornwort) was recorded in the Natural Heritage Rare Features Database.

From 1961 through 1991, Long Lake was stocked with walleye. Stocking was discontinued because walleye natural reproduction and recruitment were adequate. A DNR fisheries population assessment in 2008 found walleye, largemouth bass, northern pike, yellow perch, black crappie, bluegill, brown bullhead, golden shiner, pumpkinseed sunfish, white sucker, and yellow bullhead. Walleye, yellow perch, and black crappie abundance was normal for a lake such as Long Lake; largemouth bass, northern pike, and bluegill abundance was below average.

1.3.2 Lake Manganika

The average total phosphorus concentration in Lake Manganika is 309 µg/L (Table 5), with growing season means ranging from 281 to 349 µg/L (Figure 6). Carlson's TSI ranges from 63 to 87 (Table 4), indicating a hypereutrophic lake. The high phosphorus TSI relative to chlorophyll-*a* suggests that something other than phosphorus, such as nitrogen, limits algal productivity. This is common in lakes with extremely high phosphorus concentrations. The lake typically stratifies for one to two months during the summer, leading to low dissolved oxygen concentrations in the hypolimnion (Figure 7). Phosphorus concentrations in the water typically increase throughout the growing season (Figure 8).

In many Minnesota lakes, under oxic conditions dissolved iron forms iron hydroxides, which bind with phosphate and precipitate out of the water column. The effect of this precipitation is that phosphorus is removed from the water column and can be released from the sediments when the bottom waters become anoxic (i.e., low dissolved oxygen). However, if dissolved iron concentrations are very low, as is the case in Lake Manganika (Kelly and Berndt 2015), there is not enough iron to bind with the phosphorus and settle to the lake bottom. Instead, much of the phosphorus remains in the water column and is available for algal uptake and growth. Because of the high phosphorus loads from the Virginia WWTP effluent and the low rates of removal of phosphorus from the water column, the phosphorus concentrations in the lake remain extremely high.

A DNR fisheries survey in 1989 found northern pike, white sucker, black bullhead, yellow perch, brown bullhead, and black crappie. More recent fisheries data are not available.

Table 5. Lake Manganika surface water quality data summary (sites 69-0726-00-201 and -202)

Parameter	Years of Data	Average of Growing Season Means (Jun–Sep)	Carlson's Trophic Status Index
Total Phosphorus (µg/L)	2004–2006	309	87
Chlorophyll-a (µg/L)	2006	67	72
Secchi Transparency (m)	2004–2006	0.8	63

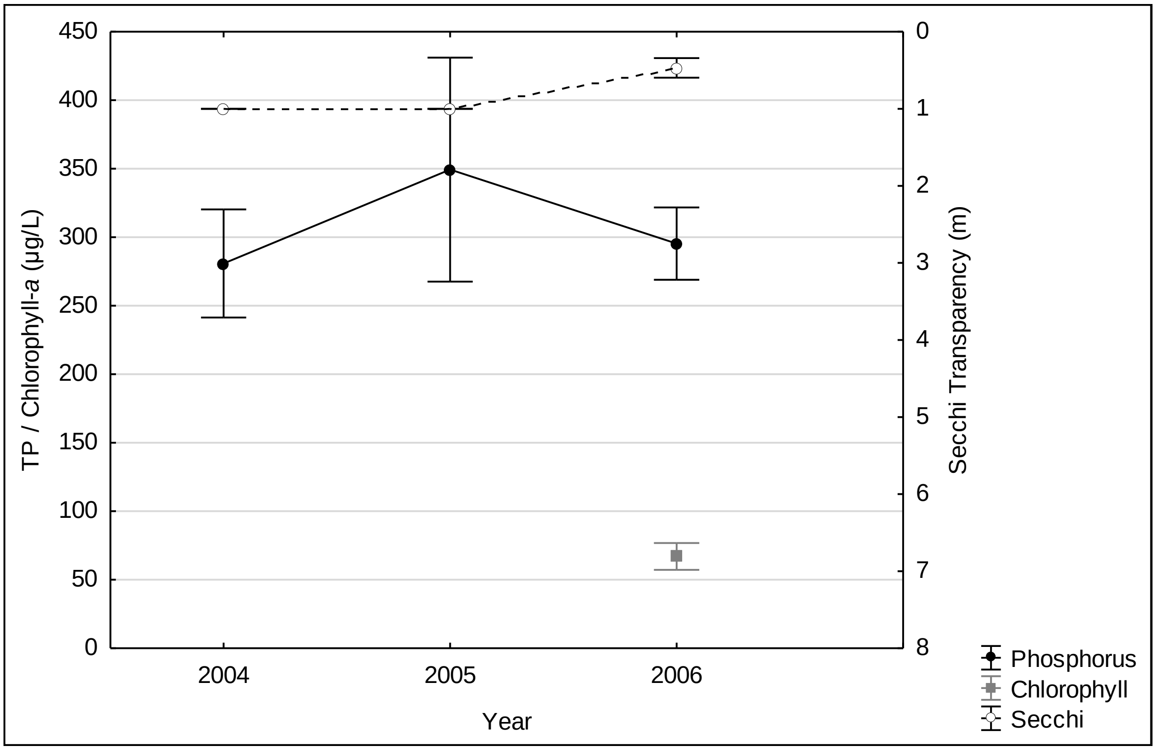


Figure 6. Lake Manganika water quality data, 2004–2006 (growing season means + / - standard error; sites 69-0726-00-201 and -202)

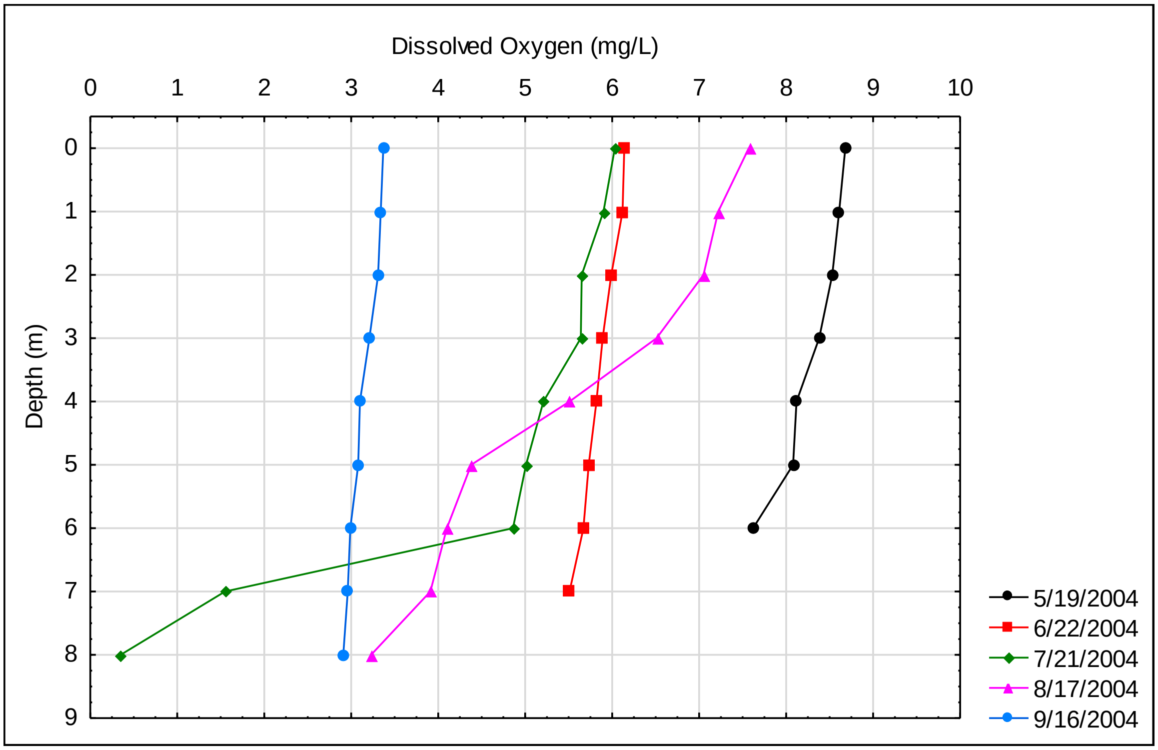


Figure 7. Lake Manganika dissolved oxygen profiles, 2004 (site 69-0726-00-201)

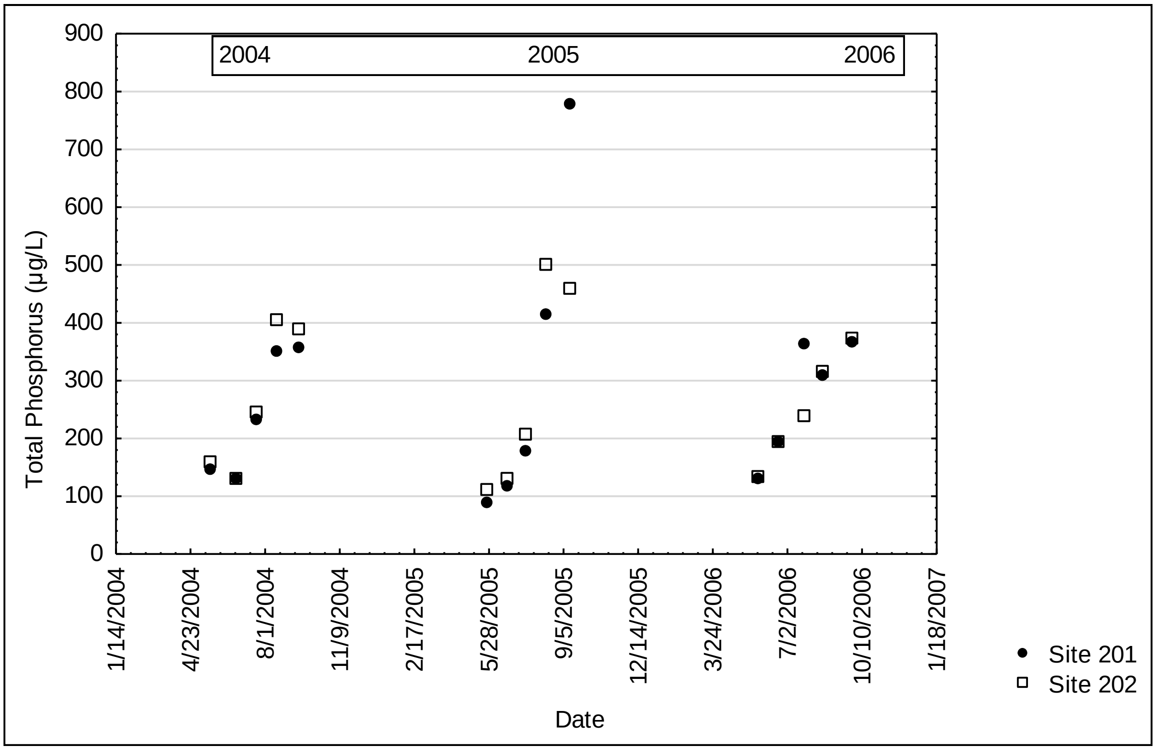


Figure 8. Lake Manganika surface phosphorus concentrations, 2004–2006

1.3.3 McQuade Lake

The average total phosphorus concentration in McQuade Lake is 67 µg/L (Table 6), with growing season means ranging from 59 to 76 µg/L (Figure 6). Carlson's TSI ranges from 53 to 65 (Table 4), indicating a eutrophic lake. The lake stratifies in the summer. In 2010 this stratification led to build-up of phosphorus in the hypolimnion in July; the phosphorus from the bottom waters mixed with the surface water at fall turnover and increased the surface phosphorus concentration (Figure 10). This effect of stratification on surface phosphorus was not as pronounced in 2009. Iron concentrations in McQuade Lake are higher than in Lake Manganika (Kelly and Berndt 2015), and iron is available to bind with phosphate and precipitate out of the water column.

Table 6. McQuade Lake surface water quality data summary (site 69-0775-00-101)

Parameter	Years of Data	Average of Growing Season Means (Jun–Sep)	Carlson's Trophic Status Index
Total Phosphorus (µg/L)	2009–2010	67	65
Chlorophyll-a (µg/L)	2009–2010	20	60
Secchi Transparency (m)	2009–2010	1.6	53

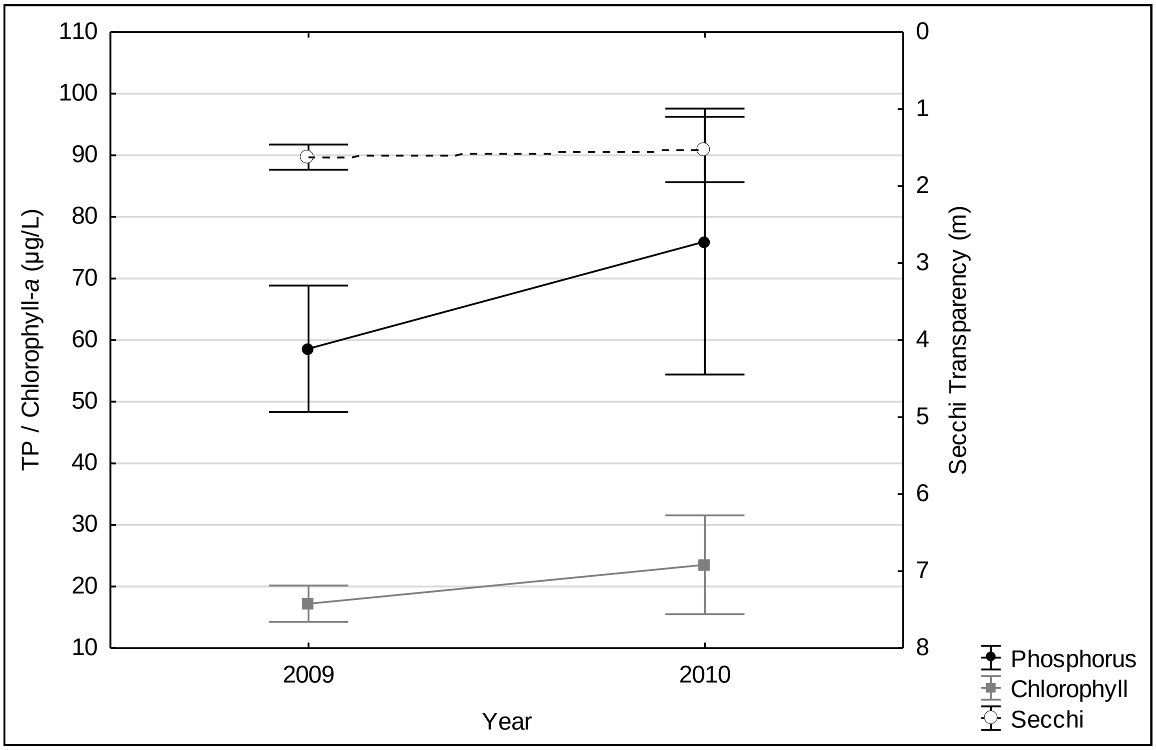


Figure 9. McQuade Lake water quality data, 2009–2010 (growing season means + / - standard error; site 69-0775-00-101)

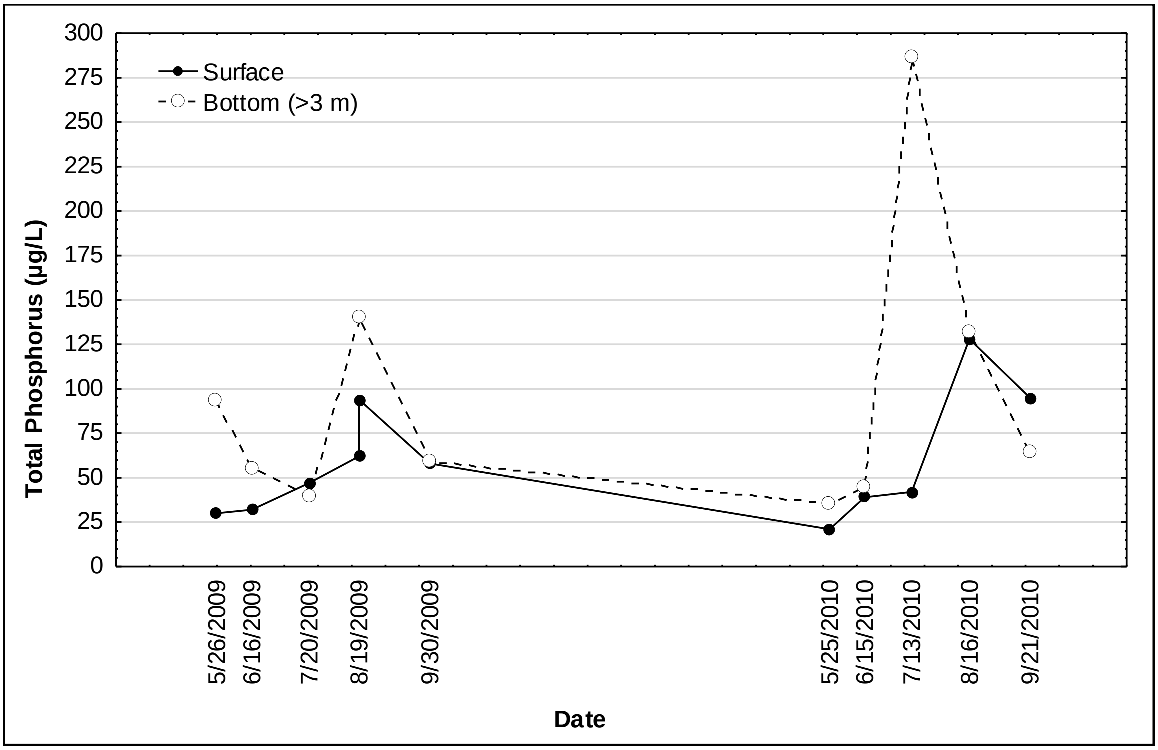


Figure 10. McQuade Lake surface versus bottom phosphorus concentrations, 2009–2010 (site 69-0775-00-101)

The most recent aquatic macrophyte survey on McQuade Lake was completed by the DNR in June of 2012. A list of plants is provided, but estimates of abundance or location are not available.

McQuade Lake was stocked with walleye in the 1980s. A DNR fisheries population assessment in 2013 found white sucker, northern pike, walleye, yellow perch, black crappie, and bluegill. Walleye, northern pike, and white sucker abundance was normal for a lake such as McQuade Lake, yellow perch and bluegill abundance was below average, and black crappie abundance was above average.

The exotic Chinese mystery snail (*Cipangopaludina chinensis malleata*) has been found in McQuade Lake. Because dead snails litter the lakeshore, the species can be a nuisance to landowners.

1.3.4 Mud Hen Lake

The average total phosphorus concentration in Mud Hen Lake is 34 µg/L (Table 7), with growing season means ranging from 31 to 37 µg/L (Figure 11). Carlson's TSI ranges from 51 to 55 (Table 7), indicating a mesotrophic to eutrophic lake. High phosphorus concentrations in 2010 led to high chlorophyll-*a* and poor transparency; however, this pattern was not observed in 2009 (Figure 12). The high phosphorus concentrations in 2010 occurred in July and August, suggesting that internal loading could have been a factor in poor water quality that year. The lake did not stratify in 2009 or 2010.

Table 7. Mud Hen Lake surface water quality data summary (site 69-0494-00-101)

Parameter	Years of Data	Average of Growing Season Means (Jun–Sep)	Carlson's Trophic Status Index
Total Phosphorus (µg/L)	2009–2010	34	55
Chlorophyll-a (µg/L)	2009–2010	7.8	51
Secchi Transparency (m)	2009–2010	1.9	51

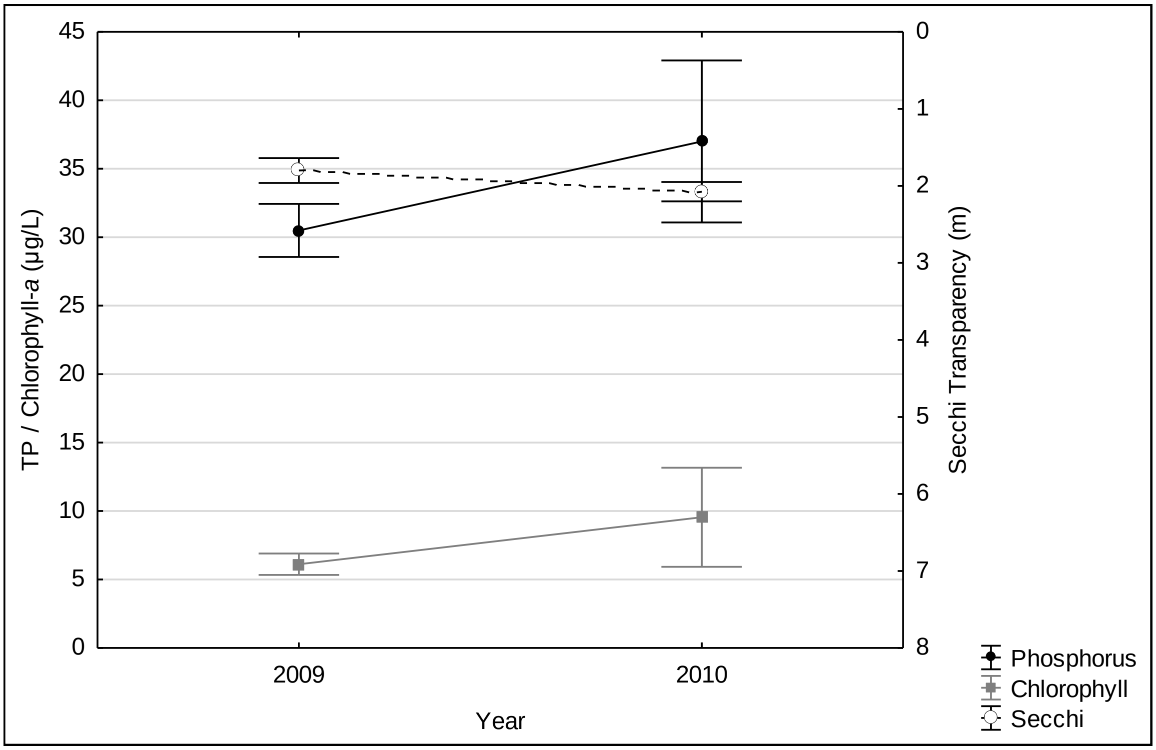


Figure 11. Mud Hen Lake water quality data, 2009–2010 (growing season means + / - standard error; site 69-0494-00-101)

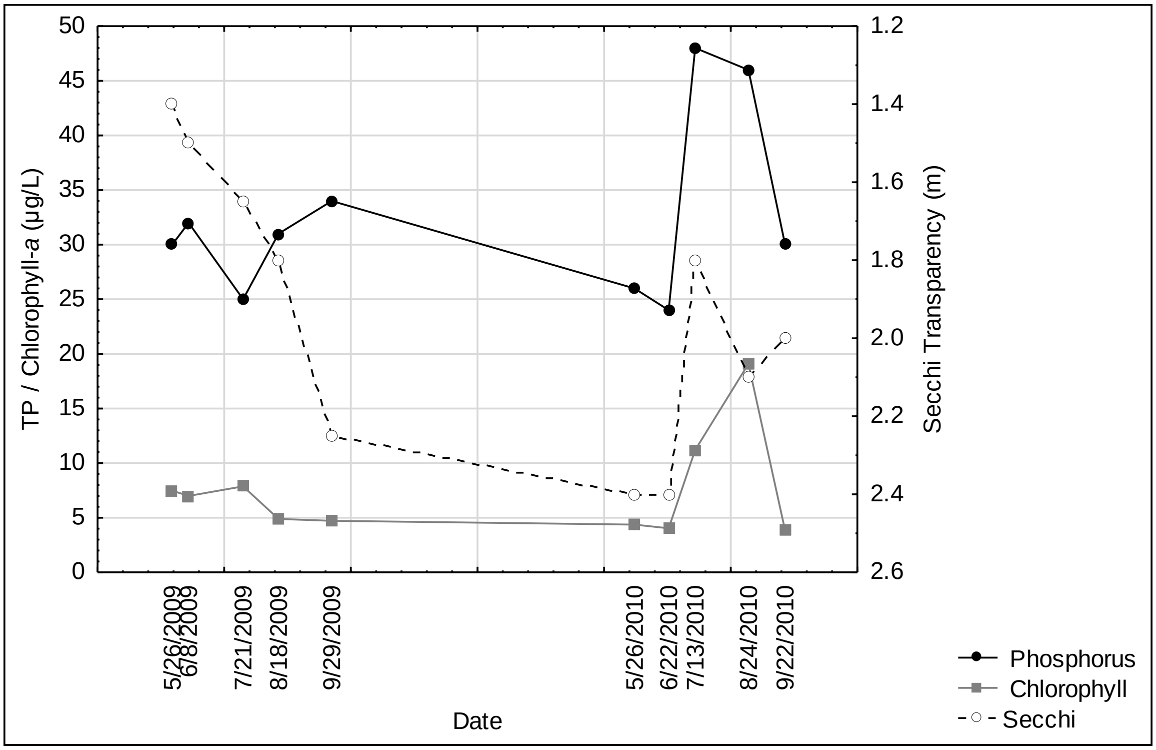


Figure 12. Mud Hen phosphorus, chlorophyll-*a*, and transparency measurements, 2009–2010 (site 69-0494-00-101)

The most recent aquatic macrophyte survey on Mud Hen Lake was completed by the DNR in July of 2012. A list of plants is provided, but estimates of abundance or location are not available. Information on aquatic vegetation was also collected in 2013 by the DNR at the time of the fisheries assessment. Filamentous algae were found at almost all of the transects. The other frequently found plants were flat-stemmed pondweed and greater duckweed.

Walleye fry are stocked every other year in Mud Hen Lake, and in any year following a winterkill. A DNR fisheries population assessment in 2013 found walleye, northern pike, yellow perch, black crappie, bluegill, largemouth bass, black bullhead, brown bullhead, yellow bullhead, pumpkinseed sunfish, golden shiner, and white sucker. Bluegill abundance was normal for a lake such as Mud Hen, black crappie and brown bullhead abundance was below average, and walleye, northern pike, yellow perch, black bullhead, and yellow bullhead abundance was above average.

1.3.5 Strand Lake

The average total phosphorus concentration in Strand Lake is 31 µg/L (Table 8), with growing season means ranging from 22 to 38 µg/L (Figure 13). Carlson's TSI ranges from 48 to 59 (Table 8), indicating a mesotrophic to eutrophic lake. The poor transparency and moderate chlorophyll-*a* suggest that non-algal particulate matter or dissolved organic matter have a greater impact on light attenuation than algae do. High phosphorus concentrations do not necessarily lead to high algal growth, as evidenced by a weak relationship between phosphorus and chlorophyll (Figure 14), yet transparency is low. In 2010, phosphorus and chlorophyll-a concentrations peaked in August, suggesting that internal phosphorus loading could have been a factor in high algal growth that year.

Table 8. Strand Lake surface water quality data summary (sites 69-0529-00-100 and -201). Years of data averaged are those with >2 samples per year.

Parameter	Years of Data	Average of Growing Season Means (Jun–Sep)	Carlson's Trophic Status Index
Total Phosphorus (µg/L)	2005, 2007–2010	31	54
Chlorophyll-a (µg/L)	2005, 2007–2010	6.1	48
Secchi Transparency (m)	2003–2013	1.1	59

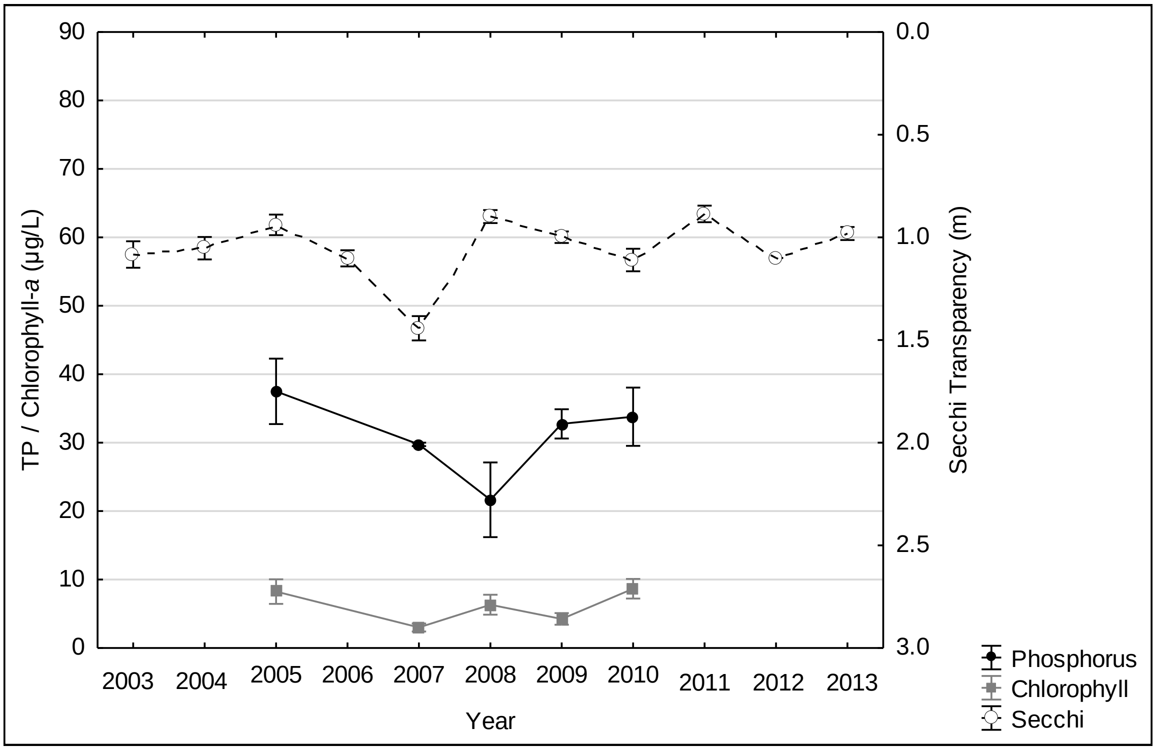


Figure 13. Strand Lake water quality data, 2003–2013 (growing season means + / - standard error; sites 69-0529-00-100 and -201). Years of data shown are those with >2 samples per year.

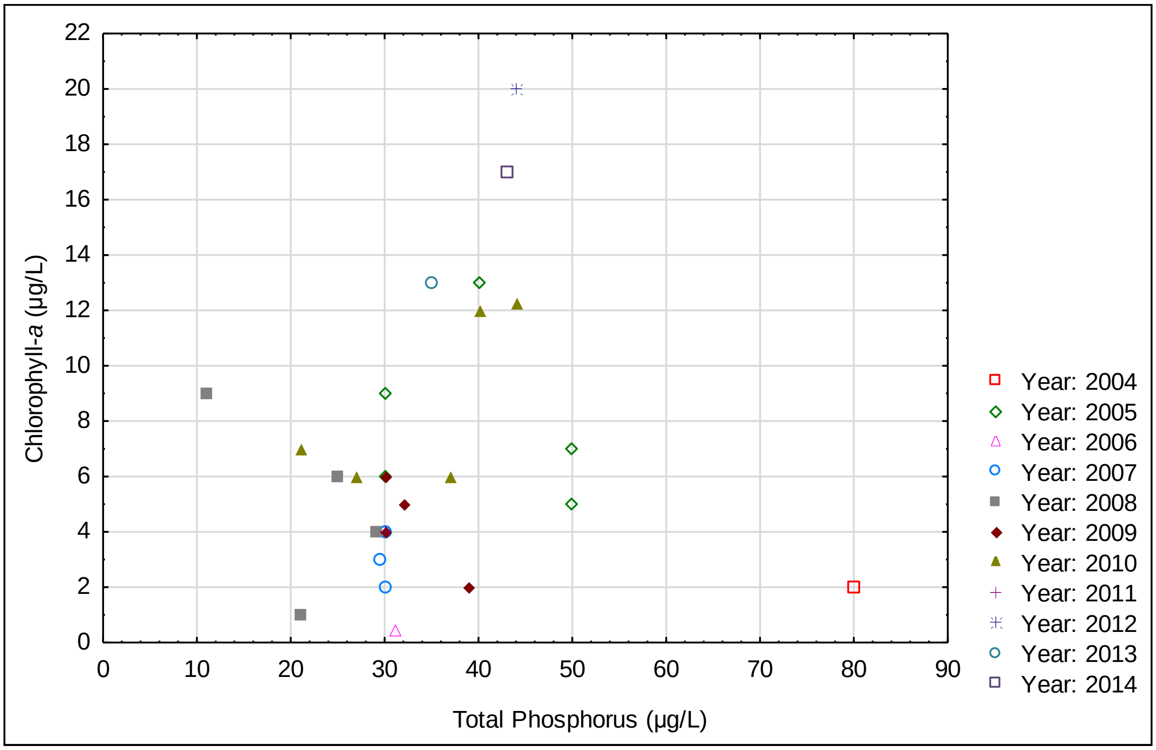


Figure 14. Strand Lake total phosphorus versus chlorophyll-a concentrations, 2003–2014

The most recent aquatic macrophyte survey on Strand Lake was completed by the DNR in August of 2012. A list of plants is provided, but estimates of abundance or location are not available. Information on aquatic vegetation was also collected in 2007 by the DNR at the time of the fisheries assessment. The horsetail group was the most frequent plant, followed by floating-leaf bur-reed and spikerush. Reed canary grass, an invasive species, was found at 5 percent of the sampling locations.

Walleye fry have been stocked every other year in Strand Lake since 2006. A DNR fisheries population assessment in 2007 found a balanced fishery, with walleye, northern pike, black crappie, bluegill, yellow perch, largemouth bass, pumpkinseed sunfish, brown bullheads, and white suckers. Black crappie, bluegill, and yellow perch abundance was normal for a lake such as Strand Lake; northern pike abundance was below average.

2.0 PHOSPHORUS SOURCE SUMMARY

Watershed and municipal and industrial wastewater phosphorus loads to the impaired lakes were primarily quantified by the watershed HSPF model (Tetra Tech 2016a and 2016b). Loads from septic systems, internal loading, and atmospheric deposition were also estimated for each lake. There are no regulated MS4 watershed runoff or permitted concentrated animal feeding operations (CAFOs) in the impaired watersheds.

2.1 APPROACH

2.1.1 Municipal Wastewater

The average annual phosphorus load from the Virginia Wastewater Treatment Facility (permit # MN0030163) in the Lake Manganika watershed was estimated with the St. Louis River watershed HSPF model (Tetra Tech 2016a and 2016b). The effluent discharge volumes and phosphorus concentrations in the model were determined from discharge monitoring records provided by the MPCA.

2.1.2 Industrial Wastewater

The average annual phosphorus loads (2003–2012) from US Steel–Minntac Mining Area in the McQuade Lake watershed and United Taconite LLC–Thunderbird Mine in the Lake Manganika watershed were estimated with the St. Louis River watershed HSPF model (Tetra Tech 2016a and 2016b) and phosphorus monitoring data, as follows:

- US Steel–Minntac Mining Area (permit #MN0052493)
    - Surface discharge stations 2, 3, and 10 are located in the McQuade Lake watershed.
    - The effluent discharge volumes in the model were determined from discharge monitoring records provided by the MPCA.
    - The discharge volumes were multiplied by a total phosphorus concentration of 0.007 mg/L, based on monitoring of US Steel–Minntac mine pit dewatering discharge in the McQuade Lake watershed from the spring of 2016 (personal communication, Erik Smith, MPCA).
- United Taconite LLC–Thunderbird Mine (permit #MN0044946)
    - Surface discharge stations 7, 8, and 9 are located in the Lake Manganika watershed.
    - The effluent discharge volumes in the model were determined from discharge monitoring records provided by the MPCA.
    - The discharge volumes were multiplied by a total phosphorus concentration of 0.025 mg/L, based on monitoring of an inlet to Lake Manganika that is dominated by flow from mine pit dewatering discharge (Kelly and Berndt 2015).

2.1.3 Watershed Runoff

Watershed loading of phosphorus to the lakes is quantified in the HSPF model (Tetra Tech 2016a and 2016b) and summarized by land cover type (Table 9). Land cover loading rates vary among watersheds because of differences in soils, slope, and weather patterns. Land cover in the model is characterized by satellite data (LANDFIRE 2008). The data differentiate among most of the major land cover types; however, low densities of development in forested areas are not recognized in the satellite data as developed. Therefore, estimates of loading from shoreland development might be underestimated in the model. A survey of shoreland development around Long, Mud Hen, and Strand Lakes could be used to determine if loading from shoreland development affects lake water quality. Characteristics that can increase phosphorus loading from shoreland areas include shoreline erosion, lawns adjacent to the lake, and impervious surfaces.

Table 9. Average upland phosphorus unit area loading rates (2003–2012)

Land Cover	Long		Manganika		McQuade		Mud Hen		Strand	
	Area (acres)	P loading (lb/ac-yr)	Area (acres)	P loading (lb/ac-yr)	Area (acres)	P loading (lb/ac-yr)	Area (acres)	P loading (lb/ac-yr)	Area (acres)	P loading (lb/ac-yr)
Forest	13,337	0.11	607	0.07	6,473	0.19	928	0.08	1,071	0.12
Wetland	15,142	0.18	846	0.14	3,464	0.27	1,628	0.14	1,330	0.20
Shrub	370	0.09	94	0.07	275	0.12	60	0.08	8	0.05
Pasture	1,208	0.27	13	0.18	354	0.30	370	0.21	22	0.19
Developed	644	0.19	709	0.18	531	0.24	179	0.18	11	0.18
Water	673	0.28	43	0.17	637	0.36	419	0.17	442	0.28
Crop	154	0.35	1	0.28	61	0.45	97	0.30	0	--
Barren	7	0.21	725	0.19	121	0.25	0	--	0	--

These loading rates take into account sources of phosphorus in the watershed that are not explicitly modeled, including loads from livestock. To the extent that the loading rates are calibrated, they include the net effect of loads from livestock and other sources. To investigate the impact of livestock on phosphorus loading to the lakes, the number of livestock per watershed was estimated using the number of registered livestock in the MPCA's feedlot database and the number of non-registered feedlots (provided by the St. Louis County Planning Department; Table 10). There are no apparent feedlots in the Lake Manganika or Strand Lake watersheds. An estimate of loading from livestock was calculated based on the number of registered animals, an average percentage of feedlots contributing to surface water runoff (Barr Engineering 2004), phosphorus production rates per animal types, and the percent of phosphorus from livestock runoff that reaches surface waters. The loading from feedlots represents less than one percent of the total load to Long Lake and McQuade Lake. Loading to Mud Hen Lake was not quantified because there are no registered feedlots. Because livestock loading represents such a small proportion of the watershed load to the lakes, it was not separated out from the watershed loads in the phosphorus source summaries.

Table 10. Livestock inventory

Impairment Watershed	Number of Animals in Registered Feedlots			Number of Non-Registered Feedlots [a]
	Bovine	Horses	Pigs	
Mud Hen	0	0	0	1
Long	25	0	0	4
McQuade	207	20	12	0

a. Data provided by St. Louis County Planning Department

2.1.4 Septic Systems

Septic systems can be sources of phosphorus to surface waters. Systems that are functioning properly (conforming) contribute less phosphorus than failing systems or systems that are considered an imminent public health threat (IPHT). Failing systems do not protect groundwater from contamination, and IPHT systems discharge partially treated sewage to the surface. For septic systems located in close proximity to surface waters, both failing and conforming systems contribute phosphorus to surface waters; a conforming system contributes on average 20 percent of the phosphorus that is found in the system, while a failing or IPHT system contributes on average 43 percent (Barr Engineering 2004).

Phosphorus loads attributed to subsurface sewage treatment systems (SSTS) adjacent to each of the lakes were calculated using aerial imagery, data provided by the St. Louis County Environmental Services Department, and the MPCA's *Detailed Assessment of Phosphorus Sources to Minnesota Watersheds* (Barr Engineering 2004). Total loading is based on the number of shoreline residences, whether the house is used as a permanent or seasonal residence, if the SSTS system is expected to be conforming or failing, the number of people using the system, and an average value for phosphorus production per person per year (MPCA 2014).

For Strand Lake, the St. Louis County Environmental Services Department provided information on the septic systems located within 1,000 feet of the lake shoreline, including whether the septic system is a seasonal or permanent residence, the year of the last inspection on record, and if the permit is expired. To estimate the number of conforming and non-conforming septic systems, it was assumed that any system that was inspected within the last twenty years is conforming. The year 1992 (twenty years before the end of the source assessment period, which is 2003–2012) was used as the cutoff year. If the system does not have an inspection on record after 1992, or if the permit is expired, it was assumed that the system is non-conforming. Sixty-one septic systems are within the shoreland of Strand Lake; approximately half of the systems are conforming and half are non-conforming (Table 11).

For Long Lake, McQuade Lake, and Mud Hen Lake, aerial imagery was used to estimate the number of residences around the lakes; city and township averages from St. Louis County's *Census Report: Mapping and Facts, Housing Characteristics* (St. Louis County 2003) were used to estimate the number of permanent and seasonal residences; and county averages from *Recommendations and Planning for Statewide Inventories, Inspections of Subsurface Sewage Treatment Systems* (MPCA 2011) were used to estimate the number of conforming and non-conforming systems.

For Lake Manganika, aerial imagery was used to determine that there were no residences along the lake shoreline. Therefore, loading from septic systems was assumed to be insignificant relative to loading from watershed runoff, and loads from septic systems were not quantified.

Table 11. Septic system inventory

Impaired Lake	Conforming SSTS	Non-Conforming SSTS
Long (69-0495-00)	49	29
McQuade (69-0775-00)	17	9
Mud Hen (69-0494-00)	9	5
Strand (69-0529-00)	29	32

2.1.5 Internal Loading

Internal phosphorus loading from lake bottom sediments can be a substantial component of the phosphorus budget in lakes. The sediment phosphorus originates as an external phosphorus load that settles out of the water column to the lake bottom. There are multiple mechanisms by which phosphorus can be released back into the water column as internal loading.

- Low oxygen concentrations (also called anoxia) in the water overlying the sediment can lead to phosphorus release. In a shallow lake that undergoes intermittent mixing of the water column throughout the growing season, the released phosphorus can mix with surface waters throughout the summer and become available for algal growth. In deeper lakes with a more stable summer stratification period, the released phosphorus will remain in the bottom water layer until the time of fall mixing, when it will mix with surface waters.
- Bottom-feeding fish such as bullhead forage in lake sediments. This physical disturbance can release phosphorus into the water column.
- Wind energy in shallow depths can mix the water column and disturb bottom sediments, which leads to phosphorus release.
- Other sources of physical disturbance, such as motorized boating in shallow areas, can disturb bottom sediments and lead to phosphorus release.

Internal loading in Lake Manganika was estimated by MPCA in the memo *Total Phosphorus Water Quality Based Effluent Limit Analysis: Virginia WWTP* (MPCA 2013b). Estimates of internal loading rates in the remaining lakes are not available, and internal loading is often estimated in conjunction with development of a lake response model. Because lake response models were not developed, internal loading was not quantified. However, based on the analysis of water quality monitoring data (in Section 1.3), internal loading can affect water quality in these lakes. A qualitative discussion of internal loading is included in Section 1.3 and in the source assessment summaries in Section 2.2.

2.1.6 Atmospheric Deposition

Phosphorus is bound to atmospheric particles, which settle out of the atmosphere and are deposited directly onto a surface water. Atmospheric deposition to the impaired lakes was estimated using the average for the Lake Superior basin in Minnesota (0.200 kg/ha-year, Barr Engineering 2007).

2.2 SUMMARY OF RESULTS

Phosphorus source assessment results are presented for each lake, and management recommendations are provided to help guide watershed restoration and protection strategies.

2.2.1 Long Lake

The primary sources of phosphorus to Long Lake are from watershed runoff (Table 12). Loading from shoreland development is not quantified but likely impacts lake water quality. Internal loading is a substantial source in some years (see Section 1.3.1).

Water Hen Creek is the main tributary to Long Lake. The macroinvertebrate assemblage in the upper reach of Water Hen Creek (AUID 04010201-A35) does not meet the MPCA's targets for biota. Low dissolved oxygen and a high daily range in dissolved oxygen concentrations negatively impact the macroinvertebrate assemblage (MPCA 2016b). This pattern in dissolved oxygen concentration is often caused by high nutrient input and excessive primary production (i.e., algal and/or plant growth). Total phosphorus concentrations were elevated (0.085 mg/L) on the two days that phosphorus was measured in Water Hen Creek. More data are needed to verify the phosphorus concentrations in the creek and potential contribution to Long Lake.

Table 12. Summary of phosphorus sources to Long Lake, 2003–2012

Source		TP Load (lb/yr)	Percent TP Load (%)
Watershed Loading	Forest	1,491	29
	Shrub	33	1
	Pasture and Crop	384	8
	Wetland and Water	2,822	56
	Developed	121	2
	Shoreland Development	-[a]	-[a]
	Barren	2	0
Septic		151	3
Internal Load		-[a]	-[a]
Atmospheric Deposition		67	1
Total		5,071	100

a. Not quantified but assumed to be a substantial source

Management Recommendations:

- Shoreland survey—evaluate the shoreland and identify areas of disturbance, such as altered vegetation (e.g., lawns), bare soil, and shoreland erosion.
- Investigate sources of internal loading, such as resuspension of sediment from bottom waters.

- Inspect septic systems within the shoreland area; upgrade those that are not conforming.
- Monitoring of Water Hen Creek, including phosphorus and chlorophyll-*a*.
- Education and outreach on best shoreland management practices.

2.2.2 Lake Manganika

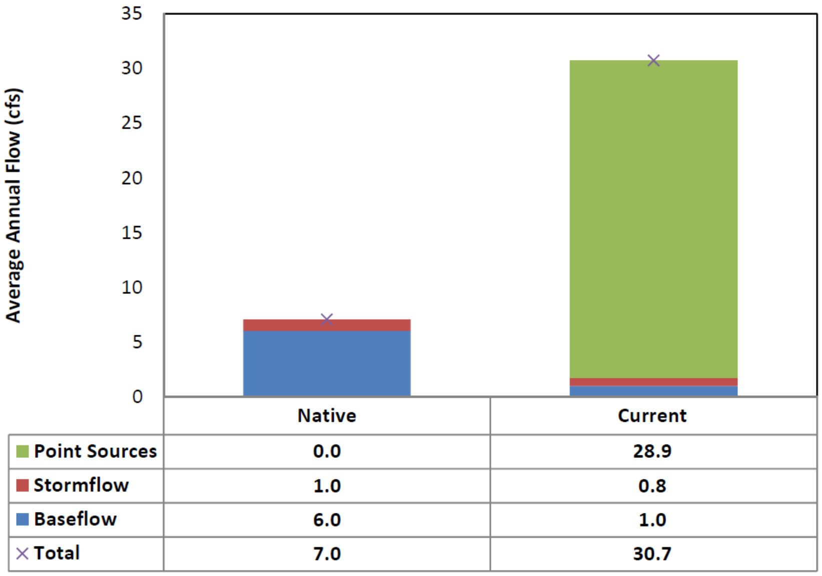
The primary sources of phosphorus to Lake Manganika are the Virginia WWTP (Table 13) and internal loading (see Section 1.3.2). Virginia WWTP's permit was reissued in 2014 with a water quality based effluent limit (WQBEL) of 279 kg/yr (615 lb/yr) and a calendar monthly average concentration limit of 0.07 mg/L (MPCA 2013b). If the load from the Virginia WWTP were reduced from the current observed load to the WQBEL, holding the other loads equal, the Virginia WWTP load would represent 7 percent of the external loading to the lake, down from 35 percent.

Table 13. Summary of phosphorus sources to Lake Manganika, 2003–2012

Source		TP Load (lb/yr)	Percent TP Load (%)
Watershed Loading	Forest	43	<1
	Shrub	6	<1
	Pasture and Crop	3	<1
	Wetland and Water	96	1
	Developed	125	1
	Barren	135	1
United Taconite LLC - Thunderbird Mine (MN0044946)		194	2
Virginia WWTP (MN0030163)		4,144	35
Internal [a]		6,997	59
Atmospheric Deposition		31	<1
Total		11,774	100

a. Estimated in MPCA (2013b)

Compared to pre-hydrologic disturbance in the mining area, the total flow to the lake has substantially increased due to the combined point source effluent (Tetra Tech 2016c; Figure 15). The contribution of baseflow has decreased, while the amount of stormwater runoff has remained relatively stable. The flow from United Taconite represents approximately half of the point source flow to the lake, with the Virginia WWTP effluent representing the other half. The net effect is increased flows and increased phosphorus loads to the lake. The increased flows reduce the residence time in the lake, which can affect the phosphorus sedimentation rate and concentration in the lake.



	Native	Current
🟩 Point Sources	0.0	28.9
🟥 Stormflow	1.0	0.8
🟦 Baseflow	6.0	1.0
× Total	7.0	30.7

Figure 15. Water balance of Manganika Creek (outlet of Lake Manganika), pre- and post-hydrologic disturbance (figure from Tetra Tech 2016c). Point sources include effluent from United Taconite LLC – Thunderbird Mine and the Virginia WWTP.

Management Recommendations:

- Reduce the load from the Virginia WWTP to meet the water quality based effluent limit.
- Evaluate the potential drivers of internal loading in Lake Manganika (e.g., iron, sulfur, sediment phosphorus content, dissolved oxygen conditions). Evaluate options to reduce internal loading after the load from the Virginia WWTP is reduced.

2.2.3 McQuade Lake

The primary sources of phosphorus to McQuade Lake are from watershed runoff (Table 14) and internal loading (see Section 1.3.3). Phosphorus was measured four times on the inlet to McQuade Lake; the average total phosphorus concentration in the inlet (MPCA site #S007-040) is 0.059 mg/L, and the range is 0.015 to 0.160 mg/L. Additional information on phosphorus concentrations and sources in the watershed would identify locations of high phosphorus loading.

Table 14. Summary of phosphorus sources to McQuade Lake, 2003–2012

Source		TP Load (lb/yr)	Percent TP Load (%)
Watershed Loading	Forest	1,235	43
	Shrub	32	1
	Pasture and Crop	134	5
	Wetland and Water	1,115	39
	Developed	125	4
	Barren	30	1
US Steel Corp – Minntac (MN0052493)		89	3
Septic		78	3
Internal		-[a]	-[a]
Atmospheric Deposition		31	1
Total		2,869	100

a. Not quantified but assumed to be a substantial source

Management Recommendations:

- Shoreland survey—evaluate the shoreland and identify areas of disturbance, such as altered vegetation, bare soil, and shoreland erosion.
- Inspect septic systems within the shoreland area; upgrade those that are not conforming.
- Investigate watershed sources of phosphorus; phosphorus monitoring of the lake tributaries.
- Evaluate the potential drivers of internal loading in McQuade Lake (e.g., iron, sulfur, sediment phosphorus content, dissolved oxygen conditions, resuspension of sediment from bottom waters). Evaluate options to reduce internal loading.
- Education and outreach on best shoreland management practices.

2.2.4 Mud Hen Lake

The primary sources of phosphorus to Mud Hen Lake are from watershed runoff, including 20 percent from pasture and crop (Table 15). The DNR's 2013 fisheries assessment observed "open yards extending to the shoreline." Loading from shoreland development is not explicitly quantified, but based on these observations it likely impacts lake water quality. Additional information on phosphorus concentrations and sources in the watershed would identify locations of high phosphorus loading. Internal loading can also be a substantial source in some years (see Section 1.3.4).

Table 15. Summary of phosphorus sources to Mud Hen Lake, 2003–2012

Source		TP Load (lb/yr)	Percent TP Load (%)
Watershed Loading	Forest	70	13
	Shrub	5	1
	Pasture and Crop	108	20
	Wetland and Water	269	50
	Developed	32	6
	Shoreland Development	-[a]	-[a]
Septic Systems		28	5
Internal		-[a]	-[a]
Atmospheric Deposition		28	5
Total		540	100

a. Not quantified but assumed to be a substantial source

Management Recommendations:

- Shoreland survey—evaluate the shoreland and identify areas of disturbance, such as altered vegetation (e.g., lawns), bare soil, and shoreland erosion.
- Investigate sources of internal loading, such as resuspension of sediment from bottom waters.
- Inspect septic systems within the shoreland area; upgrade those that are not conforming.
- Evaluate the effect of pasture and cropland on phosphorus concentrations in runoff.
- Monitoring of Water Hen Creek, including phosphorus and chlorophyll-*a*.
- Education and outreach on best shoreland management practices.

2.2.5 Strand Lake

The primary sources of phosphorus to Strand Lake are from watershed runoff and septic systems (Table 16). Additional information on phosphorus concentrations and sources in the watershed would identify locations of high phosphorus loading. Loading from shoreland development is not explicitly quantified, but it has the potential to affect lake water quality. Internal loading can also be a substantial source in some years (see Section 1.3.5).

Table 16. Summary of phosphorus sources to Strand Lake, 2003–2012

Source		TP Load (lb/yr)	Percent TP Load (%)
Watershed Loading	Forest	130	22
	Shrub	<1	<1
	Pasture and Crop	4	1
	Wetland and Water	303	51
	Developed	2	0
	Shoreland Development	-[a]	-[a]
Septic Systems		98	16
Internal		-[a]	-[a]
Atmospheric Deposition		59	10
Total		596	100

a. Not quantified but assumed to be a substantial source

Management Recommendations:

- Shoreland survey—evaluate the shoreland and identify areas of disturbance, such as altered vegetation (e.g., lawns), bare soil, and shoreland erosion.
- Investigate sources of internal loading, such as resuspension of sediment from bottom waters.
- Inspect septic systems within the shoreland area; upgrade those that are not conforming.
- Monitoring of perennial stream inlets.
- Education and outreach on best shoreland management practices.

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Appendix B. *E. coli* Source Assessment Inputs

Table B-1 through B-3 provide supplemental information to the *E. coli* source assessment in Section 3.6.1.

Table B-1. Deer population calculations

Reach	Deer Permit Area 176 [a]		Deer Permit Area 178		Deer Permit Area 181		Deer Permit Area 182 [b]		# Deer
	Density (deer/sq mile)	Upland Watershed Area (sq mile)	Density (deer/ sq mile)	Upland Watershed Area (sq mile)	Density (deer/ sq mile)	Upland Watershed Area (sq mile)	Density (deer/ sq mile)	Upland Watershed Area (sq mile)	
542	12	0.28	20	7.7	-	-	-	-	157
543	-	-	-	-	21	19	24	26	1,023
569	12	24	20	22	-	-	-	-	728
580	12	3.9	20	2.7	-	-	-	-	101
582	12	7.3	20	26	-	-	-	-	608
625	-	-	-	-	-	-	24	9.0	216
641	12	22	20	13	-	-	-	-	524
751	-	-	-	-	-	-	24	12	288
888	12	1.7	20	15	-	-	-	-	320
936	12	1.9	20	2.8	-	-	-	-	79
A22	12	0.0064	20	3.6	-	-	-	-	72

a. Previously delineated Permit Area 175 data used for Permit Area 176 from 2003–2006

b. No data prior to 2006 for Permit Area 182

Table B-2. Waterfowl population calculations

Reach	2003–12 Density (geese/acre) [a]	Watershed Area (acre)	Number of Geese	Total Waterfowl [b]
542	0.056	16	1	2
543	0.056	880	50	100
569	0.056	1,283	72	144
580	0.056	333	19	38
582	0.056	1,500	85	170
625	0.056	14	1	2
641	0.056	1,280	72	144
751	0.056	20	1	2
888	0.056	41	2	4
936	0.056	2.7	0	0
A22	0.056	0	0	0

a. Density calculated by dividing yearly geese population estimate in the Laurentian Mixed Forest Ecoregion from Rave (2014) by the area of open water.

b. Goose densities were doubled to account for ducks and other waterfowl.

TableB-3. Beaver population calculations

Reach	Density (colony/stream mile)	Perennial Stream Length (mi)	Beavers per Colony	Number of Beavers
542	0.6	9.3	7	39
543	0.6	38	7	160
569	0.6	38	7	160
580	0.6	3.1	7	13
582	0.6	25	7	105
625	0.6	10	7	42
641	0.6	22	7	92
751	0.6	15	7	63
888	0.6	19	7	80
936	0.6	7.2	7	30
A22	0.6	2.5	7	11

Assumes 0.6 beaver colonies per river mile (MNDNR Hydrography Dataset, with intermittent streams removed) and that a colony comprises two breeding adults, three yearly offspring, and two 1-year old offspring (http://www.dnr.state.mn.us/mammals/beaver.html).

Appendix C. Lake Modeling Documentation

For each impaired lake, the following supporting data from the BATHTUB model is provided: case data, diagnostics, and segment balances.

Dinham Lake

Dinham Lake Benchmark Model

Global Variables	**Mean**	**CV**
Averaging Period (yrs)	1	0.0
Precipitation (m)	0.66	0.2
Evaporation (m)	0.86	0.3
Storage Increase (m)	0	0.0

Atmos. Loads (kg/km^2-yr	**Mean**	**CV**
Conserv. Substance	0	0.00
Total P	20	0.50
Total N	1000	0.50
Ortho P	20	0.50
Inorganic N	500	0.50

Model Options	**Code**	**Description**
Conservative Substance	0	NOT COMPUTED
Phosphorus Balance	9	CANF& BACH, GENERAL
Nitrogen Balance	0	NOT COMPUTED
Chlorophyll-a	0	NOT COMPUTED
Secchi Depth	0	NOT COMPUTED
Dispersion	1	FISCHER-NUMERIC
Phosphorus Calibration	1	DECAY RATES
Nitrogen Calibration	1	DECAY RATES
Error Analysis	1	MODEL & DATA
Availability Factors	0	IGNORE
Mass-Balance Tables	1	USE ESTIMATED CONCS
Output Destination	2	EXCEL WORKSHEET

Segment Morphometry

		Outflow		Area	Depth	Length	Mixed Depth (m)		Hypol Depth		Non-Algal Turb (m^{-1})		Internal Loads (mg/m2-day) Conserv.		Total P		Total N	
Seg	**Name**	**Segment**	**Group**	**km^2**	**m**	**km**	**Mean**	**CV**	**Mean**	**CV**	**Mean**	**CV**	**Mean**	**CV**	**Mean**	**CV**	**Mean**	**CV**
1	lake	0	1	0.809	3.7	1.7	3.6	0.12	0	0	0.47	0.1	0	0	0	0	0	0

Segment Observed Water Quality

	Conserv		Total P (ppb)		Total N (ppb)		Chl-a (ppb)		Secchi (m)		Organic N (ppb)		TP - Ortho P (ppb)		HOD (ppb/day)		MOD (ppb/day)	
Seg	**Mean**	**CV**	**Mean**	**CV**	**Mean**	**CV**	**Mean**	**CV**	**Mean**	**CV**	**Mean**	**CV**	**Mean**	**CV**	**Mean**	**CV**	**Mean**	**CV**
1	0	0	36	0.13	0	0	20	0.12	1.3	0.04	0	0	0	0	0	0	0	0

Segment Calibration Factors

	Dispersion Rate		Total P (ppb)		Total N (ppb)		Chl-a (ppb)		Secchi (m)		Organic N (ppb)		TP - Ortho P (ppb)		HOD (ppb/day)		MOD (ppb/day)	
Seg	**Mean**	**CV**	**Mean**	**CV**	**Mean**	**CV**	**Mean**	**CV**	**Mean**	**CV**	**Mean**	**CV**	**Mean**	**CV**	**Mean**	**CV**	**Mean**	**CV**
1	1	0	1.45	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0

Tributary Data

				Dr Area	Flow (hm^3/yr)		Conserv.		Total P (ppb)		Total N (ppb)		Ortho P (ppb)		Inorganic N (ppb)	
Trib	**Trib Name**	**Segment**	**Type**	**km^2**	**Mean**	**CV**	**Mean**	**CV**	**Mean**	**CV**	**Mean**	**CV**	**Mean**	**CV**	**Mean**	**CV**
1	watershed runoff and septi	1	1	17.681	2.978	0	0	0	125	0	0	0	18	0	0	0

Model Coefficients	**Mean**	**CV**
Dispersion Rate	1.000	0.70
Total Phosphorus	1.000	0.45
Total Nitrogen	1.000	0.55
Chl-a Model	1.000	0.26
Secchi Model	1.000	0.10
Organic N Model	1.000	0.12
TP-OP Model	1.000	0.15
HODv Model	1.000	0.15
MODv Model	1.000	0.22
Secchi/Chla Slope (m^2/mg)	0.015	0.00
Minimum Qs (m/yr)	0.100	0.00
Chl-a Flushing Term	1.000	0.00
Chl-a Temporal CV	0.620	0
Avail. Factor - Total P	0.330	0
Avail. Factor - Ortho P	1.930	0
Avail. Factor - Total N	0.590	0
Avail. Factor - Inorganic N	0.790	0

Predicted & Observed Values Ranked Against CE Model Development Dataset

Segment: 1 lake

Variable	**Predicted Values--->** Mean	CV	Rank	**Observed Values--->** Mean	CV	Rank
TOTAL P MG/M3	35.6	0.33	37.1%	36.0	0.13	37.5%
CHL-A MG/M3				20.0	0.12	83.7%
SECCHI M				1.3	0.04	59.6%
ANTILOG PC-1				400.5	0.12	64.6%
ANTILOG PC-2				12.5	0.09	89.8%
TURBIDITY 1/M	0.5	0.10	38.4%	0.5	0.10	38.4%
ZMIX * TURBIDITY	1.7	0.16	21.2%	1.7	0.16	21.2%
ZMIX / SECCHI				2.8	0.13	17.5%
CHL-A * SECCHI				26.0	0.13	90.7%
CHL-A / TOTAL P				0.6	0.17	94.9%
FREQ(CHL-a>10) %				79.0	0.07	83.7%
FREQ(CHL-a>20) %				37.8	0.19	83.7%
FREQ(CHL-a>30) %				16.7	0.29	83.7%
FREQ(CHL-a>40) %				7.7	0.37	83.7%
FREQ(CHL-a>50) %				3.7	0.43	83.7%
FREQ(CHL-a>60) %				1.9	0.49	83.7%
CARLSON TSI-P	55.7	0.09	37.1%	55.8	0.03	37.5%
CARLSON TSI-CHLA				60.0	0.02	83.7%
CARLSON TSI-SEC				56.2	0.01	40.4%

Segment Mass Balance Based Upon Predicted Concentrations

Component: TOTAL P **Segment: 1 lake**

Trib	**Type**	**Location**	**Flow** hm^3/yr	**Flow** %Total	**Load** kg/yr	**Load** %Total	**Conc** mg/m^3
1	1	watershed runoff and se	2.978	84.8%	372.250	95.8%	125
PRECIPITATION			0.534	15.2%	16.180	4.2%	30
TRIBUTARY INFLOW			2.978	84.8%	372.250	95.8%	125
***TOTAL INFLOW			3.512	100.0%	388.430	100.0%	111
ADVECTIVE OUTFLOW			2.816	80.2%	100.252	25.8%	36
***TOTAL OUTFLOW			2.816	80.2%	100.252	25.8%	36
***EVAPORATION			0.696	19.8%	0.000	0.0%	
***RETENTION			0.000	0.0%	288.178	74.2%	

Hyd. Residence Time =	1.0629	yrs
Overflow Rate =	3.5	m/yr
Mean Depth =	3.7	m

Dinham Lake TMDL Scenario

Global Variables	Mean	CV
Averaging Period (yrs)	1	0.0
Precipitation (m)	0.66	0.2
Evaporation (m)	0.86	0.3
Storage Increase (m)	0	0.0

Atmos. Loads (kg/km^2-yr	Mean	CV
Conserv. Substance	0	0.00
Total P	20	0.50
Total N	1000	0.50
Ortho P	20	0.50
Inorganic N	500	0.50

Model Options	Code	Description
Conservative Substance	0	NOT COMPUTED
Phosphorus Balance	9	CANF& BACH, GENERAL
Nitrogen Balance	0	NOT COMPUTED
Chlorophyll-a	0	NOT COMPUTED
Secchi Depth	0	NOT COMPUTED
Dispersion	1	FISCHER-NUMERIC
Phosphorus Calibration	1	DECAY RATES
Nitrogen Calibration	1	DECAY RATES
Error Analysis	1	MODEL & DATA
Availability Factors	0	IGNORE
Mass-Balance Tables	1	USE ESTIMATED CONCS
Output Destination	2	EXCEL WORKSHEET

Segment Morphometry

		Outflow		Area	Depth	Length	Mixed Depth (m)		Hypol Depth		Non-Algal Turb (m^{-1})		Internal Loads (mg/m2-day) Conserv.		Total P		Total N	
Seg	Name	Segment	Group	km^2	m	km	Mean	CV	Mean	CV	Mean	CV	Mean	CV	Mean	CV	Mean	CV
1	lake	0	1	0.809	3.7	1.7	3.6	0.12	0	0	0.47	0.1	0	0	0	0	0	0

Segment Observed Water Quality

	Conserv		Total P (ppb)		Total N (ppb)		Chl-a (ppb)		Secchi (m)		Organic N (ppb)		TP - Ortho P (ppb)		HOD (ppb/day)		MOD (ppb/day)	
Seg	Mean	CV	Mean	CV	Mean	CV	Mean	CV	Mean	CV	Mean	CV	Mean	CV	Mean	CV	Mean	CV
1	0	0	36	0.13	0	0	20	0.12	1.3	0.04	0	0	0	0	0	0	0	0

Segment Calibration Factors

	Dispersion Rate		Total P (ppb)		Total N (ppb)		Chl-a (ppb)		Secchi (m)		Organic N (ppb)		TP - Ortho P (ppb)		HOD (ppb/day)		MOD (ppb/day)	
Seg	Mean	CV	Mean	CV	Mean	CV	Mean	CV	Mean	CV	Mean	CV	Mean	CV	Mean	CV	Mean	CV
1	1	0	1.45	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0

Tributary Data

				Dr Area	Flow (hm^3/yr)		Conserv.		Total P (ppb)		Total N (ppb)		Ortho P (ppb)		Inorganic N (ppb)	
Trib	Trib Name	Segment	Type	km^2	Mean	CV	Mean	CV	Mean	CV	Mean	CV	Mean	CV	Mean	CV
1	watershed runoff and septi	1	1	17.681	2.978	0	0	0	92	0	0	0	0	0	0	0

Model Coefficients	Mean	CV
Dispersion Rate	1.000	0.70
Total Phosphorus	1.000	0.45
Total Nitrogen	1.000	0.55
Chl-a Model	1.000	0.26
Secchi Model	1.000	0.10
Organic N Model	1.000	0.12
TP-OP Model	1.000	0.15
HODv Model	1.000	0.15
MODv Model	1.000	0.22
Secchi/Chla Slope (m^2/mg)	0.015	0.00
Minimum Qs (m/yr)	0.100	0.00
Chl-a Flushing Term	1.000	0.00
Chl-a Temporal CV	0.620	0
Avail. Factor - Total P	0.330	0
Avail. Factor - Ortho P	1.930	0
Avail. Factor - Total N	0.590	0
Avail. Factor - Inorganic N	0.790	0

Predicted & Observed Values Ranked Against CE Model Development Dataset

Segment: 1 lake

	Predicted Values--->			Observed Values--->		
Variable	**Mean**	**CV**	**Rank**	**Mean**	**CV**	**Rank**
TOTAL P MG/M3	29.9	0.31	30.0%	36.0	0.13	37.5%
CHL-A MG/M3				20.0	0.12	83.7%
SECCHI M				1.3	0.04	59.6%
ANTILOG PC-1				400.5	0.12	64.6%
ANTILOG PC-2				12.5	0.09	89.8%
TURBIDITY 1/M	0.5	0.10	38.4%	0.5	0.10	38.4%
ZMIX * TURBIDITY	1.7	0.16	21.2%	1.7	0.16	21.2%
ZMIX / SECCHI				2.8	0.13	17.5%
CHL-A * SECCHI				26.0	0.13	90.7%
CHL-A / TOTAL P				0.6	0.17	94.9%
FREQ(CHL-a>10) %				79.0	0.07	83.7%
FREQ(CHL-a>20) %				37.8	0.19	83.7%
FREQ(CHL-a>30) %				16.7	0.29	83.7%
FREQ(CHL-a>40) %				7.7	0.37	83.7%
FREQ(CHL-a>50) %				3.7	0.43	83.7%
FREQ(CHL-a>60) %				1.9	0.49	83.7%
CARLSON TSI-P	53.1	0.09	30.0%	55.8	0.03	37.5%
CARLSON TSI-CHLA				60.0	0.02	83.7%
CARLSON TSI-SEC				56.2	0.01	40.4%

Segment Mass Balance Based Upon Predicted Concentrations

Component: **TOTAL P** **Segment:** **1** **lake**

Trib	**Type**	**Location**	**Flow hm^3/yr**	**Flow %Total**	**Load kg/yr**	**Load %Total**	**Conc mg/m^3**
1	1	watershed runoff and se	2.978	84.8%	273.976	94.4%	92
PRECIPITATION			0.534	15.2%	16.180	5.6%	30
TRIBUTARY INFLOW			2.978	84.8%	273.976	94.4%	92
***TOTAL INFLOW			3.512	100.0%	290.156	100.0%	83
ADVECTIVE OUTFLOW			2.816	80.2%	84.123	29.0%	30
***TOTAL OUTFLOW			2.816	80.2%	84.123	29.0%	30
***EVAPORATION			0.696	19.8%	0.000	0.0%	
***RETENTION			0.000	0.0%	206.033	71.0%	

Hyd. Residence Time =	1.0629	yrs
Overflow Rate =	3.5	m/yr
Mean Depth =	3.7	m

West Two Rivers Reservoir

West Two Rivers Reservoir Benchmark Model

Global Variables	Mean	CV
Averaging Period (yrs)	1	0.0
Precipitation (m)	0.69	0.2
Evaporation (m)	0.84	0.3
Storage Increase (m)	0	0.0

Atmos. Loads (kg/km^2-yr	Mean	CV
Conserv. Substance	0	0.00
Total P	20	0.50
Total N	1000	0.50
Ortho P	20	0.50
Inorganic N	500	0.50

Model Options	Code	Description
Conservative Substance	0	NOT COMPUTED
Phosphorus Balance	8	CANF & BACH, LAKES
Nitrogen Balance	0	NOT COMPUTED
Chlorophyll-a	0	NOT COMPUTED
Secchi Depth	0	NOT COMPUTED
Dispersion	1	FISCHER-NUMERIC
Phosphorus Calibration	1	DECAY RATES
Nitrogen Calibration	1	DECAY RATES
Error Analysis	1	MODEL & DATA
Availability Factors	0	IGNORE
Mass-Balance Tables	1	USE ESTIMATED CONCS
Output Destination	2	EXCEL WORKSHEET

Segment Morphometry

		Outflow		Area	Depth	Length	Mixed Depth (m)		Hypol Depth		Non-Algal Turb (m^{-1})		Internal Loads (mg/m2-day) Conserv.		Total P		Total N	
Seg	Name	Segment	Group	km^2	m	km	Mean	CV	Mean	CV	Mean	CV	Mean	CV	Mean	CV	Mean	CV
1	1-upstream	2	1	0.871	2.1	3.6	2.1	0.12	0	0	0	0	0	0	0	0	0	0
2	2-middle	3	2	0.592	2.1	1.5	2.1	0.12	0	0	0	0	0	0	0	0	0	0
3	3-downstream	0	3	1.475	4	2.3	3.9	0.12	0	0	0.36	0.22	0	0	0.93	0	0	0

Segment Observed Water Quality

	Conserv		Total P (ppb)		Total N (ppb)		Chl-a (ppb)		Secchi (m)		Organic N (ppb)		TP - Ortho P (ppb)		HOD (ppb/day)		MOD (ppb/day)	
Seg	Mean	CV	Mean	CV	Mean	CV	Mean	CV	Mean	CV	Mean	CV	Mean	CV	Mean	CV	Mean	CV
1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3	0	0	40	0.11	0	0	15	0.22	1.7	0.11	0	0	0	0	0	0	0	0

Segment Calibration Factors

	Dispersion Rate		Total P (ppb)		Total N (ppb)		Chl-a (ppb)		Secchi (m)		Organic N (ppb)		TP - Ortho P (ppb)		HOD (ppb/day)		MOD (ppb/day)	
Seg	Mean	CV	Mean	CV	Mean	CV	Mean	CV	Mean	CV	Mean	CV	Mean	CV	Mean	CV	Mean	CV
1	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0
2	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0
3	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0

Tributary Data

				Dr Area	Flow (hm^3/yr)		Conserv.		Total P (ppb)		Total N (ppb)		Ortho P (ppb)		Inorganic N (ppb)	
Trib	Trib Name	Segment	Type	km^2	Mean	CV	Mean	CV	Mean	CV	Mean	CV	Mean	CV	Mean	CV
1	1-upstream watershed runc	1	1	73.563	9.391	0	0	0	63.5	0	0	0	14.5	0	0	0
2	Mountain Iron WWTP	1	3	0	0.56	0	0	0	547	0	0	0	396	0	0	0
3	US Steel Corp	1	3	0	8.533	0	0	0	5	0	0	0	5	0	0	0
4	2-middle watershed runoff	2	1	1.554	0.198	0	0	0	63.5	0	0	0	14.5	0	0	0
5	3-downstream watershed ru	3	1	2.631	0.336	0	0	0	63.5	0	0	0	14.5	0	0	0

Model Coefficients	Mean	CV
Dispersion Rate	1.000	0.70
Total Phosphorus	1.000	0.45
Total Nitrogen	1.000	0.55
Chl-a Model	1.000	0.26
Secchi Model	1.000	0.10
Organic N Model	1.000	0.12
TP-OP Model	1.000	0.15
HODv Model	1.000	0.15
MODv Model	1.000	0.22
Secchi/Chla Slope (m^2/mg)	0.015	0.00
Minimum Qs (m/yr)	0.100	0.00
Chl-a Flushing Term	1.000	0.00
Chl-a Temporal CV	0.620	0
Avail. Factor - Total P	0.330	0
Avail. Factor - Ortho P	1.930	0
Avail. Factor - Total N	0.590	0
Avail. Factor - Inorganic N	0.790	0

Segment: 4 Area-Wtd Mean

	Predicted Values--->			Observed Values--->		
Variable	**Mean**	**CV**	**Rank**	**Mean**	**CV**	**Rank**
TOTAL P MG/M3	39.7	0.19	41.7%	40.0	0.11	42.1%
CHL-A MG/M3				15.0	0.22	72.9%
SECCHI M				1.7	0.11	72.5%
ANTILOG PC-1				237.4	0.23	49.0%
ANTILOG PC-2				12.7	0.17	90.3%
TURBIDITY 1/M	0.4	0.22	27.5%	0.4	0.22	27.5%
ZMIX * TURBIDITY	1.4	0.25	14.9%	1.4	0.25	14.9%
ZMIX / SECCHI				2.3	0.16	10.4%
CHL-A * SECCHI				25.5	0.25	90.2%
CHL-A / TOTAL P				0.4	0.24	84.6%
FREQ(CHL-a>10) %				63.5	0.21	72.9%
FREQ(CHL-a>20) %				21.9	0.48	72.9%
FREQ(CHL-a>30) %				7.7	0.68	72.9%
FREQ(CHL-a>40) %				2.9	0.83	72.9%
FREQ(CHL-a>50) %				1.2	0.96	72.9%
FREQ(CHL-a>60) %				0.5	1.06	72.9%
CARLSON TSI-P	57.2	0.05	41.7%	57.3	0.03	42.1%
CARLSON TSI-CHLA				57.2	0.04	72.9%
CARLSON TSI-SEC				52.4	0.03	27.5%

Segment: 1 1-upstream

	Predicted Values--->			Observed Values--->		
Variable	**Mean**	**CV**	**Rank**	**Mean**	**CV**	**Rank**
TOTAL P MG/M3	40.4	0.12	42.5%			
CARLSON TSI-P	57.5	0.03	42.5%			

Segment: 2 2-middle

	Predicted Values--->			Observed Values--->		
Variable	**Mean**	**CV**	**Rank**	**Mean**	**CV**	**Rank**
TOTAL P MG/M3	38.7	0.22	40.7%			
CARLSON TSI-P	56.9	0.06	40.7%			

Segment: 3 3-downstream

	Predicted Values--->			Observed Values--->		
Variable	**Mean**	**CV**	**Rank**	**Mean**	**CV**	**Rank**
TOTAL P MG/M3	39.7	0.23	41.7%	40.0	0.11	42.1%
CHL-A MG/M3				15.0	0.22	72.9%
SECCHI M				1.7	0.11	72.5%
ANTILOG PC-1				237.4	0.23	49.0%
ANTILOG PC-2				12.7	0.17	90.3%
TURBIDITY 1/M	0.4	0.22	27.5%	0.4	0.22	27.5%
ZMIX * TURBIDITY	1.4	0.25	14.9%	1.4	0.25	14.9%
ZMIX / SECCHI				2.3	0.16	10.4%
CHL-A * SECCHI				25.5	0.25	90.2%
CHL-A / TOTAL P				0.4	0.24	84.6%
FREQ(CHL-a>10) %				63.5	0.21	72.9%
FREQ(CHL-a>20) %				21.9	0.48	72.9%
FREQ(CHL-a>30) %				7.7	0.68	72.9%
FREQ(CHL-a>40) %				2.9	0.83	72.9%
FREQ(CHL-a>50) %				1.2	0.96	72.9%
FREQ(CHL-a>60) %				0.5	1.06	72.9%
CARLSON TSI-P	57.2	0.06	41.7%	57.3	0.03	42.1%
CARLSON TSI-CHLA				57.2	0.04	72.9%
CARLSON TSI-SEC				52.4	0.03	27.5%

Segment Mass Balance Based Upon Predicted Concentrations

Component: TOTAL P Segment: 1 1-upstream

Trib	Type	Location	Flow hm^3/yr	Flow %Total	Load kg/yr	Load %Total	Conc mg/m^3
1	1	1-upstream watershed ru	9.391	49.2%	596.3	61.9%	64
2	3	Mountain Iron WWTP	0.560	2.9%	306.3	31.8%	547
3	3	US Steel Corp	8.533	44.7%	42.7	4.4%	5
PRECIPITATION			0.601	3.1%	17.4	1.8%	29
TRIBUTARY INFLOW			9.391	49.2%	596.3	61.9%	64
POINT-SOURCE INFLOW			9.093	47.6%	349.0	36.2%	38
***TOTAL INFLOW			19.085	100.0%	962.7	100.0%	50
ADVECTIVE OUTFLOW			18.353	96.2%	740.8	76.9%	40
NET DIFFUSIVE OUTFLOW			0.000	0.0%	11.1	1.2%	
***TOTAL OUTFLOW			18.353	96.2%	751.8	78.1%	41
***EVAPORATION			0.732	3.8%	0.0	0.0%	
***RETENTION			0.000	0.0%	210.9	21.9%	

Hyd. Residence Time = 0.0997 yrs
Overflow Rate = 21.1 m/yr
Mean Depth = 2.1 m

Component: TOTAL P Segment: 2 2-middle

Trib	Type	Location	Flow hm^3/yr	Flow %Total	Load kg/yr	Load %Total	Conc mg/m^3
4	1	2-middle watershed runc	0.198	1.0%	12.6	1.5%	64
PRECIPITATION			0.408	2.2%	11.8	1.4%	29
TRIBUTARY INFLOW			0.198	1.0%	12.6	1.5%	64
ADVECTIVE INFLOW			18.353	96.8%	740.8	85.8%	40
NET DIFFUSIVE INFLOW			0.000	0.0%	97.8	11.3%	
***TOTAL INFLOW			18.960	100.0%	863.0	100.0%	46
ADVECTIVE OUTFLOW			18.463	97.4%	715.2	82.9%	39
***TOTAL OUTFLOW			18.463	97.4%	715.2	82.9%	39
***EVAPORATION			0.497	2.6%	0.0	0.0%	
***RETENTION			0.000	0.0%	147.8	17.1%	

Hyd. Residence Time = 0.0673 yrs
Overflow Rate = 31.2 m/yr
Mean Depth = 2.1 m

Component: TOTAL P Segment: 3 3-downstream

Trib	Type	Location	Flow hm^3/yr	Flow %Total	Load kg/yr	Load %Total	Conc mg/m^3
5	1	3-downstream watershe	0.336	1.7%	21.3	1.7%	64
PRECIPITATION			1.018	5.1%	29.5	2.3%	29
INTERNAL LOAD			0.000	0.0%	501.0	39.5%	
TRIBUTARY INFLOW			0.336	1.7%	21.3	1.7%	64
ADVECTIVE INFLOW			18.463	93.2%	715.2	56.4%	39
***TOTAL INFLOW			19.816	100.0%	1267.1	100.0%	64
ADVECTIVE OUTFLOW			18.577	93.7%	736.9	58.2%	40
NET DIFFUSIVE OUTFLOW			0.000	0.0%	86.8	6.8%	
***TOTAL OUTFLOW			18.577	93.7%	823.7	65.0%	44
***EVAPORATION			1.239	6.3%	0.0	0.0%	
***RETENTION			0.000	0.0%	443.4	35.0%	

Hyd. Residence Time = 0.3176 yrs
Overflow Rate = 12.6 m/yr
Mean Depth = 4.0 m

West Two Rivers Reservoir TMDL Scenario

Global Variables	Mean	CV
Averaging Period (yrs)	1	0.0
Precipitation (m)	0.69	0.2
Evaporation (m)	0.84	0.3
Storage Increase (m)	0	0.0

Atmos. Loads (kg/km^2-yr	Mean	CV
Conserv. Substance	0	0.00
Total P	20	0.50
Total N	1000	0.50
Ortho P	20	0.50
Inorganic N	500	0.50

Model Options	Code	Description
Conservative Substance	0	NOT COMPUTED
Phosphorus Balance	8	CANF & BACH, LAKES
Nitrogen Balance	0	NOT COMPUTED
Chlorophyll-a	0	NOT COMPUTED
Secchi Depth	0	NOT COMPUTED
Dispersion	1	FISCHER-NUMERIC
Phosphorus Calibration	1	DECAY RATES
Nitrogen Calibration	1	DECAY RATES
Error Analysis	1	MODEL & DATA
Availability Factors	0	IGNORE
Mass-Balance Tables	1	USE ESTIMATED CONCS
Output Destination	2	EXCEL WORKSHEET

Segment Morphometry

													Internal Loads (mg/m2-day)					
		Outflow		Area	Depth	Length	Mixed Depth (m)		Hypol Depth		Non-Algal Turb (		Conserv.		Total P		Total N	
Seg	Name	Segment	Group	km^2	m	km	Mean	CV	Mean	CV	Mean	CV	Mean	CV	Mean	CV	Mean	CV
1	1-upstream	2	1	0.871	2.1	3.6	2.1	0.12	0	0	0	0	0	0	0	0	0	0
2	2-middle	3	2	0.592	2.1	1.5	2.1	0.12	0	0	0	0	0	0	0	0	0	0
3	3-downstream	0	3	1.475	4	2.3	3.9	0.12	0	0	0.36	0.22	0	0	0.27	0	0	0

Segment Observed Water Quality

	Conserv		Total P (ppb)		Total N (ppb)		Chl-a (ppb)		Secchi (m)		Organic N (ppb)		TP - Ortho P (ppb		HOD (ppb/day)		MOD (ppb/day)	
Seg	Mean	CV	Mean	CV	Mean	CV	Mean	CV	Mean	CV	Mean	CV	Mean	CV	Mean	CV	Mean	CV
1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3	0	0	40	0.11	0	0	15	0.22	1.7	0.11	0	0	0	0	0	0	0	0

Segment Calibration Factors

	Dispersion Rate		Total P (ppb)		Total N (ppb)		Chl-a (ppb)		Secchi (m)		Organic N (ppb)		TP - Ortho P (ppb		HOD (ppb/day)		MOD (ppb/day)	
Seg	Mean	CV	Mean	CV	Mean	CV	Mean	CV	Mean	CV	Mean	CV	Mean	CV	Mean	CV	Mean	CV
1	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0
2	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0
3	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0

Tributary Data

				Dr Area	Flow (hm^3/yr)		Conserv.		Total P (ppb)		Total N (ppb)		Ortho P (ppb)		Inorganic N (ppb)	
Trib	Trib Name	Segment	Type	km^2	Mean	CV	Mean	CV	Mean	CV	Mean	CV	Mean	CV	Mean	CV
1	1-upstream watershed runc	1	1	73.563	9.391	0	0	0	63.5	0	0	0	0	0	0	0
2	Mountain Iron WWTP	1	3	0	0.76	0	0	0	230	0	0	0	0	0	0	0
3	US Steel Corp	1	3	0	8.5	0	0	0	5	0	0	0	5	0	0	0
4	2-middle watershed runoff	2	1	1.554	0.198	0	0	0	63.5	0	0	0	0	0	0	0
5	3-downstream watershed ru	3	1	2.631	0.336	0	0	0	63.5	0	0	0	0	0	0	0

Model Coefficients	Mean	CV
Dispersion Rate	1.000	0.70
Total Phosphorus	1.000	0.45
Total Nitrogen	1.000	0.55
Chl-a Model	1.000	0.26
Secchi Model	1.000	0.10
Organic N Model	1.000	0.12
TP-OP Model	1.000	0.15
HODv Model	1.000	0.15
MODv Model	1.000	0.22
Secchi/Chla Slope (m^2/mg)	0.015	0.00
Minimum Qs (m/yr)	0.100	0.00
Chl-a Flushing Term	1.000	0.00
Chl-a Temporal CV	0.620	0
Avail. Factor - Total P	0.330	0
Avail. Factor - Ortho P	1.930	0
Avail. Factor - Total N	0.590	0
Avail. Factor - Inorganic N	0.790	0

Segment: **4** **Area-Wtd Mean**

	Predicted Values--->			Observed Values--->		
Variable	**Mean**	**CV**	**Rank**	**Mean**	**CV**	**Rank**
TOTAL P MG/M3	30.2	0.18	30.5%	40.0	0.11	42.1%
CHL-A MG/M3				15.0	0.22	72.9%
SECCHI M				1.7	0.11	72.5%
ANTILOG PC-1				237.4	0.23	49.0%
ANTILOG PC-2				12.7	0.17	90.3%
TURBIDITY 1/M	0.4	0.22	27.5%	0.4	0.22	27.5%
ZMIX * TURBIDITY	1.4	0.25	14.9%	1.4	0.25	14.9%
ZMIX / SECCHI				2.3	0.16	10.4%
CHL-A * SECCHI				25.5	0.25	90.2%
CHL-A / TOTAL P				0.4	0.24	84.6%
FREQ(CHL-a>10) %				63.5	0.21	72.9%
FREQ(CHL-a>20) %				21.9	0.48	72.9%
FREQ(CHL-a>30) %				7.7	0.68	72.9%
FREQ(CHL-a>40) %				2.9	0.83	72.9%
FREQ(CHL-a>50) %				1.2	0.96	72.9%
FREQ(CHL-a>60) %				0.5	1.06	72.9%
CARLSON TSI-P	53.3	0.05	30.5%	57.3	0.03	42.1%
CARLSON TSI-CHLA				57.2	0.04	72.9%
CARLSON TSI-SEC				52.4	0.03	27.5%

Segment: **1** **1-upstream**

	Predicted Values--->			Observed Values--->		
Variable	**Mean**	**CV**	**Rank**	**Mean**	**CV**	**Rank**
TOTAL P MG/M3	34.0	0.12	35.2%			
CARLSON TSI-P	55.0	0.03	35.2%			

Segment: **2** **2-middle**

	Predicted Values--->			Observed Values--->		
Variable	**Mean**	**CV**	**Rank**	**Mean**	**CV**	**Rank**
TOTAL P MG/M3	29.0	0.20	28.8%			
CARLSON TSI-P	52.7	0.06	28.8%			

Segment: **3** **3-downstream**

	Predicted Values--->			Observed Values--->		
Variable	**Mean**	**CV**	**Rank**	**Mean**	**CV**	**Rank**
TOTAL P MG/M3	28.5	0.22	28.2%	40.0	0.11	42.1%
CHL-A MG/M3				15.0	0.22	72.9%
SECCHI M				1.7	0.11	72.5%
ANTILOG PC-1				237.4	0.23	49.0%
ANTILOG PC-2				12.7	0.17	90.3%
TURBIDITY 1/M	0.4	0.22	27.5%	0.4	0.22	27.5%
ZMIX * TURBIDITY	1.4	0.25	14.9%	1.4	0.25	14.9%
ZMIX / SECCHI				2.3	0.16	10.4%
CHL-A * SECCHI				25.5	0.25	90.2%
CHL-A / TOTAL P				0.4	0.24	84.6%
FREQ(CHL-a>10) %				63.5	0.21	72.9%
FREQ(CHL-a>20) %				21.9	0.48	72.9%
FREQ(CHL-a>30) %				7.7	0.68	72.9%
FREQ(CHL-a>40) %				2.9	0.83	72.9%
FREQ(CHL-a>50) %				1.2	0.96	72.9%
FREQ(CHL-a>60) %				0.5	1.06	72.9%
CARLSON TSI-P	52.5	0.06	28.2%	57.3	0.03	42.1%
CARLSON TSI-CHLA				57.2	0.04	72.9%
CARLSON TSI-SEC				52.4	0.03	27.5%

Segment Mass Balance Based Upon Predicted Concentrations

Component: TOTAL P Segment: 1 1-upstream

Trib	Type	Location	Flow hm^3/yr	Flow %Total	Load kg/yr	Load %Total	Conc mg/m^3
1	1	1-upstream watershed ru	9.4	48.8%	596.3	71.8%	64
2	3	Mountain Iron WWTP	0.8	3.9%	174.8	21.0%	230
3	3	US Steel Corp	8.5	44.2%	42.5	5.1%	5
PRECIPITATION			0.6	3.1%	17.4	2.1%	29
TRIBUTARY INFLOW			9.4	48.8%	596.3	71.8%	64
POINT-SOURCE INFLOW			9.3	48.1%	217.3	26.1%	23
***TOTAL INFLOW			19.3	100.0%	831.0	100.0%	43
ADVECTIVE OUTFLOW			18.5	96.2%	630.2	75.8%	34
NET DIFFUSIVE OUTFLOW			0.0	0.0%	34.7	4.2%	
***TOTAL OUTFLOW			18.5	96.2%	664.8	80.0%	36
***EVAPORATION			0.7	3.8%	0.0	0.0%	
***RETENTION			0.0	0.0%	166.2	20.0%	

Hyd. Residence Time = 0.0988 yrs
Overflow Rate = 21.3 m/yr
Mean Depth = 2.1 m

Component: TOTAL P Segment: 2 2-middle

Trib	Type	Location	Flow hm^3/yr	Flow %Total	Load kg/yr	Load %Total	Conc mg/m^3
4	1	2-middle watershed runc	0.2	1.0%	12.6	1.9%	64
PRECIPITATION			0.4	2.1%	11.8	1.8%	29
TRIBUTARY INFLOW			0.2	1.0%	12.6	1.9%	64
ADVECTIVE INFLOW			18.5	96.8%	630.2	96.3%	34
***TOTAL INFLOW			19.1	100.0%	654.6	100.0%	34
ADVECTIVE OUTFLOW			18.6	97.4%	540.0	82.5%	29
NET DIFFUSIVE OUTFLOW			0.0	0.0%	11.6	1.8%	
***TOTAL OUTFLOW			18.6	97.4%	551.6	84.3%	30
***EVAPORATION			0.5	2.6%	0.0	0.0%	
***RETENTION			0.0	0.0%	103.0	15.7%	

Hyd. Residence Time = 0.0667 yrs
Overflow Rate = 31.5 m/yr
Mean Depth = 2.1 m

Component: TOTAL P Segment: 3 3-downstream

Trib	Type	Location	Flow hm^3/yr	Flow %Total	Load kg/yr	Load %Total	Conc mg/m^3
5	1	3-downstream watershe	0.3	1.7%	21.3	2.7%	64
PRECIPITATION			1.0	5.1%	29.5	3.8%	29
INTERNAL LOAD			0.0	0.0%	145.5	18.6%	
TRIBUTARY INFLOW			0.3	1.7%	21.3	2.7%	64
ADVECTIVE INFLOW			18.6	93.2%	540.0	69.0%	29
NET DIFFUSIVE INFLOW			0.0	0.0%	46.3	5.9%	
***TOTAL INFLOW			20.0	100.0%	782.6	100.0%	39
ADVECTIVE OUTFLOW			18.7	93.8%	534.2	68.3%	28
***TOTAL OUTFLOW			18.7	93.8%	534.2	68.3%	28
***EVAPORATION			1.2	6.2%	0.0	0.0%	
***RETENTION			0.0	0.0%	248.4	31.7%	

Hyd. Residence Time = 0.3148 yrs
Overflow Rate = 12.7 m/yr
Mean Depth = 4.0 m

Appendix D. Wyman Creek QUAL2K Model Report

Wyman Creek QUAL2K Model Report

St. Louis County, Minnesota

June 16, 2017

PREPARED FOR

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EXECUTIVE SUMMARY

An in-stream response model was developed for Wyman Creek, located in the Partridge River watershed in St. Louis County. The model was developed to simulate in-stream temperature and dissolved oxygen conditions in an effort to understand the effect of stressors on aquatic biota in the stream. Wyman Creek's headwaters begin in the Iron Range and have been historically altered due to mining activity. The rest of the watershed is primarily forested.

There are many stressors affecting Wyman Creek including:

- Outflow from mine pits that is warm relative to ambient conditions and has moderate dissolved oxygen (close to or above standard)
- Anoxic groundwater contributions that are a significant source of low dissolved oxygen water to the stream
- Reduced iron that causes direct exertion of oxygen demand in the water column
- Low-gradient wetlands that are naturally low in dissolved oxygen, with low rates of reaeration
- Riparian shade that decreases water temperature, and areas with lack of shade correlate with higher stream temperature
- Beaver ponds and ponded water from a perched culvert that are wide, shallow, and stagnant, leading to diurnal variation in water temperature, high rates of plant and/or algae growth, and relatively large diurnal swings in dissolved oxygen

The modeling objectives were:

1. Identify the causes of high temperature and low dissolved oxygen in Wyman Creek
2. Determine the effect that restoration of the upper portion of Wyman Creek will have on conditions in the lower portion
3. Determine if there are feasible activities that can be conducted in the lower reaches to improve water quality

Detailed simulation of Wyman Creek was conducted to simulate in-stream processes using the QUAL2K model. The stream was divided into ten segments, with finer-scale segmentation in the upper portion of the stream where anthropogenic effects are common. The model was calibrated and validated to a robust dataset collected in 2016. Under existing conditions, Wyman Creek does not attain water temperature and dissolved oxygen criteria in most locations.

A series of model scenarios were developed to explore the stream system's response to different options that may help improve water temperature and dissolved oxygen conditions. The scenarios included the following:

1. Improved direct inflow conditions
2. Decreased streambed sediment oxygen demand rate to simulate beaver management
3. Improved shade conditions
4. Improved upstream reach conditions to meet standards in the upper reaches only
5. Improved upstream conditions from Scenario 4 paired with improved downstream conditions
6. Improved downstream reach conditions only
7. Removed impact of one perched culvert

Results of the model scenarios indicated that there were certain reaches in the middle of Wyman Creek that will not likely attain water quality standards using feasible implementation activities. A TMDL scenario was also developed that focused on the lower reaches of Wyman Creek. This scenario resulted in meeting both the temperature target and dissolved oxygen standard and includes the following implementation targets:

1. Removal of the West Braid.
2. Increased shade along Reaches 7, 8, and 10: average daylight hours shade of 57%.
3. Water temperature improvements to Reach 6: average daylight hours shade of 57% or equivalent implementation to reduce in-stream temperatures entering Reach 7 to 19.7 °C.

These implementation targets, or other activities that result in the same temperature outcomes, are needed to comply with the water quality standards for both temperature and dissolved oxygen.

1.0 INTRODUCTION

Wyman Creek is located in the Partridge River HUC10 watershed (401020101) and the Wyman Creek watershed is 7,075 acres (Figure 1). Land use in the watershed is a mix of forest and grassland, extensive wetland along Wyman Creek, and a number of large mine features. Elevation in the watershed ranges from 417.2 – 590.7 meters (Figure 2).

The headwaters originate from a series of abandoned mine pits, which are referred to as the Headwater Mine and the West Mine Pit in this document. These mine pits provide a fairly constant supply of baseflow to the stream. In addition to the mine pits, there are stockpile areas present throughout the upper watershed. These iron range mine features as illustrated in Figure 1 have altered the natural hydrology of the watershed and potentially impact the stream's water quality. Wyman Creek downstream of the mine pits is fairly low gradient and beaver activity is common. Logging activities have also historically altered the watershed and stream.

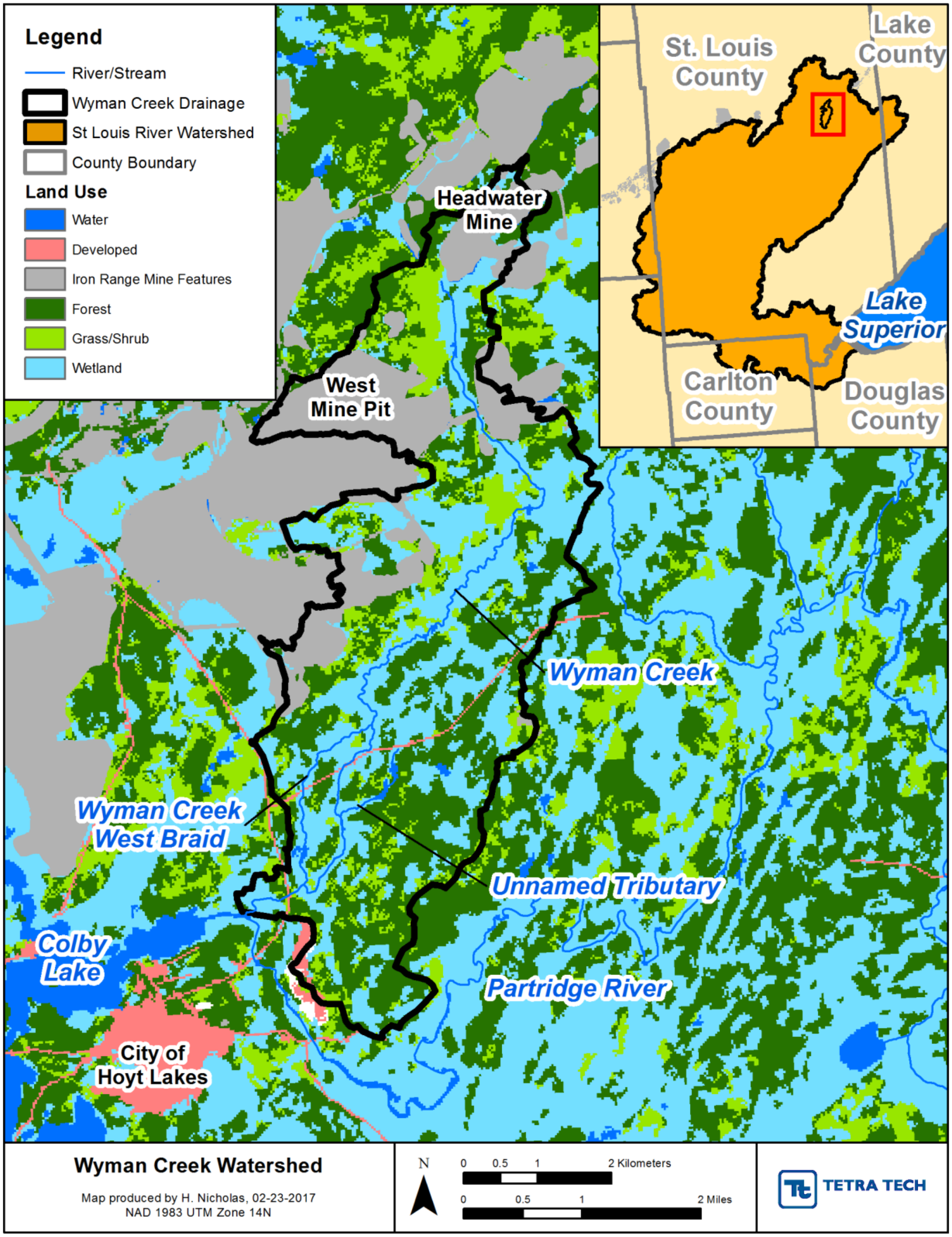


Figure 1. Wyman Creek watershed location map.

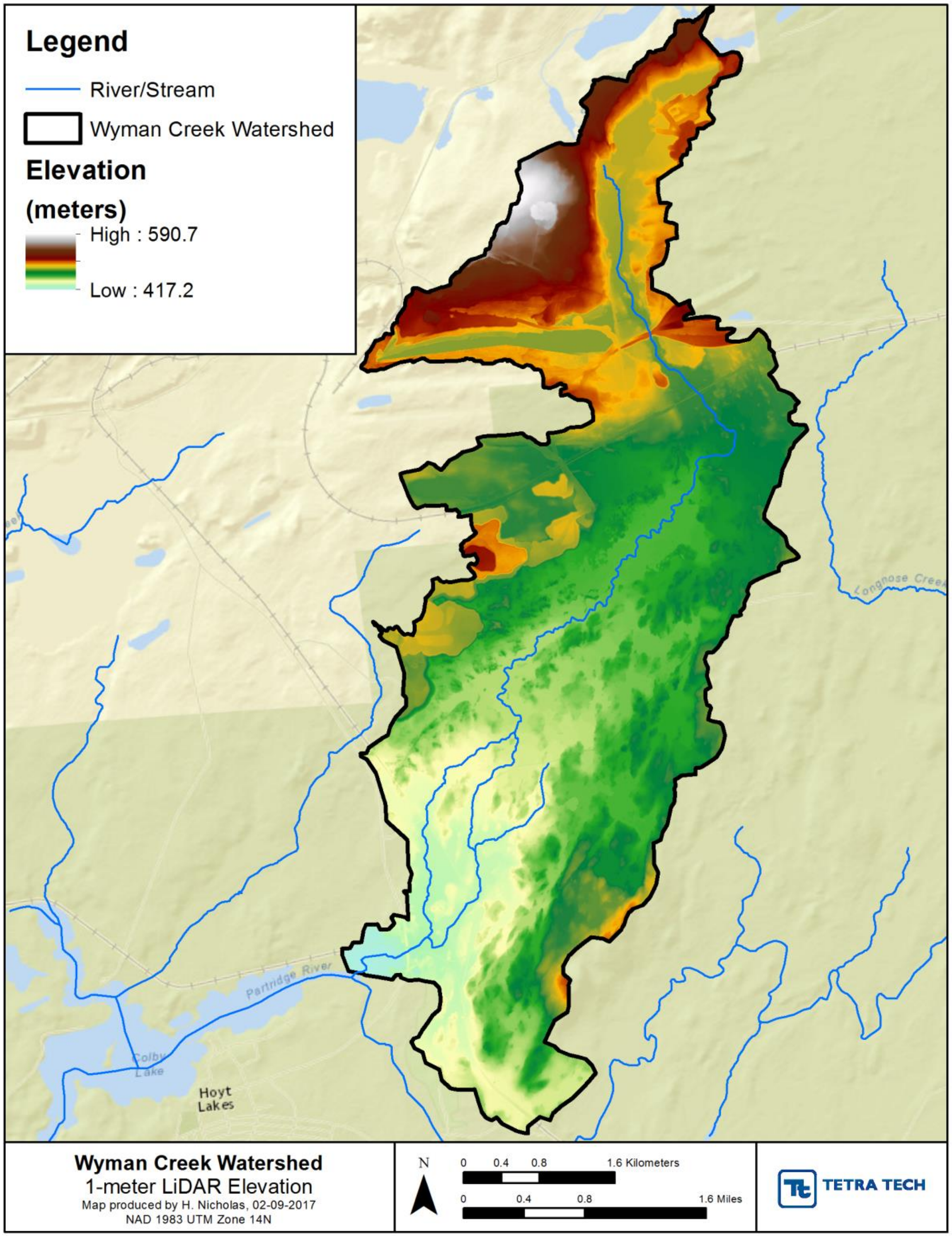


Figure 2. Wyman Creek watershed elevation map.

1.1 IMPAIRMENTS AND WATER QUALITY STANDARDS

Wyman Creek is impaired for aquatic life due to a poor quality fish community. MPCA determined that the principal causes, or "stressors" contributing to impaired fish and aquatic macroinvertebrate communities in Wyman Creek were elevated water temperatures, low DO, and loss of connectivity due to beaver dams and road crossings (MPCA 2016l). A potential but unconfirmed stressor is habitat loss due to iron precipitate, iron toxicity, and sulfate toxicity.

Mine pit drainage near the headwaters potentially impacts Wyman Creek. MPCA (2016) concluded that mine features that cover more than 10 percent of a watershed may have detrimental impacts on stream ecosystems due to changes in the functions of headwaters related to hydrology and water quality. Minnesota Department of Natural Resources Division of Lands and Minerals spatial data indicated that 19 percent of the Wyman Creek watershed is mining features, which exceeds the MPCA threshold for potential detrimental impacts (MN DNR, 2011; MPCA, 2016).

Fish populations were assessed at two locations near the downstream end of Wyman Creek. Brook trout were not observed; however, a number of species with similar environmental requirements were observed, suggesting that brook trout could be supported. Stressor identification monitoring during 2012 and 2013 included

- Sampling and evaluating fish and benthic macroinvertebrates
- Measuring stream gradient
- Monitoring continuous water temperature
- Collecting water quality samples that were evaluated for total iron concentration, total suspended solids, turbidity, sulfate, magnesium, calcium, hardness, chloride, DO, biochemical oxygen demand
- Recording observations of iron precipitate formation and beaver dams.

The stressor identification work found 42 beaver dams along the 10-mile length of Wyman Creek, which equates to about one impoundment for every 1,200 feet of stream (MPCA, 2016).

Wyman Creek is a Class 2A stream, and water quality standards that are applicable year-round are:

- **Dissolved Oxygen:** 7.0 mg/l as a daily minimum. The standard must be met 50 percent of the days at which the flow of the stream is critically low based on the lowest seven-day average flow occurring once every ten years (7Q10). Since there is not enough flow data available for Wyman Creek to compute low-flow statistics, the standard will be conservatively assumed to be 7.0 mg/l to be met at all times.
- **Water temperature:** no permitted material increase. The St. Louis River Watershed Stressor Identification Report (MPCA, 2016) identifies a water temperature maximum of 20 degrees Celsius at least 70 percent of the time to support brook trout growth. For this project, the conservative water temperature standard is assumed to be 20 degrees Celsius at all times, and determination that permitted discharge point sources are less than 20 degrees Celsius as well.

1.2 LINKING IMPAIRMENTS TO CAUSES AND POLLUTANTS

Dissolved oxygen and temperature impairments require additional analysis to determine if one or more pollutants or specific sources are responsible for the impairment. Detailed simulation of Wyman Creek was conducted to simulate in-stream processes using the QUAL2K model. QUAL2K is a steady state (but diurnally variable), one-dimensional model that can simulate in-stream water temperatures and DO concentrations on an hourly time step (Chapra et al., 2012). Typically, one 24-hour period of forcing data is simulated during critical conditions (e.g., low flow and warm temperatures) and iterated over multiple repeated days to achieve convergence. QUAL2K represents streams as a series of segments, each of which has approximately constant characteristics (e.g., slope, shading, bottom width). Each segment is further divided into a series of equally spaced model computational elements, which are assumed fully mixed.

Most of the factors that affect in-stream temperature and DO concentrations are represented in QUAL2K, including solar inputs, stream shading, air temperature, sediment oxygen demand, channel reaeration, oxidation of suspended and dissolved organic matter, plankton growth and respiration, and bottom algae (which can be used to approximate impacts of macrophyte growth). The relative magnitude of these factors can be determined through model application, and scenarios can be developed to evaluate if management actions can improve in-stream conditions.

QUAL2K modeling has been used extensively for TMDL development and point source permitting across the country. The QUAL2K model is suitable for simulating hydraulics and water quality conditions of small rivers and creeks such as Wyman Creek. A process-based model of temperature and DO in Wyman Creek enables a TMDL scenario to be evaluated. A TMDL scenario can be developed through modification of pollutant inputs and other factors such as shading to meet water quality standards and targets for DO and water temperature; the TMDL scenario can demonstrate the extent that natural characteristics of the watershed make attainment of water quality standards infeasible.

2.0 SUMMARY OF AVAILABLE DATA

The two primary datasets used to support QUAL2K modeling include monitoring conducted as part of watershed stressor identification (MPCA, 2016) and a large sampling effort conducted during summer 2016 in support of QUAL2K model development (Figure 3). Monitoring results from these two efforts are described in the following section. In addition to these data, historical data were collected to support permit compliance in the upper portion of the watershed.

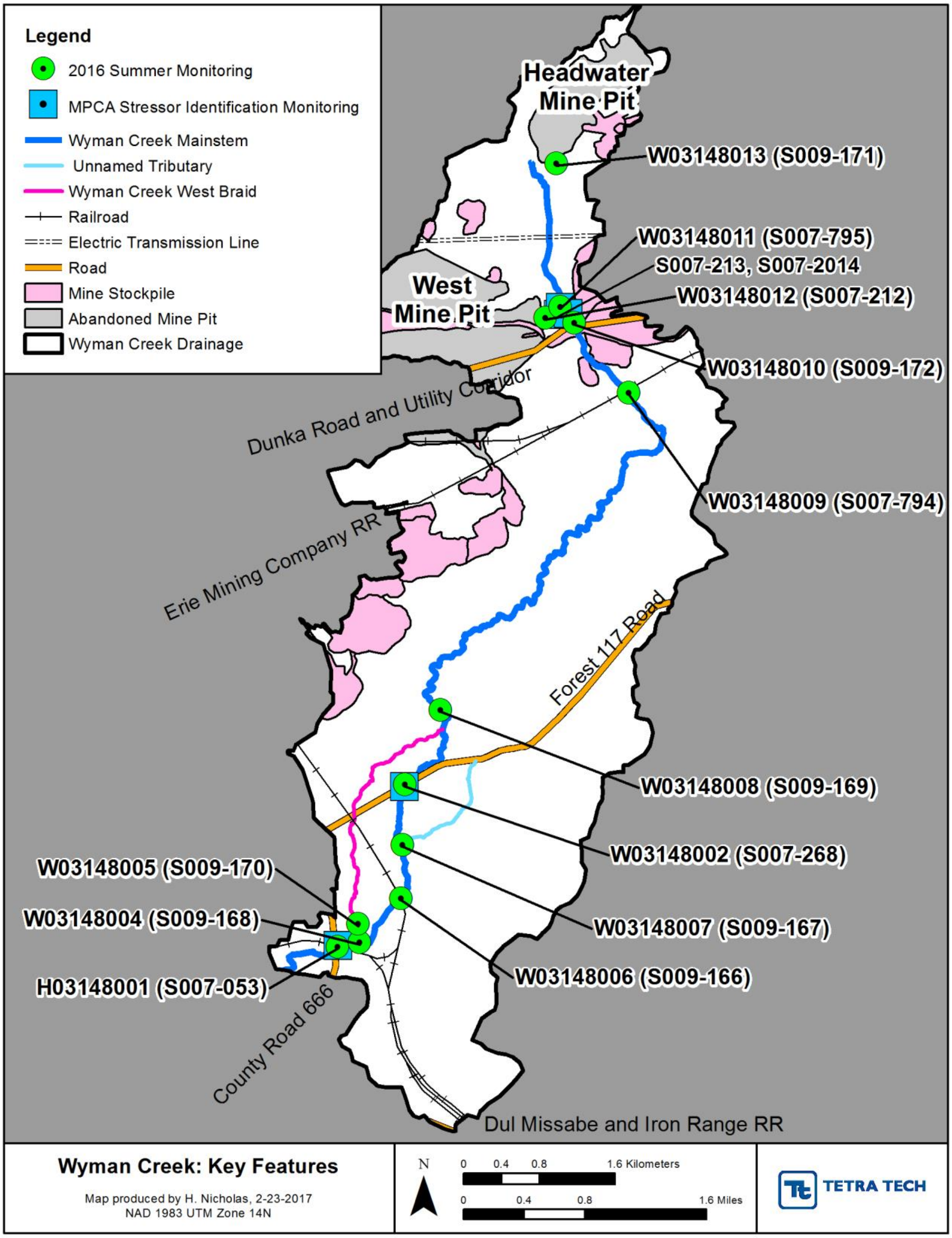


Figure 3. Wyman Creek monitoring sites.

2.1 MPCA STRESSOR IDENTIFICATION MONITORING

MPCA conducted water quality sampling in 2009, 2012, and 2013 for the St. Louis River Watershed Stressor Identification Report (MPCA, 2016). Water temperature, DO, pH, and conductivity were measured with sondes at 15-minute intervals. Monitoring was conducted at two sites along Wyman Creek (Figure 3):

- Wyman Creek near Hoyt Lakes, Superior National Forest Rd 117 (site 12LS006/W03148002, S007-268) from 8/24/2012 to 8/26/2012 and 8/30/2013 to 9/5/2013 (temperature only was also measured from June to September 2012)
- Wyman Creek at Hoyt Lakes, CR666 (site 81LS008/H03148001, S007-053) from 8/24/2012 to 8/30/2012 and 8/30/2013 to 9/5/2013 (temperature only was also measured from June to September 2012, and from May to September 2009)

The observed DO during these periods at both sampling sites did not meet the numeric water quality standard of 7.0 mg/l at any time (Figure 4, Figure 5).

Continuous sondes also monitored 15-minute interval water temperature at three sites to characterize the impacts of the West Mine Pit:

- Wyman Creek upstream of the West Mine Pit (site S007-213) from 6/6/2012 to 9/10/2012
- West Mine Pit outfall (site S007-212) from 6/6/2012 to 9/6/2012
- Wyman Creek downstream of the West Mine Pit (site S007-214) from 6/6/2012 to 9/10/2012

The relative influence of the mine pits, beaver dams, and other factors that can increase water temperature changed throughout the summer of 2012, when continuous temperature was monitored at multiple sites on Wyman Creek. At the beginning of July (Figure 6), the water from the West Mine Pit (site S007-212) was cooler than the water in Wyman Creek (site S007-213) and lowered the creek's temperature (S007-214). Towards the downstream end of the impaired reach, the creek's water temperature increased along the braided section of the reach (between sites S007-268 and S007-053), where there are fewer anthropogenic disturbances. Later in the month, water from the West Mine Pit was warmer than in the creek, leading to higher temperatures in the creek downstream of the West Mine Pit inflow (Figure 7). Water temperatures were cooler downstream, and water temperature decreased along the braided section. Temperature at two sites was monitored in 2013; temperature generally decreased during the monitoring period (Figure 8). DO increased over the same time period (Figure 5). This relationship is expected because cooler water can hold more DO.

Conductivity was relatively stable at both monitored sites during both summers. Average conductivity at the more upstream site (W03148002) was 360 µmhos/cm during summer 2012, and 366 µmhos/cm during summer 2013. Average conductivity at the most downstream site (H03148001) was 297 µmhos/cm during summer 2012, and 315 µmhos/cm during summer 2013.

pH data was relatively stable at both sites during both summers as well, suggesting that plant and algae photosynthesis and respiration were a relatively small part of the DO balance. Average pH at the more upstream site (W03148002) was 7.3 during the monitored summer of 2012. Average pH at the most downstream site (H03148001) was 7.1 and 7.2 for summer 2012 and 2013, respectively.

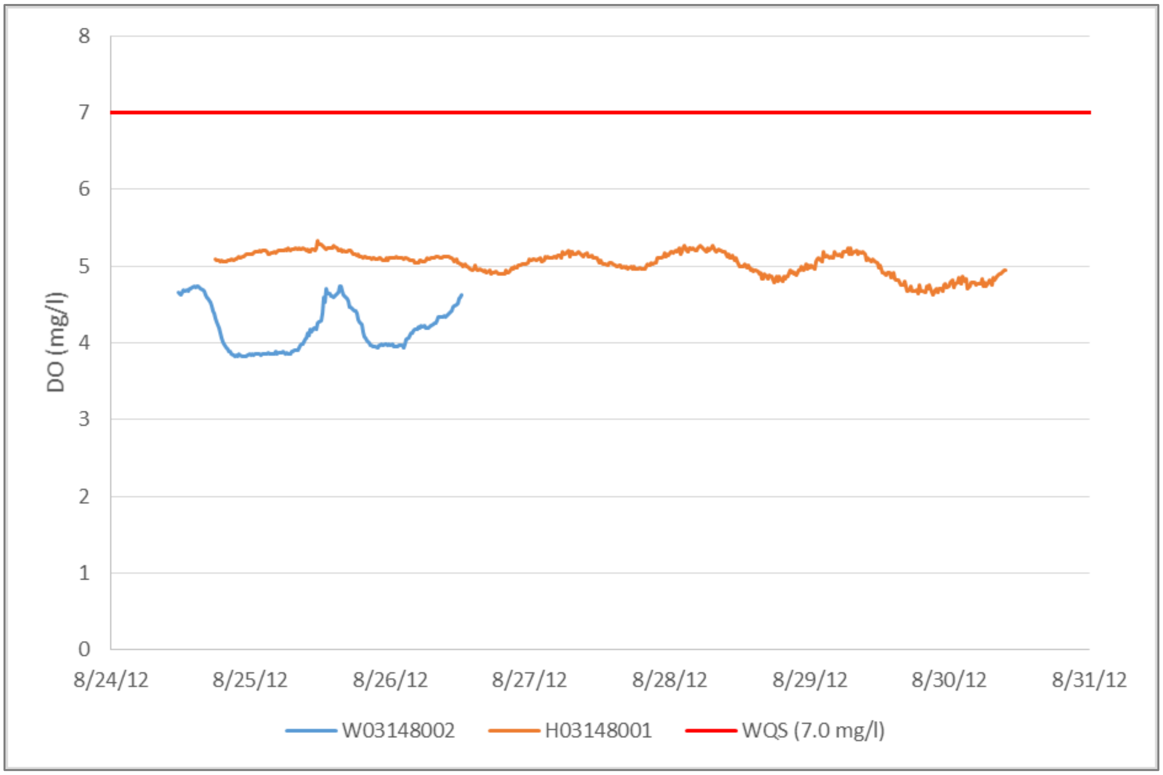


Figure 4. Continuous DO data along Wyman Creek, summer 2012.

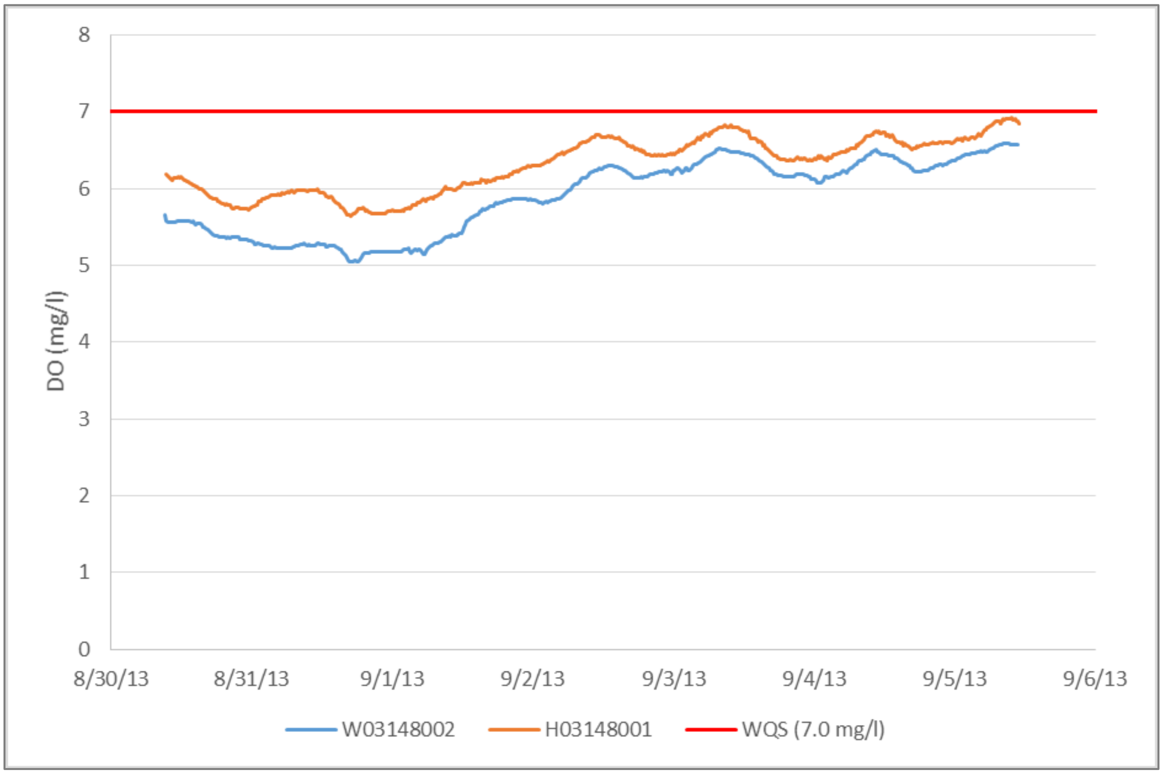


Figure 5. Continuous DO data along Wyman Creek, summer 2013.

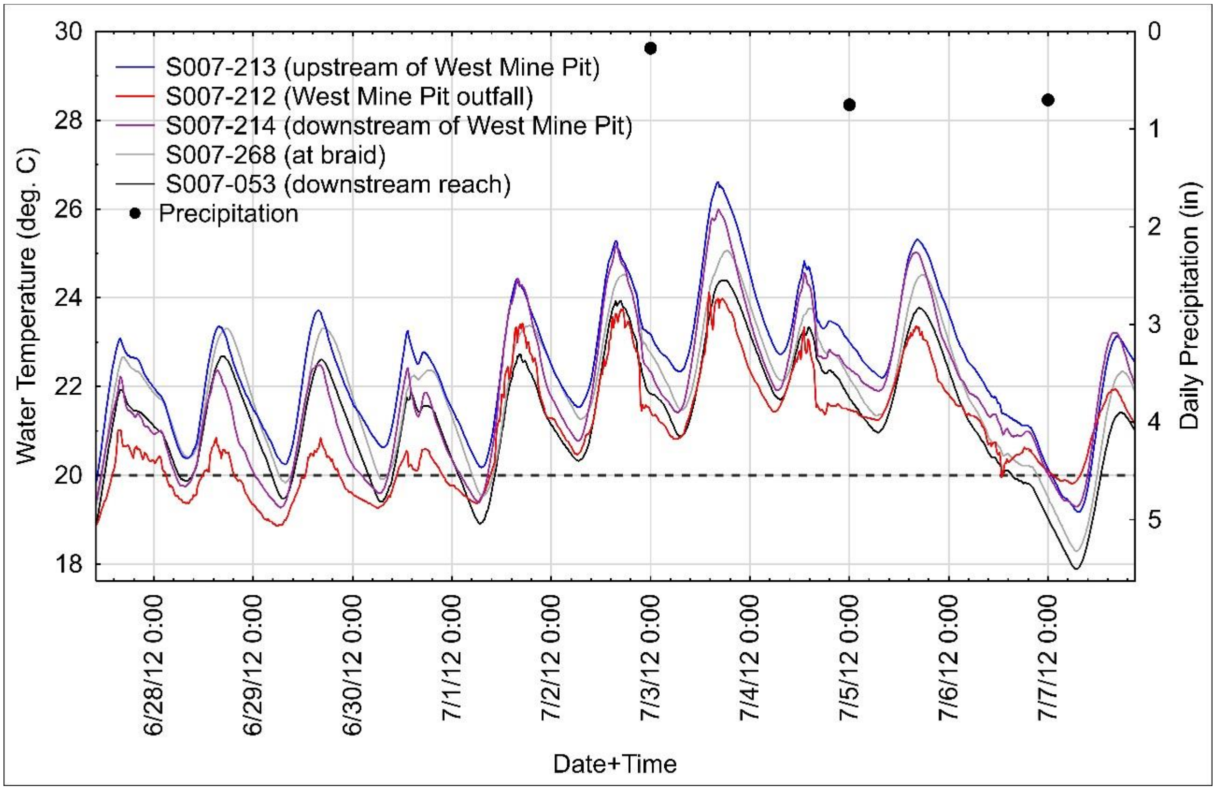


Figure 6. Wyman Creek water temperature, June 28–July 12, 2012.

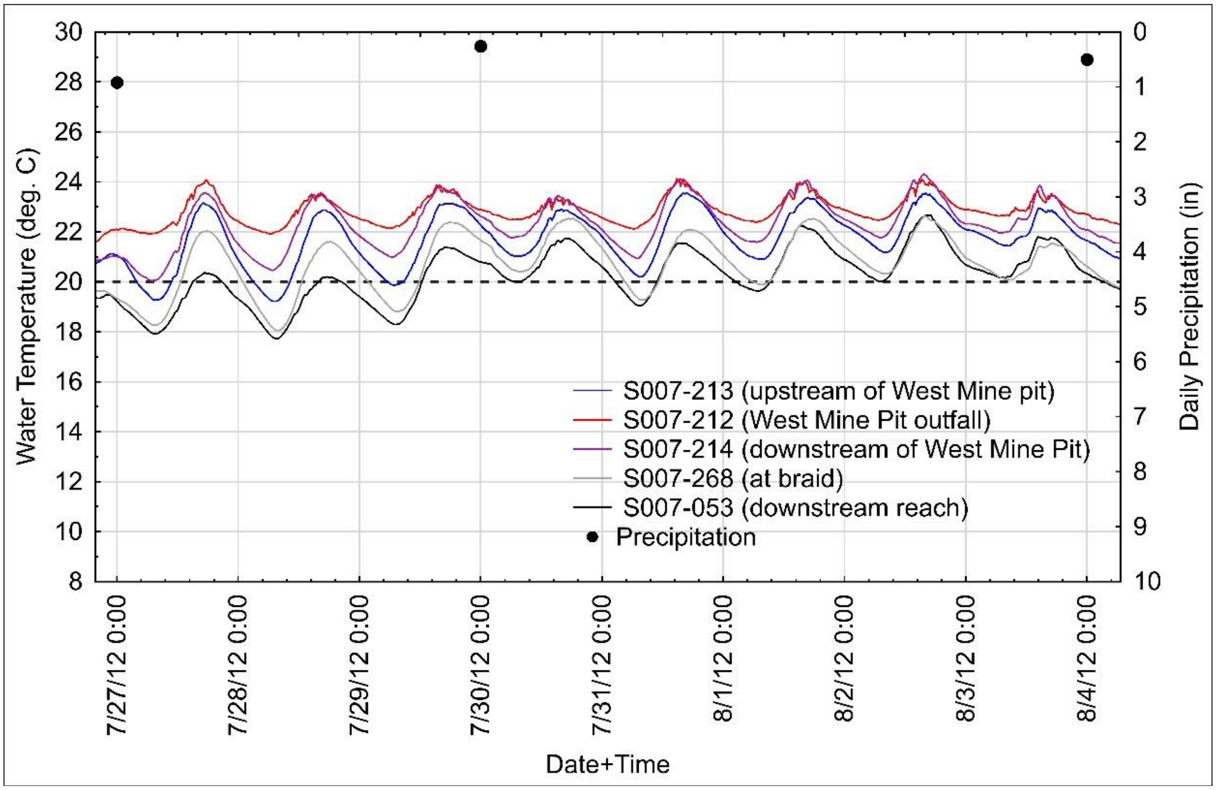


Figure 7. Wyman Creek water temperature, July 27–August 4, 2012.

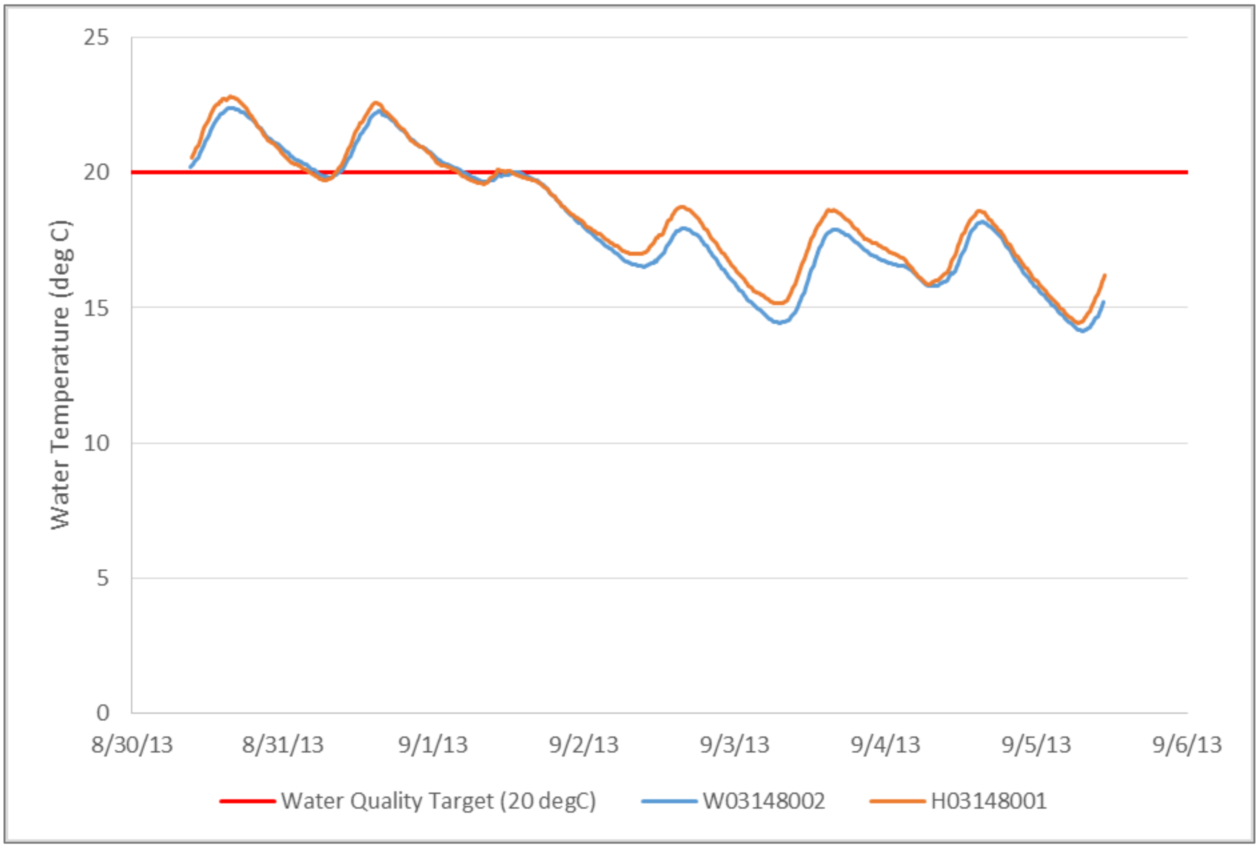


Figure 8. Continuous water temperature data along Wyman Creek, summer 2013.

2.2 2016 SUMMER MONITORING

An extensive sampling effort was undertaken during critical summer conditions in 2016 to support the Wyman Creek QUAL2K modeling effort. Data were collected at 12 sites (Table 1, Figure 3) along Wyman Creek and included the following:

- Channel geometry measurements
- Instantaneous flow measurements
- Instantaneous air temperature measurements
- Continuous measurements of in-stream water temperature, DO, pH, and conductivity
- Collection of water quality samples evaluated for total and dissolved iron, orthophosphate, alkalinity, ammonia, chlorophyll-*a*, inorganic nitrogen, Kjeldahl nitrogen, total phosphorus, sulfate, total suspended solids, biochemical oxygen demand
- Sediment samples evaluated for total organic carbon
- Photographs and notes about vegetation and bed sediment

Table 1. Sampling sites along Wyman Creek (2016 monitoring). Sites are ordered from upstream to downstream

HYDSTRA ID	EQUIS ID	MPCA Site Name	Descriptions Used in Memo
W03148013	S009-171	Wyman Creek near Hoyt Lakes, 1.1 mi upstream of Mining Rd	Mainstem, most upstream reach originating near the Headwater Mine
W03148011	S007-795	Wyman Creek near Hoyt Lakes, 0.1mi upstream of Mining Rd (upstream of West Mine Pit)	Mainstem, above West Mine Pit
W03148012	S007-212	West Mine Pit outflow Tributary near Hoyt Lakes, 0.1mi upstream of Wyman Cr	West Mine pit outflow
W03148010	S009-172	Wyman Creek near Hoyt Lakes, Mining Rd (downstream of West Mine Pit)	Mainstem, below West Mine Pit
W03148009	S007-794	Wyman Creek near Hoyt Lakes, 0.6 mi downstream of Mining Rd	Mainstem, downstream of railroad
W03148008	S009-169	Wyman Creek near Hoyt Lakes, 0.7 mi upstream of FR117	Mainstem, above braid split
W03148002	S007-268	Wyman Creek near Hoyt Lakes, Superior National Forest Rd 117	Mainstem, below braid split
W03148007	S009-167	Unnamed Tributary near Hoyt Lakes, 0.85 mi downstream of FR117	Unnamed Tributary
W03148006	S009-166	Wyman Creek near Hoyt Lakes, 0.8mi downstream of FR117	Mainstem, below unnamed tributary
W03148004	S009-168	Wyman Creek near Hoyt Lakes, 0.25mi upstream of CR666	Mainstem, above braid confluence
W03148005	S009-170	Wyman Creek Braid near Hoyt Lakes, 0.25mi upstream of CR666	West braid, downstream end
H03148001	S007-053	Wyman Creek at Hoyt Lakes, CR666	Mainstem, most downstream

2.2.1 2016 Data Inventory

2.2.1.1 Reach Hydraulics

FlowTracker handheld devices were used to log channel cross sections (width, depth, velocity, area, and total discharge) at all 12 sampling sites. The suite of data logged and graphed by FlowTracker can be found in Appendix B. A basic summary of channel geometry and sediment/bed composition is compiled below (Table 2). Channel geometry presented in Table 2 represents the average of the cross-sections taken during the first and second sampling trips on August 8 and August 18, 2016.

Table 2. Stream geometry summary along Wyman Creek

HYDSTRA ID	EQUIS ID	Average Width (m)	Average Depth (m)	Maximum Depth (m)	Cross-Sectional Area (m^2)	Channel Field Notes
W03148013	S009-171	2.47	0.18	0.35	0.51	Woody debris, some muck
W03148011	S007-795	2.07	0.54	0.76	1.13	Mucky, black organic materials, cloudy water
W03148012	S007-212	1.52	0.18	0.24	0.28	Gravel/sand hard bottom, little muck
W03148010	S009-172	1.60	0.08	0.12	0.13	1-2 feet of silty muck over gravel/sand bottom
W03148009	S007-794	1.04	0.12	0.18	0.12	Hard sandy bottom, some silty muck with woody debris
W03148008	S009-169	3.78	1.00	1.37	3.75	Muck, detritus, organic streambed, flow not perceived visually although registered with flow meter
W03148002	S007-268	2.26	0.16	0.23	0.36	Rocky substrate, grasses, clear water
W03148007	S009-167	1.39	0.39	0.50	0.54	Soft and mucky streambed, many sticks from beaver activity, muddy, iron-colored water
W03148006	S009-166	23.62	0.61	1.14	14.77	1-2 feet of organic muck and weeds, abundant lily pads and aquatic plants. Cross section was measured immediately upstream of the railroad crossing; large width is representative of the overpass length.
W03148004	S009-168	5.79	0.92	1.30	5.32	Boulders and cobbles with organic muck
W03148005	S009-170	1.52	0.73	1.02	1.13	1 foot of organic muck with small woody debris and iron precipitate coating channel bottom
H03148001	S007-053	4.40	0.08	0.14	0.35	Rocky, shallow, clear/tea-stained water, steady low swift flow, rocky bedrock

Instantaneous streamflow was observed at all twelve monitoring sites on both sampling dates. These flow observations were used to parameterize the hydraulic data for Wyman Creek and drive the selection of dates for model calibration and validation (Table 3). In general, baseflow increases from upstream to downstream with the exception of the reach between the railroad crossing (S007-794) and the braid split (S009-169) where the stream loses flow, which may be due to evaporation from wetland complexes.

Table 3. Streamflow monitoring summary along Wyman Creek, summer 2016

HYDSTRA ID	EQUIS ID	Location	Velocity (m/s) on 8/8/2016	Velocity (m/s) on 8/18/2016	Flow (cfs) on 8/8/2016	Flow (cfs) on 8/18/2016
W03148013	S009-171	Mainstem, most upstream	0.017 [a]	0.020 [a]	0.16 [a]	0.18 [a]
W03148011	S007-795	Mainstem, above West Mine Pit	0.014	0.008	0.57	0.29
W03148012	S007-212	West Mine Pit outflow	0.086	0.066	0.94	0.58
W03148010	S009-172	Mainstem, below West Mine Pit	0.356	0.326	2.02	1.08
W03148009	S007-794	Mainstem, downstream of railroad	-0.336 [b]	0.318	-1.72 [b]	1.17
W03148008	S009-169	Mainstem, above braid split	0.012	0.005	1.41	0.78
W03148002	S007-268	Mainstem, below braid split	0.185	0.151	2.50	1.81
W03148007	S009-167	Unnamed Tributary	0.027	0.027	0.57	0.46
W03148006	S009-166	Mainstem, below unnamed tributary	0.004 [c]	0.003 [c]	2.91[c]	2.47 [c]
W03148004	S009-168	Mainstem, above braid confluence	0.011	0.005	2.18	0.86
W03148005	S009-170	West Braid, downstream end	0.006	0.030	0.28	0.89
H03148001	S007-053	Mainstem, most downstream	0.251	0.217	3.09	2.66

a. Flows were measured along two adjacent braiding streams flowing from the “Headwater Mine”.
b. Some flow was registered in the upstream direction due to stagnation, eddies, wind influence, etc. This site is immediately downstream of the Erie Mining Company Railroad crossing containing a perched culvert, which dramatically impacts streamflow and connectivity underneath the railroad.
c. Flows were measured in four segments across the stream width, corresponding with the four openings between concrete bridge supports.

2.2.1.2 Water Quality Grab Sampling

Grab sampling of water and streambed sediment was conducted on August 8 and 16, 2016 when flow cross sections were measured. The sediment samples were analyzed for total organic carbon (TOC) at all 12 sampling sites on both sample dates (Table 4, Table 5). TOC content in sediment can be used to estimate relative sediment oxygen demand due to chemical reactions in the streambed that deplete the water column of DO (see Section 3.2.3 for further discussion of this process). The water samples were analyzed for the following constituents: total and dissolved iron, 5-day biochemical oxygen demand (BOD5), dissolved orthophosphate (PO_4), total phosphorus (TP), alkalinity, total ammonia (NH_3), chlorophyll-*a* (Chla), inorganic nitrogen (NOX), total Kjeldahl nitrogen (TKN), sulfate, and total suspended solids (TSS). Sampling results for BOD5 are non-detect (less than 2.4 mg/L) for nearly all samples. Nitrogen and phosphorus constituents are generally low across the watershed. As expected, total iron concentrations are high in this watershed, which is indicative of elevated background concentrations and/or the impact of historic local mining operations (MPCA, 2016).

Table 4. Water quality and sediment grab sample results for Wyman Creek: 8/8/2016

HYDSTRA ID	EQUIS ID	Alkalinity (mg/l)	BOD5 (mg/l)	Chla (µg/l)	Dslv Iron (µg/l)	Total NH_3 (mg/l)	NO_x (mg/l)	Total Iron (µg/l)	TKN (mg/l)	TOC in sediment (mg/kg)	TP (mg/l)	TSS (mg/l)
W03148013	S009-171	160	ND	0.75	347	ND	0.07	920	0.58	238,000	0.014	5.2
W03148011	S007-795	170	ND	1.52	776	ND	ND	3,490	0.64	170,000	0.052	3.6
W03148012	S007-212	170	ND	0.33	ND	ND	0.46	2,080	ND	2,800	0.016	1.2
W03148010	S009-172	170	ND	1.51	548	ND	0.1	1,510	0.35	73,800	0.018	2.4
W03148009	S007-794	180	ND	2.14	364	ND	0.07	965	0.34	121,000	0.017	2
W03148008	S009-169	160	ND	3	402	ND	0.07	831	0.68	20,000	0.023	3.6
W03148002	S007-268	160	ND	1.09	477	ND	ND	1,280	0.64	16,500	0.035	4.4
W03148007	S009-167	–	ND	–	–	–	–	–	–	237,000	–	–
W03148006	S009-166	150	ND	2.85	1160	ND	ND	2,030	0.83	123,000	0.03	6.4
W03148004	S009-168	140	ND	0.42	1340	ND	0.06	1,990	0.83	173,000	0.023	1.6
W03148005	S009-170	140	ND	0.81	2850	0.06	ND	5,980	1.01	138,000	0.034	6.4
H03148001	S007-053	140	ND	0.89	1,570	0.05	ND	6,120	1.07	37,900	0.068	22

Parameter abbreviations: BOD5 = 5-day biochemical oxygen demand; Chla = chlorophyll-*a*; Dslv Iron = dissolved iron; Total NH_3 = total ammonia; NO_x = nitrate plus nitrite-nitrogen; TKN = total Kjeldahl nitrogen, TOC = total organic carbon; TP = total phosphorus; TSS = total suspended solids

ND: non-detect. Method detection limits: 2.4 mg/l BOD; 6.42 µg/l dissolved iron; 0.003 mg/l total ammonia, 0.005 mg/l NO_x, 0.09 mg/L TKN

–: not sampled

Table 5. Water quality and sediment grab sample results for Wyman Creek: 8/18/2016

HYDSTRA ID	EQUIS ID	Alkalinity (mg/l)	BOD5 (mg/l)	Chla (µg/l)	Dslv Iron (µg/l)	Dslv PO$_4$ (mg/l)	Total NH$_3$ (mg/l)	NOX (mg/l)	Sulfate (mg/l)	Total Iron (µg/l)	TKN (mg/l)	TOC in sediment (mg/kg)	TP (mg/l)	TSS (mg/l)
W03148013	S009-171	160	ND	1.02	422	0.006	ND	0.07	64.3	565	0.27	260,000	0.007	2
W03148011	S007-795	180	ND	4.82	997	0.012	ND	ND	3.04	3,720	0.67	97,200	0.061	17
W03148012	S007-212	170	ND	0.29	ND	ND	ND	0.46	62.6	37.4	ND	4,350	0.004	2
W03148010	S009-172	180	ND	0.87	446	0.007	ND	0.09	37.1	1750	0.34	31,100	0.023	4.8
W03148009	S007-794	–	ND	1.72	570	0.007	ND	0.06	64.6	1,100	0.36	75,600	0.021	–
W03148008	S009-169	170	ND	3.64	338	0.01	ND	0.1	39	749	0.65	214,000	0.025	5.2
W03148002	S007-268	170	ND	0.68	437	0.014	ND	0.09	27.1	1,020	0.74	61,000	0.032	4
W03148007	S009-167	–	2.5	–	–	–	–	–	–	–	–	115,000	–	–
W03148006	S009-166	150	ND	5.73	1,270	0.007	0.06	ND	19.3	5,330	1.22	180,000	0.075	26
W03148004	S009-168	150	ND	1.59	1,630	0.011	ND	ND	13.1	2930	0.88	141,000	0.03	2.4
W03148005	S009-170	160	ND	0.69	2,480	0.01	ND	ND	ND	5280	0.93	249,000	0.029	5.6
H03148001	S007-053	150	ND	0.7	1,400	0.01	0.05	ND	ND	3,280	0.91	55,700	0.031	7.6

Parameter abbreviations: BOD5 = 5-day biochemical oxygen demand; Chla = chlorophyll-*a*; Dslv Iron = dissolved iron; Dslv PO$_4$ = dissolved orthophosphate, Total NH$_3$ = total ammonia; NO$_x$ = nitrate plus nitrite-nitrogen; TKN = total Kjeldahl nitrogen, TOC = total organic carbon; TP = total phosphorus; TSS = total suspended solids

ND: non-detect. Method detection limits: 2.4 mg/l BOD; 6.42 µg/l dissolved iron; 0.005 mg/l dissolved orthophosphate, 0.003 mg/l total ammonia, 0.005 mg/l NO$_x$, 0.15 mg/l sulfate, 0.09 mg/L TKN

–: not sampled

2.2.1.3 2016 Continuous Data: DO, pH, Conductivity

DO, pH, and conductivity were measured at 15-minute intervals at either 5 or 10 sites along Wyman Creek (depending on the parameter) from 7/28/2016 to 8/18/2016 (Table 6). The majority of the sites rarely or never met the water quality standard DO minimum of 7.0 mg/l; sample site W03148012 at the West Mine Pit outflow is the only site that met the DO standard at all times (Figure 9). For reference, the typical DO saturation along Wyman Creek at the observed water temperatures presented in Section 2.2.1.4 is in the range of 8.0–9.9 mg/l.

Continuous DO data show large diel variation downstream of the railroad crossing (W03148009; Figure 10) and relatively low variation at other sampling locations. The sites with the lowest average DO are located upstream of the West Mine Pit outflow (W03148011; Figure 10) and along the west braid (W03148005; Figure 11), both of which are controlled by the presence of very large beaver dams and stagnant ponding. The lowest diel swings are observed in the West Mine Pit outflow (W03148012), which met the DO standard at all times, and the most upstream site (W03148013), which originates from the headwater mine pit outflow and met the DO standard infrequently.

Table 6. Continuous DO, pH, and conductivity sampling data statistics along Wyman Creek

HYDSTRA ID	Dissolved Oxygen (mg/l) [a]				pH			Conductivity (µmhos/cm)		
	Mean	Min	Max	Percent of Samples < WQS (7.0 mg/L)	Mean	Min	Max	Mean	Min	Max
W03148013 [b]	6.35	5.10	7.30	96%	7.85	7.53	8.02	438	389	443
W03148011 [b]	0.35	0.00	2.14	100%	N/A	N/A	N/A	N/A	N/A	N/A
W03148012	8.12	7.82	8.71	0%	N/A	N/A	N/A	N/A	N/A	N/A
W03148010	3.16	2.06	4.67	100%	7.46	7.40	7.57	403	381	428
W03148009	6.74	3.89	16.55	66%	7.67	7.42	8.53	443	413	481
W03148008	5.31	3.24	7.57	96%	7.39	7.24	7.53	383	360	405
W03148002	5.78	4.72	6.61	100%	N/A	N/A	N/A	N/A	N/A	N/A
W03148007	3.20	0.03	6.76	100%	N/A	N/A	N/A	N/A	N/A	N/A
W03148005 [b]	0.05	0.00	0.99	100%	N/A	N/A	N/A	N/A	N/A	N/A
H03148001	5.67	5.17	6.29	100%	7.37	7.24	7.45	297	274	324

a. DO sensor (HOBO U26-001) accuracy is +/- 0.2 mg/l up to 8 mg/l; +/- 0.5 mg/l up to 20 mg/l.

b. DO data at this site include some data flagged as “poor” quality which indicates a large difference between the sonde measurement and a spot measurement taken for sensor validation. Data quality flag indicates potential sensor drift as per DNR/MPCA flagging protocol (difference between field sonde and handheld logger between 0.5-2.0 mg/l is flagged as “poor”). As per DNR/MPCA protocol, DO measurements of zero which are matched by handheld loggers and bracketed by good quality data are considered reliable.

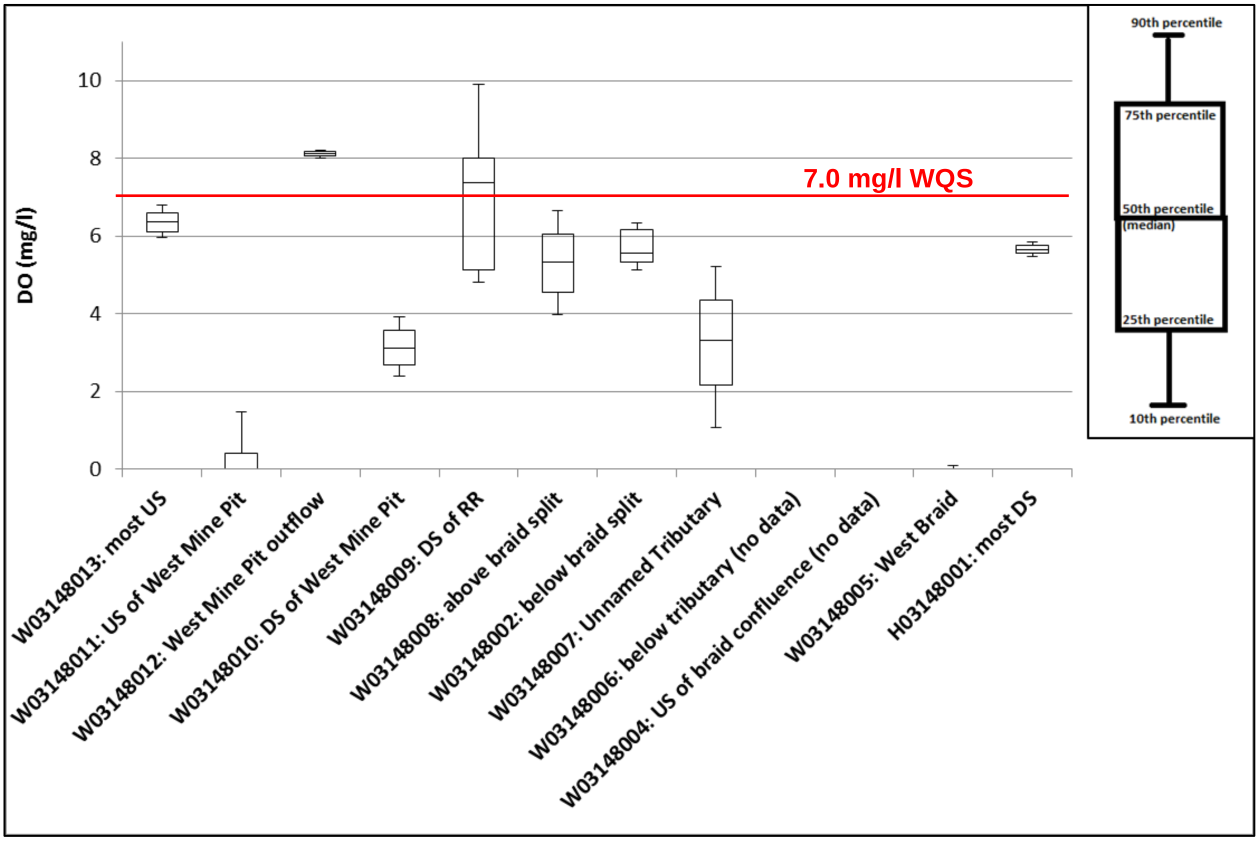


Figure 9. Box-and-whisker plots of DO from 2016 along Wyman Creek.

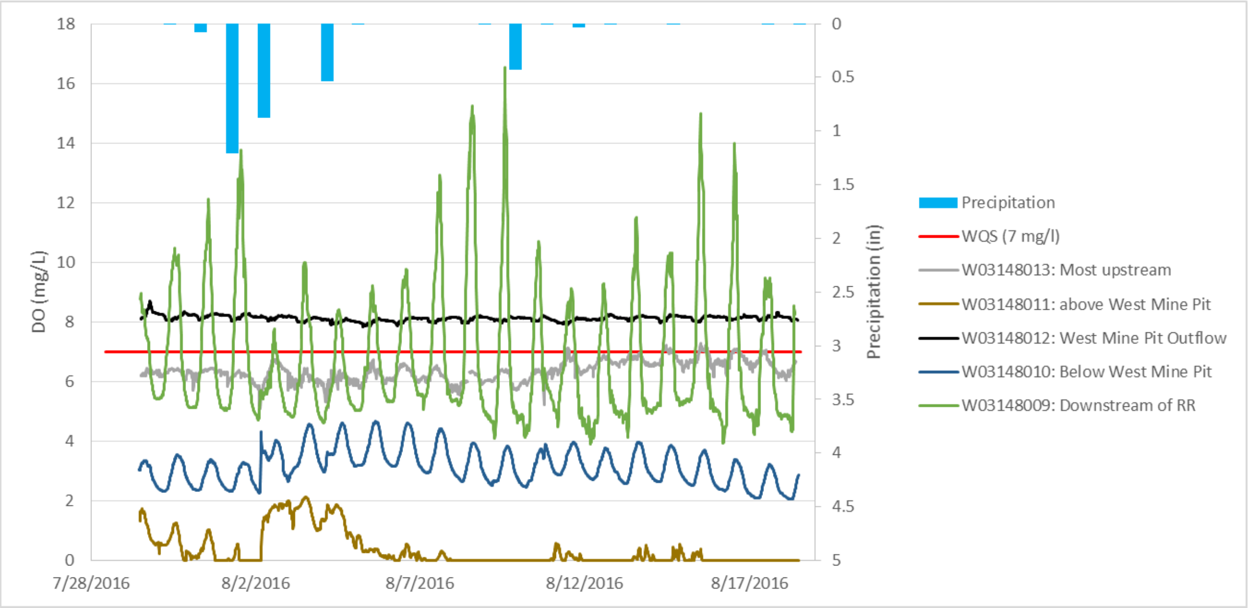


Figure 10. Continuous hourly DO monitoring, five most upstream sites along Wyman Creek.

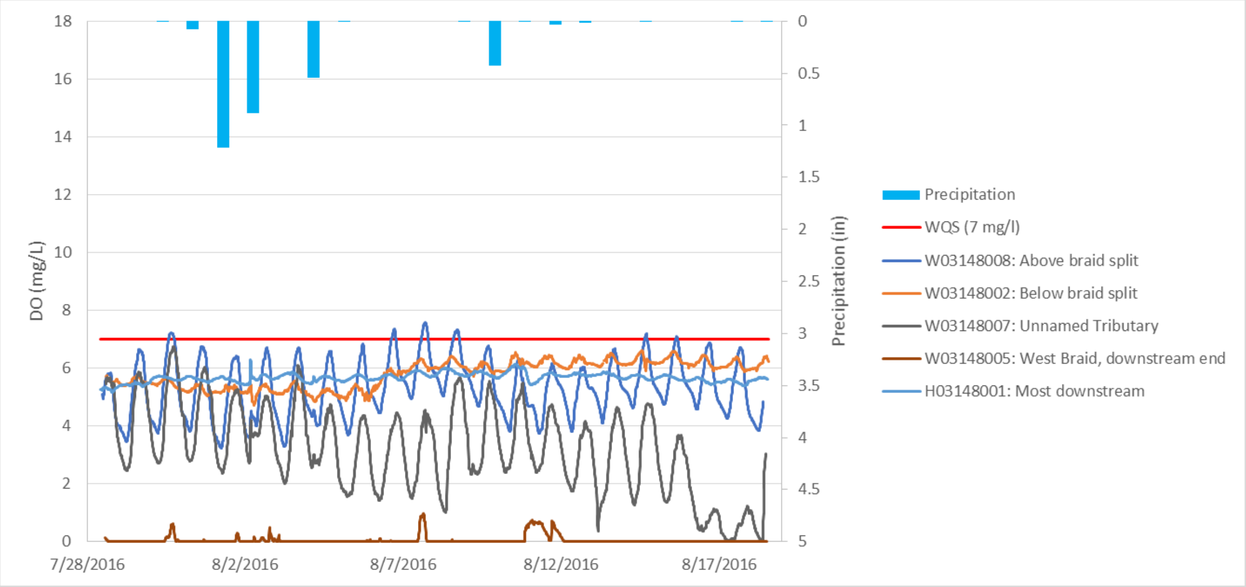


Figure 11. Continuous hourly DO monitoring, six most downstream sites along Wyman Creek.

Upstream of the West Mine Pit (W03148011) the observed DO is low, with a maximum observed DO of 2 mg/l. The higher DO concentrations in the outflow from the West Mine Pit (8 mg/l average) increase the DO in Wyman Creek immediately downstream to an average of 3 mg/l (Figure 12).

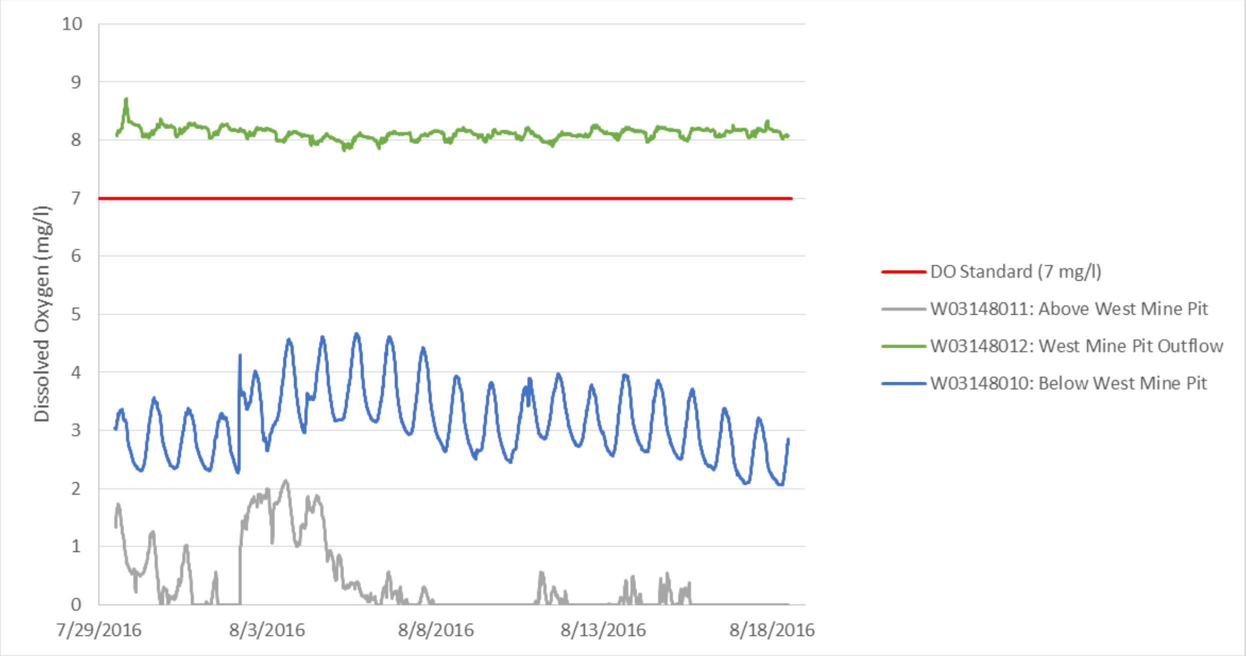


Figure 12. Continuous DO around the West Mine Pit outflow along Wyman Creek.

The largest diel fluctuation in pH was observed at the railroad crossing site (W03148009; Figure 13). The high diel fluctuation in pH at the railroad crossing is likely a result of high rates of algal and macrophyte photosynthesis during the day (producing oxygen and consuming bicarbonate, which raises pH), followed by nighttime respiration (which consumes oxygen and generates carbon dioxide, lowering pH; Figure 14). The relatively sharp decreases in conductivity that occur simultaneously across all sites occurred after precipitation events. All pH readings meet the state water quality standards (pH range of 6.5–8.5).

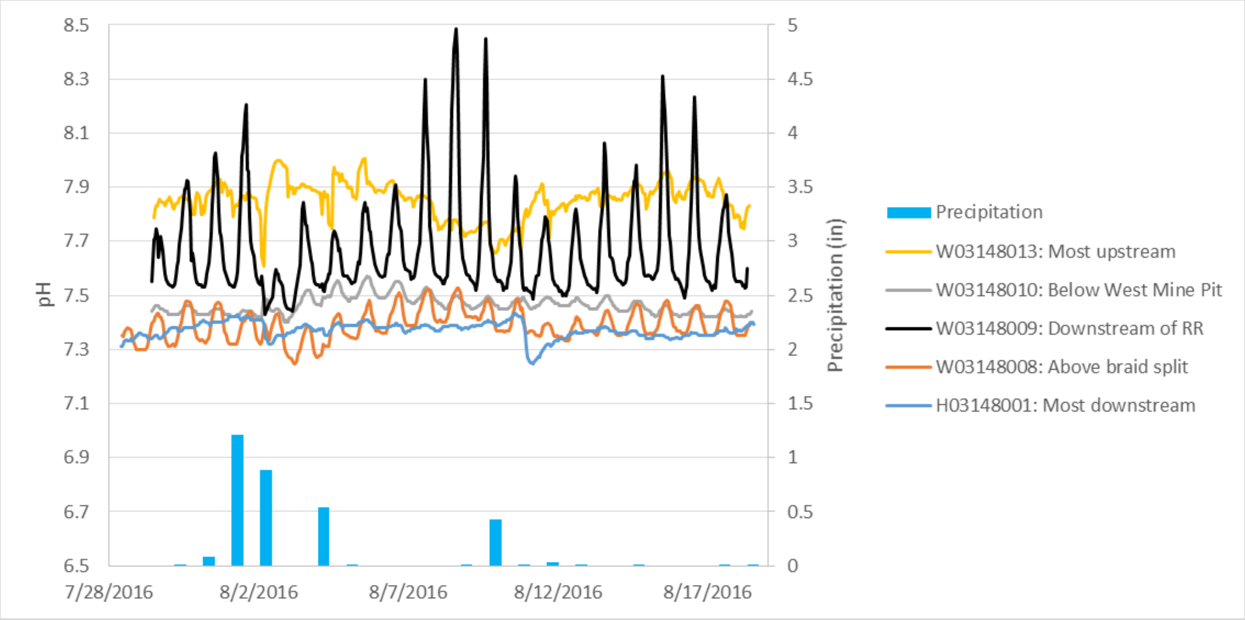


Figure 13. Continuous hourly pH monitoring along Wyman Creek

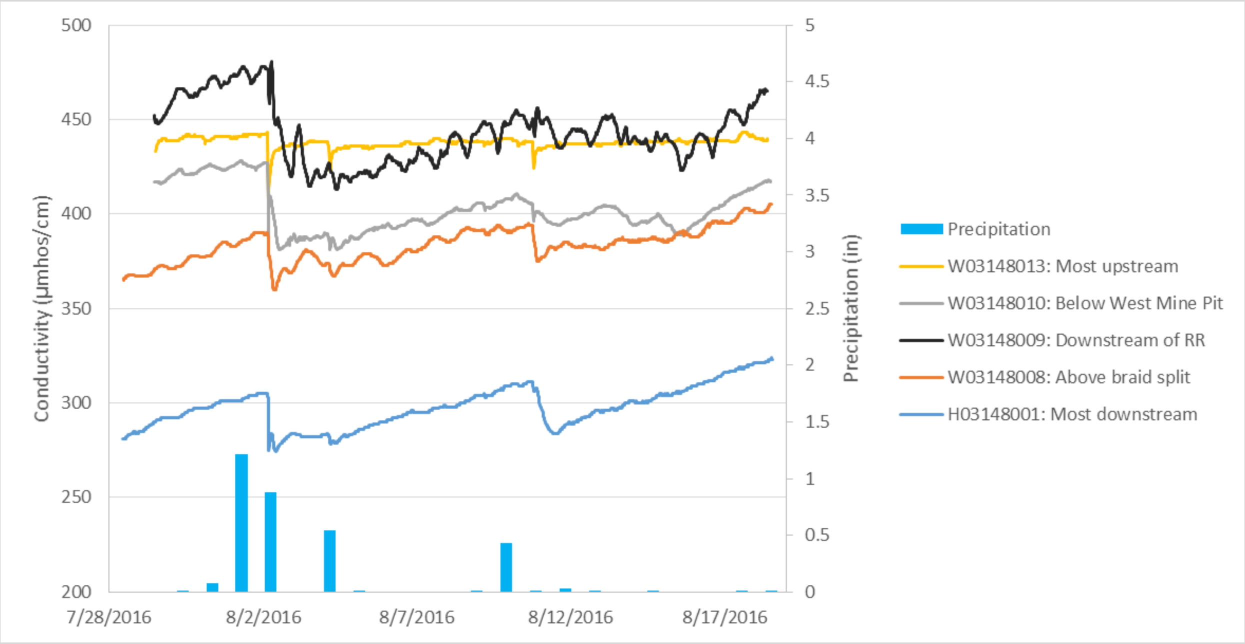


Figure 14. Continuous hourly conductivity monitoring along Wyman Creek

2.2.1.4 2016 Continuous Data: Water Temperature

Continuous water temperature was measured at all 12 sampling sites at 15-minute intervals from 7/28/2016 to 8/18/2016 (Table 7, Figure 15). Although there is not a numeric criterion for water temperature in Wyman Creek, growth of brook trout is optimal at temperatures less than 20 degrees Celsius for at least 70 percent of the time (MPCA 2016); therefore 20 degrees Celsius is considered the Wyman Creek temperature target. During the sampling period, only two sites maintained temperatures less than 20 degrees Celsius for at least 70 percent of the time—sites W03148004 and W03148005, which are located on Wyman Creek upstream of the braid confluence and on the downstream end of the west braid, respectively.

The largest diel water temperature fluctuations were observed on Wyman Creek downstream of the perched culvert (W03148009; Figure 16) and on the unnamed tributary (W03148007; Figure 17), both of which are influenced by ponded water. The large fluctuations are likely due to the low shade and the ponded water, which forms a wide but shallow water body that is highly controlled by the diel pattern of air temperature. The smallest diel temperature swings occur at the West Mine Pit outflow (W03148012; Figure 16), and the only sites with temperatures over 20 degrees Celsius at all times were those originating directly from abandoned mine pits (W03148012 and W03148013; Figure 16). Although the water originating from the abandoned mine pits also is associated with low shade, the pits are less controlled by daily fluctuations in air temperature due to great depth and volume.

Table 7. Continuous water temperature data statistics on Wyman Creek, summer 2016 data

HYDSTRA ID	Location	Mean Water Temperature (°C)	Min Water Temperature (°C)	Max Water Temperature (°C)	Temperature Range [Max-Min] (°C)	Percent of Samples above 20 °C
W03148013	Mainstem, most upstream	23.03	21.39	25.71	4.32	100%
W03148011	Mainstem, above West Mine Pit	20.43	17.61	23.76	6.15	61%
W03148012	West Mine Pit outflow	21.98	21.09	23.77	2.68	100%
W03148010	Mainstem, below West Mine Pit	20.64	18.22	23.62	5.40	70%
W03148009	Mainstem: downstream of railroad	20.84	16.11	26.36	10.25	56%
W03148008	Mainstem: above braid split	21.44	19.12	24.58	5.46	90%
W03148002	Mainstem, below braid split	20.55	18.26	23.20	4.94	70%
W03148007	Unnamed tributary	22.00	17.26	27.11	9.85	79%
W03148006	Mainstem, below unnamed tributary	20.22	18.61	23.14	4.53	60%
W03148004	Mainstem, above braid confluence	19.56	17.87	21.24	3.37	29%
W03148005	West Braid, downstream end	18.69	16.56	20.86	4.30	5%
H03148001	Mainstem: most downstream	19.77	17.14	22.72	5.58	41%

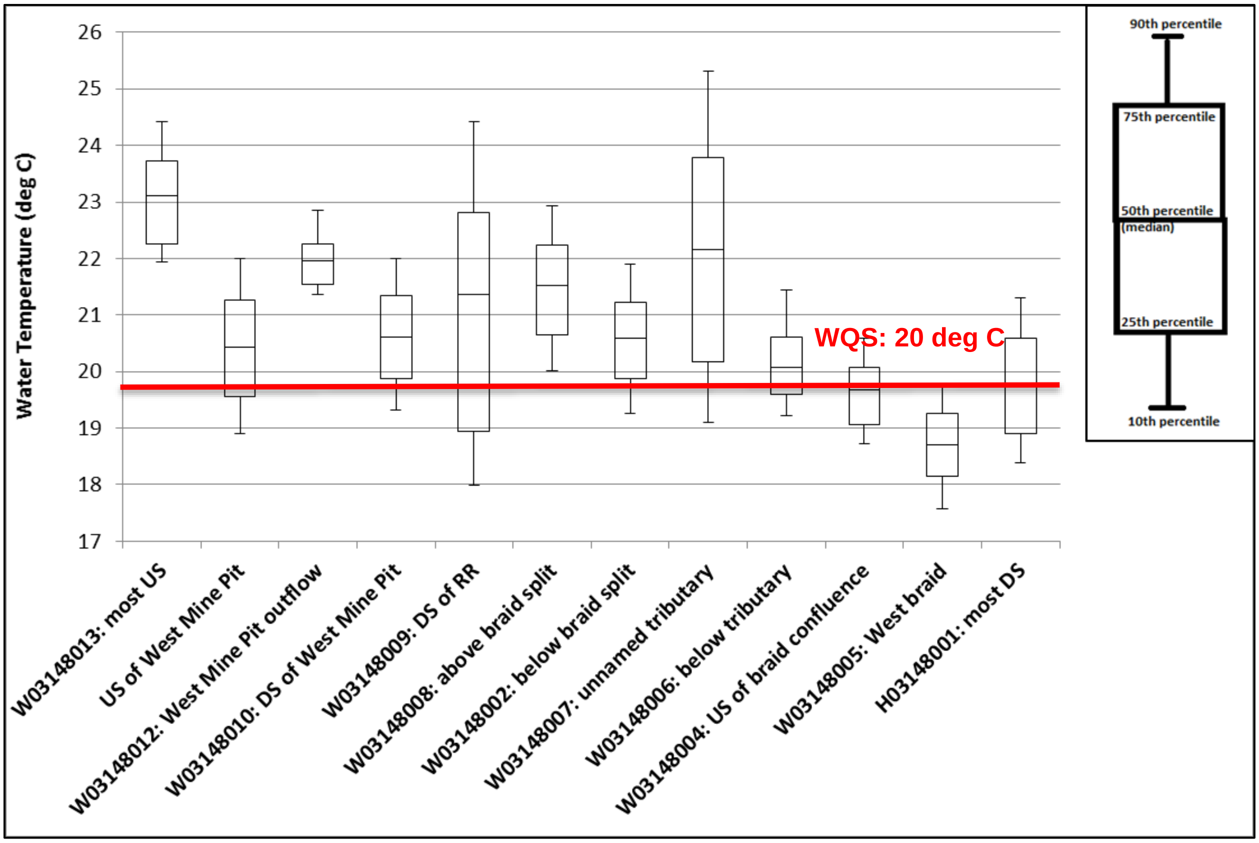


Figure 15. Box-and-whisker plots of water temperature data along Wyman Creek.

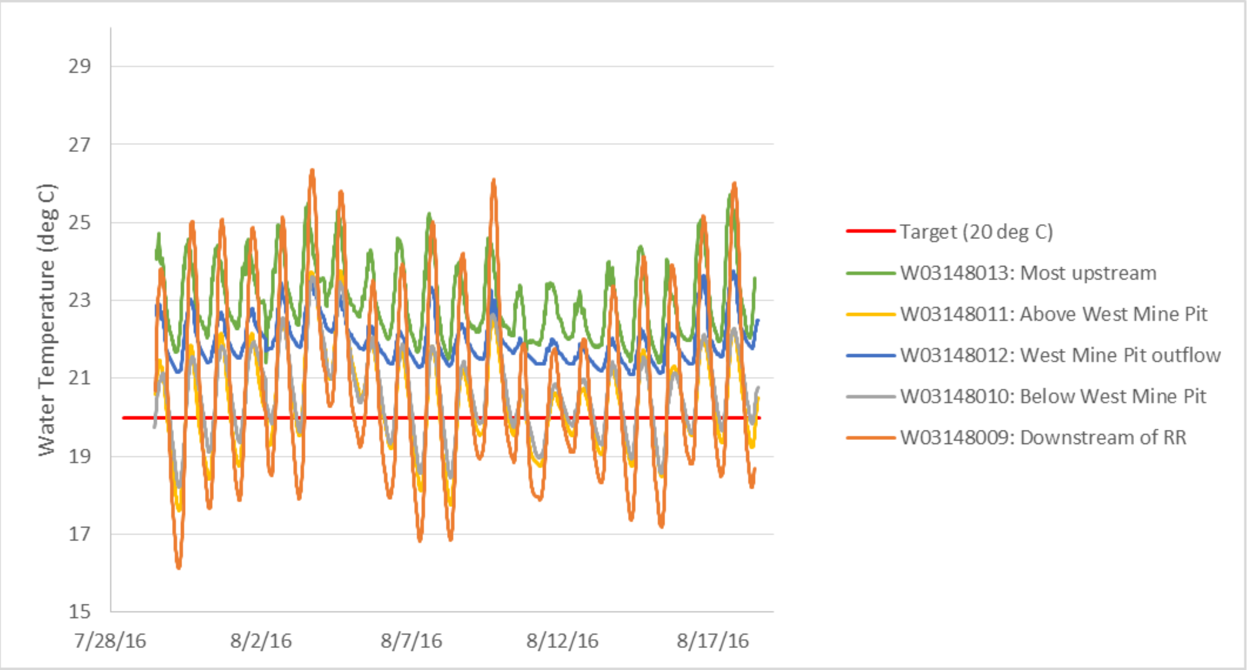


Figure 16. Continuous water temperature, five most upstream sites along Wyman Creek.

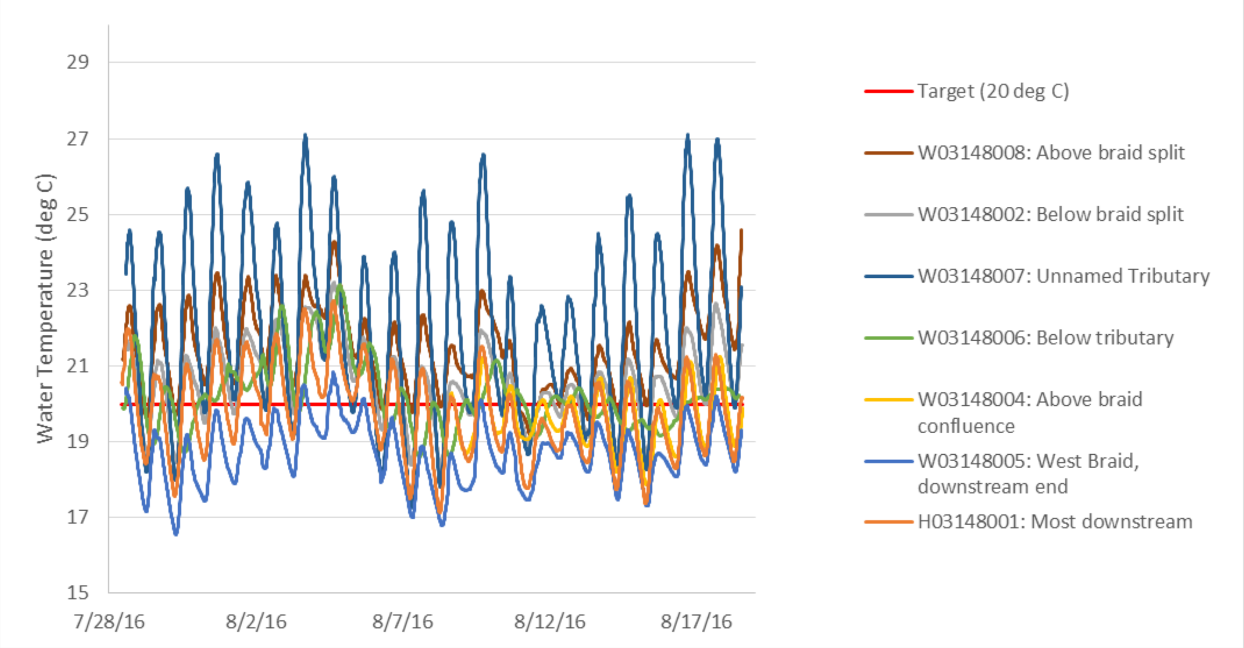


Figure 17. Continuous water temperature, seven most downstream sites along Wyman Creek.

While the West Mine Pit outflow had a noticeably positive impact on DO concentrations immediately downstream in Wyman Creek, the warmer water temperatures from the West Mine Pit had a smaller relative impact on instream water temperatures (Figure 18). The warm temperatures of the West Mine Pit outflow increase downstream water temperatures by less than one degree Celsius, although recall from the Stressor ID Report sampling that the West Mine Pit outflow is cooler than instream waters during other parts of the year.

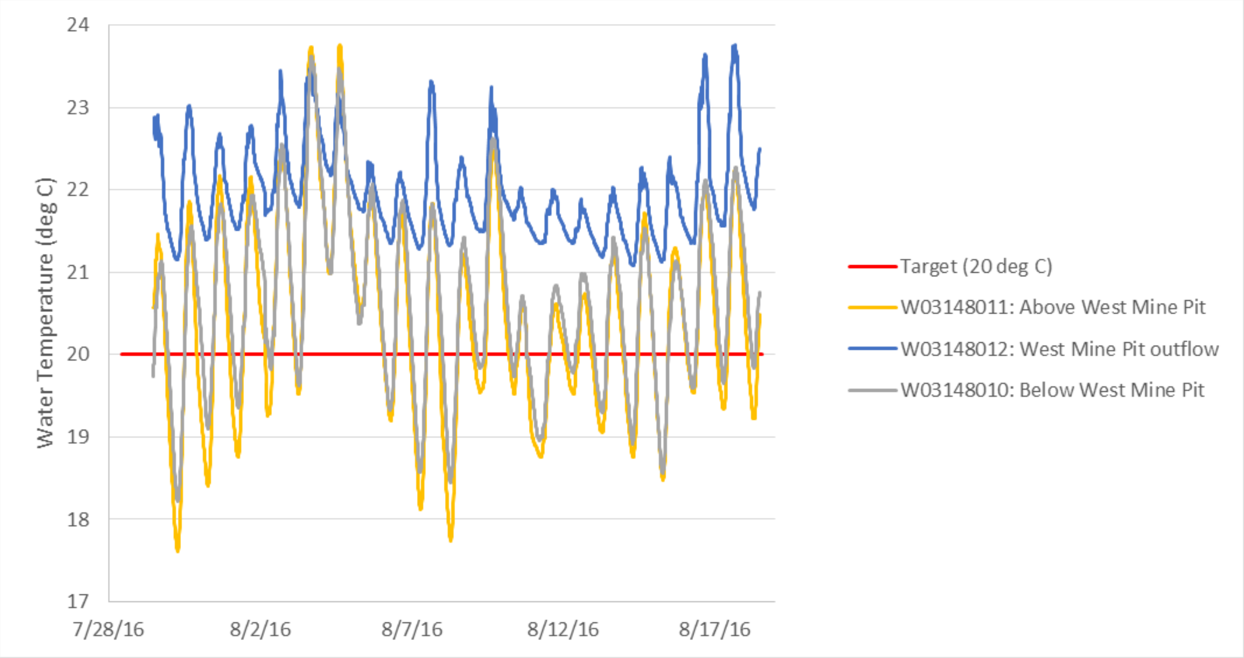


Figure 18. Continuous water temperature around the West Mine Pit outflow along Wyman Creek

2.2.2 Data Analysis

The general relationships between water temperature and DO concentration are well-documented. Cold water can hold more DO than warm water, and DO can have both daily and seasonal cycles in response to changes in air and water temperature. DO is also influenced by aquatic organisms; for example most organisms use oxygen for cellular respiration (including bacteria and algae), and photosynthetic organisms (plants and algae) produce oxygen when they are photosynthesizing.

High water temperatures and low DO in Wyman Creek appear to be caused by a combination of natural and anthropogenic factors. Natural factors include the low gradient system, natural wetlands, peaty soils that have naturally low DO in baseflow discharge, organic material in the stream that exerts sediment oxygen demand, ponded water from beaver dams, and oxygen demand caused by the presence of iron reducing bacteria. Anthropogenic factors include mine pits, ponded water from a perched culvert, altered hydrology, and lack of riparian shade.

The following summary presents a synthesis of the temperature, DO, and shade data to tease apart the importance of the multiple factors controlling temperature and DO in Wyman Creek. Paired observations of average hourly water temperature versus DO at each monitoring site for which both parameters are available are presented in Figure 19. The graphic in the top left of the figure serves as a key: values in the top left quadrant of each inset meet both the water temperature and DO targets; values in the top right quadrant meet the DO target but not the temperature, etc.

Starting at the most upstream monitoring site on Wyman Creek (W03148013), which represents outflow from the Headwater Mine at the northern tip of the watershed, water temperatures were high and DO concentrations moderately high. Moving downstream (W03148011), DO dropped substantially and temperatures decreased. The drop in DO was likely due to low gradient wetlands and the stagnation of water and ponding that occurs immediately in the vicinity of the DO logger, which is downstream of a series of beaver dam debris ponds. The temperature decrease was likely due to the increased shade from riparian vegetation between the two monitoring locations and groundwater inflows.

Moving downstream to the outflow from the West Mine Pit (W03148012), Figure 20 shows the local air temperature, water temperature, and DO for the outflow from August 8 through August 11. DO in the West Mine Pit outflow was greater than 7 mg/l during the entire monitoring period, and the water temperature was higher than the temperature target for the entire monitoring period. As water temperatures rose in the morning, DO typically reached its daily minimum at around 10:00 AM; as water temperatures fell in the evening, DO reached its daily maximum at around 6:00–7:00 PM. The DO fluctuations were minor and are not evident in Figure 20, which has been scaled for comparison. Air temperatures fluctuated daily on the order of 10 degrees Celsius over the course of the day, while water temperatures fluctuated in the West Mine Pit outflow on the order of only 1 or 2 degrees Celsius. This small fluctuation provides insight into the temperature buffering capacity of the mine pit. The outflow of the West Mine Pit (W03148012) had relatively high DO and warm temperatures; the outflow increased DO in Wyman Creek and slightly increased temperature (W03148010) relative to upstream of West Mine Pit outflow.

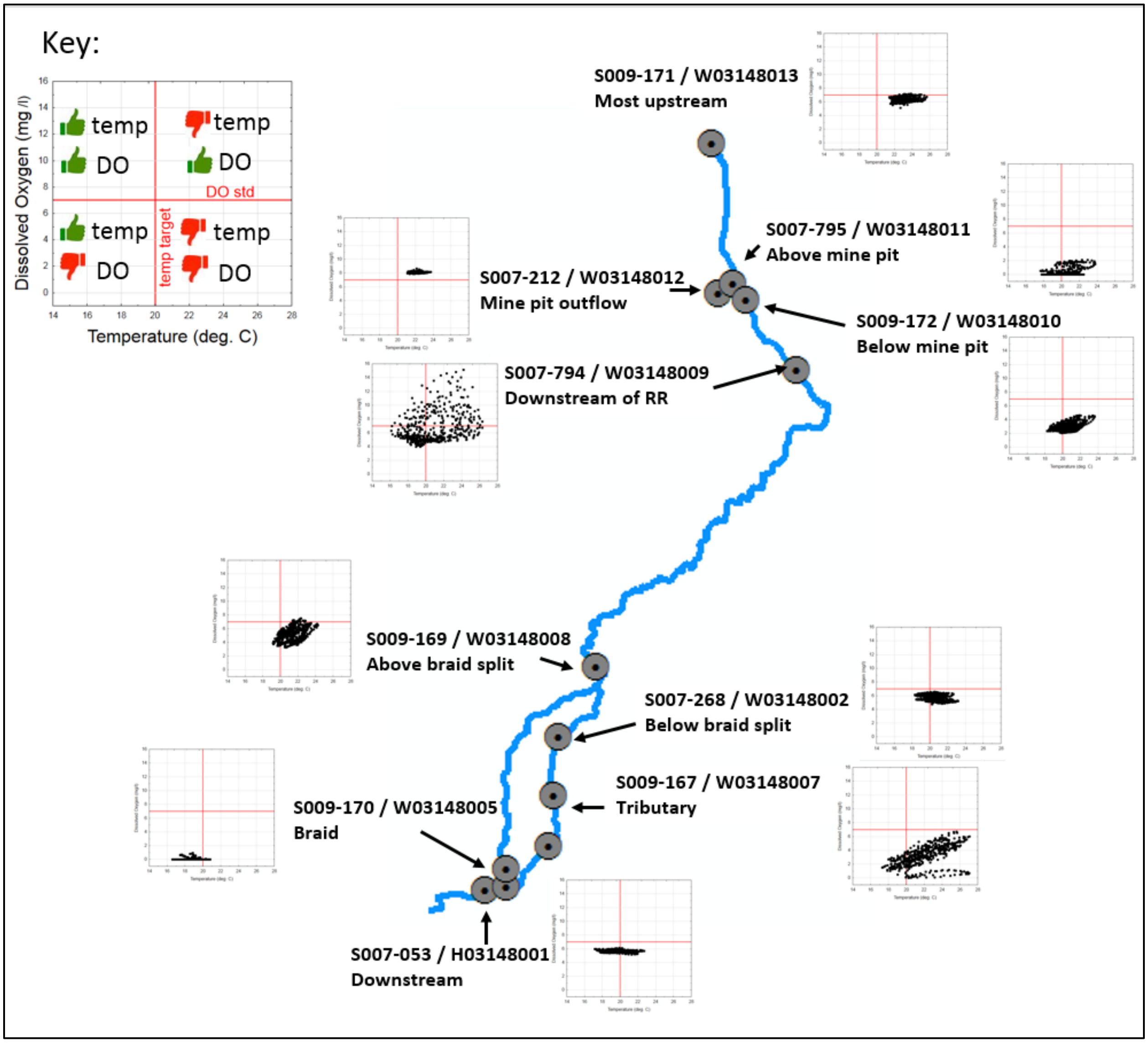


Figure 19. Schematic of DO and temperature along Wyman Creek.

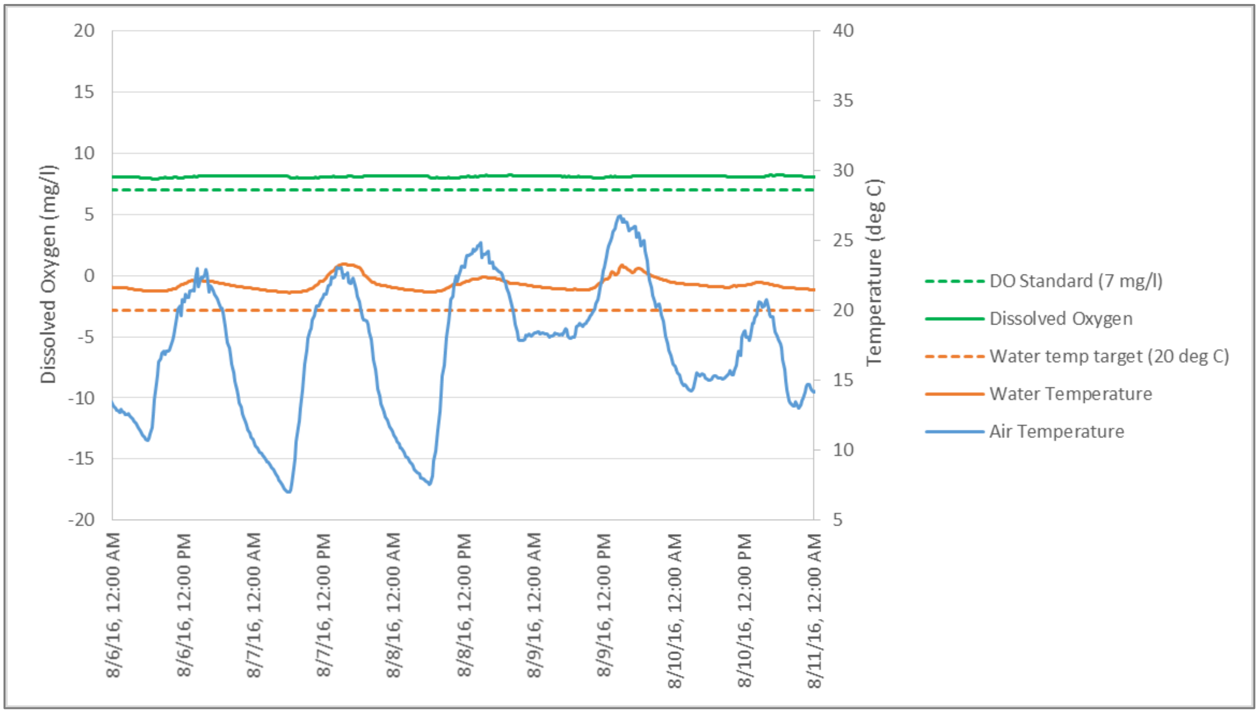


Figure 20. Continuous water, air temperature, and DO at the West Mine Pit outflow (W03148012), August 6–11.

The site downstream of the Erie Mining Company Railroad crossing (W03148009) represents outflow from a large, shallow ponded area that is a result of a perched culvert. DO and temperature were highly variable—diurnal fluctuations in DO were likely caused by plant photosynthesis, and diurnal fluctuations in temperature were due to the ponded area, which is shallow with a relatively large and unshaded surface area (Figure 21). The daily maxima are similar to the daily air temperature maxima, which are higher than the instream target. The large diel fluctuations in DO suggest high rates of photosynthesis. Aerial photos suggest that the large pond immediately upstream contains large amounts of macrophytes and is fairly shallow.

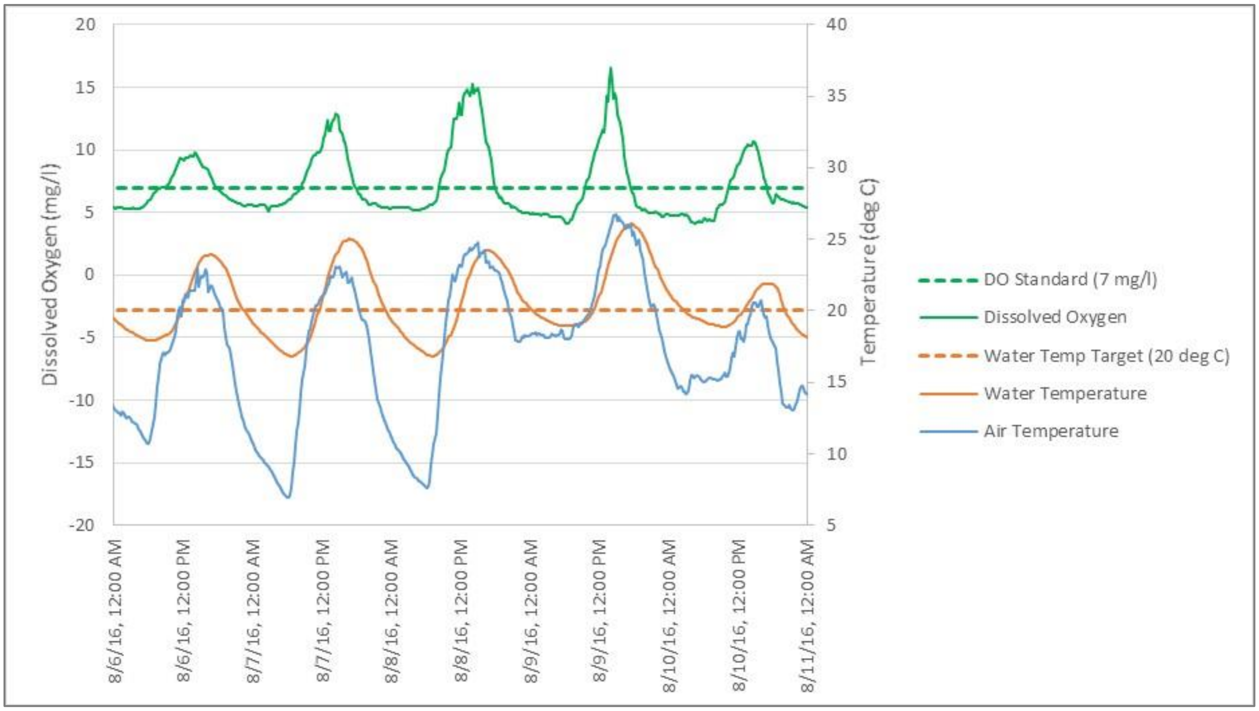


Figure 21. Continuous water and air temperature, and DO downstream of the Erie Mining Company Railroad crossing on Wyman Creek (W03148009)

The next monitoring site is above the braid split (W03148008), where temperatures were high and DO low (Figure 19). This site, which has been historically difficult to monitor due to inaccessibility, is located at the downstream end of a 6-mile stretch of Wyman Creek that flows through wetlands and is punctuated by approximately 12 to 15 beaver dams. The impact of beavers on Wyman Creek can be seen in the character of riparian vegetation as well as the changes in channel width due to debris dam ponds. Beavers will not only remove shade-providing riparian vegetation to construct their dams, but they also create what are known as “beaver meadows” adjacent to their ponds due to subsequent flooding and soil saturation in the preexisting riparian corridor of the channel (Johnston et al. 1995; Wright et al. 2002). This segment also appears to lose water, having less flow at the bottom of the reach. Below the braid split (W03148002), conditions were similar although with slightly cooler temperatures. Baseflows increase over the length of the east side of the braid. The unnamed tributary input (W03148007) had high temperatures and high diel temperature and DO fluctuations due to ponding from beaver dams and relatively high instream plant and/or algae growth. The downstream end of the west side of the braid (W03148005) had extremely low DO and cool water temperatures. This side of the braid is less than two meters wide and has low flows compared to the east side of the braid. The cool water temperatures suggest that the braid is reasonably well shaded, despite the presence of a number of beaver dams and beaver meadow environments along the channel. It is likely that the low DO at this site on the braid is attributed to a combination of water stagnation in the beaver dams (lack of reaeration) and a build-up of organic matter and mucky sediment.

The most downstream site of Wyman Creek (H03148001), after the braid confluence, had moderately low DO and moderate temperatures (Figure 19); water temperature typically exceeds the standard during the warmest part of the day (Figure 22). The diel DO range at this gage is much lower than seen upstream as well, ranging overall by about 0.2 mg/l daily, which reflects that this stream reach is much less dominated by the presence of photosynthetic organisms.

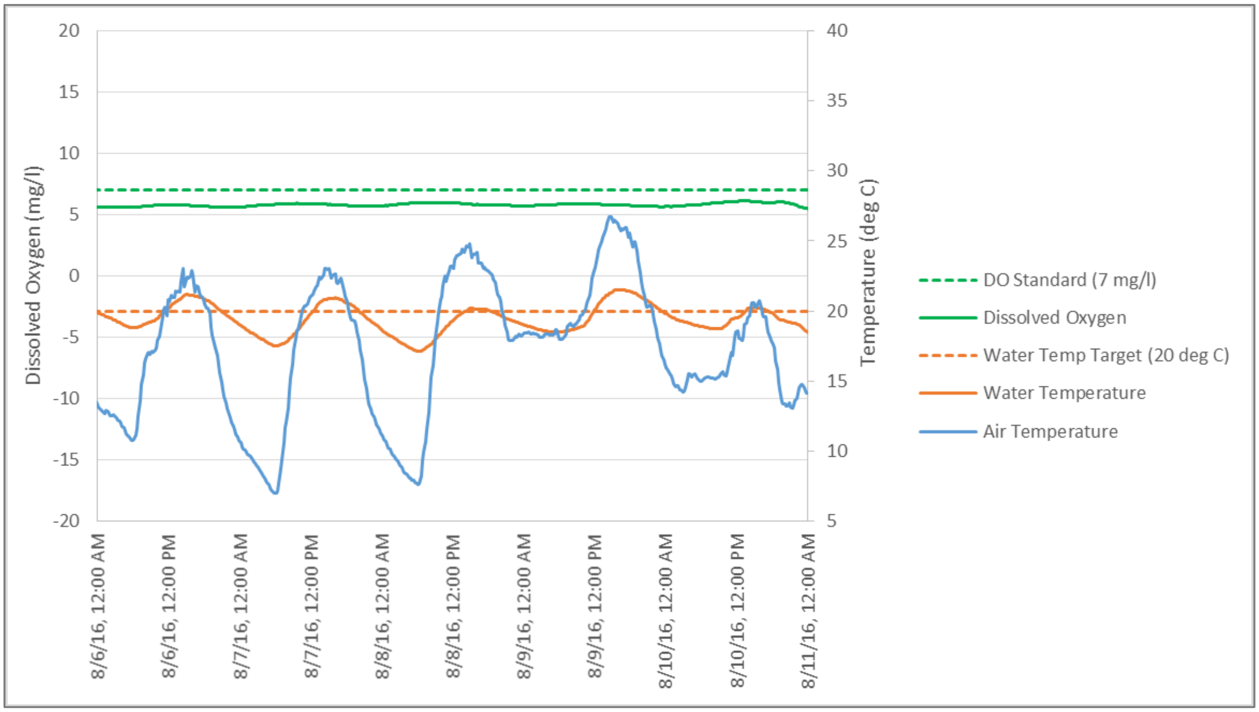


Figure 22. Continuous water and air temperature, and DO near Wyman Creek outlet (H03148001).

2.2.3 Summary

In summary, the 2016 summer observations indicate that high water temperatures in Wyman Creek are likely exacerbated by a combination of beaver dams and mine pits, both of which impound water and expose more surface water to ambient air. The creek flows through numerous wetlands, generated by backwater flooding from beaver dams, which provide minimal shade. The relative influence of mine pits, beaver dams, and other factors changes throughout the year as air temperature influences water temperature, especially in locations where unshaded bodies of water are highly exposed due to ponding or in abandoned mine pits (Figure 20 and Figure 21). Warm, stagnant water and high aquatic plant and/or algae productivity and the presence of mucky oxygen-demanding sediment can influence in-stream DO concentrations. The water drained from mine pits does not have as low observed DO or as large daily DO fluctuations as some stream channels with similarly high temperatures due to the depth of these pits and the relative absence of macrophyte growth.

3.0 QUAL2K MODEL SETUP

A QUAL2K model (Chapra et al., 2012) has been constructed to simulate existing conditions in Wyman Creek. The steady-state QUAL2K model was used for detailed evaluation of temperature and DO, heat budget, and water quality with variations in input parameters and boundary conditions. QUAL2K is well matched to the short-period, intensive/continuous monitoring work conducted by MPCA in the summer of 2016. The QUAL2K model building process for Wyman Creek involves stream segmentation into model reaches, reach parameterization based on observed characteristics, meteorological inputs, light and heat parameterization, and development of inputs to the mainstem of a diffuse nature (groundwater) and a direct nature (point sources, tributaries, etc.).

The completed, calibrated QUAL2K model was used to evaluate TMDL loading capacity and development of allocations associated with water temperature, DO, and other parameters that influence these key constituents.

3.1 MODEL DOCUMENTATION

The most recent version of the QUAL2K model available at the time of this report was used for modeling Wyman Creek: QUAL2K version 2.12b1. QUAL2K is a river and stream water quality model that is intended to represent a modernized version of the QUAL2E model (Brown and Barnwell, 1987). QUAL2K was developed at Tufts University and has been funded partly by the United States Environmental Protection Agency (Chapra et al., 2012). For detailed model description visit http://www.qual2k.com/.

3.2 SIMULATION OF SPECIAL CONDITIONS

3.2.1 Iron

There is evidence that iron concentrations along Wyman Creek significantly exceed EPA’s water quality criteria for protection of aquatic life of 1,000 µg/L (MPCA, 2016). Total and dissolved iron in the water column were sampled during the summer of 2016 (Table 8). Dissolved iron concentrations ranged from 338 – 2,850 µg/L along Wyman Creek, and total iron concentrations ranged from 565 – 6,120 µg/L. Iron concentrations are generally significantly lower immediately downstream of the abandoned mine pits as seen at the most upstream site W03148013 downstream of the Headwater Mine, and site W03148010 which is the outlet from the West Mine Pit. The largest observed concentrations of total and dissolved iron tend to occur downstream of the Wyman Creek braid split, which indicate that the abandoned mine pits are not a significant iron source to the system, but rather high iron concentrations are likely a result of the naturally iron-rich sediments in the watershed. The formation of iron precipitates along Wyman Creek (as seen in other areas of northern Minnesota) are likely naturally occurring due the iron-rich groundwater sources in the system; iron precipitates are most prevalent during low-flow conditions (Figure 23; MPCA, 2016). According to the Stressor ID Report, there are 18 different types of bacteria classified as “iron bacteria” which “feed” on iron and secrete slime as a bi-product. Iron bacteria oxidize ferrous iron into ferric iron which is insoluble and precipitates out of the water, using dissolved oxygen in the process (MPCA, 2016).

Table 8. Summer 2016 iron concentration data from Wyman Creek

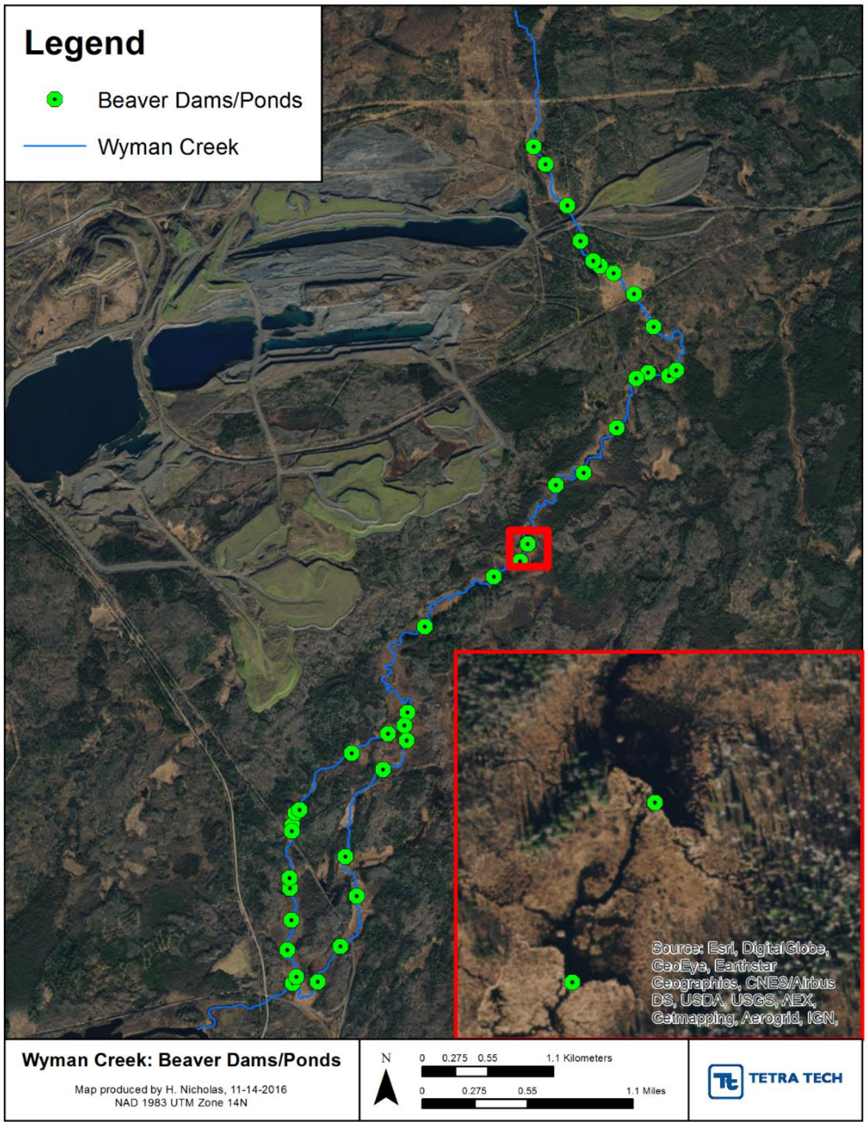
HYDSTRA ID	Location	Dissolved Iron (µg/l)		Total Iron (µg/l)	
		8/8/16	8/18/16	8/8/16	8/18/16
W03148013	Mainstem, most upstream	347	422	920	565
W03148011	Mainstem, above West Mine Pit	776	997	3,490	3,720
W03148012	West Mine Pit outflow	ND	ND	2,080	37
W03148010	Mainstem, below West Mine Pit	548	446	1,510	1,750
W03148009	Mainstem, downstream of railroad	364	570	965	1,100
W03148008	Mainstem, above braid split	402	338	831	749
W03148002	Mainstem, below braid split	477	437	1,280	1,020
W03148006	Mainstem, below unnamed tributary	1,160	1,270	2,030	5,330
W03148004	Mainstem, above braid confluence	1,340	1,630	1,990	2,930
W03148005	West Braid, downstream end	2,850	2,480	5,980	5,280
H03148001	Mainstem, most downstream	1,570	1,400	6,120	3,280

ND: non-detect. Method detection limits: 6.42 µg/l dissolved iron

Figure 23. Iron precipitate observed along Wyman Creek (MPCA, 2016).

3.2.2 Beaver Dams

Beaver dams play a significant role in channel dynamics in Wyman Creek, as there are approximately 40 dams and associated ponded areas based on an aerial imagery survey (Figure 24). These beaver dams cause Wyman Creek to widen and pond upstream. Historic logging may have impacted or increased the presence of beavers in the creek, however there are limited data to quantify this change. A review of aerial photos from the 1930s to present (see Appendix B) was conducted in an effort to trace the history of beaver activities in the watershed. Based on this review, beavers have always been present within the creek, however there appears to be an increase in beaver activity since the 1930s and 1940s. Dramatic changes in mining operations and the increase of logging in the area are well-documented, however the marshy environment around the Wyman Creek channel itself appears to have been present since the 1940s due to natural conditions. Beaver dams can cause significant buildup of woody debris, sediment, and decaying organic matter which create a conducive environment for proliferation of iron-reducing bacteria.



Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AEX, Getmapping, Aerogrid, IGN,

Figure 24. Wyman Creek beaver dams and ponds based on aerial imagery from 2017

3.2.3 Simulating Iron and Beaver Dams

QUAL2K cannot directly simulate the presence of iron in the stream. Also, there is not enough data to justify model segmentation on a fine scale to simulate every beaver dam along Wyman Creek. Since the relative impact of the beaver dam ponding and the iron-reducing bacteria cannot be untangled without extensive and expensive monitoring and experimentation, the combined impact of these two stressors are captured as an aggregate impact of natural oxygen-demanding processes approximated using sediment oxygen demand (SOD). In theory, SOD is exclusively the biological consumption of organic material at the sediment-water interface, however in the QUAL2K model for Wyman Creek it is used as a composite term to account for various combined impacts. In effect, SOD in the model acts as a surrogate for an array of complex interactions that are outside of the capabilities of QUAL2K. The model was aggregated spatially to capture the combined impact of multiple beaver dams across a region, so SOD can be used to approximate larger-scale oxygen demand from both accumulated organic deposits as well as iron-reducing bacteria. SOD was not measured directly along Wyman Creek, however it may be estimated as a function of total organic carbon (TOC) in the sediment.

Literature describing swampy blackwater stream systems in Georgia found that SOD was significantly correlated with TOC, with a coefficient of determination of 0.358 (Todd et al, 2009). The swampy Georgia stream was found to have TOC measurements ranging from 7.76 – 317.72 mg/g, and SOD rates of 0.25 – 16.97 g/m^2/d (Todd et al, 2009). Generating a linear regression using the data presented by Todd et al. (2009), SOD rates can be approximated in the Wyman Creek system using average SOD rates from the two sampling trips at each location:

$$SOD\left[\frac{g}{m^2/d}\right] = 0.031\ \times TOC\ \left[\frac{mg}{g}\right] + 2.5$$

For Wyman Creek, observed average TOC ranged from 3.58 – 249.00 mg/g, and resulting SOD rates were estimated as 2.61 – 10.23 g/m^2/d along Wyman Creek (Table 9).

Table 9. Summer 2016 TOC data and SOD estimates from Wyman Creek

EQUIS ID	Location	Observed Average Total Organic Carbon in sediment (mg/g)	Estimated Sediment Oxygen Demand (g/m^2/d)
S009-171	Mainstem, most upstream	249	10.23
S007-795	Mainstem, above West Mine Pit	134	6.65
S007-212	West Mine Pit outflow	4	2.61
S009-172	Mainstem, below West Mine Pit	52	4.13
S007-794	Mainstem, downstream of railroad	98	5.55
S009-169	Mainstem, above braid split	117	6.13
S007-268	Mainstem, below braid split	39	3.70
S009-167	Unnamed Tributary	176	7.96
S009-166	Mainstem, below unnamed tributary	152	7.20
S009-168	Mainstem, above braid confluence	157	7.37
S009-170	West Braid, downstream end	194	8.51
S007-053	Mainstem, most downstream	47	3.95

3.3 MODEL DATE SELECTION

The QUAL2K model is setup and run for a specific date, and information about latitude, longitude, and time zone are used to inform solar energy forcing. Based on the summer 2016 sampling effort conducted by MPCA, the QUAL2K model for Wyman Creek was setup for calibration and validation on two dates in August. For the 2016 sampling efforts, grab samples and flow measurements were taken on August 8 and August 18, 2016. The DO and water temperature sondes were present and logging from July 28 to August 18, however there is not a full day of DO data on August 18, so August 17 was selected for the model calibration date, and August 8 was selected for the validation date.

3.4 MODEL SEGMENTATION

The Wyman Creek QUAL2K model was setup for the full extent of the creek from its headwaters near abandoned mine pits, to the confluence of Wyman Creek and the Partridge River at Colby Lake. Wyman Creek was divided into model segments (reaches) that were parameterized with specific aggregated channel geometry, hydraulics, temperature, shade, and atmospheric conditions. These model reaches were identified based on field measurements, aerial imagery, shade estimates, key point source contributions, and other unique physical features, such as areas with frequent beaver dams. The upstream portion of the stream was further segmented to represent potential implementation activities (e.g., the pond upstream of the railroad bridge was its own segment).

Wyman Creek was segmented into 10 reaches (Table 10, Figure 25, and Figure 26). The west braid of Wyman Creek is modeled as Reach 9, a tributary flowing into the mainstem between Reaches 8 and 10.

The model reaches are made up of 0.1-kilometer computational “elements”. Hydraulic parameterization for each model reach was based on GIS spatial analyses of NHDPlusV2 flowlines, a 1-meter LIDAR elevation grid obtained from the USDA Data Gateway, and field data from surveys conducted on August 8 and August 18, 2016.

Table 10. Wyman Creek QUAL2K reach segmentation scheme

Reach	Length (km)	Monitoring Station on Reach	Location Shorthand	Description
Head-water	N/A	W03148013	Headwaters	Headwaters are represented by monitoring of two small tributaries of drainage from the Headwater Mine Pit area. Headwaters was parameterized based on this most upstream monitoring site and represent the upstream extent. This reach has a relatively narrow channel and very high shade.
1	1.05	None	Headwaters to first beaver dam	Most upstream model reach stretching from the headwater gage location, past the electric transmission line crossing, down to before the start of a series of beaver dams. There are no beaver dams present in this most upstream reach.
2	0.65	W03148011	First beaver dam to West Mine Pit inflow	Located downstream of the electric transmission line crossing to the inflow of the West Mine Pit, which is modeled as a direct input or “point source.” There are two large beaver dams along this reach, which lead to ponded areas and low shade to the stream channel.

Reach	Length (km)	Monitoring Station on Reach	Location Shorthand	Description
3	0.21	W03148010	West Mine Pit inflow to Dunka Rd	From the West Mine Pit inflow to the Dunka Road mining transportation and utility crossing. There is one beaver dam located along the stretch, with an overall narrow channel that is reasonably exposed with moderate to low shade.
4	0.43	None	Dunka Rd to ponded meadow	From the Dunka Road mining corridor crossing to the tree line and exposed beaver meadow. This reach has moderately high shade and very few beaver dams.
5	0.50	None	Ponded meadow to perched culvert	This reach represents the large saturated meadow upstream of the Erie Mining Company Railroad, which is significantly impacted due to a perched culvert. This perched culvert was identified in the MPCA Stressor Identification Report as the cause for significant sediment degradation and periodic extreme ponding events.
6	6.20	W0314800, W03148008	Perched culvert to braid split	Located downstream of the RR crossing, this is the longest model reach encompassing about fourteen beaver dams and has relatively low shade. The reach flows from the RR crossing downstream of the perched culvert to the split of the east and west braids of Wyman Creek. This reach is highly secluded and has not been adequately monitored throughout due to inaccessibility.
7	1.60	W03148002	East braid from split to unnamed tributary inflow	Reach extends as the eastern braid (mainstem) of Wyman Creek from the braid split, under Forest Road 117, down to the inflow of a small unnamed tributary. The reach is moderately well shaded, with four beaver dams.
8	1.45	W03148006, W03148004	East braid from unnamed tributary to braids confluence	Located from the confluence of the east braid with a small unnamed tributary (modeled as a direct inflow) down to the confluence of the east and west braids. This reach has low shade and highly variable width due to a number of small beaver dams and/or debris jams.
9	2.92	W03148005	West braid	The west braid from its separation from the mainstem to where it rejoins downstream. The western braid is moderately shaded. There are approximately eleven beaver dams located along this reach. Note that the upstream boundary conditions of this reach will be estimated based on in-stream conditions observed at gage W03148008.
10	1.08	H03148001	Braids confluence to outlet	Located downstream of the confluence of the east and west braids of Wyman Creek, flows underneath CR666 and a RR line until it reaches the confluence with Partridge River at Colby Lake. The reach is heavily shaded on the upstream half and minimally shaded along the downstream half. Monitoring station H03148001 is located halfway down this reach: reach parameterization emphasized the conditions of the upstream half of the reach. Monitoring station H03148001 is the most downstream monitoring gage, and also the location of air temperature monitoring.

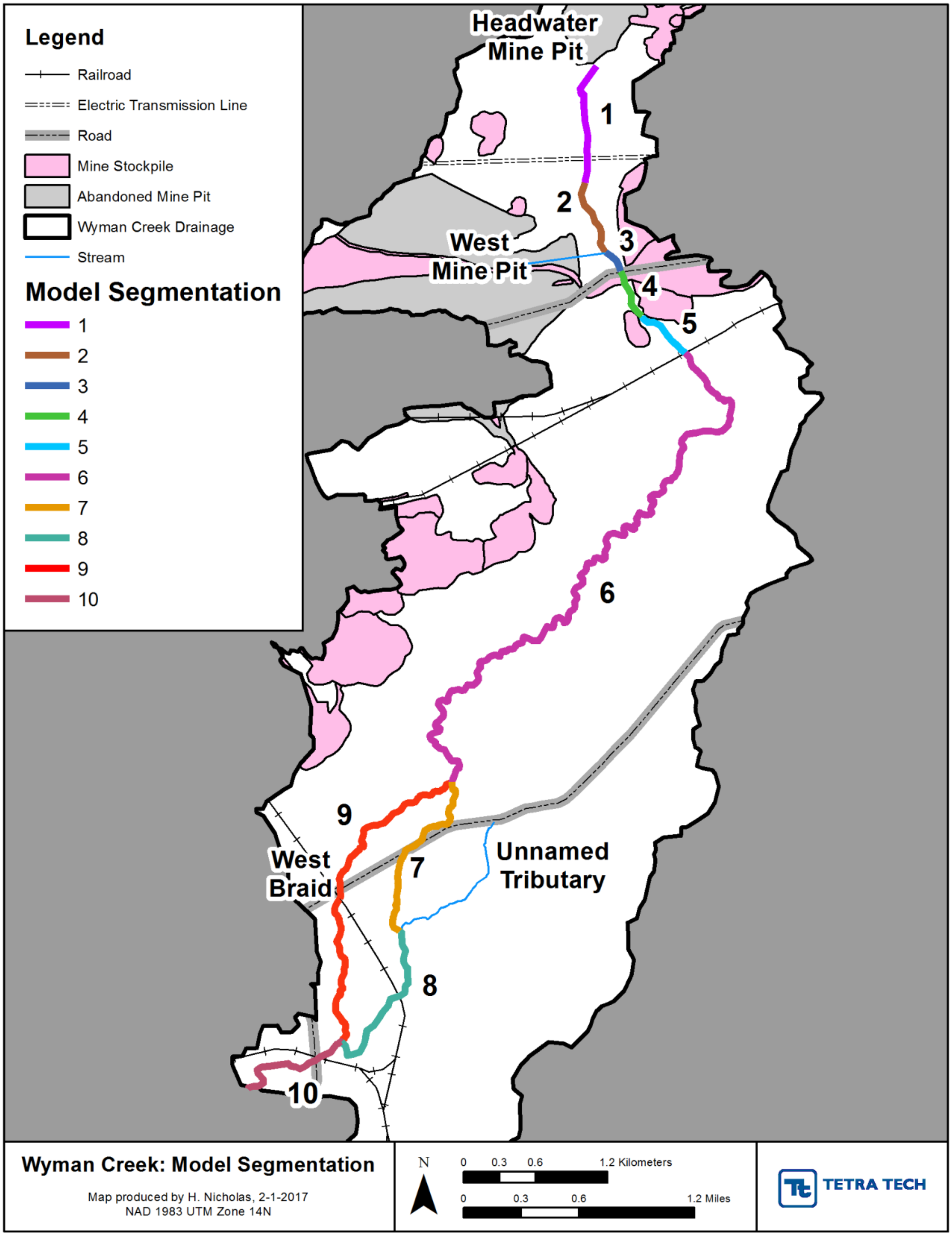


Figure 25. Wyman Creek model reach segmentation.

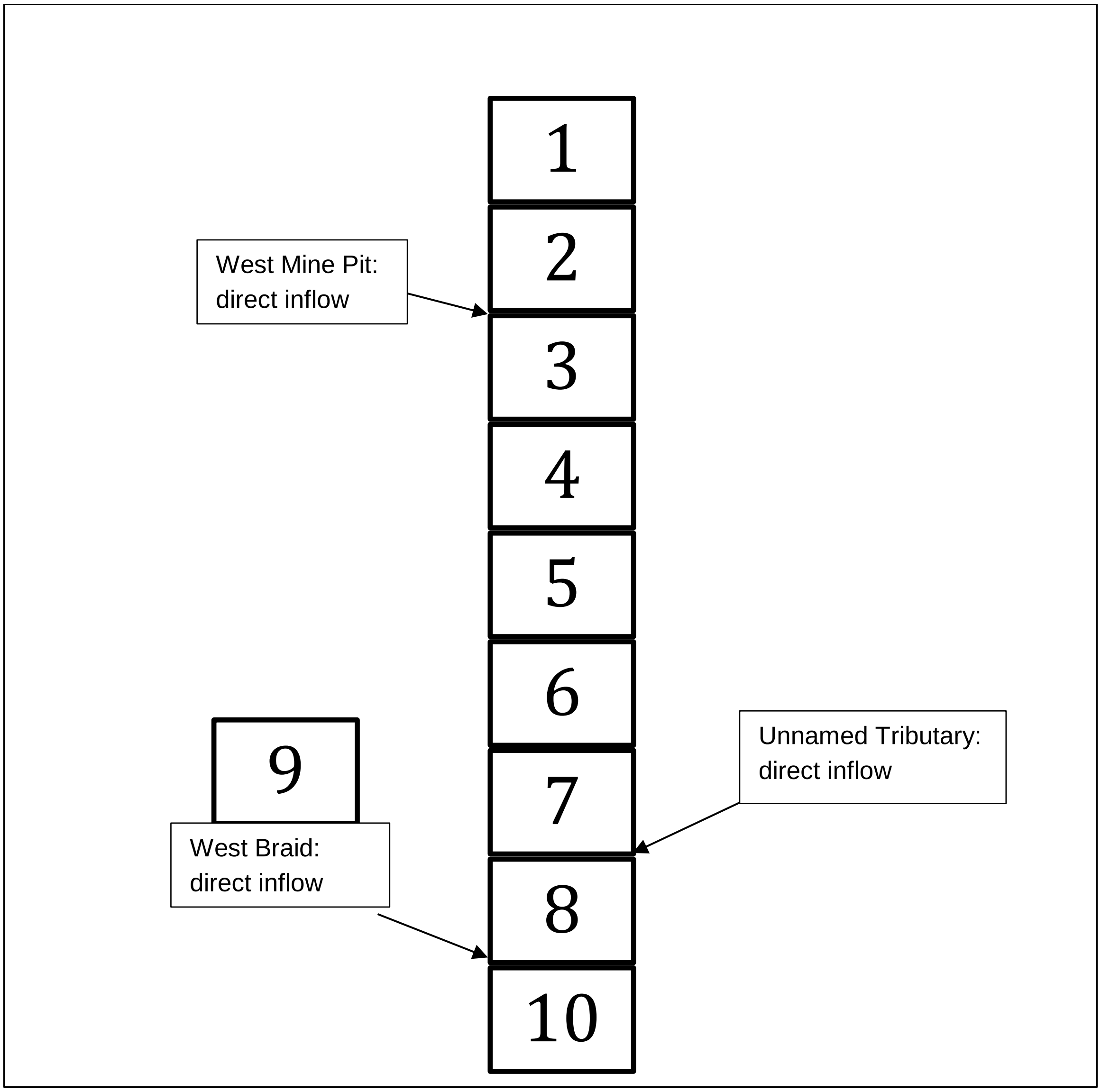


Figure 26. Wyman Creek model reach schematic as QUAL2K reach representation.

Figure 27. Aerial imagery of Reach 5 and the impact of ponding upstream of the perched culvert.

3.5 REACH HYDRAULICS

Stream hydraulics were simulated using the Manning's Formula method within QUAL2K. Model inputs related to Manning's Formula may vary for each reach and are represented as average conditions based on the 2016 field survey cross sectional data. There were 12 locations surveyed twice during summer 2016, and channel geometry characteristics are used to approximate average conditions for each model reach. These channel cross-sections correspond with the 12 grab sampling sites: one at the lower end of the west braid, one along the West Mine Pit discharge, one along the unnamed tributary discharge, and the remaining nine sites were along the mainstem. The channel cross-sections from the calibration date setup (8/18/2016) were used to parameterize hydraulics for each model reach for channel bottom width and channel side slopes.

Channel slopes were calculated as the difference between upstream and downstream elevations (determined using a 1-meter elevation digital elevation model) divided by the model reach length as estimated using NHDPlusV2 flowlines. Manning's n (roughness coefficient) typically ranges from 0.025 – 0.150 for natural free-flowing streams (Chow, 1959). However, Manning's roughness coefficient (or n) is heavily influenced by pool-riffle structures, debris, and obstructions, for which Wyman Creek is heavily obstructed (Beven, et al., 1979). Manning's n was initialized for all reaches as 0.1, a value that indicates "mountain streams with boulders," since there is significant data suggesting high debris content and irregular channel bottoms along the entire stream (Chow, 1959). Average natural channels have had roughness coefficient values increase by orders of magnitude when going from bankfull to low flow magnitudes (Yochum et al., 2014). By analyzing 29 streams in a number of countries, Yochum et al.

(2014) found that bankfull Manning's n values ranged from 0.048 to 0.30 for bankfull streams, and found that low flow Manning's n values ranged from 0.057 to 0.96 due to the presence of rocks, logs, and other obstructions to flow and impacts on channel energy loss. Manning's n for the Wyman Creek QUAL2K model was altered during the model calibration process to be reach-specific. Other parameters such as channel bottom width and side slopes were adjusted during calibration for a few reaches because the locations of the cross-sections are not necessarily representative of the character of the entire model reach. Cross-sections were not measured in reaches 4 and 5 were, so details of channel characteristics were approximated there.

Table 11. Reach hydraulic model setup inputs

Reach	Location Shorthand	Channel Slope	Manning's n	Channel Bottom Width (m)	Side Slope 1	Side Slope 2
1	Headwaters to first beaver dam	0.0029	0.1	0.19	0.4745	0.4842
2	First beaver dam to West Mine Pit inflow	0.0040	0.1	1.34	2.9280	1.2333
3	West Mine Pit inflow to Dunka Rd	0.0038	0.1	0.30	0.1605	0.3389
4	Dunka Rd to ponded meadow	0.0029	0.1	0.30	0.1605	0.3389
5	Ponded meadow to perched culvert	0.0057	0.1	0.50	0.1600	0.3400
6	Perched culvert to braid split	0.0031	0.1	0.80	0.7497	0.6411
7	East braid from split to unnamed tributary inflow	0.0040	0.1	0.30	0.1746	0.2987
8	East braid from unnamed tributary to braids confluence	0.0023	0.1	4.27	1.8000	1.7000
9	West braid	0.0030	0.1	0.61	2.7516	2.8433
10	Braids confluence to outlet	0.0034	0.1	0.31	0.0535	0.0626

3.6 REACH WATER QUALITY PARAMETERS

Modeled water quality parameters that can vary by reach include sediment oxygen demand (SOD) rates and coverage; prescribed nutrient flux rates from sediment; channel reaeration rates; nutrient hydrolysis and settling rates; phytoplankton growth, respiration, and death rates; and bottom algae coverage, growth, respiration, and death rates. If not otherwise specified for a given reach, water quality parameterization was tabulated using default values and suggested ranges of model inputs.

Model inputs related to reaeration, SOD, bottom algae, and phytoplankton can have large influence on average DO and the diurnal range of DO. The DO sondes were used to identify the diurnal variation in DO observed at specific points along Wyman Creek. DO sondes were also used to identify the relative impact of bottom algae (surrogate for macrophyte growth) along Wyman Creek based on observed diel DO variation. The daily DO range was greatest at site W03148009 on Reach 6 which had a daily swing of about 5.3 mg/l on 8/17/22016, while the lowest DO range for the Wyman Creek mainstem on that date is upstream of the West Mine Pit inflow where the DO is approximately zero all day (W03148009). Bottom algae coverage was initiated at 10% for all reaches to initialize the model, and adjusted during calibration that higher algae will be simulated in the vicinity of where high diurnal DO is observed along Reach 6.

Average in-stream DO concentrations are sensitive to SOD, which is the consumption of DO at the soil-water interface. SOD was not measured in-stream along Wyman Creek, however in-stream sediment samples of total organic carbon (TOC) were used to approximate the relative SOD at different locations. As described in Section 3.2.3, SOD was estimated from TOC measurements using the relationship identified in Todd et al. (2009). To simulate observed DO measurements in the channel, the background SOD rate was initialized to cover 100% of the streambed at the estimated rates of 2.61 – 10.23 g/m^2/d, and the percent bottom coverage of the streambed was adjusted during calibration so the relative SOD would remain consistent although the accuracy of the estimated rate has reasonably uncertainty (Table 12).

Table 12. Reach water quality model setup inputs (initialization, pre-calibration)

Reach	Location Shorthand	SOD Coverage	SOD Rate (g/m^2/d)	Note/Source
1	Headwaters to first beaver dam	100%	10.23	Estimated from site S009-171 TOC
2	First beaver dam to West Mine Pit inflow	100%	6.65	Estimated from site S007-795 TOC
3	West Mine Pit inflow to Dunka Rd	100%	4.13	Estimated from site S009-172 TOC
4	Dunka Rd to ponded meadow	100%	4.13	Estimated from site S009-172 TOC
5	Ponded meadow to perched culvert	100%	5.55	Estimated from site S007-794 TOC
6	Perched culvert to braid split	100%	6.13	Estimated from site S009-169 TOC
7	East braid from split to unnamed tributary inflow	100%	3.70	Estimated from site S007-268 TOC
8	East braid from unnamed tributary to braids confluence	100%	7.29	Estimated from average of TOC at sites S009-166 and S009-168
9	West braid	100%	8.51	Estimated from site S009-170 TOC
10	Braids confluence to outlet	100%	3.95	Estimated from site S007-053 TOC

Channel reaeration is the natural input of oxygen to a waterbody through the transfer of atmospheric oxygen into the water column at the air-water interface. Rates of reaeration are typically higher for shallow, fast moving streams, and lower for slow, deep streams. Although reaeration was not measured directly in Wyman Creek, flow measurements, channel cross-sections, and aerial imagery suggest that the creek is quite sluggish with a great deal of obstructions to flow. The Tsivoglou-Neal reaeration formula was identified as likely appropriate for Wyman Creek as it computes reaeration based on mean water velocity and channel slope, and is appropriate for low flow streams where flow ranges from 0.0283 to 0.4247 m^3/s, and the average observed flow along Wyman Creek is 0.0345 m^3/s (Tsivoglou and Neal, 1976).

For model setup, reach parameters related to nutrient processing, settling rates, and decay were held at model default values and suggested rates (Appendix C).

3.7 METEOROLOGICAL INPUTS, SHADE, LIGHT AND HEAT

3.7.1 Hourly Inputs

Metrological inputs to the QUAL2K model include air temperature, dew point temperature, wind speed, cloud cover percentage, and percent of solar radiation blocked by stream shade. Only shade varied by reach. Atmospheric monitoring at major airports is included as NOAA's Quality-Controlled Local Climatological Data (QCLCD) and is available online. The closest station to Wyman Creek is the Chisolm-Hibbing Municipal Airport, located approximately 60 kilometers southwest. The atmospheric conditions at the airport are reasonable to approximate conditions of air temperature, dew point, cloud cover, and wind speed for Wyman Creek based on the agreement between observed air temperature at the airport and a sonde located at the downstream end of Wyman Creek (Figure 28).

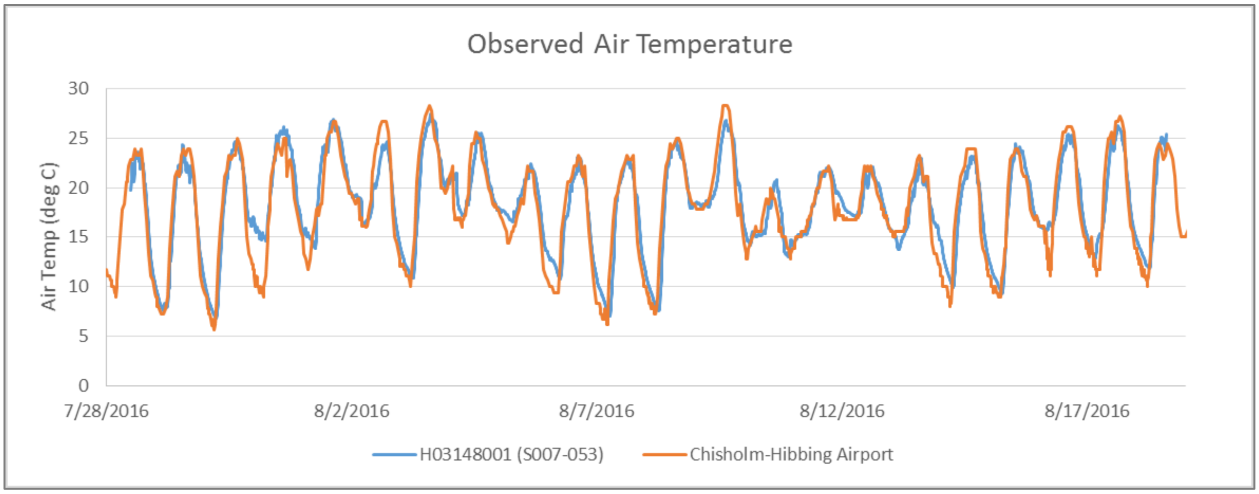


Figure 28. Observed air temperature at Wyman Creek and Chisolm-Hibbing Airport

QUAL2K model inputs require wind speed at a height of 7 meters. Observed wind speeds are available at the Chisolm-Hibbing Airport at a height of 10 meters, which may be converted to 7 meters based on the wind profile power law for neutral stability conditions (Peterson and Hennessey 1978):

$$Wind\ speed\ at\ 7\ meters = (Wind\ speed\ at\ 10\ meters) * (7/10)\hat{}0.143.$$

Table 13 and Table 14 provide hourly model inputs of each meteorological parameter for the calibration and validation periods.

Table 13. Meteorological Inputs for model calibration period (8/17/2016)

Hour	Air Temperature (°C)	Dew Point Temperature (°C)	Wind Speed (m/s)	Cloud Cover (%)
1	13.90	13.9	0.00	0.0%
2	12.80	12.8	0.00	0.0%
3	12.20	12.2	0.00	0.0%
4	11.70	11.7	0.00	0.0%
5	11.10	11.1	0.00	12.5%
6	11.10	11.1	0.00	50.0%
7	11.10	11.1	0.00	50.0%
8	14.40	14.4	0.00	100.0%
9	18.90	16.7	0.00	0.0%
10	22.80	17.2	1.27	0.0%
11	23.90	17.2	2.12	0.0%
12	24.40	17.8	2.55	12.5%
13	23.90	17.2	3.40	12.5%
14	22.80	17.2	4.25	12.5%
15	23.30	17.8	0.00	50.0%
16	24.40	18.9	3.40	0.0%
17	23.90	17.8	5.95	12.5%
18	23.30	17.8	3.40	0.0%
19	22.80	17.2	2.97	0.0%
20	21.10	17.2	0.00	0.0%
21	17.80	17.2	0.00	0.0%
22	16.10	16.1	0.00	0.0%
23	15.00	15.0	0.00	0.0%
24	15.00	14.4	0.00	0.0%

Table 14. Meteorological Inputs for model validation period (8/8/2016)

Hour	Air Temperature (°C)	Dew Point Temperature (°C)	Wind Speed (m/s)	Cloud Cover (%)
1	9.30	9.18	0.00	0.0%
2	8.60	8.60	0.00	0.0%
3	8.20	8.10	0.25	0.0%
4	7.73	7.73	0.21	0.0%
5	7.60	7.60	0.00	0.0%
6	8.90	8.90	0.00	0.0%
7	13.90	12.80	1.27	0.0%
8	16.70	13.90	1.27	0.0%
9	20.00	15.00	2.12	0.0%
10	22.20	15.60	2.97	0.0%
11	22.80	14.40	2.55	12.5%
12	24.40	15.00	2.97	12.5%
13	23.90	13.90	2.97	75.0%
14	24.40	15.00	4.25	75.0%
15	25.00	14.40	4.67	12.5%
16	25.00	13.90	2.97	12.5%
17	24.40	13.90	4.67	50.0%
18	23.30	13.30	2.97	12.5%
19	21.70	13.90	2.55	0.0%
20	20.00	14.40	2.12	0.0%
21	19.40	14.40	2.55	0.0%
22	18.90	15.00	2.55	0.0%
23	18.30	15.00	2.12	0.0%
24	18.30	15.60	2.55	0.0%

3.7.2 Shade Analysis and Inputs

The shading characteristics of the riparian corridor were estimated using a combination of the GIS-based TTools (ArcMap toolbox extension) and the Shade.xls spreadsheet tool (“Shade”).

3.7.2.1 TTools and Shade

TTools was developed by Oregon Department of Environmental Quality (ODEQ, http://www.oregon.gov/deq/wq/tmdls/Pages/TMDLs-Tools.aspx). TTools uses input coverages and grids to develop vegetation and topography data perpendicular to the stream channel and samples longitudinal stream channel characteristics such as the near-stream disturbance zone (NSDZ) and elevation. TTools can sample spatial data within the riparian zone. Typically, these include digital elevation models, and riparian vegetation digitized from aerial imagery or developed using LiDAR returns. For this project, TTools was used to sample stream width, aspect, topographic shade angles, elevation, and riparian vegetation for incorporation into the *Shade* model described below. The riparian vegetation coverage contains four specific attributes: vegetation height, general species type or combinations of species, percent vegetation overhang, and average canopy density.

Washington Department of Ecology’s Shade model (Shade.xls—a Microsoft Excel spreadsheet available at http://www.ecy.wa.gov/programs/eap/models.html; Ecology, 2003) was adapted from a program that ODEQ developed as part of its HeatSource model version 6 (http://www.deq.state.or.us/wq/TMDLs/TMDLs.htm).

Shade quantifies the potential daily solar load and generates the percent effective shade. Effective shade is the fraction of shortwave solar radiation that does not reach the stream surface because vegetative cover and topography intercept it. Effective shade is influenced by latitude and longitude, time of year, stream geometry, topography, and vegetative buffer characteristics, such as height, width, overhang, and density. TTools output serves as input for *Shade*, which is then used to generate longitudinal effective shade profiles. Reach-averaged integrated hourly effective shade (i.e., the fraction of potential solar radiation blocked by topography and vegetation) in turn can serve as input into a QUAL2K model, which is discussed below.

3.7.2.2 Inputs for Shade Analysis

Spatial data inputs to TTools include stream bank and stream centerline shapefiles, a digital elevation model, and a riparian landcover raster. For the purposes of modeling Wyman Creek, the entire mainstem channel centerline and stream banks were manually digitized using aerial imagery in Google Earth, including the secondary channel (west braid) present along the downstream extent. The bare earth elevation raster was based on Light Detection And Ranging (LiDAR) returns available from MN TOPO, the Minnesota Department of Natural Resources web application for high-resolution elevation data. The landcover raster was developed using a combination of the bare earth raster and the 4-band aerial imagery available from the National Agricultural Imagery Program (NAIP). Two surfaces were created from the LiDAR data: first-returns were used to create a “Digital Surface Model” which represents the elevations of the tallest features, and ground-returns were used to create a “Digital Elevation Model” which represents the lowest detected (ground) surface.

Aerial imagery was used to estimate the extent and quality of vegetation cover. The fourth band (infrared) and first band (visible red) were compared using the Normalized Differential Vegetation Index (NDVI), which results in a value between -1 and 1 for all pixels. Values of NDVI greater than zero indicate vegetated surfaces, with increasing health (growth rate) trending toward 1. Values below zero indicate highly stressed vegetation or developed surfaces. The vegetative cover and elevation rasters were combined into a high resolution layer indicating land cover type and height, which was used as input to the Shade Model with various additional parameters such as riparian overhang and vegetation density. Field notes were reviewed to develop an understanding of density and overhang. Model inputs for land cover density were assumed to be 75 percent for vegetation, and 100 percent for non-vegetated surfaces. Land cover features less than 3 meters tall were assumed to have no overhang, and features taller than 3 meters were assigned an overhang equal to 10 percent of the feature height.

Shade was modeled along the entire main channel as well as the west braid. TTools sampled the land cover type and height raster along the channel at defined intervals, and *Shade* calculated the impact of topography and vegetation on blocking solar radiation to the stream channel. Results from *Shade* (which must be run for the specific model calibration date to account for solar aspect) along the stream were aggregated. Hourly shade estimates (as a percentage of blocked solar radiation) can be input into QUAL2K by reach. Figure 30 shows how shade varies along the full length of Wyman Creek, while Figure 31 shows modeled shade along the west braid. Locations with 100 percent shade are associated with railroad and highway overpasses that provide full blocking of solar radiation to the channel below.

The *Shade* model outputs were averaged for each hour by model reach for model input (Table 15). The *Shade* model was run only once as a representative condition for August 2016 therefore shade inputs were identical for the calibration and validation periods.

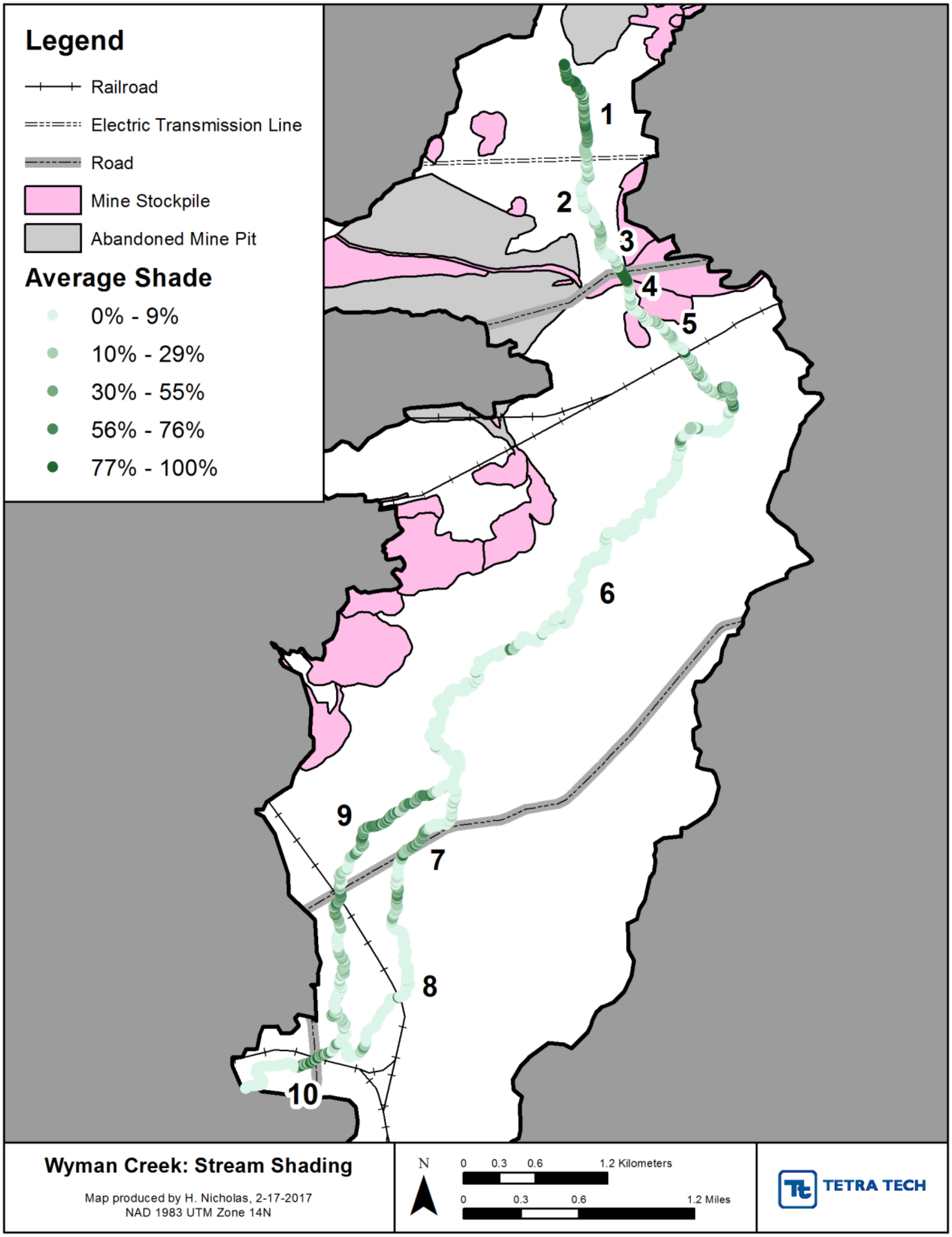


Figure 29. Average daily shade model results along Wyman Creek.

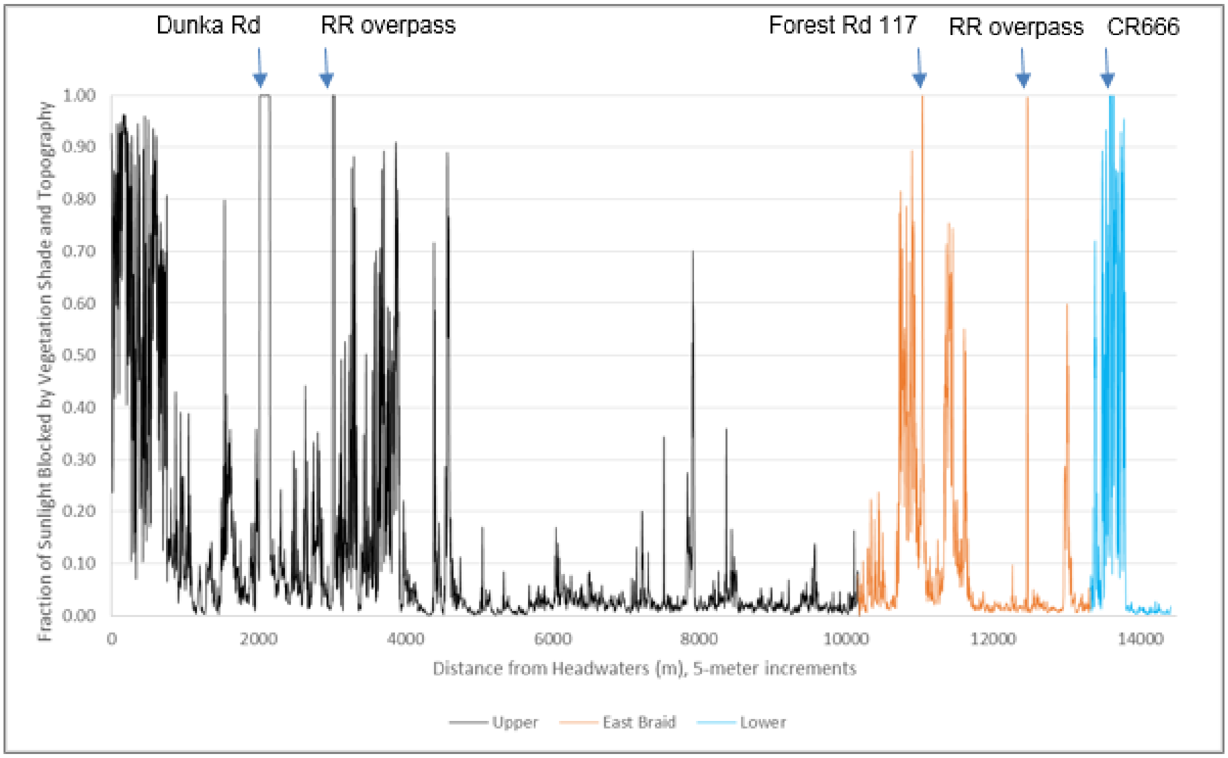


Figure 30. Shade model results on Wyman Creek (headwater to outlet, excluding the west braid).

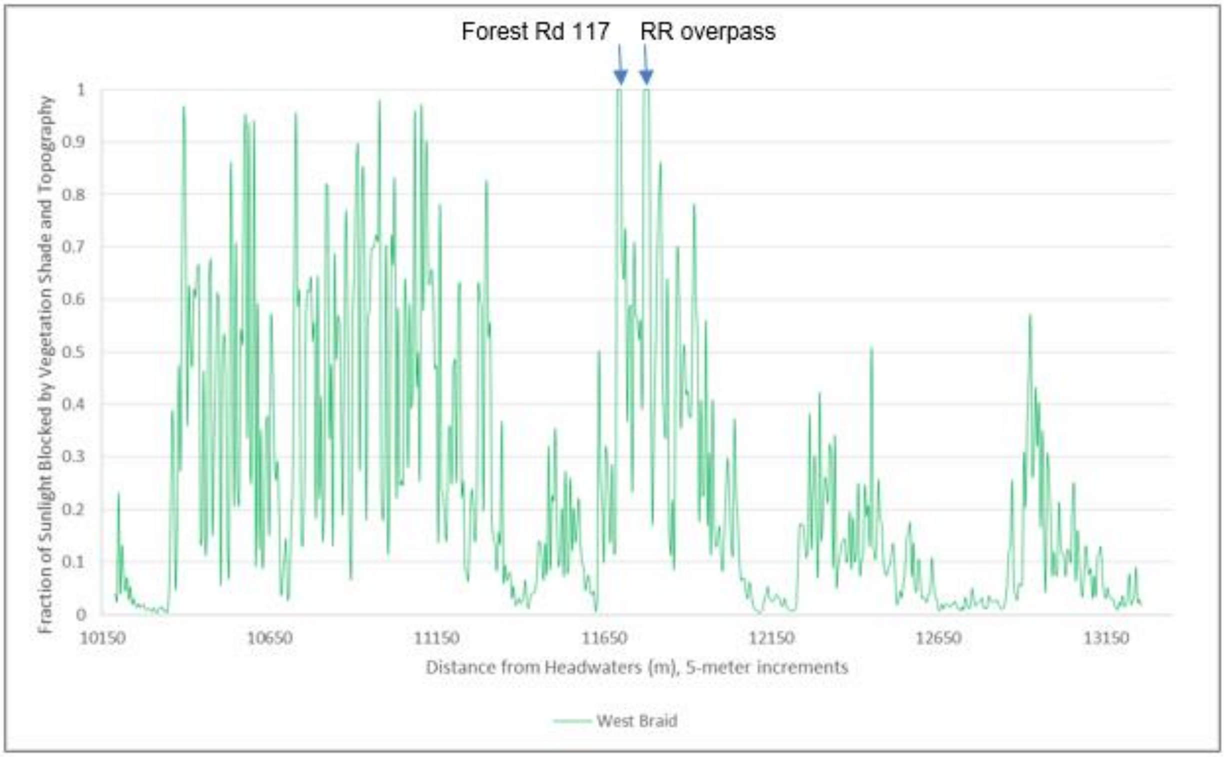


Figure 31. Shade model results on the Wyman Creek west braid.

Table 15. Average shade conditions for model calibration and validation periods by reach

Hour	Reach 1	Reach 2	Reach 3	Reach 4	Reach 5	Reach 6	Reach 7	Reach 8	Reach 9	Reach 10
1	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
2	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
3	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
4	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
5	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
6	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
7	86%	62%	54%	83%	73%	31%	57%	21%	60%	34%
8	74%	34%	23%	54%	44%	16%	38%	9%	44%	22%
9	61%	18%	13%	34%	21%	10%	28%	6%	35%	22%
10	54%	11%	9%	28%	12%	8%	24%	5%	30%	22%
11	47%	8%	6%	26%	7%	6%	21%	4%	27%	21%
12	43%	5%	5%	25%	5%	5%	17%	3%	23%	20%
13	36%	4%	3%	25%	5%	5%	14%	3%	20%	19%
14	30%	4%	3%	25%	6%	4%	11%	2%	19%	18%
15	40%	6%	5%	25%	8%	5%	9%	2%	18%	17%
16	48%	8%	7%	27%	9%	6%	11%	2%	19%	14%
17	54%	11%	10%	28%	11%	7%	15%	3%	22%	11%
18	59%	15%	12%	33%	14%	9%	22%	4%	28%	14%
19	67%	22%	16%	51%	17%	13%	29%	8%	36%	22%
20	77%	33%	26%	76%	27%	22%	46%	16%	52%	31%
21	93%	71%	55%	92%	80%	50%	74%	46%	76%	52%
22	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
23	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
24	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%

3.7.3 Light and Heat Inputs

Parameters related to light and heat functions may be adjusted for a given QUAL2K model. For model setup, solar inputs are calculated within the model based on latitude, time zone, and Julian day. These were calculated based on the location of Wyman Creek and the model dates of 8/17/2016 for calibration and 8/8/2016 for validation.

Most light and heat parameters were estimated based on suggested values from the QUAL2K manual. There are a number of options for modeling atmospheric attenuation of solar energy, atmospheric longwave emissivity, and wind speed function for evaporation and air convection/conduction. There are also a number of sediment heat parameters that may be specified based on known bed sediment information or adjusted during calibration (Table 16).

Table 16. Light and Heat Model Setup Inputs

Parameter	Model Input	Note
Light Parameters		
Photosynthetically Available Radiation	0.47	Light parameters initialized based on QUAL2K example file.
Background light extinction (/m)	0.2	
Linear chlorophyll light extinction (/m)	0.0088	
Chlorophyll light extinction (/m)	0.054	
ISS light extinction (/m)	0.052	
Detritus light extinction (/m)	0.174	
Model Parameters		
Atmospheric attenuation model for solar	Bras	Default atmospheric formula for QUAL2K.
Atmospheric Turbidity Coefficient	2	Default value suggested by QUAL2K Manual
Atmospheric longwave emissivity model	Brutsaert	This equation tends to allow for warmer water temperatures to be achieved.
Wind speed function	Adams 2	Wind function takes into consideration the difference between air and water temperatures.
Sediment Heat Parameters		
Sediment thermal thickness (cm)	12	Model default suggestions from QUAL2K manual.
Sediment thermal diffusivity (cm^2/s)	0.005	
Sediment density (g/cm^3)	1.6	
Sediment heat capacity (cal/g °C)	0.4	

3.8 BOUNDARY CONDITIONS

3.8.1 Headwater Flows and Water Quality

Flow measured at the headwaters of Wyman Creek on 8/18/2016 was 0.005 m^3/s, and on 8/8/2016 was 0.004 m^3/s. These flows were used at the headwaters for the calibration and validation models respectively. Grab samples for water quality were used to parameterize headwater conditions, as was the sonde located at the headwaters which was recording hourly DO, conductivity, pH, and water temperature (site W03148013). Model inputs are detailed in Table 17, Table 18, and Table 19. Reach hydraulics associated with the headwaters are assumed to be the same as Reach 1. Within the model, the downstream extent was not a prescribed boundary.

Table 17. Headwater water quality initial model inputs, calibration and validation periods

Parameter	Model Input: Calibration	Model Input: Validation	Data Source
Streamflow (m^3/s)	0.005	0.0044	Measured flow from 8/18/16 and 8/8/16 respectively
Water Temperature (°C)	See Table 18	See Table 19	Sonde hourly data
Conductivity (µmhos)	See Table 18	See Table 19	Sonde hourly data
Inorganic Solids (mgD/L)	2	5.2	Grab samples from 8/18/16 and 8/8/16 respectively
Dissolved Oxygen (mg/L)	See Table 18	See Table 19	Sonde hourly data
CBODslow (mgO_2/L)	1	1	Grab samples from 8/18/16 and 8/8/16 of BOD_5 were non-detect, so a low background concentration of $CBOD_{slow}$ was estimated.
CBODfast (mgO_2/L)	0	0	
Organic Nitrogen (µgN/L)	245	555	Grab samples from 8/18/16 and 8/8/16 of TKN minus model inputs for NH4
NH4-Nitrogen (µgN/L)	25	25	Grab samples from 8/18/16 and 8/8/16 were non-detect, set to half the detection limit
NO3-Nitrogen (µgN/L)	70	70	Grab samples from 8/18/16 and 8/8/16 respectively
Inorganic Phosphorus (µgP/L)	6	12	Grab sample from 8/18/16, no grab sample from 8/8/16, so estimated as same fraction of TP as from 8/18/16
Organic Phosphorus (µgP/L)	1	2	Grab samples from 8/18/16 and 8/8/16 of TP minus model inputs for Inorganic P
Alkalinity (mg/L)	160	160	Grab samples from 8/18/16 and 8/8/16 respectively
Phytoplankton (mgA/L)	1.02	0.75	Grab samples from 8/18/16 and 8/8/16 respectively
pH	See Table 18	See Table 19	Sonde hourly data

Table 18. Headwater hourly model inputs, calibration period

Hour	Calibration Period			
	Water Temperature (°C)	Dissolved Oxygen (mg/l)	Conductivity (µmhos)	pH
1	22.40	6.48	439	7.92
2	22.30	6.63	439	7.87
3	22.19	6.40	439	7.88
4	22.06	6.55	439	7.88
5	21.98	6.55	438	7.88
6	21.97	6.65	438	7.88
7	22.03	6.67	438	7.88
8	22.31	6.76	438	7.88
9	22.79	6.87	438	7.88
10	23.35	6.97	439	7.88
11	24.11	6.99	440	7.88
12	24.88	6.96	441	7.88
13	25.36	6.98	442	7.89
14	25.66	6.73	443	7.88
15	25.62	6.69	443	7.89
16	25.47	6.60	443	7.88
17	25.29	6.60	443	7.89
18	24.99	6.53	443	7.88
19	24.55	6.44	442	7.89
20	24.13	6.36	441	7.88
21	23.73	6.31	441	7.89
22	23.37	6.18	441	7.89
23	23.12	6.23	441	7.89
24	22.92	6.21	441	7.89

Table 19. Headwater hourly model inputs, validation period

Hour	Validation Period			
	Water Temperature (°C)	Dissolved Oxygen (mg/l)	Conductivity (µmhos)	pH
1	22.03	5.74	438	7.74
2	21.92	5.87	438	7.75
3	21.79	5.78	438	7.75
4	21.68	5.75	438	7.75

Hour	Validation Period			
	Water Temperature (°C)	Dissolved Oxygen (mg/l)	Conductivity (µmhos)	pH
5	21.59	5.76	438	7.76
6	21.52	5.76	437	7.76
7	21.67	5.98	437	7.77
8	22.07	5.99	438	7.78
9	22.53	5.98	438	7.78
10	23.02	6.02	439	7.78
11	23.47	6.01	439	7.77
12	23.66	6.32	439	7.74
13	23.89	6.33	439	7.78
14	23.92	6.34	439	7.78
15	23.82	6.30	438	7.78
16	23.65	6.25	438	7.77
17	23.32	6.24	438	7.77
18	23.16	6.18	438	7.76
19	22.94	6.07	438	7.76
20	22.73	6.04	438	7.74
21	22.53	5.94	438	7.74
22	22.43	5.98	438	7.72
23	22.42	6.02	438	7.72
24	22.36	5.74	439	7.73

3.8.2 Diffuse Groundwater Flows and Water Quality

Based on flow measurements from 8/8/2016 and 8/18/2016, a water balance was computed along Wyman Creek for the calibration and validation periods. Flows at the creek outlet minus flows at the headwaters and point source inflows were used to estimate an overall net gain of diffuse groundwater along Wyman Creek of 0.04 m^3/s along the mainstem during both calibration and validation periods (Figure 32). This net diffuse inflow was applied along the entire model extent. Parameterization of the groundwater inflow is detailed in Table 20. Since groundwater plays such a large role in the volume of water in the stream, the water quality temperature associated with groundwater inputs play a large role toward in-stream conditions.

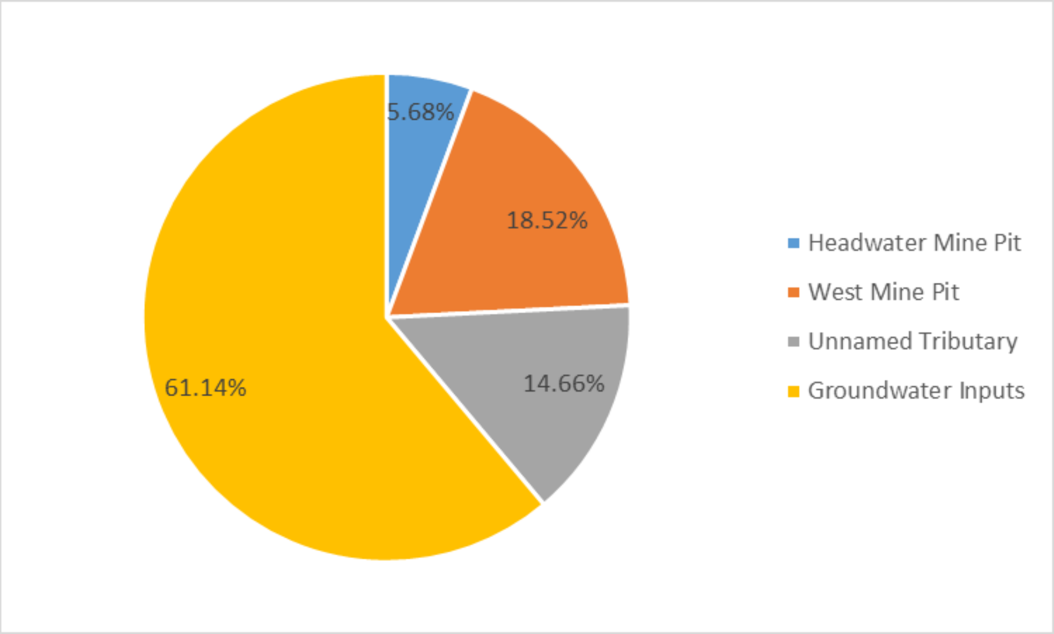


Figure 32. Flow contributions to Wyman Creek based on water balance estimates

Table 20. Diffuse groundwater flow and water quality inputs

Parameter	Diffuse Inflow	Data Source Information
Inflow (m^3/s)	0.04 for mainstem 0.01 for west braid	Water balance calculations
Water Temperature (°C)	6.14	Average shallow groundwater temperature observed during August from 2013-2015 data available at Bear Head Lake, identified as the closest shallow well to the area of-interest (data provided by MPCA)
Conductivity (µmhos)	400	Approximate average of in-stream conductivity samples.
Dissolved Oxygen (mg/L)	1.6	Estimated based on the "mean of published groundwater data" for the Jewitts Creek TMDL (MPCA, 2010)
Alkalinity (mg/l)	160	Model default input
pH	7	Model default input
Phytoplankton (µg/l)	5	Low concentrations of these nutrient-based parameters were included to ensure the possibility of bottom algae growth even though the system is not nutrient-driven.
Organic Nitrogen (µgN/L)	100	
Organic Phosphorus (µgP/L)	50	
Inorganic Phosphorus (µgP/L)	50	

3.8.3 Point Source Flows and Water Quality

Modeled point sources in the Wyman Creek QUAL2K model include:

1. West Mine Pit flowing into Wyman Creek between model reaches 2 and 3
2. Unnamed Tributary flowing into Wyman Creek between model reaches 7 and 8

Model inputs for flow and water quality for these point sources to the mainstem were based on sonde data and grab samples similarly to the parameterization of the headwaters (Table 21, Table 22). Note that there are no nutrient-related concentrations for the unnamed tributary inflow because there were no data collected.

Table 21. Point source flow and water quality inputs for calibration and validation period for the West Mine Pit discharge (W03148012, S007-212)

Parameter	West Mine Pit Inputs: Calibration	West Mine Pit Inputs: Validation	Data Source Information
Inflow (m^3/s)	0.0163	0.0266	Measured on 8/8/16 and 8/18/16
Water Temperature (°C)	22.47	21.81	Observed statistics from 8/8/16 and 8/17/16 sonde measurements
Water Temperature Range / 2 (°C)	1.11	0.55	
Conductivity (µmhos)	400	400	No data, estimated based on in-stream data
Inorganic Solids (mgD/L)	2	1.2	Observed from grab samples on 8/8/16 and 8/18/16
Dissolved Oxygen (mg/L)	8.16	8.11	Observed statistics from 8/8/16 and 8/17/16 sonde measurements
Dissolved Oxygen Range /2 (mg/l)	0.15	0.14	
Alkalinity (mg/l)	170	170	Observed from grab samples on 8/8/16 and 8/18/16
Phytoplankton (µg/l)	0.29	0.33	Observed from grab samples on 8/8/16 and 8/18/16
pH	7	7	No data, model default
Slow CBOD (mg/L)	1.2	1.2	BOD_5 was not detected in either grab sample, assumed half detection limit as slow CBOD
Fast CBOD (mg/L)	0	0	
Ammonia Nitrogen (µgN/L)	25	25	Non-detect in grab samples, set to half detection limit
Organic Nitrogen (µgN/L)	75	75	TKN and NH3 grab samples were both non-detects on both sample dates, so organic N was estimated as the model inputs of TKN minus NH3.
Nitrate+ Nitrite Nitrogen (µgN/L)	460	460	Observed from grab samples on 8/8/16 and 8/18/16
Organic Phosphorus (µgP/L)	1.5	6.0	Difference between observed TP on 8/8/16 and 8/18/16 and model inputs for inorganic P
Inorganic Phosphorus (µgP/L)	2.5	10	Grab sample from 8/18/16 only, estimated for 8/8/16 based on fraction of TP

Table 22. Point source flow and water quality inputs for calibration and validation period for the unnamed tributary (W03148007, S009-167)

Parameter	Unnamed Tributary: Calibration	Unnamed Tributary: Validation	Data Source Information
Inflow (m^3/s)	0.0129	0.0161	Measured on 8/8/16 and 8/18/16
Water Temperature (°C)	23.42	21.41	Observed statistics from 8/8/16 and 8/17/16 sonde measurements
Water Temperature Range / 2 (°C)	3.40	3.50	
Conductivity (µmhos)	400	400	No data, estimated based on in-stream data
Dissolved Oxygen (mg/L)	0.47	3.50	Observed statistics from 8/8/16 and 8/17/16 sonde measurements
Dissolved Oxygen Range /2 (mg/l)	0.60	2.34	
Alkalinity (mg/l)	100	100	No data, model default
pH	7	7	No data, model default
Slow CBOD (mg/L)	2.5	1.2	BOD_5 from grab samples estimated as slow CBOD (validation period was set to half detection limit)
Fast CBOD (mg/L)	0	0	

3.8.4 West Braid Flow and Water Quality

The west braid is modeled as a tributary to the mainstem, flowing into the stream between Reach 8 and Reach 10. The west braid (Reach 9) was initialized at its upstream end based on flow observed at the downstream end, and water quality observed along the Wyman Creek mainstem. Water balance calculations reveal that the mainstem of Wyman Creek receives about 45% of its streamflow from groundwater, therefore the measured flow at the downstream end of the west braid was used to estimate 45% to be sourced from groundwater, and 55% to be originating at the top of the west braid (Table 23). Water quality inputs for the west braid were largely approximated based on grab samples and sonde measurements near the upstream end, and channel hydraulics were assumed to be similar to the downstream end.

Table 23. West braid flow and water quality inputs

Parameter	West Braid: Calibration	West Braid: Validation	Data Source Information
Inflow (m^3/s)	0.011	0.004	Estimated based on observed flows and water balance calculations
Water Temperature (°C)	22.81	20.82	Average observed water temperature from sonde data immediately upstream of the braid split on 8/8/16 and 8/17/16
Conductivity (µmhos)	399.2	389.7	Average observed conductivity from sonde data immediately upstream of the braid split on 8/8/16 and 8/17/16
Inorganic Solids (mgD/L)	5.6	6.4	Observed from grab samples on 8/8/16 and 8/18/16 at downstream end of braid
Dissolved Oxygen (mg/L)	5.26	6.14	Average observed DO from sonde data immediately upstream of the braid split on 8/8/16 and 8/17/16

Parameter	West Braid: Calibration	West Braid: Validation	Data Source Information
Alkalinity (mg/l)	160	140	Observed from grab samples on 8/8/16 and 8/18/16 at downstream end of braid
Phytoplankton (µg/l)	0.69	0.81	Observed from grab samples on 8/8/16 and 8/18/16 at downstream end of braid
pH	7.40	7.45	Average observed pH from sonde data immediately upstream of the braid split on 8/8/16 and 8/17/16
Slow CBOD (mg/L)	1.0	1.0	Grab samples from 8/18/16 and 8/8/16 of BOD_5 at the downstream end of the braid were non-detect, so a low background concentration of $CBOD_{slow}$ was estimated.
Fast CBOD (mg/L)	0	0	
Ammonia Nitrogen (µgN/L)	25	60	Observed from grab sample on 8/18/16 and on 8/8/16 set to half detection limit (grabs from downstream end of braid)
Organic Nitrogen (µgN/L)	905	950	Organic N was estimated as the observed grab sample TKN at the downstream end of the braid minus the model inputs for NH3.
Nitrate+ Nitrite Nitrogen (µgN/L)	25	25	Observed as non-detect from grab samples on 8/8/16 and 8/18/16 at downstream end of braid, so set to half detection limit
Organic Phosphorus (µgP/L)	10	12	Difference between observed TP at downstream end of braid on 8/8/16 and 8/18/16 and model inputs for inorganic P
Inorganic Phosphorus (µgP/L)	19	23	Grab sample from 8/18/16 only at downstream end of braid, estimated for 8/8/16 based on fraction of TP

4.0 MODEL CALIBRATION AND VALIDATION

Model calibration involves comparing how well model simulations match observed data. Model calibration is designed to ensure that the model is adequately and appropriately representing the system in order to answer the study questions. The model must be able to provide credible representations of the movement of water and the DO interactions and temperatures within the stream. Validation is applied using a different time period to confirm that model calibration is robust, provide additional evaluation of model performance, and to guard against over-fitting to the calibration data.

The QUAL2K model for Wyman Creek was calibrated to data collected on August 17 and August 18, 2016. The model was setup for these conditions using available data and calibrated to reproduce observed water temperature and DO. Once the model was calibrated, inputs were altered for meteorological and boundary conditions associated with the validation period (August 8, 2016) to ensure that model parameterization could be validated for a different date and different set of flow and water quality circumstances.

4.1 MODEL CALIBRATION RESULTS

4.1.1 Hydrology Calibration

Reach hydraulics were calibrated in order to approximate known data of flow, depth, and velocity along Wyman Creek on 8/18/2016. Manning's n was a key calibration parameter, and channel bottom widths and slopes were also adjusted where needed to capture the observed flow dynamics since the measured cross-sections were not necessarily representative of the entire model reach length. The calibrated reach hydraulic inputs are summarized in Table 24.

Travel time for the full extent of Wyman Creek was estimated by the model to be just over three days, and model results of flow along the mainstem compared to observations may be seen in Figure 33. Along the entire reach, simulated stream velocity ranged from 0.012 – 0.215 m/s (observed range was 0.003 – 0.316 m/s), and simulated water depth ranged from 0.18 – 0.70 m (observed range was 0.07 – 0.97 m).

Table 24. Calibrated reach hydraulic inputs

Reach	Location Shorthand	Manning's n	Channel Bottom Width (m)	Side Slope 1	Side Slope 2
1	Headwaters to first beaver dam	0.35	0.19	0.4745	0.4842
2	First beaver dam to West Mine Pit inflow	0.60	1.34	2.9280	1.2333
3	West Mine Pit inflow to Dunka Rd	0.25	0.30	0.1605	0.3389
4	Dunka Rd to ponded meadow	0.08	0.30	0.1605	0.3389
5	Ponded meadow to perched culvert	0.70	2.50	0.75	0.64
6	Perched culvert to braid split	0.70	2.50	0.7497	0.6411
7	East braid from split to unnamed tributary inflow	0.40	1.00	0.0000	0.0000
8	East braid from unnamed tributary to braids confluence	0.10	0.80	0.0000	0.0000
9	West braid	0.90	0.61	2.7500	2.8400

Reach	Location Shorthand	Manning's n	Channel Bottom Width (m)	Side Slope 1	Side Slope 2
10	Braids confluence to outlet	0.10	0.80	0.0000	0.0000

Travel time for the full extent of Wyman Creek was estimated by the model to be just over three days, and model results of flow along the mainstem compared to observations may be seen in Figure 33. Along the entire reach, simulated stream velocity ranged from 0.012 – 0.215 m/s (observed range was 0.003 – 0.316 m/s), and simulated water depth ranged from 0.18 – 0.70 m (observed range was 0.07 – 0.97 m).

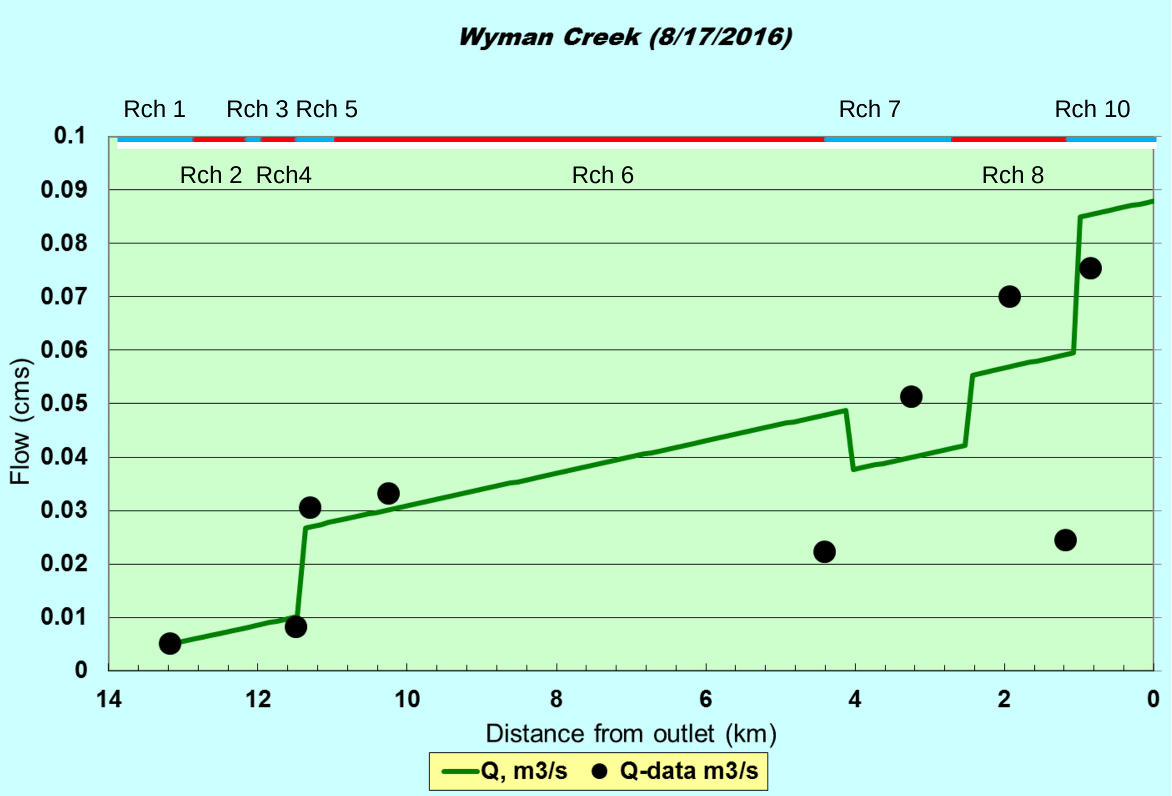


Figure 33. Simulated an observed flow data for Wyman Creek (calibration model).

4.1.2 Water Temperature Calibration

In general the parameters which control water temperature are channel geometry, meteorological inputs, atmospheric heat models, and sediment heat parameters. Sediment heat parameters were adjusted to calibrate simulated water temperature to observed water temperature. Sediment thermal thickness, thermal diffusivity, density, and heat capacity were adjusted during calibration within the range of natural thermal properties (Lapham, 1989). Sediment thermal inputs after calibration were: thermal thickness of 25 cm, thermal diffusivity of 0.0155 cm^2/s, density of 2.3, and heat capacity of 0.85 cal/g °C. The longitudinal comparison of the calibrated model simulation and observed minimum, maximum, and average water temperatures are depicted in Figure 34.

Water temperature along Wyman Creek generally matches well with the observed average, minimum, and maximum temperatures observed on the calibration date at discrete locations along the mainstem (Figure 34).

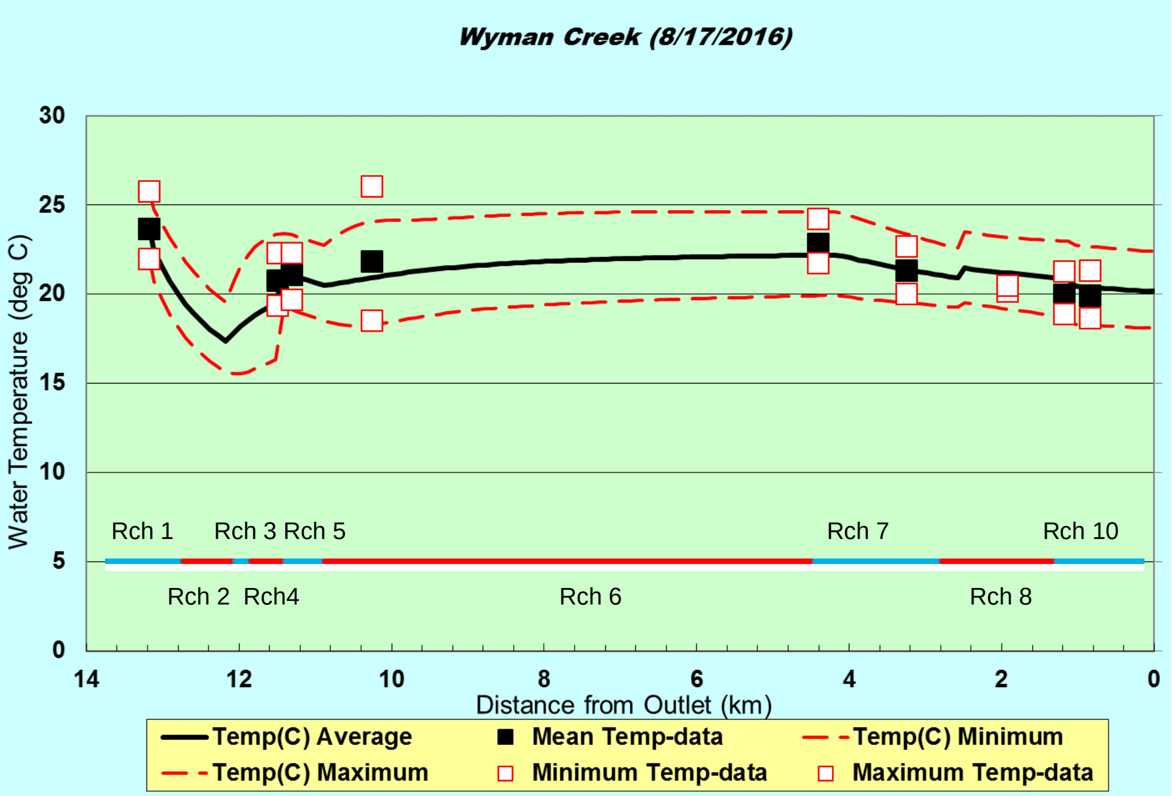


Figure 34. Simulated and observed water temperature data for Wyman Creek (calibration model).

4.1.3 Dissolved Oxygen Calibration

The primary focus of water quality calibration is related to DO along Wyman Creek. The key parameters which control average DO concentrations were identified to be sediment oxygen demand (SOD) rate and bottom of stream coverage and channel reaeration. The magnitude of daily minimum and maximum DO are controlled by the streambed coverage of bottom algae as an aggregate term for all macrophyte growth exerting photosynthetic processes within the water column. Reaeration rates were simulated using the Tsivoglou-Neal model, and were estimated as 2.0 – 22.8 /d, with an average reaeration rate of 6.4 /d, and the lowest values occurring along the marshy and long stretch of model Reach 6. Reaeration rates have been observed for shallow, low-flow streams on the order of 1 – 100 /d, so reaeration rates estimated along Wyman Creek are likely appropriates (Melching and Flores, 1999; Bowie et al., 1985).

SOD rates were estimated as described in Section3.2.3. SOD was calibrated based on altering the bottom SOD coverage across the streambed to scale the estimated SOD rates in the same manner across the system, for which 90% coverage most accuracy produced the observed average DO (Table 25, Figure 35).

In order to simulate the observed minimum and maximum DO, the bottom algae coverage was adjusted to either 1% or 5% for most reaches. 10% bottom algae coverage was maintained along reaches 4, 5, and 6 because of the large observed in-stream diel fluctuation in DO observed immediately downstream of the perched culvert located between reaches 5 and 6.

Table 25. Calibrated reach water quality inputs related to DO simulation

Reach	Location Shorthand	Bottom Algae Coverage	Bottom SOD Coverage
1	Headwaters to first beaver dam	5%	90%
2	First beaver dam to Mine Pit inflow	5%	90%
3	Mine Pit inflow to Dunka Rd	5%	90%
4	Dunka Rd to ponded meadow	10%	90%
5	Ponded meadow to perched culvert	10%	90%
6	Perched culvert to braid split	10%	90%
7	East braid from split to unnamed tributary inflow	1%	90%
8	East braid from unnamed tributary to braids confluence	1%	90%
9	West braid	1%	90%
10	Braids confluence to outlet	1%	90%

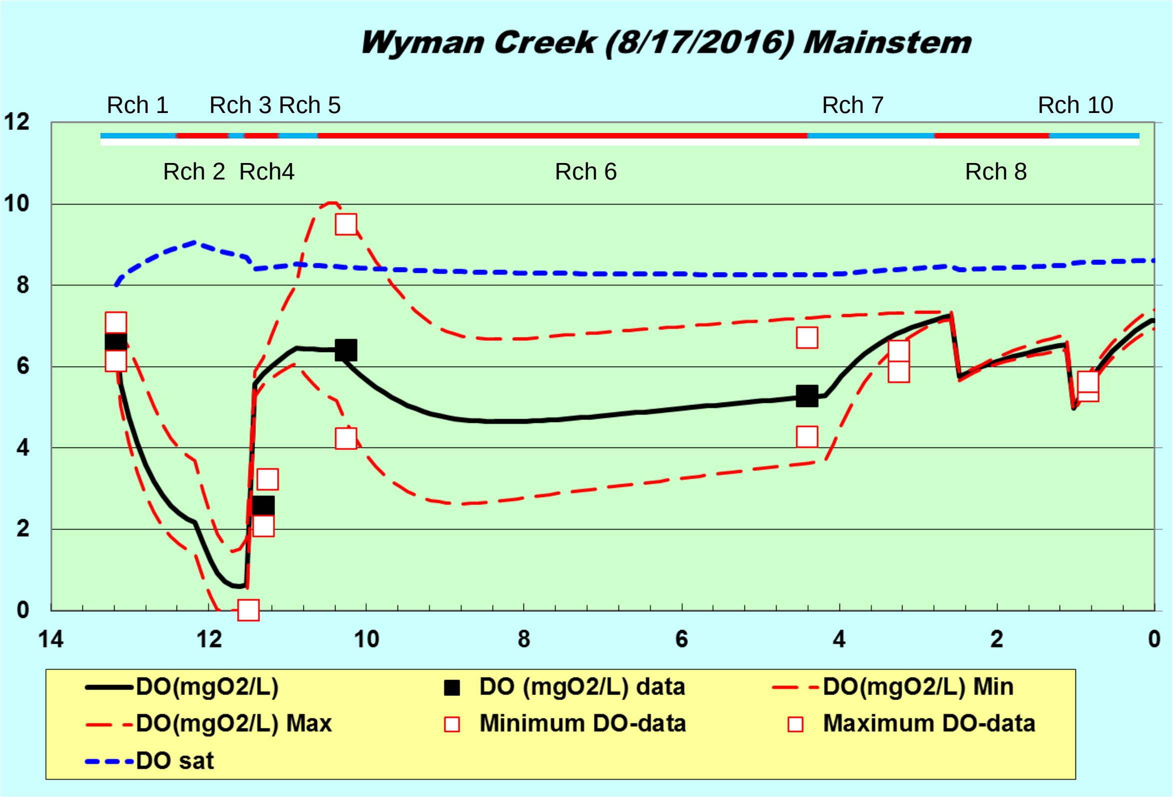


Figure 35. Simulated an observed dissolved oxygen data for Wyman Creek (calibration model).

The DO saturation (or “DO sat” as seen in Figure 35) is a temperature-dependent term which reveals how much DO the water is capable of sustaining (although supersaturation of DO is possible, as seen 10 km from the outlet. The relationship between water temperature and DO is inverse: cold water is able to “hold” more DO than warm water. As seen in Figure 35, at existing water temperatures, Wyman Creek can support in-stream DO concentrations around 8.5 mg/l. Average observed DO concentrations are far less than 8.5 mg/l, and the difference between DO saturation and observed DO is considered the “DO deficit” which occurs due to either natural or anthropogenic oxygen sinks in the system. The interplay between channel reaeration, groundwater inflows, point source inflows, headwater conditions, bottom algae, and SOD drive the in-stream DO, and change to any of these parameters will have an impact on in-stream DO, which is explored further in the modeled scenarios.

The steep drops in DO observed along the downstream end of Wyman Creek correspond to the inflows of the Unnamed Tributary and the west braid, both of which have extreme low DO due in large part to anoxic groundwater contributions.

Note that the Wyman Creek system is not nutrient-driven, therefore model representation of nitrogen and phosphorus species were not the focus of simulation and calibration. Total nitrogen observed during the calibration period was about 0.7 mg/l, and the average simulated nitrogen concentration along Wyman Creek was 1.0 mg/l. Average longitudinal observed phosphorus was 0.03 mg/l, and the average simulate phosphorus concentration was 0.05 mg/l. There is reasonable approximation of nitrogen and phosphorus species as well.

4.2 MODEL VALIDATION RESULTS

In order to verify that the model reasonably approximates conditions along Wyman Creek, the model was also setup and run for a different date and compared to an alternative set of observed hydrology, water temperature, and water quality data. This validation model was setup for 8/8/2016 and run with the same parameterization and the calibrated model.

4.2.1 Hydrology Validation

Reach hydraulics are similarly well-matched during the validation period as during the calibration period (Figure 36).

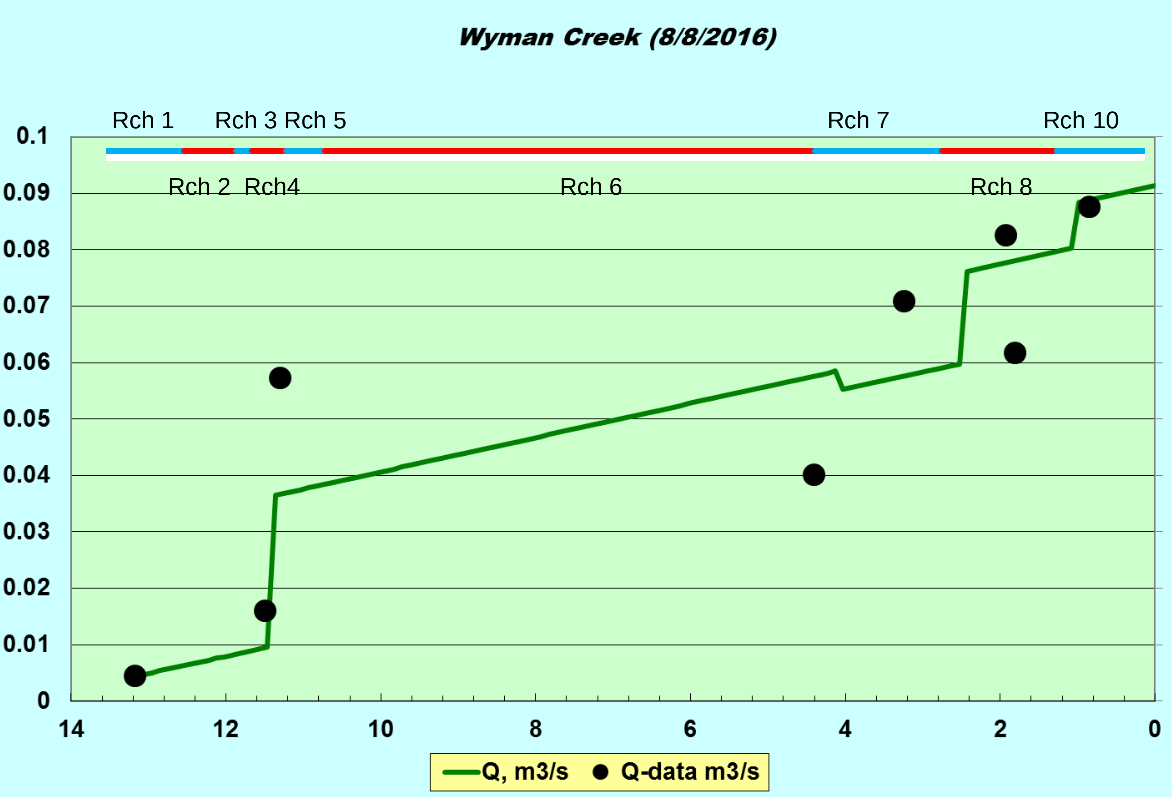


Figure 36. Simulated an observed flow data for Wyman Creek (validation model).

4.2.2 Water Temperature Validation

The water temperature results during the validation period are also similarly matched as they are during the calibration period (Figure 37).

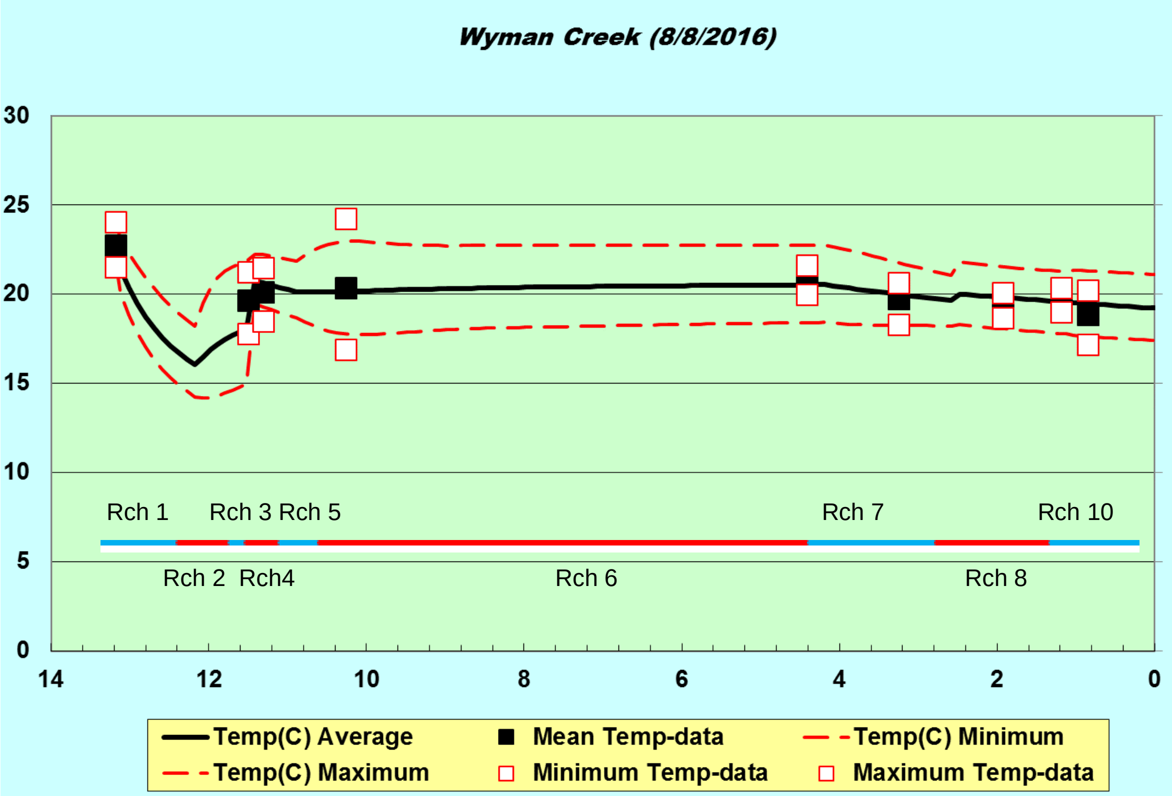


Figure 37. Simulated an observed water temperature data for Wyman Creek (validation model).

4.2.3 Water Quality Validation

Dissolved oxygen concentrations are generally well-represented during the model validation period, although the simulated maximum DO along Reach 5 is too low, and the model over-predicts average DO along the downstream end of the model (Figure 38). The high observed maximum and average DO along Reach 5 can be achieved by the model when bottom algae coverage is increased along that reach during the model calibration period from 10% to 30% along that reach.

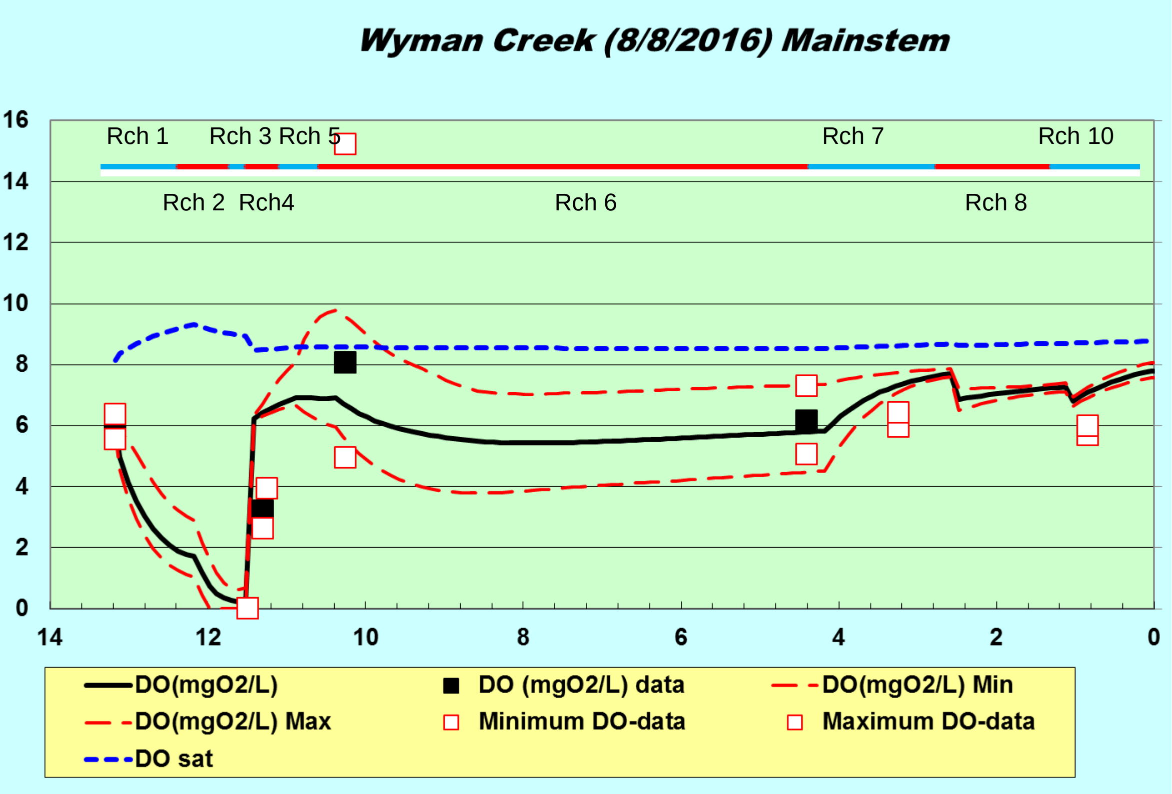


Figure 38. Simulated an observed dissolved oxygen data for Wyman Creek (validation model).

Observed conditions of nitrogen and phosphorus are very similar during the validation period as during the calibration period. Average observed nitrogen and phosphorus from the validation period along Wyman Creek were 0.7 mg/l and 0.03 mg/l respectively, while simulated concentrations were on average 0.9 mg/l and 0.04 mg/l respectively.

5.0 MODEL SCENARIOS

Under existing conditions, Wyman Creek does not attain water temperature targets and dissolved oxygen criteria in most locations. A series of model scenarios were developed to explore the stream system's response to different options which may help improve water temperature and dissolved oxygen conditions. The scenarios included the following:

1. Improved direct inflow conditions (decreased temperature and increased dissolved oxygen for the following inputs: Unnamed Tributary, Headwater Mine Pit, and West Mine Pit)
2. Decreased streambed sediment oxygen demand rate for all reaches by half to simulate beaver management
3. Improved shade conditions (shade from Reach 1 was applied to all reaches)
4. Improved upstream reach conditions (a suite of changes were made to ensure that water quality conditions meet the standards for temperature and DO for reaches 1 through 5). Changes included: decreased temperatures and increased DO from the Headwater Mine Pit and West Mine Pit, increased shade and decreased SOD for reaches 1 through 5, decreased algae for reaches 1 through 5, and improved hydraulic geometry for Reach 2.
5. Improved upstream conditions from Scenario 4 paired with improved downstream conditions: removal of west braid, increased DO of Unnamed Tributary, and increased shade for all reaches downstream of Reach 6.
6. Improved downstream reach conditions: removal of west braid, increased DO of Unnamed Tributary, and increased shade for all reaches downstream of Reach 6.
7. Removed impact of one perched culvert by improving conditions of Reach 5 (increased shade, decreased SOD, decreased algae, altered hydraulic parameters)

5.1 RESULTS

Scenario results are summarized in Table 26, Figure 39, Figure 40, Figure 41, and Figure 42. Under all of these scenarios, the maximum water temperature target (20 degrees Celsius) could not be met across the entire system at any time. There were no scenarios for which the entire system met the dissolved oxygen WQS, however there are a number of scenarios where the dissolved oxygen WQS can be met for specific regions such as above and below Reach 6. Note that for scenarios in which the west braid was removed from the system, the tributary flows and diffuse inflows to that braid were all re-directed to be accounted for along the mainstem such that the total flow at the outlet for all scenarios is the same (0.088 cms or about 3.11 cfs).

Table 26. QUAL2K scenario results (maximum temperature in degrees C, minimum dissolved oxygen [DO] in mg/l)

Scenario→	Baseline		1		2		3		4		5*		6*		7	
Detail→	Calibrated Model		Improved direct inflows		Decreased SOD, all reaches		Increased shade, all reaches		Improved upstream conditions		Improved upstream and downstream conditions		Improved downstream conditions		Removed perched culvert	
Reach	Max Temp	Min DO	Max Temp	Min DO	Max Temp	Min DO	Max Temp	Min DO	Max Temp	Min DO	Max Temp	Min DO	Max Temp	Min DO	Max Temp	Min DO
1	25.66	1.40	18.44	2.36	25.66	3.75	25.66	1.40	16.86	7.02	16.37	6.76	25.66	1.64	25.66	1.40
2	23.35	0.00	22.34	0.00	23.35	2.65	20.20	0.00	16.38	7.07	15.53	6.84	22.18	0.09	23.35	0.00
3	23.40	5.27	19.84	6.33	23.40	6.20	22.10	5.27	16.04	8.40	15.59	8.29	22.85	5.04	23.40	5.27
4	23.17	5.72	19.80	6.57	23.17	6.51	21.81	5.73	16.10	8.42	15.58	8.32	22.53	5.55	23.17	5.72
5	23.95	5.15	21.96	5.68	23.95	6.25	21.61	5.27	17.93	8.36	17.26	8.35	23.08	5.36	22.58	6.23
6	24.63	2.61	24.54	2.76	24.63	4.63	21.53	2.79	24.37	3.06	23.39	3.62	23.75	3.11	24.58	2.74
7	24.52	4.04	24.43	4.06	24.52	5.58	20.27	4.39	24.27	4.11	23.21	4.80	23.56	4.74	24.48	4.05
8	23.51	5.64	21.65	7.15	23.51	6.01	20.73	5.93	23.37	5.67	21.50	7.41	21.73	7.38	23.48	5.65
9	24.26	0.00	24.26	0.00	24.26	1.82	23.41	0.00	24.26	0.00	n/a	n/a	n/a	n/a	24.26	0.00
10	22.72	4.87	21.82	5.35	22.72	5.92	19.87	5.08	22.64	4.89	20.34	7.48	20.54	7.45	22.71	4.87

*Note that these two scenarios involve removing the west braid, therefore there is no Reach 9 present.

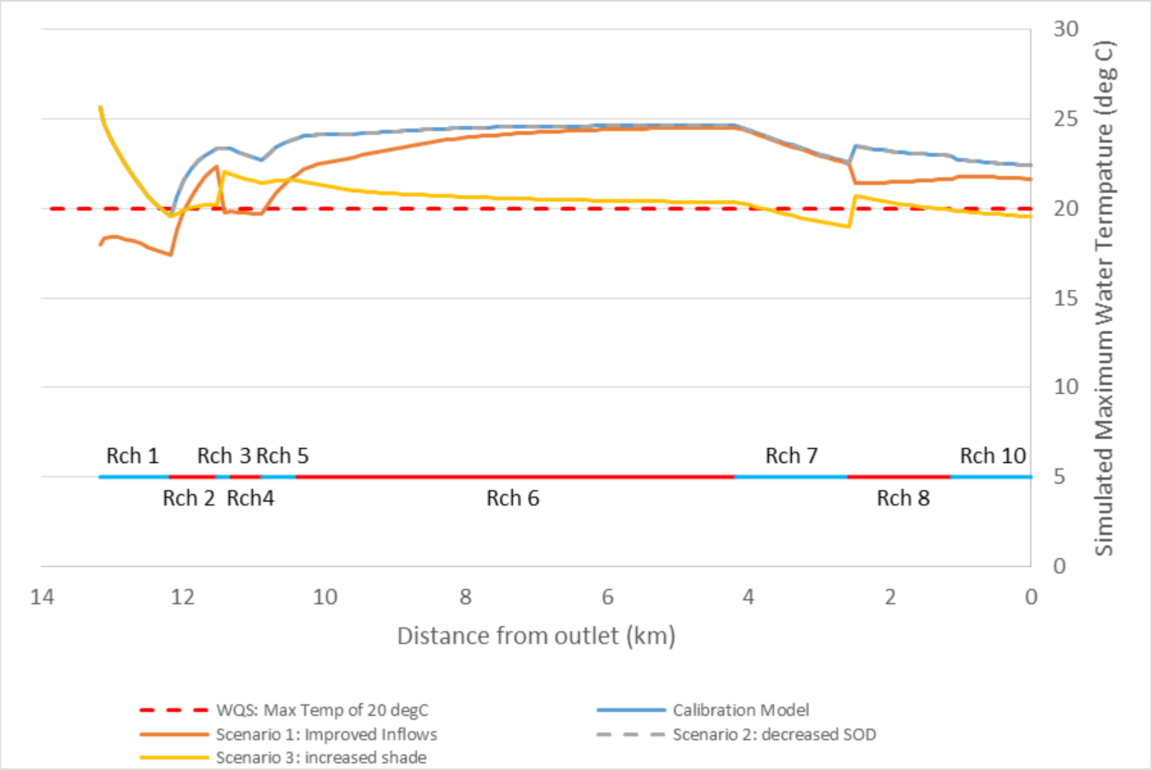


Figure 39. Scenario results for maximum water temperature along Wyman Creek (Scenarios 1-3).

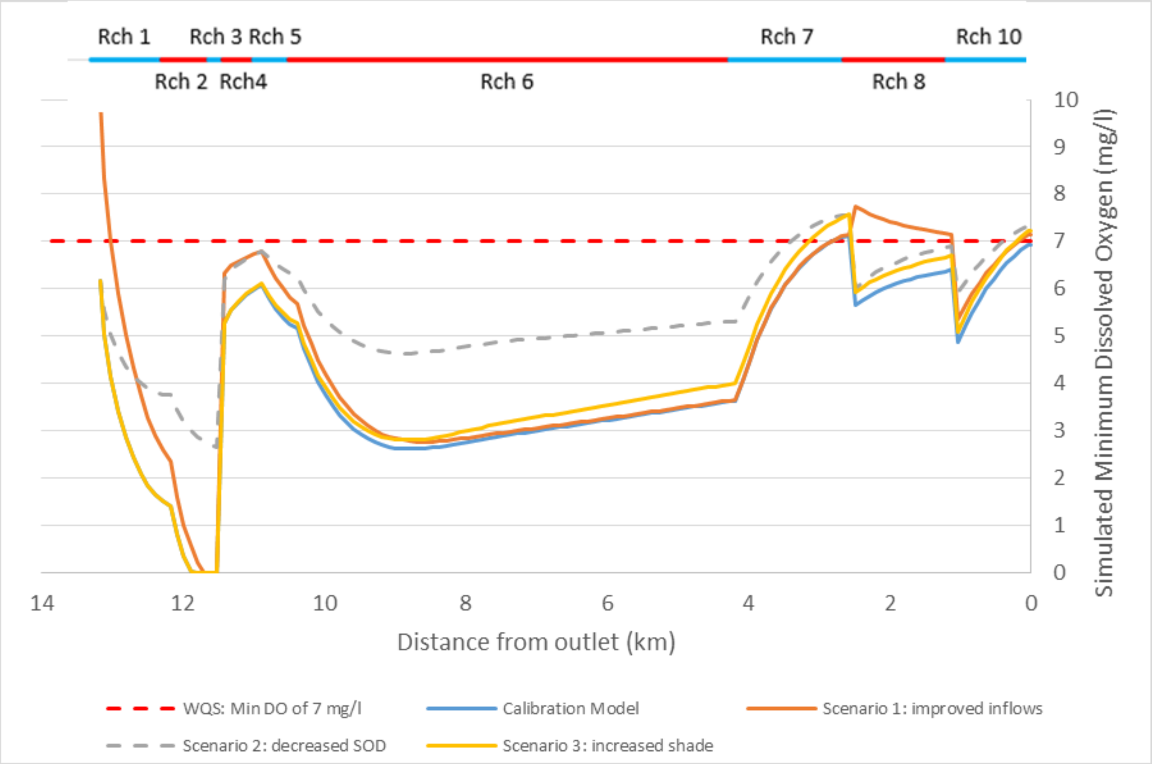


Figure 40. Scenario results for minimum dissolved oxygen along Wyman Creek (Scenarios 1-3).

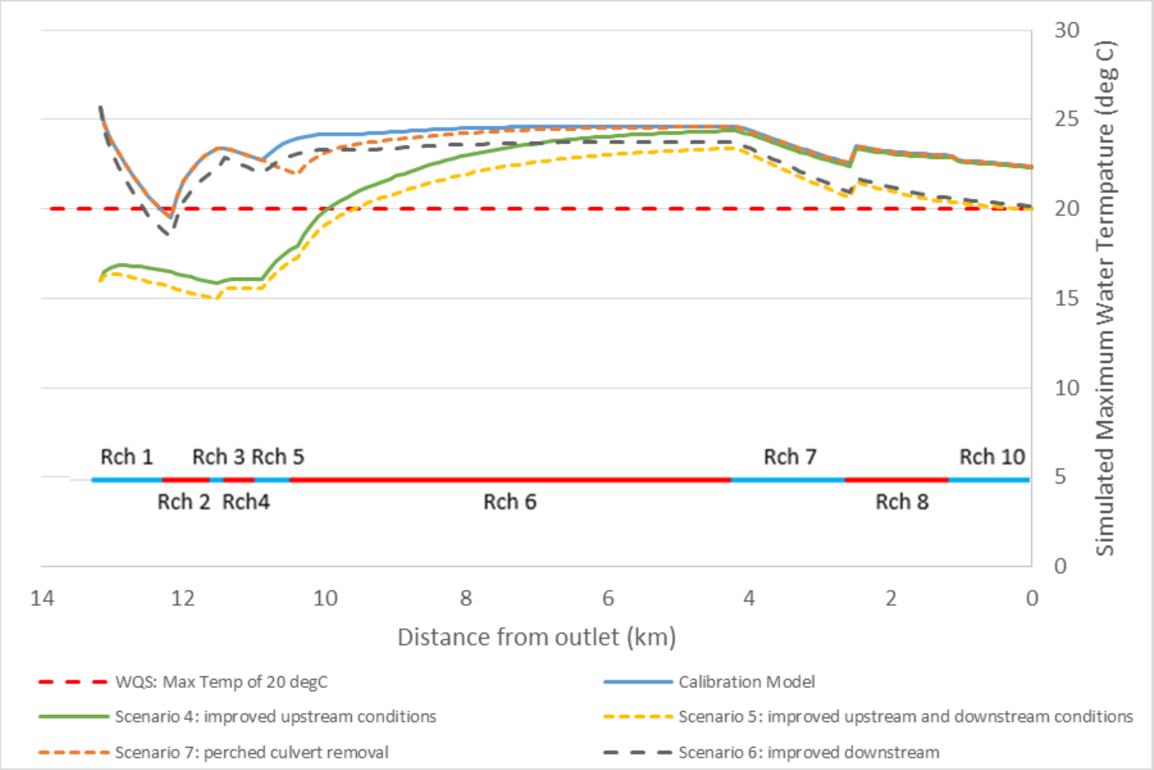


Figure 41. Scenario results for maximum water temperature along Wyman Creek (Scenarios 4-7).

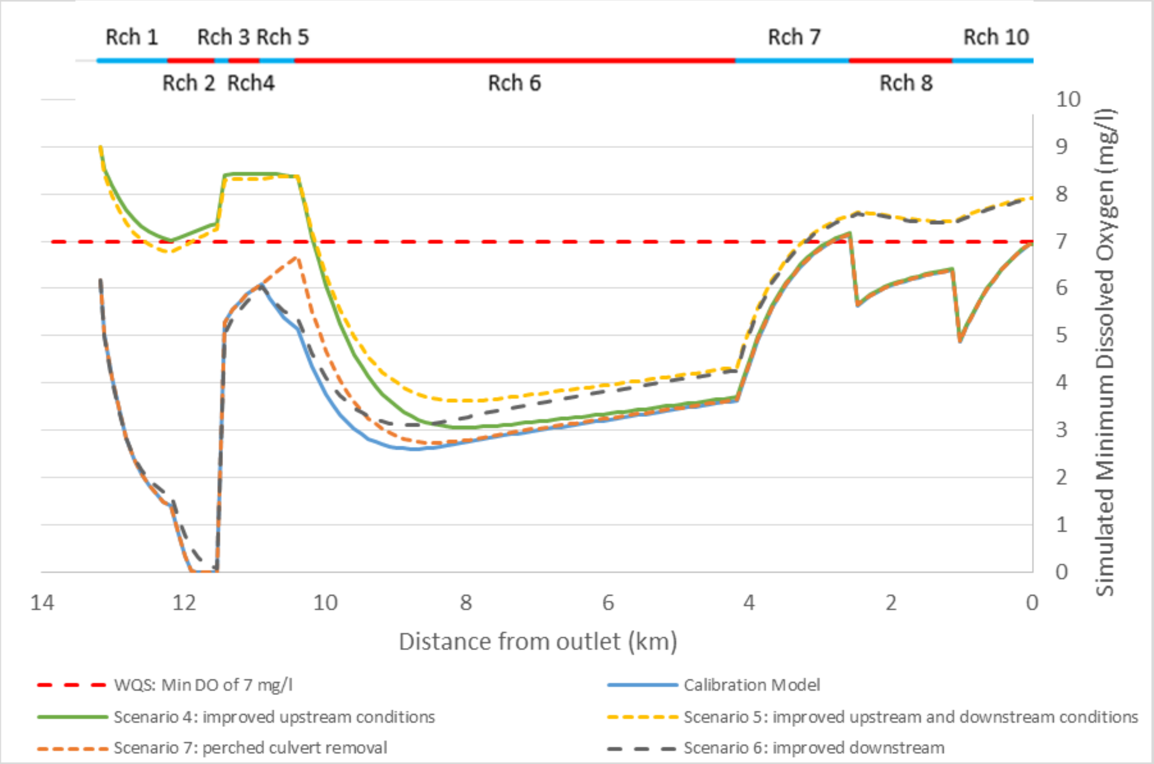


Figure 42. Scenario results for minimum dissolved oxygen along Wyman Creek (Scenarios 4-7).

5.2 SUMMARY OF RESULTS BY SCENARIO

Reach 6 in the model represents the central stretch of Wyman Creek that is sluggish, has many beaver dams, receives little shade, and most notably is highly inaccessible due to saturated soils and no road crossings. Implementation would not be reasonably possible along Reach 6, therefore implementation efforts upstream of Dunka Road (reaches 1-5) and/or downstream (reaches 7-10) are most realistic.

Scenario 1 reflects improved direct inflow conditions from mine pits and tributaries that has a noticeable but insignificant impact on the entire system. Lowering temperatures for the Headwater Mine and West Mine Pit inflows is likely possible based on the depth of water in the mine pit and observed temperature stratification in Minnesota abandoned mine pits in general (Piece and Tomcko, 1989). Higher dissolved oxygen may be possible to achieve for all three direct inflows (2 mine pits and the Unnamed Tributary) through implementation of reaeration facilitators (e.g., waterfalls or riffles).

Scenarios 2 and 3 reflect systematic implementation in all reaches, with decreased sediment oxygen demand and increased shade respectively. Such systematic changes like this are not likely possible for all reaches (particularly Reach 6), however even with the systematic changes, neither the water temperature target or dissolved oxygen standard was achieved along most of the stream.

Scenario 4 involves significant changes to reaches 1 – 5 which allow the stream to meet the water temperature target and dissolved oxygen standard for reaches 1 - 5. Even with these improved upstream conditions the target for temperature was not met downstream, although the dissolved oxygen standard is met at a few points at the downstream end. Reach 6 effectively resets the system and brings water temperatures up and dissolved oxygen down back to the observed conditions from the calibration model setup.

Scenario 5 involves all of the upstream conditions of Scenario 4, with the additional impacts of removing the West Braid (re-directing all flow to the mainstem), improving dissolved oxygen conditions from the Unnamed Tributary, and increased shade for reaches 7-10. Water temperature results for Scenario 5 are improved downstream relative to Scenario 4 due to the increase in shade, and minimum dissolved oxygen of 7.0 mg/l is attained along Reach 7 and maintained downstream. The impact of removing the West Braid has a positive impact on streamflow in the main channel, and overall the removal of the two very low dissolved oxygen sources of the West Braid and Unnamed Tributary have the greatest overall impact downstream.

Scenario 6 includes only the downstream improvements from Scenario 5 without any of the upstream improvements associated with Scenario 4. In this scenario, no matter what occurs upstream of Reach 6, downstream improvements may be possible to improve dissolved oxygen and water temperature conditions near the outlet.

Scenario 7 is a targeted example of what may be possible when the perched culvert located at the downstream end of Reach 5 is removed. Water temperature and dissolved oxygen conditions in Reach 5 can be improved from the removal of the culvert, but the influence of those changes dissipates along Reach 6. Although this targeted approach is clear from an implementation standpoint, the results show that the most detrimental reach to water quality in the upstream area is Reach 2.

5.3 CONCLUSIONS

The results of these scenarios indicate that dramatic changes to the upstream end of Wyman Creek will not have a significant impact downstream of Reach 5. A targeted approach to improvements downstream of Reach 6 likely has the best chance for successfully improving conditions.

6.0 TMDL ANALYSIS

Loading capacity is the amount of loading from all pollutant sources (natural or anthropogenic) that waterbody can assimilate to still meet applicable water quality standards. Qual2K is used to calculate the loading capacity for Wyman Creek. Wyman Creek is impaired due to high temperatures and low DO conditions. Dissolved oxygen concentrations are dependent on in-stream temperature. Water can contain higher concentrations of dissolved oxygen when stream temperatures are cooler.

For the purposes of TMDL analysis within Wyman Creek, DO saturation concentration (DO_{sat}) is an important consideration when estimating assimilative capacity for DO. The DO_{sat} and the stream's assimilative capacity decline with increasing water temperature (Figure 43). The capacity of a water body to assimilate loads of pollutants that affect the oxygen balance varies as a function of water temperature.

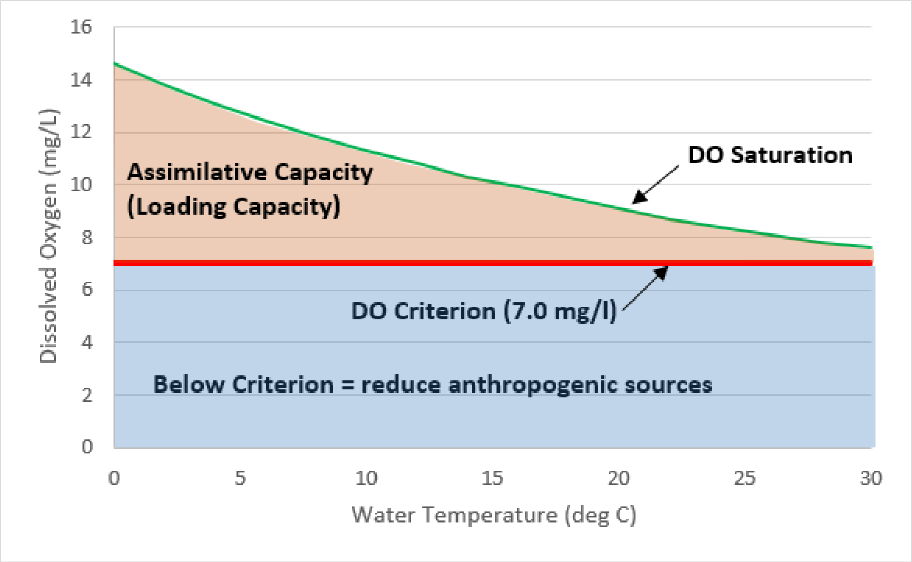


Figure 43. DO assimilative capacity as a function of DO saturation and water temperature.

Water temperature in a stream is controlled by the incoming thermal load from solar radiation, tributaries and point sources, as well as groundwater and sediment. The thermal load to the stream not only impacts the DO capacity of the waterway, but also determines the state of water quality in the stream relative to aquatic life. Although there is not specific numeric criteria for water temperature in Wyman Creek, there are a suite of temperature ranges which reflect thermal metrics used by MN DNR and MPCA for Brook Trout growth, stress, and lethality (Table 27).

Table 27. Brook Trout water temperature ranges

Classification	Temperature Range (°C)	Description
Growth	7.8 to 20.0 °C	Temperature range favorable for growth
Stress	>20.0 to 25.0 °C	Stress and avoidance behaviors

Classification	Temperature Range (°C)	Description
Lethal	>25.0 °C	Mortality can be expected at prolonged exposure

The following plot shows the schematic of allowable loading capacity of DO in reference to Brook Trout growth, stress, and lethality such that the overlapping area which is dark/shaded represents a condition for which both DO and water temperature criteria are met (Figure 44).

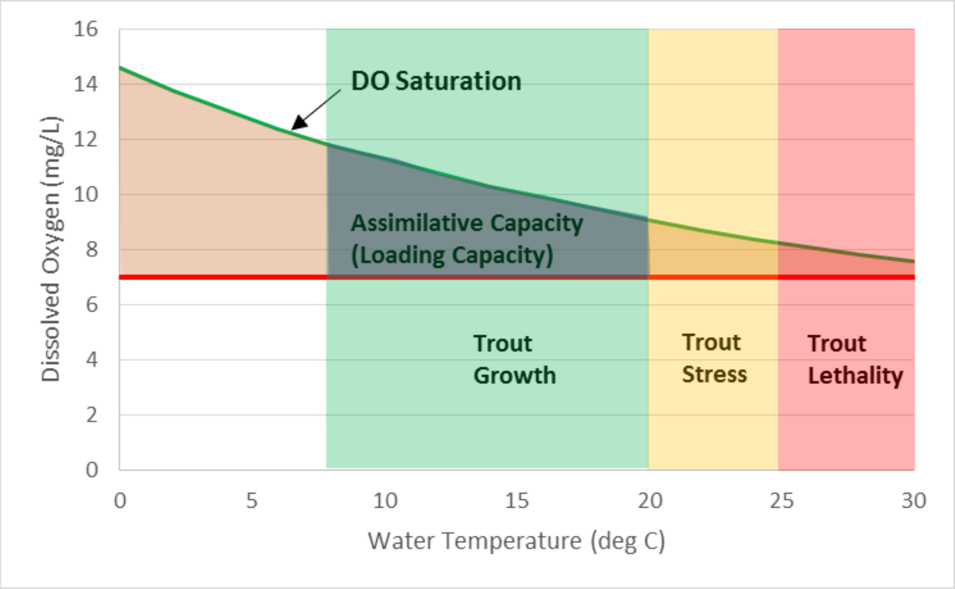


Figure 44. DO assimilative capacity as a function of DO saturation and water temperature metrics.

6.1 TMDL SCENARIO

A TMDL scenario was developed to simulate attainment of the water temperature target and DO standard along the downstream portion of Wyman Creek (Reaches 7, 8, and 10 in Figure 25). The water quality targets at the downstream end of each model reach in lower Wyman Creek include:

1. Maximum daily water temperature does not exceed 20 °C, which is the upper limit for standard Brook Trout favorable growth conditions according to MPCA and MN DNR
2. Minimum daily dissolved oxygen does not drop below 7.0 mg/l, which is associated with sustaining aquatic life

The TMDL scenario involved the following modifications in order to attain standards in Reaches 7, 8, and 10:

1. Removal of the West Braid: this reach was removed from the system so there is no associated abstraction and re-entry points from the mainstem. The final downstream flow is the same as when the West Braid was present.
2. Increased shade along Reaches 7, 8, and 10: hourly shade inputs were made identical to those of Reach 1 which is much more shaded (average daylight hours shade of 57%).

3. Water temperature improvements to Reach 6: hourly shade inputs were made identical for those of Reach 1 (average daylight hours shade of 57%) or equivalent implementation to reduce in-stream temperatures entering Reach 7 to 19.7 °C.

Without making any improvements upstream of Reach 7, the maximum water temperature at the downstream end of Reach 6 is 24.6 °C, therefore additional improvements were included along Reach 6. For the purposes of the TMDL model, Reach 6 shade conditions were improved to match the improved shade conditions of Reach 7, 8, and 10, although there may be alternative methods to bring down water temperatures along Reach 6. The TMDL scenario results in water quality standards being met at the downstream ends of Reaches 7, 8, and 10 as seen in Table 28.

Table 28. Water quality results at the downstream end of Reaches 7, 8, and 10: TMDL Scenario

Reach	Maximum Daily Water Temperature (°C)	Minimum Daily DO (mg/L)
7	18.25	7.93
8	18.84	7.30
10	18.54	8.01

6.2 TMDL CALCULATIONS

Thermal loading at the Wyman Creek outlet can be calculated to determine the total allowable thermal load at the water quality standard of 20 °C, the existing thermal load, and the excess thermal load which is the difference between the first two loads. Thermal loads are calculated based on water temperature, the volumetric flow rate, and a conversion factor:

$$Thermal\ Load \left[\frac{Kcal}{d}\right] = Water\ Temperature\ [°C]\ x\ Flow\ [cms]\ x\ (86.4x10^6)[conversion\ factor]$$

The thermal loads at the Wyman Creek outlet were calculated based on the calibrated model results and water quality standards:

$$Existing\ Thermal\ Load \left[\frac{Kcal}{d}\right] = 22.26\ [°C]\ x\ 0.088\ [cms]\ x\ (86.4x10^6) = 169.2\ million\ \frac{Kcal}{d}$$

$$Allowable\ Thermal\ Load \left[\frac{Kcal}{d}\right] = 20\ [°C]\ x\ 0.088\ [cms]\ x\ (86.4x10^6) = 152.1\ million\ \frac{Kcal}{d}$$

$$Excess\ Thermal\ Load \left[\frac{Kcal}{d}\right] = Allowable\ Load - Existing\ Load = 17.1\ million\ \frac{Kcal}{d}$$

When the excess thermal load is resolved for Wyman Creek and the water temperature target is met, the DO standard is also met.

7.0 REFERENCES

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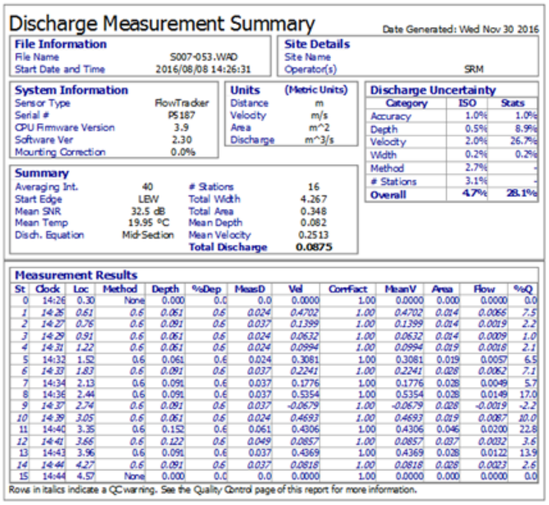
APPENDIX A: CHANNEL CROSS SECTIONS

Channel cross section data logged using a FlowTracker handheld device is presented below for each site on each sampling date.

Sample Date 8/8/2016



Discharge Measurement Summary

Date Generated: Wed Nov 30 2016

File Information

File Name	S007-053.WAD
Start Date and Time	2016/08/08 14:26:31

Site Details

Site Name	
Operator(s)	SRM

System Information

Sensor Type	FlowTracker
Serial #	P5187
CPU Firmware Version	3.9
Software Ver	2.30
Mounting Correction	0.0%

Units	(Metric Units)
Distance	m
Velocity	m/s
Area	m^2
Discharge	m^3/s

Discharge Uncertainty

Category	ISO	Stats
Accuracy	1.0%	1.0%
Depth	0.5%	8.9%
Velocity	2.0%	26.7%
Width	0.2%	0.2%
Method	2.7%	-
# Stations	3.1%	-
Overall	**4.7%**	**28.1%**

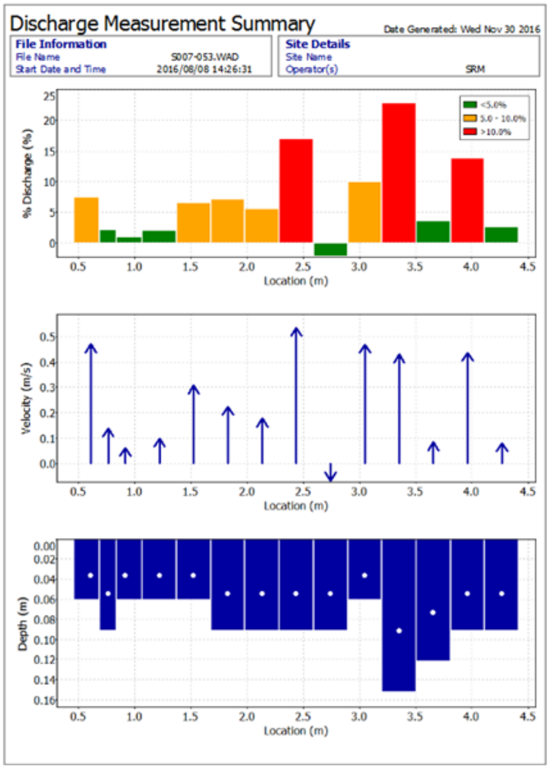
Summary

Averaging Int.	40	# Stations	16
Start Edge	LEW	Total Width	4.267
Mean SNR	32.5 dB	Total Area	0.348
Mean Temp	19.95 °C	Mean Depth	0.082
Disch. Equation	Mid-Section	Mean Velocity	0.2513
		Total Discharge	**0.0875**

Measurement Results

St	Clock	Loc	Method	Depth	%Dep	MeasD	Vel	CorrFact	MeanV	Area	Flow	%Q
0	14:26	0.30	None	0.000	0.0	0.0	0.0000	1.00	0.0000	0.000	0.0000	0.0
1	*14:26*	*0.61*	*0.6*	*0.061*	*0.6*	*0.024*	*0.4702*	*1.00*	*0.4702*	*0.014*	*0.0066*	*7.5*
2	*14:27*	*0.76*	*0.6*	*0.091*	*0.6*	*0.037*	*0.1399*	*1.00*	*0.1399*	*0.014*	*0.0019*	*2.2*
3	*14:29*	*0.91*	*0.6*	*0.061*	*0.6*	*0.024*	*0.0632*	*1.00*	*0.0632*	*0.014*	*0.0009*	*1.0*
4	*14:31*	*1.22*	*0.6*	*0.061*	*0.6*	*0.024*	*0.0994*	*1.00*	*0.0994*	*0.019*	*0.0018*	*2.1*
5	14:32	1.52	0.6	0.061	0.6	0.024	0.3081	1.00	0.3081	0.019	0.0057	6.5
6	*14:33*	*1.83*	*0.6*	*0.091*	*0.6*	*0.037*	*0.2241*	*1.00*	*0.2241*	*0.028*	*0.0062*	*7.1*
7	14:34	2.13	0.6	0.091	0.6	0.037	0.1776	1.00	0.1776	0.028	0.0049	5.7
8	14:36	2.44	0.6	0.091	0.6	0.037	0.5354	1.00	0.5354	0.028	0.0149	17.0
9	*14:37*	*2.74*	*0.6*	*0.091*	*0.6*	*0.037*	*-0.0679*	*1.00*	*-0.0679*	*0.028*	*-0.0019*	*-2.2*
10	*14:39*	*3.05*	*0.6*	*0.061*	*0.6*	*0.024*	*0.4693*	*1.00*	*0.4693*	*0.019*	*0.0087*	*10.0*
11	14:40	3.35	0.6	0.152	0.6	0.061	0.4306	1.00	0.4306	0.046	0.0200	22.8
12	*14:41*	*3.66*	*0.6*	*0.122*	*0.6*	*0.049*	*0.0857*	*1.00*	*0.0857*	*0.037*	*0.0032*	*3.6*
13	14:43	3.96	0.6	0.091	0.6	0.037	0.4369	1.00	0.4369	0.028	0.0122	13.9
14	*14:44*	*4.27*	*0.6*	*0.091*	*0.6*	*0.037*	*0.0818*	*1.00*	*0.0818*	*0.028*	*0.0023*	*2.6*
15	14:44	4.57	None	0.000	0.0	0.0	0.0000	1.00	0.0000	0.000	0.0000	0.0

Rows in italics indicate a QC warning. See the Quality Control page of this report for more information.



Discharge Measurement Summary

Date Generated: Wed Nov 30 2016

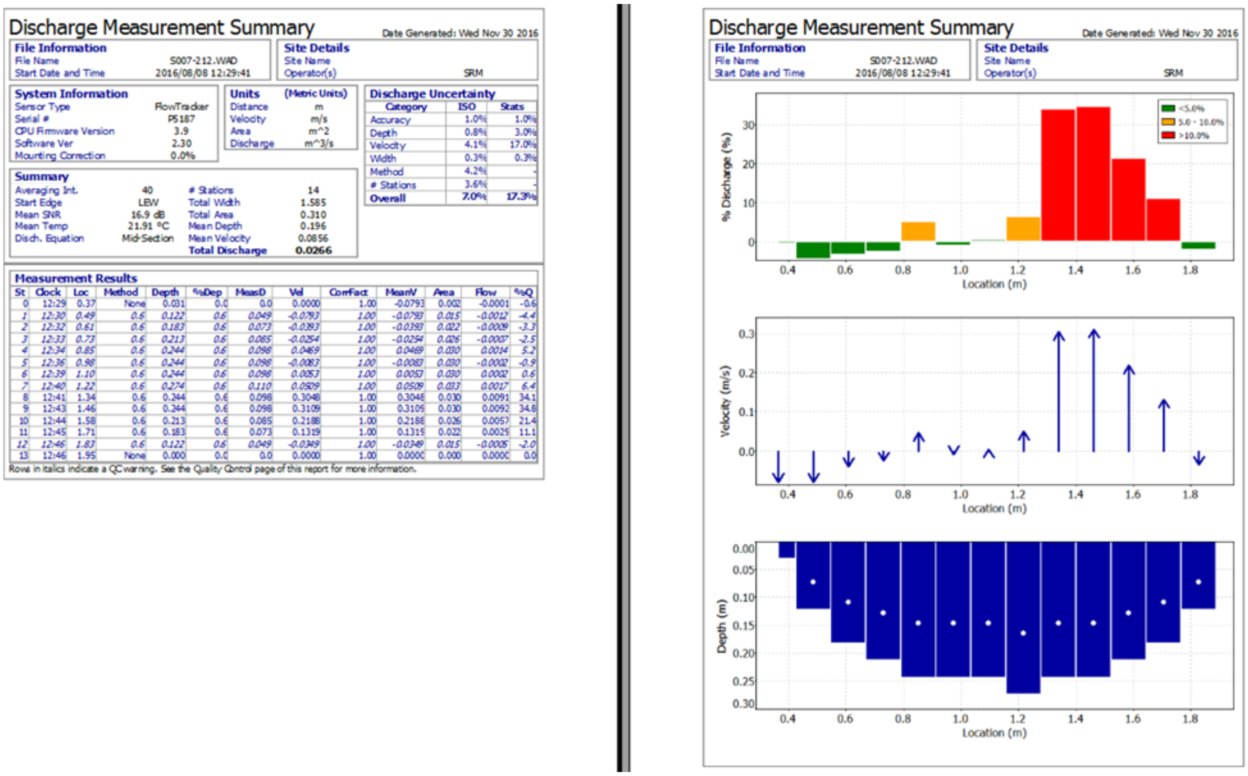
File Information

File Name	S007-053.WAD
Start Date and Time	2016/08/08 14:26:31

Site Details

Site Name	
Operator(s)	SRM

Figure 45. Site S007-053 flow cross section



Discharge Measurement Summary

Date Generated: Wed Nov 30 2016

File Information	
File Name	S007-212.WAD
Start Date and Time	2016/08/08 12:29:41

Site Details	
Site Name	
Operator(s)	SRM

System Information	
Sensor Type	FlowTracker
Serial #	P5187
CPU Firmware Version	3.9
Software Ver	2.30
Mounting Correction	0.0%

Units	(Metric Units)
Distance	m
Velocity	m/s
Area	m^2
Discharge	m^3/s

Discharge Uncertainty

Category	ISO	Stats
Accuracy	1.0%	1.0%
Depth	0.8%	3.0%
Velocity	4.1%	17.0%
Width	0.3%	0.3%
Method	4.2%	-
# Stations	3.6%	-
Overall	**7.0%**	**17.3%**

Summary			
Averaging Int.	40	# Stations	14
Start Edge	LEW	Total Width	1.585
Mean SNR	16.9 dB	Total Area	0.310
Mean Temp	21.91 °C	Mean Depth	0.196
Disch. Equation	Mid-Section	Mean Velocity	0.0856
		Total Discharge	**0.0266**

Measurement Results

St	Clock	Loc	Method	Depth	%Dep	MeasD	Vel	CorrFact	MeanV	Area	Flow	%Q
0	12:29	0.37	None	0.031	0.0	0.0	0.0000	1.00	-0.0793	0.002	-0.0001	-0.6
1	*12:30*	*0.49*	*0.6*	*0.122*	*0.6*	*0.049*	*-0.0793*	*1.00*	*-0.0793*	*0.015*	*-0.0012*	*-4.4*
2	*12:32*	*0.61*	*0.6*	*0.183*	*0.6*	*0.073*	*-0.0393*	*1.00*	*-0.0393*	*0.022*	*-0.0009*	*-3.3*
3	*12:33*	*0.73*	*0.6*	*0.213*	*0.6*	*0.085*	*-0.0254*	*1.00*	*-0.0254*	*0.026*	*-0.0007*	*-2.5*
4	*12:34*	*0.85*	*0.6*	*0.244*	*0.6*	*0.098*	*0.0469*	*1.00*	*0.0469*	*0.030*	*0.0014*	*5.2*
5	*12:36*	*0.98*	*0.6*	*0.244*	*0.6*	*0.098*	*-0.0083*	*1.00*	*-0.0083*	*0.030*	*-0.0002*	*-0.9*
6	*12:39*	*1.10*	*0.6*	*0.244*	*0.6*	*0.098*	*0.0053*	*1.00*	*0.0053*	*0.030*	*0.0002*	*0.6*
7	*12:40*	*1.22*	*0.6*	*0.274*	*0.6*	*0.110*	*0.0509*	*1.00*	*0.0509*	*0.033*	*0.0017*	*6.4*
8	12:41	1.34	0.6	0.244	0.6	0.098	0.3048	1.00	0.3048	0.030	0.0091	34.1
9	12:43	1.46	0.6	0.244	0.6	0.098	0.3109	1.00	0.3109	0.030	0.0092	34.8
10	12:44	1.58	0.6	0.213	0.6	0.085	0.2188	1.00	0.2188	0.026	0.0057	21.4
11	12:45	1.71	0.6	0.183	0.6	0.073	0.1319	1.00	0.1319	0.022	0.0029	11.1
12	*12:46*	*1.83*	*0.6*	*0.122*	*0.6*	*0.049*	*-0.0349*	*1.00*	*-0.0349*	*0.015*	*-0.0005*	*-2.0*
13	12:46	1.95	None	0.000	0.0	0.0	0.0000	1.00	0.0000	0.000	0.0000	0.0

Rows in italics indicate a QC warning. See the Quality Control page of this report for more information.

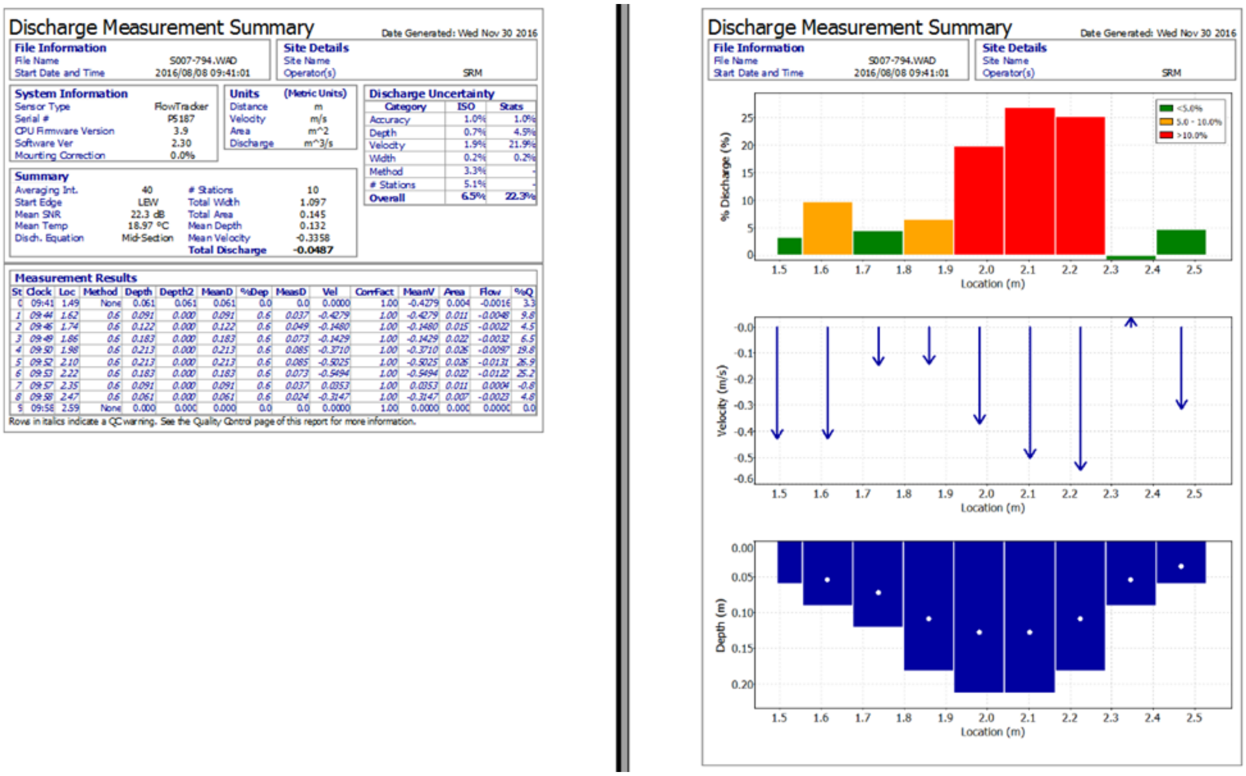
Discharge Measurement Summary

Date Generated: Wed Nov 30 2016

File Information	
File Name	S007-212.WAD
Start Date and Time	2016/08/08 12:29:41

Site Details	
Site Name	
Operator(s)	SRM

Figure 46. Site S007-212 flow cross section



Discharge Measurement Summary

Date Generated: Wed Nov 30 2016

File Information	
File Name	S007-794.WAD
Start Date and Time	2016/08/08 09:41:01

Site Details	
Site Name	
Operator(s)	SRM

System Information	
Sensor Type	FlowTracker
Serial #	P5187
CPU Firmware Version	3.9
Software Ver	2.30
Mounting Correction	0.0%

Units	(Metric Units)
Distance	m
Velocity	m/s
Area	m^2
Discharge	m^3/s

Discharge Uncertainty

Category	ISO	Stats
Accuracy	1.0%	1.0%
Depth	0.7%	4.5%
Velocity	1.9%	21.9%
Width	0.2%	0.2%
Method	3.3%	-
# Stations	5.1%	-
Overall	**6.5%**	**22.3%**

Summary			
Averaging Int.	40	# Stations	10
Start Edge	LEW	Total Width	1.097
Mean SNR	22.3 dB	Total Area	0.145
Mean Temp	18.97 °C	Mean Depth	0.132
Disch. Equation	Mid-Section	Mean Velocity	-0.3358
		Total Discharge	**-0.0487**

Measurement Results

St	Clock	Loc	Method	Depth	Depth2	MeanD	%Dep	MeasD	Vel	CorrFact	MeanV	Area	Flow	%Q
0	09:41	1.49	None	0.061	0.061	0.061	0.0	0.0	0.0000	1.00	-0.4279	0.004	-0.0016	3.3
1	*09:44*	*1.62*	*0.6*	*0.091*	*0.000*	*0.091*	*0.6*	*0.037*	*-0.4279*	*1.00*	*-0.4279*	*0.011*	*-0.0048*	*9.8*
2	*09:46*	*1.74*	*0.6*	*0.122*	*0.000*	*0.122*	*0.6*	*0.049*	*-0.1480*	*1.00*	*-0.1480*	*0.015*	*-0.0022*	*4.5*
3	*09:49*	*1.86*	*0.6*	*0.183*	*0.000*	*0.183*	*0.6*	*0.073*	*-0.1429*	*1.00*	*-0.1429*	*0.022*	*-0.0032*	*6.5*
4	*09:50*	*1.98*	*0.6*	*0.213*	*0.000*	*0.213*	*0.6*	*0.085*	*-0.3710*	*1.00*	*-0.3710*	*0.026*	*-0.0097*	*19.8*
5	*09:52*	*2.10*	*0.6*	*0.213*	*0.000*	*0.213*	*0.6*	*0.085*	*-0.5025*	*1.00*	*-0.5025*	*0.026*	*-0.0131*	*26.9*
6	*09:53*	*2.22*	*0.6*	*0.183*	*0.000*	*0.183*	*0.6*	*0.073*	*-0.5494*	*1.00*	*-0.5494*	*0.022*	*-0.0122*	*25.2*
7	*09:57*	*2.35*	*0.6*	*0.091*	*0.000*	*0.091*	*0.6*	*0.037*	*0.0353*	*1.00*	*0.0353*	*0.011*	*0.0004*	*-0.8*
8	*09:58*	*2.47*	*0.6*	*0.061*	*0.000*	*0.061*	*0.6*	*0.024*	*-0.3147*	*1.00*	*-0.3147*	*0.007*	*-0.0023*	*4.8*
9	09:58	2.59	None	0.000	0.000	0.000	0.0	0.0	0.0000	1.00	0.0000	0.000	0.0000	0.0

Rows in italics indicate a QC warning. See the Quality Control page of this report for more information.

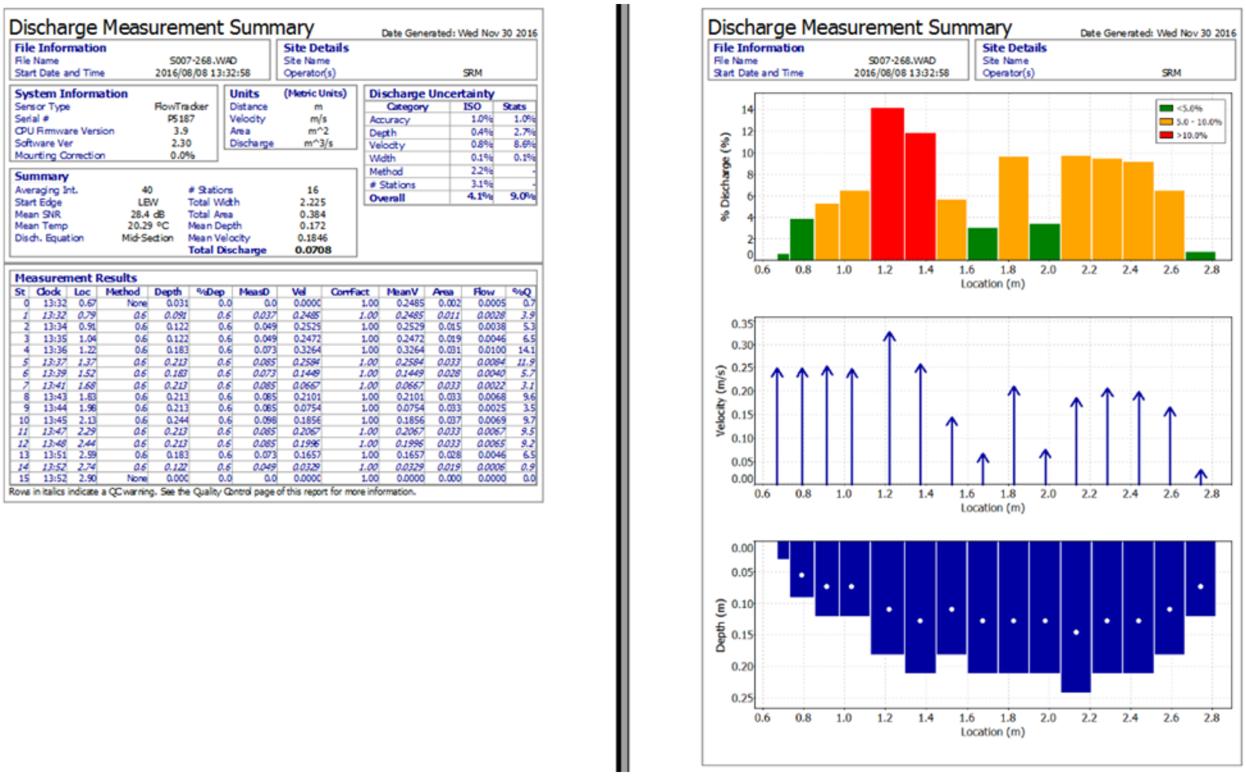
Discharge Measurement Summary

Date Generated: Wed Nov 30 2016

File Information	
File Name	S007-794.WAD
Start Date and Time	2016/08/08 09:41:01

Site Details	
Site Name	
Operator(s)	SRM

Figure 47. Site S007-268 flow cross section



Discharge Measurement Summary

Date Generated: Wed Nov 30 2016

File Information

File Name	S007-268.WAD
Start Date and Time	2016/08/08 13:32:58

Site Details

Site Name	
Operator(s)	SRM

System Information

Sensor Type	FlowTracker
Serial #	P5187
CPU Firmware Version	3.9
Software Ver	2.30
Mounting Correction	0.0%

Units	(Metric Units)
Distance	m
Velocity	m/s
Area	m^2
Discharge	m^3/s

Discharge Uncertainty

Category	ISO	Stats
Accuracy	1.0%	1.0%
Depth	0.4%	2.7%
Velocity	0.8%	8.6%
Width	0.1%	0.1%
Method	2.2%	-
# Stations	3.1%	-
Overall	**4.1%**	**9.0%**

Summary

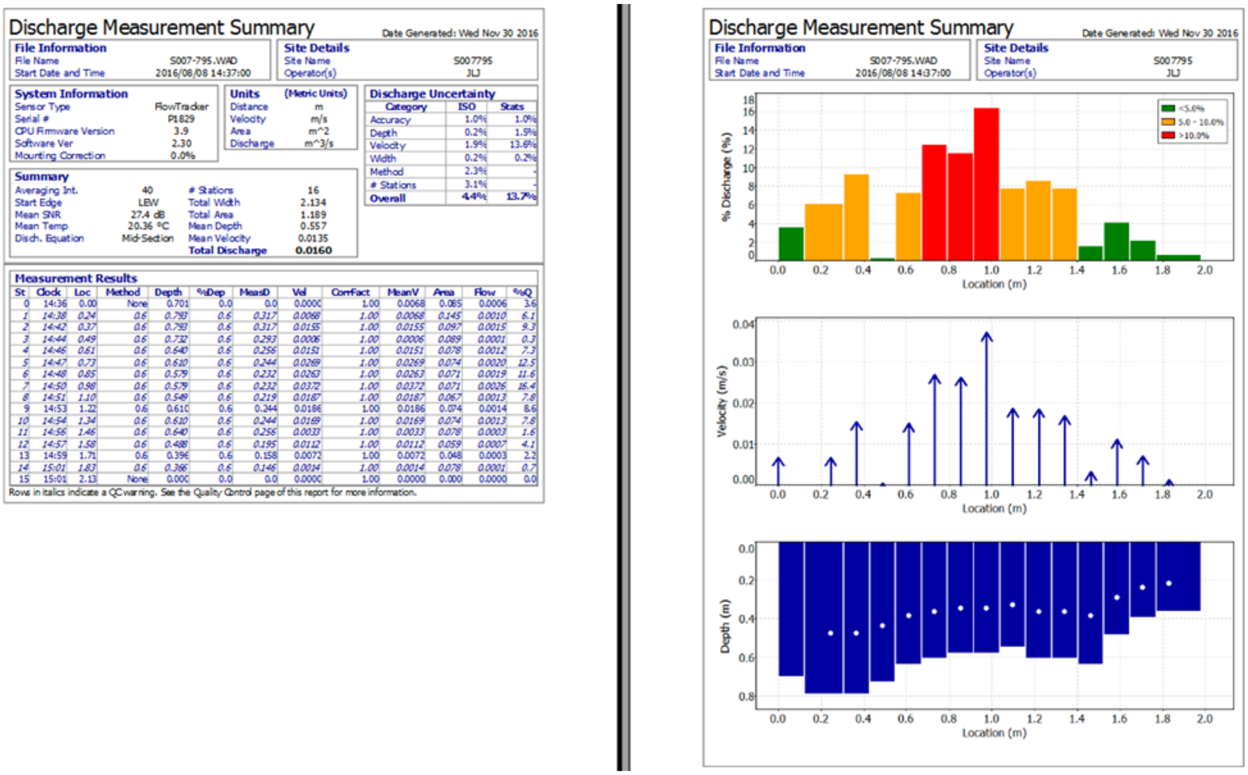
Averaging Int.	40	# Stations	16
Start Edge	LEW	Total Width	2.225
Mean SNR	28.4 dB	Total Area	0.384
Mean Temp	20.29 °C	Mean Depth	0.172
Disch. Equation	Mid-Section	Mean Velocity	0.1846
		Total Discharge	**0.0708**

Measurement Results

St	Clock	Loc	Method	Depth	%Dep	MeasD	Vel	CorrFact	MeanV	Area	Flow	%Q
0	13:32	0.67	None	0.031	0.0	0.0	0.0000	1.00	0.2485	0.002	0.0005	0.7
1	*13:32*	*0.79*	*0.6*	*0.091*	*0.6*	*0.037*	*0.2485*	*1.00*	*0.2485*	*0.011*	*0.0028*	*3.9*
2	13:34	0.91	0.6	0.122	0.6	0.049	0.2525	1.00	0.2529	0.015	0.0038	5.3
3	13:35	1.04	0.6	0.122	0.6	0.049	0.2472	1.00	0.2472	0.019	0.0046	6.5
4	13:36	1.22	0.6	0.183	0.6	0.073	0.3264	1.00	0.3264	0.031	0.0100	14.1
5	*13:37*	*1.37*	*0.6*	*0.213*	*0.6*	*0.085*	*0.2584*	*1.00*	*0.2584*	*0.033*	*0.0084*	*11.9*
6	*13:39*	*1.52*	*0.6*	*0.183*	*0.6*	*0.073*	*0.1449*	*1.00*	*0.1449*	*0.028*	*0.0040*	*5.7*
7	*13:41*	*1.68*	*0.6*	*0.213*	*0.6*	*0.085*	*0.0667*	*1.00*	*0.0667*	*0.033*	*0.0022*	*3.1*
8	13:43	1.83	0.6	0.213	0.6	0.085	0.2101	1.00	0.2101	0.033	0.0068	9.6
9	13:44	1.98	0.6	0.213	0.6	0.085	0.0754	1.00	0.0754	0.033	0.0025	3.5
10	13:45	2.13	0.6	0.244	0.6	0.098	0.1856	1.00	0.1856	0.037	0.0069	9.7
11	*13:47*	*2.29*	*0.6*	*0.213*	*0.6*	*0.085*	*0.2067*	*1.00*	*0.2067*	*0.033*	*0.0067*	*9.5*
12	*13:48*	*2.44*	*0.6*	*0.213*	*0.6*	*0.085*	*0.1996*	*1.00*	*0.1996*	*0.033*	*0.0065*	*9.2*
13	13:51	2.59	0.6	0.183	0.6	0.073	0.1657	1.00	0.1657	0.028	0.0046	6.5
14	*13:52*	*2.74*	*0.6*	*0.122*	*0.6*	*0.049*	*0.0329*	*1.00*	*0.0329*	*0.019*	*0.0006*	*0.9*
15	13:52	2.90	None	0.000	0.0	0.0	0.0000	1.00	0.0000	0.000	0.0000	0.0

Rows in italics indicate a QC warning. See the Quality Control page of this report for more information.

Figure 48. Site S007-794 flow cross section



Discharge Measurement Summary

Date Generated: Wed Nov 30 2016

File Information

File Name	S007-795.WAD
Start Date and Time	2016/08/08 14:37:00

Site Details

Site Name	S007795
Operator(s)	JLJ

System Information

Sensor Type	FlowTracker
Serial #	P1829
CPU Firmware Version	3.9
Software Ver	2.30
Mounting Correction	0.0%

Units	(Metric Units)
Distance	m
Velocity	m/s
Area	m^2
Discharge	m^3/s

Discharge Uncertainty

Category	ISO	Stats
Accuracy	1.0%	1.0%
Depth	0.2%	1.5%
Velocity	1.9%	13.6%
Width	0.2%	0.2%
Method	2.3%	-
# Stations	3.1%	-
Overall	**4.4%**	**13.7%**

Summary

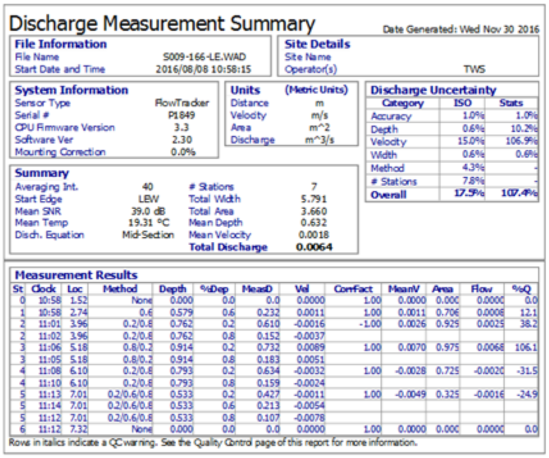
Averaging Int.	40	# Stations	16
Start Edge	LEW	Total Width	2.134
Mean SNR	27.4 dB	Total Area	1.189
Mean Temp	20.36 °C	Mean Depth	0.557
Disch. Equation	Mid-Section	Mean Velocity	0.0135
		Total Discharge	**0.0160**

Measurement Results

St	Clock	Loc	Method	Depth	%Dep	MeasD	Vel	CorrFact	MeanV	Area	Flow	%Q
0	14:36	0.00	None	0.701	0.0	0.0	0.0000	1.00	0.0068	0.085	0.0006	3.6
1	*14:38*	*0.24*	*0.6*	*0.793*	*0.6*	*0.317*	*0.0068*	*1.00*	*0.0068*	*0.145*	*0.0010*	*6.1*
2	*14:42*	*0.37*	*0.6*	*0.793*	*0.6*	*0.317*	*0.0155*	*1.00*	*0.0155*	*0.097*	*0.0015*	*9.3*
3	*14:44*	*0.49*	*0.6*	*0.732*	*0.6*	*0.293*	*0.0006*	*1.00*	*0.0006*	*0.089*	*0.0001*	*0.3*
4	*14:46*	*0.61*	*0.6*	*0.640*	*0.6*	*0.256*	*0.0151*	*1.00*	*0.0151*	*0.078*	*0.0012*	*7.3*
5	*14:47*	*0.73*	*0.6*	*0.610*	*0.6*	*0.244*	*0.0269*	*1.00*	*0.0269*	*0.074*	*0.0020*	*12.5*
6	*14:48*	*0.85*	*0.6*	*0.579*	*0.6*	*0.232*	*0.0263*	*1.00*	*0.0263*	*0.071*	*0.0019*	*11.6*
7	*14:50*	*0.98*	*0.6*	*0.579*	*0.6*	*0.232*	*0.0372*	*1.00*	*0.0372*	*0.071*	*0.0026*	*16.4*
8	*14:51*	*1.10*	*0.6*	*0.549*	*0.6*	*0.219*	*0.0187*	*1.00*	*0.0187*	*0.067*	*0.0013*	*7.8*
9	14:53	1.22	0.6	0.610	0.6	0.244	0.0186	1.00	0.0186	0.074	0.0014	8.6
10	*14:54*	*1.34*	*0.6*	*0.610*	*0.6*	*0.244*	*0.0169*	*1.00*	*0.0169*	*0.074*	*0.0013*	*7.8*
11	*14:56*	*1.46*	*0.6*	*0.640*	*0.6*	*0.256*	*0.0033*	*1.00*	*0.0033*	*0.078*	*0.0003*	*1.6*
12	*14:57*	*1.58*	*0.6*	*0.488*	*0.6*	*0.195*	*0.0112*	*1.00*	*0.0112*	*0.059*	*0.0007*	*4.1*
13	14:59	1.71	0.6	0.396	0.6	0.158	0.0072	1.00	0.0072	0.048	0.0003	2.2
14	*15:01*	*1.83*	*0.6*	*0.366*	*0.6*	*0.146*	*0.0014*	*1.00*	*0.0014*	*0.078*	*0.0001*	*0.7*
15	15:01	2.13	None	0.000	0.0	0.0	0.0000	1.00	0.0000	0.000	0.0000	0.0

Rows in italics indicate a QC warning. See the Quality Control page of this report for more information.

Figure 49. Site S007-795 flow cross section



Discharge Measurement Summary

Date Generated: Wed Nov 30 2016

File Information	
File Name	S009-166-LE.WAD
Start Date and Time	2016/08/08 10:58:15

Site Details	
Site Name	
Operator(s)	TWS

System Information	
Sensor Type	FlowTracker
Serial #	P1849
CPU Firmware Version	3.3
Software Ver	2.30
Mounting Correction	0.0%

Units	**(Metric Units)**
Distance	m
Velocity	m/s
Area	m^2
Discharge	m^3/s

Discharge Uncertainty

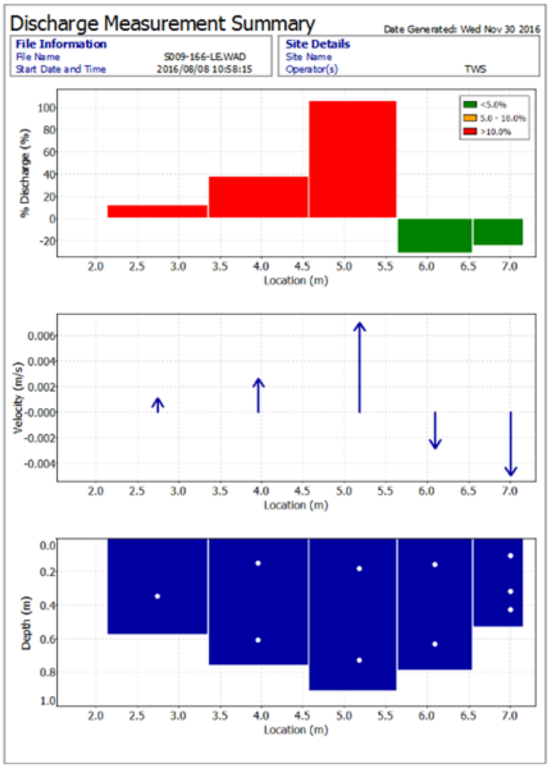
Category	ISO	Stats
Accuracy	1.0%	1.0%
Depth	0.6%	10.2%
Velocity	15.0%	106.9%
Width	0.6%	0.6%
Method	4.3%	-
# Stations	7.8%	-
Overall	**17.5%**	**107.4%**

Summary			
Averaging Int.	40	# Stations	7
Start Edge	LEW	Total Width	5.791
Mean SNR	39.0 dB	Total Area	3.660
Mean Temp	19.31 °C	Mean Depth	0.632
Disch. Equation	Mid-Section	Mean Velocity	0.0018
		Total Discharge	**0.0064**

Measurement Results

St	Clock	Loc	Method	Depth	%Dep	MeasD	Vel	CorrFact	MeanV	Area	Flow	%Q
0	10:58	1.52	None	0.000	0.0	0.0	0.0000	1.00	0.0000	0.000	0.0000	0.0
1	10:58	2.74	0.6	0.579	0.6	0.232	0.0011	1.00	0.0011	0.706	0.0008	12.1
2	11:01	3.96	0.2/0.8	0.762	0.2	0.610	-0.0016	-1.00	0.0026	0.929	0.0025	38.2
2	11:02	3.96	0.2/0.8	0.762	0.8	0.152	-0.0037					
3	11:06	5.18	0.8/0.2	0.914	0.2	0.732	0.0089	1.00	0.0070	0.975	0.0068	106.1
3	11:05	5.18	0.8/0.2	0.914	0.8	0.183	0.0051					
4	11:08	6.10	0.2/0.8	0.793	0.2	0.634	-0.0032	1.00	-0.0028	0.725	-0.0020	-31.5
4	11:10	6.10	0.2/0.8	0.793	0.8	0.159	-0.0024					
5	11:13	7.01	0.2/0.6/0.8	0.533	0.2	0.427	-0.0011	1.00	-0.0049	0.325	-0.0016	-24.9
5	11:14	7.01	0.2/0.6/0.8	0.533	0.6	0.213	-0.0054					
5	11:12	7.01	0.2/0.6/0.8	0.533	0.8	0.107	-0.0078					
6	11:12	7.32	None	0.000	0.0	0.0	0.0000	1.00	0.0000	0.000	0.0000	0.0

Rows in italics indicate a QC warning. See the Quality Control page of this report for more information.



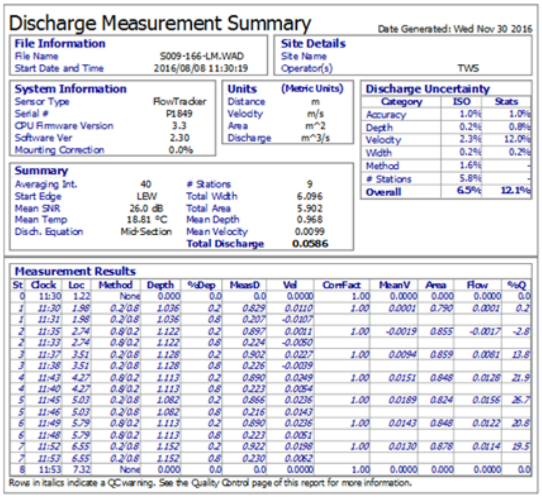
Discharge Measurement Summary

Date Generated: Wed Nov 30 2016

File Information	
File Name	S009-166-LE.WAD
Start Date and Time	2016/08/08 10:58:15

Site Details	
Site Name	
Operator(s)	TWS

Figure 50. Site S009-166-LE flow cross section



Discharge Measurement Summary

Date Generated: Wed Nov 30 2016

File Information	
File Name	S009-166-LM.WAD
Start Date and Time	2016/08/08 11:30:19

Site Details	
Site Name	
Operator(s)	TWS

System Information	
Sensor Type	FlowTracker
Serial #	P1849
CPU Firmware Version	3.3
Software Ver	2.30
Mounting Correction	0.0%

Units	**(Metric Units)**
Distance	m
Velocity	m/s
Area	m^2
Discharge	m^3/s

Discharge Uncertainty

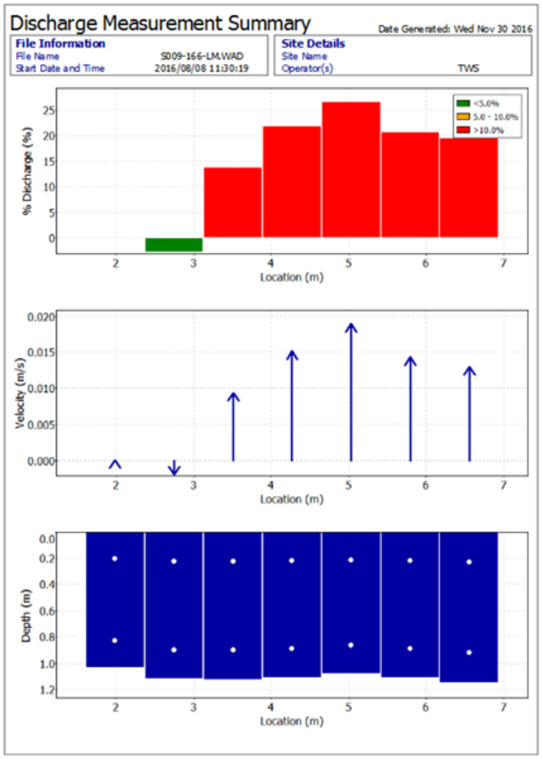
Category	ISO	Stats
Accuracy	1.0%	1.0%
Depth	0.2%	0.8%
Velocity	2.3%	12.0%
Width	0.2%	0.2%
Method	1.6%	-
# Stations	5.8%	-
Overall	**6.5%**	**12.1%**

Summary			
Averaging Int.	40	# Stations	9
Start Edge	LEW	Total Width	6.096
Mean SNR	26.0 dB	Total Area	5.902
Mean Temp	18.81 °C	Mean Depth	0.968
Disch. Equation	Mid-Section	Mean Velocity	0.0099
		Total Discharge	**0.0586**

Measurement Results

St	Clock	Loc	Method	Depth	%Dep	MeasD	Vel	CorrFact	MeanV	Area	Flow	%Q
0	11:30	1.22	None	0.000	0.0	0.0	0.0000	1.00	0.0000	0.000	0.0000	0.0
1	*11:30*	*1.98*	*0.2/0.8*	*1.036*	*0.2*	*0.829*	*0.0110*	*1.00*	*0.0001*	*0.790*	*0.0001*	*0.2*
1	*11:31*	*1.98*	*0.2/0.8*	*1.036*	*0.8*	*0.207*	*-0.0107*					
2	*11:35*	*2.74*	*0.8/0.2*	*1.122*	*0.2*	*0.897*	*0.0011*	*1.00*	*-0.0019*	*0.855*	*-0.0017*	*-2.8*
2	*11:33*	*2.74*	*0.8/0.2*	*1.122*	*0.8*	*0.224*	*-0.0050*					
3	*11:37*	*3.51*	*0.2/0.8*	*1.128*	*0.2*	*0.902*	*0.0227*	*1.00*	*0.0094*	*0.859*	*0.0081*	*13.8*
3	*11:38*	*3.51*	*0.2/0.8*	*1.128*	*0.8*	*0.226*	*-0.0039*					
4	*11:43*	*4.27*	*0.8/0.2*	*1.113*	*0.2*	*0.890*	*0.0249*	*1.00*	*0.0151*	*0.848*	*0.0128*	*21.9*
4	*11:40*	*4.27*	*0.8/0.2*	*1.113*	*0.8*	*0.223*	*0.0054*					
5	*11:45*	*5.03*	*0.2/0.8*	*1.082*	*0.2*	*0.866*	*0.0236*	*1.00*	*0.0189*	*0.824*	*0.0156*	*26.7*
5	*11:46*	*5.03*	*0.2/0.8*	*1.082*	*0.8*	*0.216*	*0.0143*					
6	*11:49*	*5.79*	*0.8/0.2*	*1.113*	*0.2*	*0.890*	*0.0236*	*1.00*	*0.0143*	*0.848*	*0.0122*	*20.8*
6	*11:48*	*5.79*	*0.8/0.2*	*1.113*	*0.8*	*0.223*	*0.0051*					
7	*11:52*	*6.55*	*0.2/0.8*	*1.152*	*0.2*	*0.922*	*0.0198*	*1.00*	*0.0130*	*0.878*	*0.0114*	*19.5*
7	*11:53*	*6.55*	*0.2/0.8*	*1.152*	*0.8*	*0.230*	*0.0062*					
8	11:53	7.32	None	0.000	0.0	0.0	0.0000	1.00	0.0000	0.000	0.0000	0.0

Rows in italics indicate a QC warning. See the Quality Control page of this report for more information.



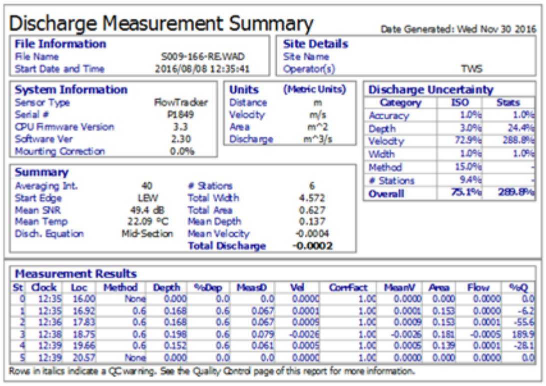
Discharge Measurement Summary

Date Generated: Wed Nov 30 2016

File Information	
File Name	S009-166-LM.WAD
Start Date and Time	2016/08/08 11:30:19

Site Details	
Site Name	
Operator(s)	TWS

Figure 51. Site S009-166-LM flow cross section



Discharge Measurement Summary

Date Generated: Wed Nov 30 2016

File Information	
File Name	S009-166-RE.WAD
Start Date and Time	2016/08/08 12:35:41

Site Details	
Site Name	
Operator(s)	TWS

System Information	
Sensor Type	FlowTracker
Serial #	P1849
CPU Firmware Version	3.3
Software Ver	2.30
Mounting Correction	0.0%

Units	(Metric Units)
Distance	m
Velocity	m/s
Area	m^2
Discharge	m^3/s

Summary			
Averaging Int.	40	# Stations	6
Start Edge	LEW	Total Width	4.572
Mean SNR	49.4 dB	Total Area	0.627
Mean Temp	22.09 °C	Mean Depth	0.137
Disch. Equation	Mid-Section	Mean Velocity	-0.0004
		Total Discharge	**-0.0002**

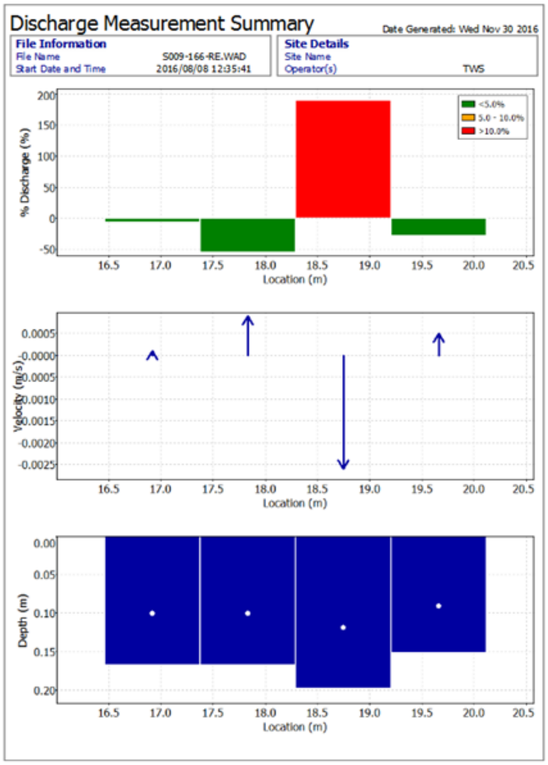
Discharge Uncertainty

Category	ISO	Stats
Accuracy	1.0%	1.0%
Depth	3.0%	24.4%
Velocity	72.9%	288.8%
Width	1.0%	1.0%
Method	15.0%	-
# Stations	9.4%	-
Overall	**75.1%**	**289.8%**

Measurement Results

St	Clock	Loc	Method	Depth	%Dep	MeasD	Vel	CorrFact	MeanV	Area	Flow	%Q
0	12:35	16.00	None	0.000	0.0	0.0	0.0000	1.00	0.0000	0.000	0.0000	0.0
1	12:35	16.92	0.6	0.168	0.6	0.067	0.0001	1.00	0.0001	0.153	0.0000	-6.2
2	12:36	17.83	0.6	0.168	0.6	0.067	0.0009	1.00	0.0009	0.153	0.0001	-55.6
3	12:38	18.75	0.6	0.198	0.6	0.079	-0.0026	1.00	-0.0026	0.181	-0.0005	189.9
4	12:39	19.66	0.6	0.152	0.6	0.061	0.0005	1.00	0.0005	0.139	0.0001	-28.1
5	12:39	20.57	None	0.000	0.0	0.0	0.0000	1.00	0.0000	0.000	0.0000	0.0

Rows in italics indicate a QC warning. See the Quality Control page of this report for more information.



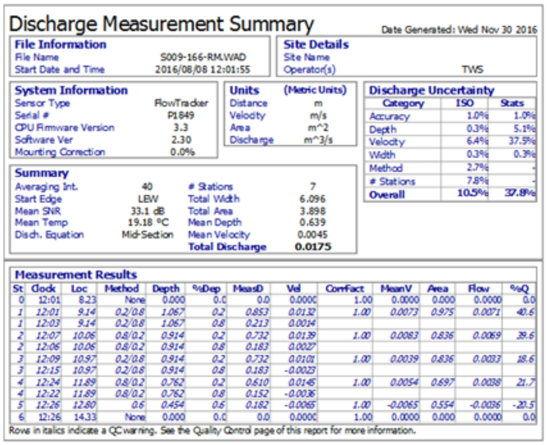
Discharge Measurement Summary

Date Generated: Wed Nov 30 2016

File Information
File Name S009-166-RE.WAD
Start Date and Time 2016/08/08 12:35:41

Site Details
Site Name
Operator(s) TWS

Figure 52. Site S009-166-RE flow cross section



Discharge Measurement Summary

Date Generated: Wed Nov 30 2016

File Information	
File Name	S009-166-RM.WAD
Start Date and Time	2016/08/08 12:01:55

Site Details	
Site Name	
Operator(s)	TWS

System Information	
Sensor Type	FlowTracker
Serial #	P1849
CPU Firmware Version	3.3
Software Ver	2.30
Mounting Correction	0.0%

Units	(Metric Units)
Distance	m
Velocity	m/s
Area	m^2
Discharge	m^3/s

Summary			
Averaging Int.	40	# Stations	7
Start Edge	LEW	Total Width	6.096
Mean SNR	33.1 dB	Total Area	3.898
Mean Temp	19.18 °C	Mean Depth	0.639
Disch. Equation	Mid-Section	Mean Velocity	0.0045
		Total Discharge	**0.0175**

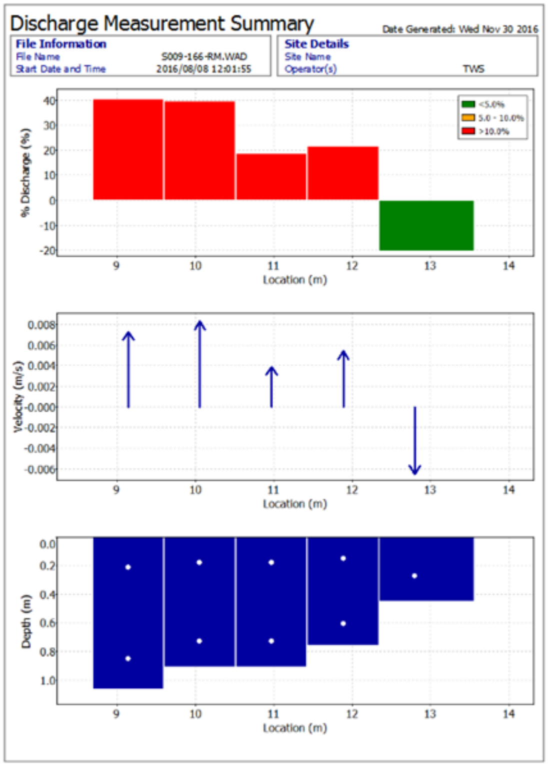
Discharge Uncertainty

Category	ISO	Stats
Accuracy	1.0%	1.0%
Depth	0.3%	5.1%
Velocity	6.4%	37.5%
Width	0.3%	0.3%
Method	2.7%	-
# Stations	7.8%	-
Overall	**10.5%**	**37.8%**

Measurement Results

St	Clock	Loc	Method	Depth	%Dep	MeasD	Vel	CorrFact	MeanV	Area	Flow	%Q
0	12:01	8.23	None	0.000	0.0	0.0	0.0000	1.00	0.0000	0.000	0.0000	0.0
1	*12:01*	*9.14*	*0.2/0.8*	*1.067*	*0.2*	*0.853*	*0.0132*	*1.00*	*0.0073*	*0.975*	*0.0071*	*40.6*
1	*12:03*	*9.14*	*0.2/0.8*	*1.067*	*0.8*	*0.213*	*0.0014*					
2	*12:07*	*10.06*	*0.8/0.2*	*0.914*	*0.2*	*0.732*	*0.0139*	*1.00*	*0.0083*	*0.836*	*0.0069*	*39.6*
2	*12:06*	*10.06*	*0.8/0.2*	*0.914*	*0.8*	*0.183*	*0.0027*					
3	*12:09*	*10.97*	*0.2/0.8*	*0.914*	*0.2*	*0.732*	*0.0101*	*1.00*	*0.0039*	*0.836*	*0.0033*	*18.6*
3	*12:15*	*10.97*	*0.2/0.8*	*0.914*	*0.8*	*0.183*	*-0.0023*					
4	*12:24*	*11.89*	*0.8/0.2*	*0.762*	*0.2*	*0.610*	*0.0145*	*1.00*	*0.0054*	*0.697*	*0.0038*	*21.7*
4	*12:22*	*11.89*	*0.8/0.2*	*0.762*	*0.8*	*0.152*	*-0.0036*					
5	*12:26*	*12.80*	*0.6*	*0.454*	*0.6*	*0.182*	*-0.0065*	*1.00*	*-0.0065*	*0.554*	*-0.0036*	*-20.5*
6	12:26	14.33	None	0.000	0.0	0.0	0.0000	1.00	0.0000	0.000	0.0000	0.0

Rows in italics indicate a QC warning. See the Quality Control page of this report for more information.



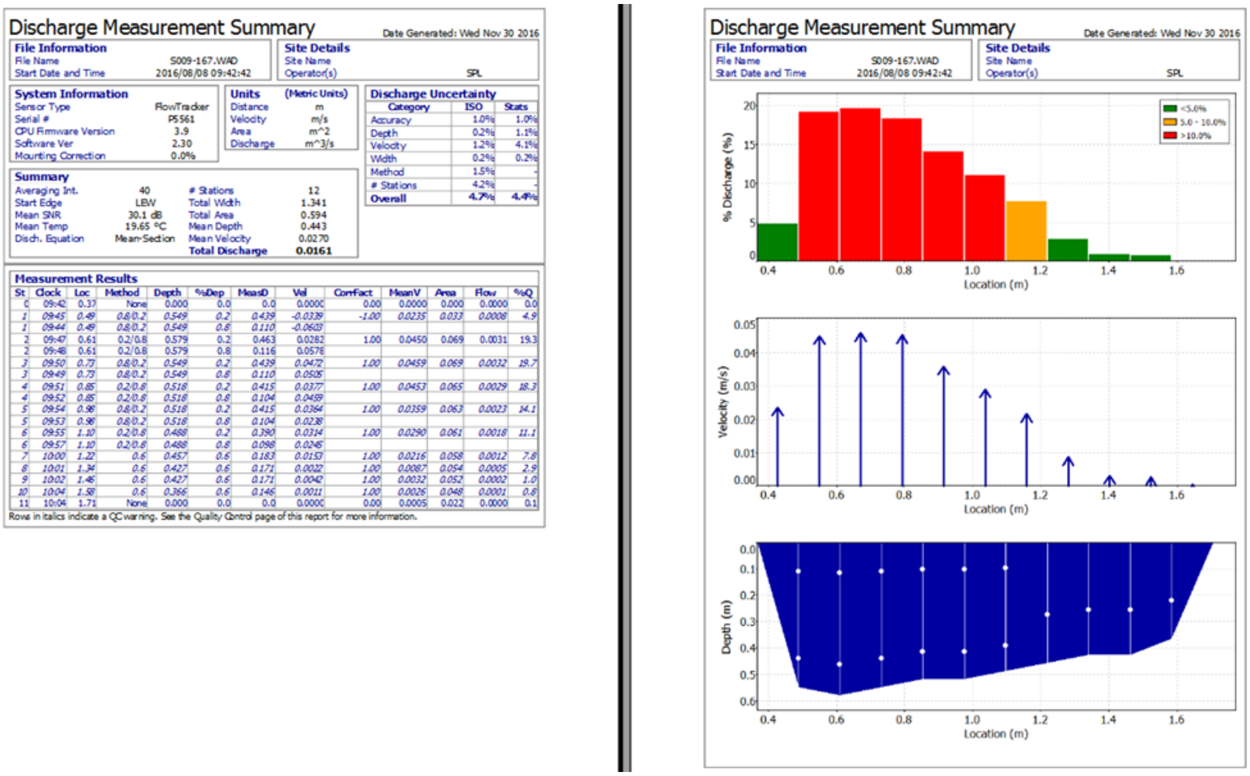
Discharge Measurement Summary

Date Generated: Wed Nov 30 2016

File Information
File Name S009-166-RM.WAD
Start Date and Time 2016/08/08 12:01:55

Site Details
Site Name
Operator(s) TWS

Figure 53. Site S009-166-RM flow cross section



Discharge Measurement Summary

Date Generated: Wed Nov 30 2016

File Information	
File Name	S009-167.WAD
Start Date and Time	2016/08/08 09:42:42

Site Details	
Site Name	
Operator(s)	SPL

System Information	
Sensor Type	FlowTracker
Serial #	P5561
CPU Firmware Version	3.9
Software Ver	2.30
Mounting Correction	0.0%

Units	(Metric Units)
Distance	m
Velocity	m/s
Area	m^2
Discharge	m^3/s

Discharge Uncertainty

Category	ISO	Stats
Accuracy	1.0%	1.0%
Depth	0.2%	1.1%
Velocity	1.2%	4.1%
Width	0.2%	0.2%
Method	1.5%	-
# Stations	4.2%	-
Overall	**4.7%**	**4.4%**

Summary			
Averaging Int.	40	# Stations	12
Start Edge	LEW	Total Width	1.341
Mean SNR	30.1 dB	Total Area	0.594
Mean Temp	19.65 °C	Mean Depth	0.443
Disch. Equation	Mean-Section	Mean Velocity	0.0270
		Total Discharge	**0.0161**

Measurement Results

St	Clock	Loc	Method	Depth	%Dep	MeasD	Vel	CorrFact	MeanV	Area	Flow	%Q
0	09:42	0.37	None	0.000	0.0	0.0	0.0000	0.00	0.0000	0.000	0.0000	0.0
1	*09:45*	*0.49*	*0.8/0.2*	*0.549*	*0.2*	*0.439*	*-0.0339*	*-1.00*	*0.0235*	*0.033*	*0.0008*	*4.9*
1	*09:44*	*0.49*	*0.8/0.2*	*0.549*	*0.8*	*0.110*	*-0.0603*					
2	09:47	0.61	0.2/0.8	0.579	0.2	0.463	0.0282	1.00	0.0450	0.069	0.0031	19.3
2	09:48	0.61	0.2/0.8	0.579	0.8	0.116	0.0578					
3	*09:50*	*0.73*	*0.8/0.2*	*0.549*	*0.2*	*0.439*	*0.0472*	*1.00*	*0.0459*	*0.069*	*0.0032*	*19.7*
3	*09:49*	*0.73*	*0.8/0.2*	*0.549*	*0.8*	*0.110*	*0.0505*					
4	*09:51*	*0.85*	*0.2/0.8*	*0.518*	*0.2*	*0.415*	*0.0377*	*1.00*	*0.0453*	*0.065*	*0.0029*	*18.3*
4	*09:52*	*0.85*	*0.2/0.8*	*0.518*	*0.8*	*0.104*	*0.0459*					
5	*09:54*	*0.98*	*0.8/0.2*	*0.518*	*0.2*	*0.415*	*0.0364*	*1.00*	*0.0359*	*0.063*	*0.0023*	*14.1*
5	*09:53*	*0.98*	*0.8/0.2*	*0.518*	*0.8*	*0.104*	*0.0238*					
6	*09:55*	*1.10*	*0.2/0.8*	*0.488*	*0.2*	*0.390*	*0.0314*	*1.00*	*0.0290*	*0.061*	*0.0018*	*11.1*
6	*09:57*	*1.10*	*0.2/0.8*	*0.488*	*0.8*	*0.098*	*0.0245*					
7	*10:00*	*1.22*	*0.6*	*0.457*	*0.6*	*0.183*	*0.0153*	*1.00*	*0.0216*	*0.058*	*0.0012*	*7.8*
8	*10:01*	*1.34*	*0.6*	*0.427*	*0.6*	*0.171*	*0.0022*	*1.00*	*0.0087*	*0.054*	*0.0005*	*2.9*
9	*10:02*	*1.46*	*0.6*	*0.427*	*0.6*	*0.171*	*0.0042*	*1.00*	*0.0032*	*0.052*	*0.0002*	*1.0*
10	*10:04*	*1.58*	*0.6*	*0.366*	*0.6*	*0.146*	*0.0011*	*1.00*	*0.0026*	*0.048*	*0.0001*	*0.8*
11	10:04	1.71	None	0.000	0.0	0.0	0.0000	0.00	0.0005	0.022	0.0000	0.1

Rows in italics indicate a QC warning. See the Quality Control page of this report for more information.

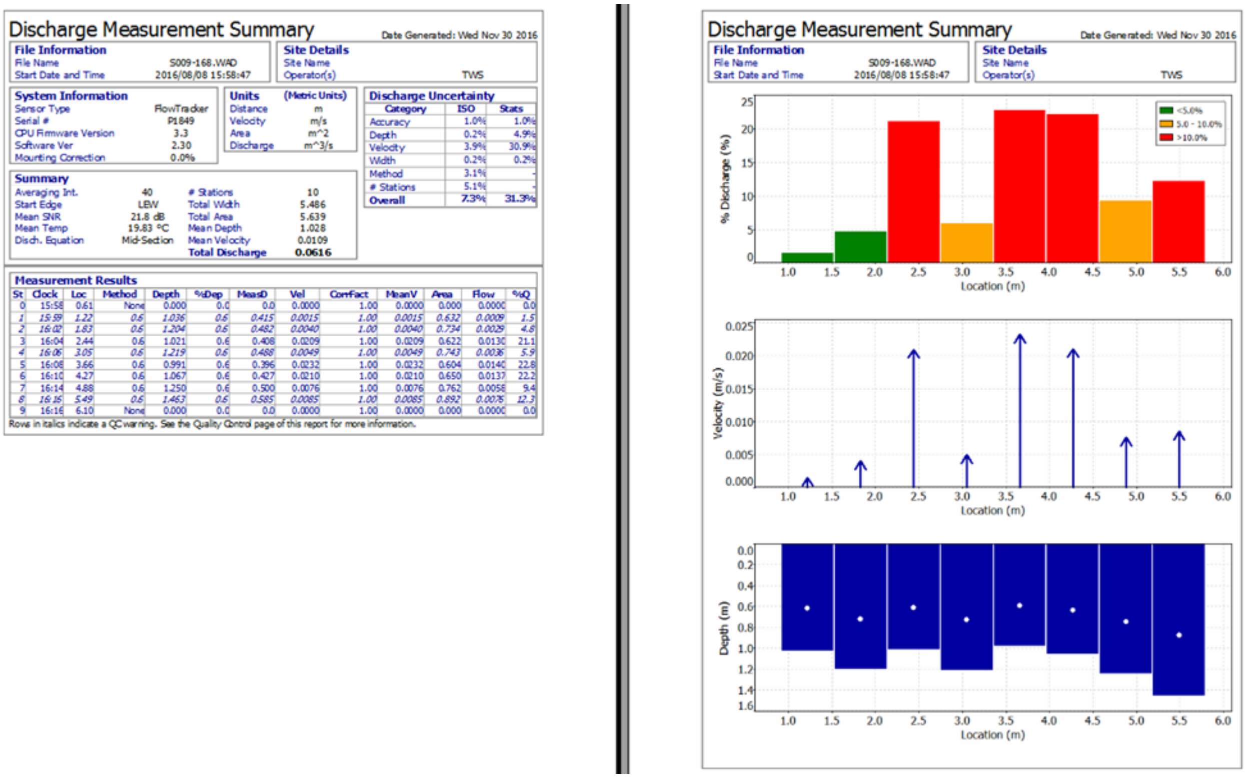
Discharge Measurement Summary

Date Generated: Wed Nov 30 2016

File Information	
File Name	S009-167.WAD
Start Date and Time	2016/08/08 09:42:42

Site Details	
Site Name	
Operator(s)	SPL

Figure 54. Site S009-167 flow cross section



Discharge Measurement Summary

Date Generated: Wed Nov 30 2016

File Information	
File Name	S009-168.WAD
Start Date and Time	2016/08/08 15:58:47

Site Details	
Site Name	
Operator(s)	TWS

System Information	
Sensor Type	FlowTracker
Serial #	P1849
CPU Firmware Version	3.3
Software Ver	2.30
Mounting Correction	0.0%

Units	(Metric Units)
Distance	m
Velocity	m/s
Area	m^2
Discharge	m^3/s

Discharge Uncertainty

Category	ISO	Stats
Accuracy	1.0%	1.0%
Depth	0.2%	4.9%
Velocity	3.9%	30.9%
Width	0.2%	0.2%
Method	3.1%	-
# Stations	5.1%	-
Overall	**7.3%**	**31.3%**

Summary			
Averaging Int.	40	# Stations	10
Start Edge	LEW	Total Width	5.486
Mean SNR	21.8 dB	Total Area	5.639
Mean Temp	19.83 °C	Mean Depth	1.028
Disch. Equation	Mid-Section	Mean Velocity	0.0109
		Total Discharge	**0.0616**

Measurement Results

St	Clock	Loc	Method	Depth	%Dep	MeasD	Vel	CorrFact	MeanV	Area	Flow	%Q
0	15:58	0.61	None	0.000	0.0	0.0	0.0000	1.00	0.0000	0.000	0.0000	0.0
1	*15:59*	*1.22*	*0.6*	*1.036*	*0.6*	*0.415*	*0.0015*	*1.00*	*0.0015*	*0.632*	*0.0009*	*1.5*
2	*16:02*	*1.83*	*0.6*	*1.204*	*0.6*	*0.482*	*0.0040*	*1.00*	*0.0040*	*0.734*	*0.0029*	*4.8*
3	16:04	2.44	0.6	1.021	0.6	0.408	0.0209	1.00	0.0209	0.622	0.0130	21.1
4	*16:06*	*3.05*	*0.6*	*1.219*	*0.6*	*0.488*	*0.0049*	*1.00*	*0.0049*	*0.743*	*0.0036*	*5.9*
5	16:08	3.66	0.6	0.991	0.6	0.396	0.0232	1.00	0.0232	0.604	0.0140	22.8
6	16:10	4.27	0.6	1.067	0.6	0.427	0.0210	1.00	0.0210	0.650	0.0137	22.2
7	16:14	4.88	0.6	1.250	0.6	0.500	0.0076	1.00	0.0076	0.762	0.0058	9.4
8	*16:16*	*5.49*	*0.6*	*1.463*	*0.6*	*0.585*	*0.0085*	*1.00*	*0.0085*	*0.892*	*0.0076*	*12.3*
9	16:16	6.10	None	0.000	0.0	0.0	0.0000	1.00	0.0000	0.000	0.0000	0.0

Rows in italics indicate a QC warning. See the Quality Control page of this report for more information.

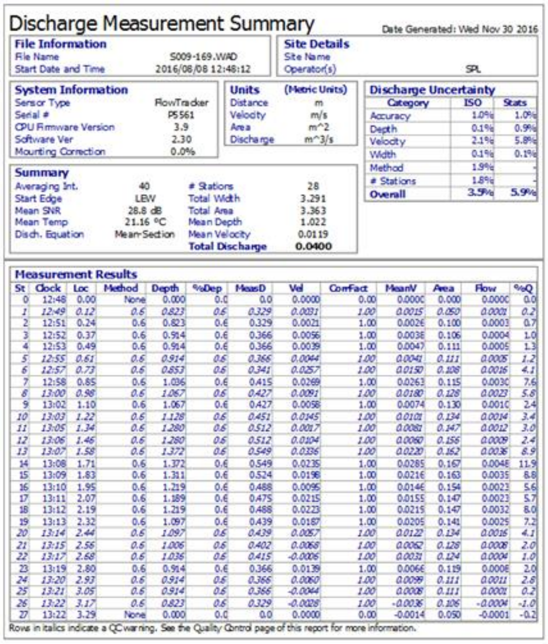
Discharge Measurement Summary

Date Generated: Wed Nov 30 2016

File Information	
File Name	S009-168.WAD
Start Date and Time	2016/08/08 15:58:47

Site Details	
Site Name	
Operator(s)	TWS

Figure 55. Site S009-168 flow cross section



Discharge Measurement Summary

Date Generated: Wed Nov 30 2016

File Information	
File Name	S009-169.WAD
Start Date and Time	2016/08/08 12:48:12

Site Details	
Site Name	
Operator(s)	SPL

System Information	
Sensor Type	FlowTracker
Serial #	P5561
CPU Firmware Version	3.9
Software Ver	2.30
Mounting Correction	0.0%

Units	(Metric Units)
Distance	m
Velocity	m/s
Area	m^2
Discharge	m^3/s

Discharge Uncertainty

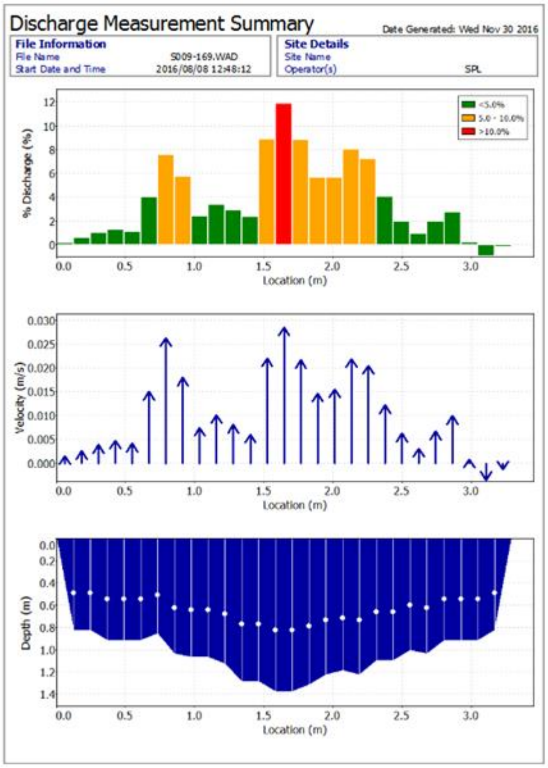
Category	ISO	Stats
Accuracy	1.0%	1.0%
Depth	0.1%	0.9%
Velocity	2.1%	5.8%
Width	0.1%	0.1%
Method	1.9%	-
# Stations	1.8%	-
Overall	**3.5%**	**5.9%**

Summary			
Averaging Int.	40	# Stations	28
Start Edge	LEW	Total Width	3.291
Mean SNR	28.8 dB	Total Area	3.363
Mean Temp	21.16 °C	Mean Depth	1.022
Disch. Equation	Mean-Section	Mean Velocity	0.0119
		Total Discharge	**0.0400**

Measurement Results

St	Clock	Loc	Method	Depth	%Dep	MeasD	Vel	CorrFact	MeanV	Area	Flow	%Q
0	12:48	0.00	None	0.000	0.0	0.0	0.0000	0.00	0.0000	0.000	0.0000	0.0
1	*12:49*	*0.12*	*0.6*	*0.823*	*0.6*	*0.329*	*0.0031*	*1.00*	*0.0015*	*0.050*	*0.0001*	*0.2*
2	12:51	0.24	0.6	0.823	0.6	0.329	0.0021	1.00	0.0026	0.100	0.0003	0.7
3	12:52	0.37	0.6	0.914	0.6	0.366	0.0056	1.00	0.0038	0.106	0.0004	1.0
4	12:53	0.49	0.6	0.914	0.6	0.366	0.0039	1.00	0.0047	0.111	0.0005	1.3
5	*12:55*	*0.61*	*0.6*	*0.914*	*0.6*	*0.366*	*0.0044*	*1.00*	*0.0041*	*0.111*	*0.0005*	*1.2*
6	*12:57*	*0.73*	*0.6*	*0.853*	*0.6*	*0.341*	*0.0257*	*1.00*	*0.0150*	*0.108*	*0.0016*	*4.1*
7	12:58	0.85	0.6	1.036	0.6	0.415	0.0269	1.00	0.0263	0.115	0.0030	7.6
8	*13:00*	*0.98*	*0.6*	*1.067*	*0.6*	*0.427*	*0.0091*	*1.00*	*0.0180*	*0.128*	*0.0023*	*5.8*
9	13:02	1.10	0.6	1.067	0.6	0.427	0.0058	1.00	0.0074	0.130	0.0010	2.4
10	*13:03*	*1.22*	*0.6*	*1.128*	*0.6*	*0.451*	*0.0145*	*1.00*	*0.0101*	*0.134*	*0.0014*	*3.4*
11	*13:05*	*1.34*	*0.6*	*1.280*	*0.6*	*0.512*	*0.0017*	*1.00*	*0.0081*	*0.147*	*0.0012*	*3.0*
12	*13:06*	*1.46*	*0.6*	*1.280*	*0.6*	*0.512*	*0.0104*	*1.00*	*0.0060*	*0.156*	*0.0009*	*2.4*
13	*13:07*	*1.58*	*0.6*	*1.372*	*0.6*	*0.549*	*0.0336*	*1.00*	*0.0220*	*0.162*	*0.0036*	*8.9*
14	13:08	1.71	0.6	1.372	0.6	0.549	0.0235	1.00	0.0285	0.167	0.0046	11.9
15	13:09	1.83	0.6	1.311	0.6	0.524	0.0198	1.00	0.0216	0.163	0.0035	8.8
16	13:10	1.95	0.6	1.219	0.6	0.488	0.0095	1.00	0.0146	0.154	0.0023	5.6
17	13:11	2.07	0.6	1.189	0.6	0.475	0.0215	1.00	0.0155	0.147	0.0023	5.7
18	13:12	2.19	0.6	1.219	0.6	0.488	0.0223	1.00	0.0215	0.147	0.0032	8.0
19	13:13	2.32	0.6	1.097	0.6	0.439	0.0187	1.00	0.0205	0.141	0.0025	7.2
20	*13:14*	*2.44*	*0.6*	*1.097*	*0.6*	*0.439*	*0.0057*	*1.00*	*0.0122*	*0.134*	*0.0016*	*4.1*
21	*13:15*	*2.56*	*0.6*	*1.006*	*0.6*	*0.402*	*0.0068*	*1.00*	*0.0062*	*0.128*	*0.0008*	*2.0*
22	*13:17*	*2.68*	*0.6*	*1.036*	*0.6*	*0.415*	*-0.0006*	*1.00*	*0.0031*	*0.124*	*0.0004*	*1.0*
23	13:19	2.80	0.6	0.914	0.6	0.366	0.0139	1.00	0.0066	0.119	0.0008	2.0
24	*13:20*	*2.93*	*0.6*	*0.914*	*0.6*	*0.366*	*0.0060*	*1.00*	*0.0099*	*0.111*	*0.0011*	*2.8*
25	*13:21*	*3.05*	*0.6*	*0.914*	*0.6*	*0.366*	*-0.0044*	*1.00*	*0.0008*	*0.111*	*0.0001*	*0.2*
26	*13:22*	*3.17*	*0.6*	*0.823*	*0.6*	*0.329*	*-0.0028*	*1.00*	*-0.0036*	*0.106*	*-0.0004*	*-1.0*
27	13:22	3.29	None	0.000	0.0	0.0	0.0000	0.00	-0.0014	0.050	-0.0001	-0.2

Rows in italics indicate a QC warning. See the Quality Control page of this report for more information.



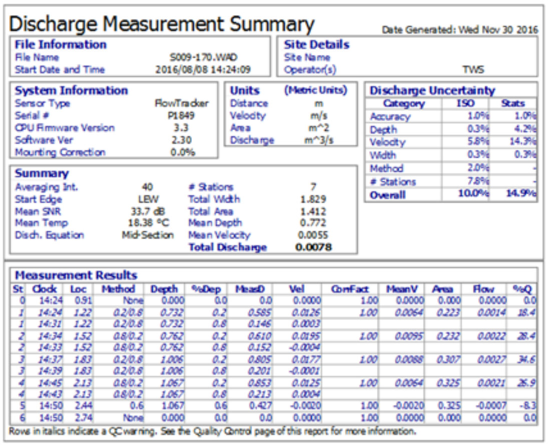
Discharge Measurement Summary

Date Generated: Wed Nov 30 2016

File Information
File Name S009-169.WAD
Start Date and Time 2016/08/08 12:48:12

Site Details
Site Name
Operator(s) SPL

Figure 56. Site S009-169 flow cross section



Discharge Measurement Summary

Date Generated: Wed Nov 30 2016

File Information	
File Name	S009-170.WAD
Start Date and Time	2016/08/08 14:24:09

Site Details	
Site Name	
Operator(s)	TWS

System Information	
Sensor Type	FlowTracker
Serial #	P1849
CPU Firmware Version	3.3
Software Ver	2.30
Mounting Correction	0.0%

Units	(Metric Units)
Distance	m
Velocity	m/s
Area	m^2
Discharge	m^3/s

Discharge Uncertainty

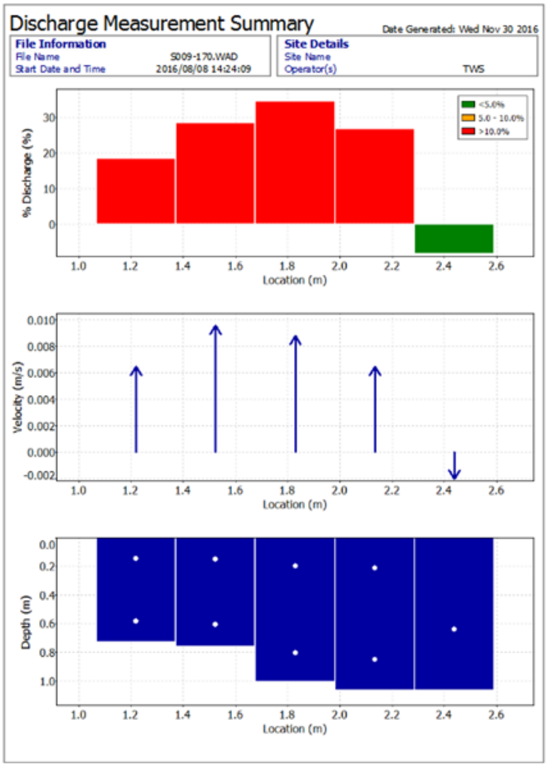
Category	ISO	Stats
Accuracy	1.0%	1.0%
Depth	0.3%	4.2%
Velocity	5.8%	14.3%
Width	0.3%	0.3%
Method	2.0%	-
# Stations	7.8%	-
Overall	**10.0%**	**14.9%**

Summary			
Averaging Int.	40	# Stations	7
Start Edge	LEW	Total Width	1.829
Mean SNR	33.7 dB	Total Area	1.412
Mean Temp	18.38 °C	Mean Depth	0.772
Disch. Equation	Mid-Section	Mean Velocity	0.0055
		Total Discharge	**0.0078**

Measurement Results

St	Clock	Loc	Method	Depth	%Dep	MeasD	Vel	CorrFact	MeanV	Area	Flow	%Q
0	14:24	0.91	None	0.000	0.0	0.0	0.0000	1.00	0.0000	0.000	0.0000	0.0
1	*14:24*	*1.22*	*0.2/0.8*	*0.732*	*0.2*	*0.585*	*0.0126*	*1.00*	*0.0064*	*0.223*	*0.0014*	*18.4*
1	*14:31*	*1.22*	*0.2/0.8*	*0.732*	*0.8*	*0.146*	*0.0003*					
2	*14:34*	*1.52*	*0.8/0.2*	*0.762*	*0.2*	*0.610*	*0.0195*	*1.00*	*0.0095*	*0.232*	*0.0022*	*28.4*
2	*14:33*	*1.52*	*0.8/0.2*	*0.762*	*0.8*	*0.152*	*-0.0004*					
3	*14:37*	*1.83*	*0.2/0.8*	*1.006*	*0.2*	*0.805*	*0.0177*	*1.00*	*0.0088*	*0.307*	*0.0027*	*34.6*
3	*14:39*	*1.83*	*0.2/0.8*	*1.006*	*0.8*	*0.201*	*-0.0001*					
4	*14:45*	*2.13*	*0.8/0.2*	*1.067*	*0.2*	*0.853*	*0.0125*	*1.00*	*0.0064*	*0.325*	*0.0021*	*25.9*
4	*14:43*	*2.13*	*0.8/0.2*	*1.067*	*0.8*	*0.213*	*0.0004*					
5	14:50	2.44	0.6	1.067	0.6	0.427	-0.0020	1.00	-0.0020	0.325	-0.0007	-8.3
6	14:50	2.74	None	0.000	0.0	0.0	0.0000	1.00	0.0000	0.000	0.0000	0.0

Rows in italics indicate a QC warning. See the Quality Control page of this report for more information.



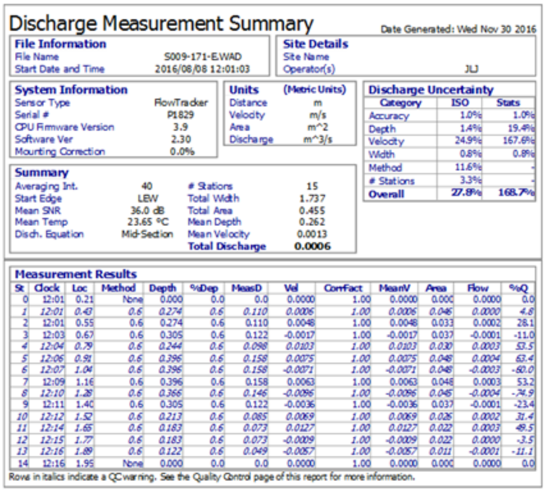
Discharge Measurement Summary

Date Generated: Wed Nov 30 2016

File Information
File Name S009-170.WAD
Start Date and Time 2016/08/08 14:24:09

Site Details
Site Name
Operator(s) TWS

Figure 57. Site S009-170 flow cross section



Discharge Measurement Summary

Date Generated: Wed Nov 30 2016

File Information

File Name	S009-171-E.WAD
Start Date and Time	2016/08/08 12:01:03

Site Details

Site Name	
Operator(s)	JLJ

System Information

Sensor Type	FlowTracker
Serial #	P1829
CPU Firmware Version	3.9
Software Ver	2.30
Mounting Correction	0.0%

Units	(Metric Units)
Distance	m
Velocity	m/s
Area	m^2
Discharge	m^3/s

Discharge Uncertainty

Category	ISO	Stats
Accuracy	1.0%	1.0%
Depth	1.4%	19.4%
Velocity	24.9%	167.6%
Width	0.8%	0.8%
Method	11.6%	-
# Stations	3.3%	-
Overall	**27.8%**	**168.7%**

Summary

Averaging Int.	40	# Stations	15
Start Edge	LEW	Total Width	1.737
Mean SNR	36.0 dB	Total Area	0.455
Mean Temp	23.65 °C	Mean Depth	0.262
Disch. Equation	Mid-Section	Mean Velocity	0.0013
		Total Discharge	**0.0006**

Measurement Results

St	Clock	Loc	Method	Depth	%Dep	MeasD	Vel	CorrFact	MeanV	Area	Flow	%Q
0	12:01	0.21	None	0.000	0.0	0.0	0.0000	1.00	0.0000	0.000	0.0000	0.0
1	*12:01*	*0.43*	*0.6*	*0.274*	*0.6*	*0.110*	*0.0006*	*1.00*	*0.0006*	*0.046*	*0.0000*	*4.8*
2	12:01	0.55	0.6	0.274	0.6	0.110	0.0048	1.00	0.0048	0.033	0.0002	28.1
3	12:03	0.67	0.6	0.305	0.6	0.122	-0.0017	1.00	-0.0017	0.037	-0.0001	-11.0
4	*12:04*	*0.79*	*0.6*	*0.244*	*0.6*	*0.098*	*0.0103*	*1.00*	*0.0103*	*0.030*	*0.0003*	*53.5*
5	*12:06*	*0.91*	*0.6*	*0.396*	*0.6*	*0.158*	*0.0075*	*1.00*	*0.0075*	*0.048*	*0.0004*	*63.4*
6	*12:07*	*1.04*	*0.6*	*0.396*	*0.6*	*0.158*	*-0.0071*	*1.00*	*-0.0071*	*0.048*	*-0.0003*	*-60.0*
7	12:09	1.16	0.6	0.396	0.6	0.158	0.0063	1.00	0.0063	0.048	0.0003	53.2
8	*12:10*	*1.28*	*0.6*	*0.366*	*0.6*	*0.146*	*-0.0096*	*1.00*	*-0.0096*	*0.045*	*-0.0004*	*-74.9*
9	12:11	1.40	0.6	0.305	0.6	0.122	-0.0036	1.00	-0.0036	0.037	-0.0001	-23.4
10	*12:12*	*1.52*	*0.6*	*0.213*	*0.6*	*0.085*	*0.0069*	*1.00*	*0.0069*	*0.026*	*0.0002*	*31.4*
11	*12:14*	*1.65*	*0.6*	*0.183*	*0.6*	*0.073*	*0.0127*	*1.00*	*0.0127*	*0.022*	*0.0003*	*49.5*
12	*12:15*	*1.77*	*0.6*	*0.183*	*0.6*	*0.073*	*-0.0009*	*1.00*	*-0.0009*	*0.022*	*0.0000*	*-3.5*
13	*12:16*	*1.89*	*0.6*	*0.122*	*0.6*	*0.049*	*-0.0057*	*1.00*	*-0.0057*	*0.011*	*-0.0001*	*-11.1*
14	12:16	1.95	None	0.000	0.0	0.0	0.0000	1.00	0.0000	0.000	0.0000	0.0

Rows in italics indicate a QC warning. See the Quality Control page of this report for more information.

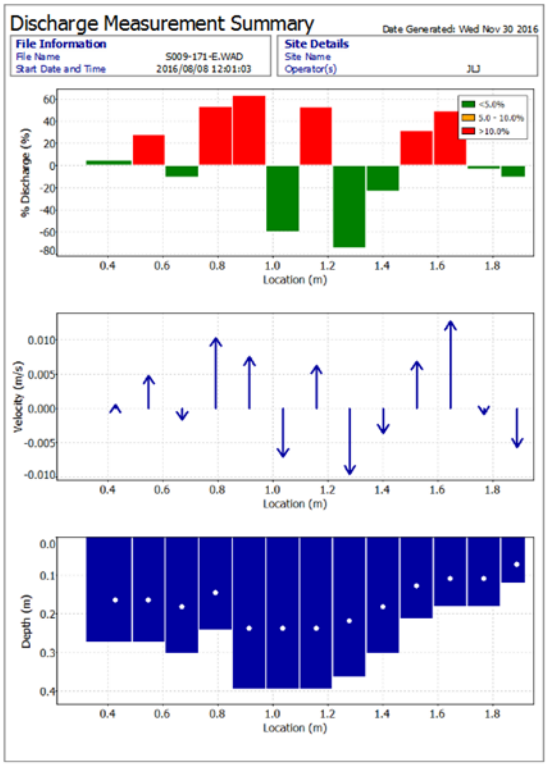
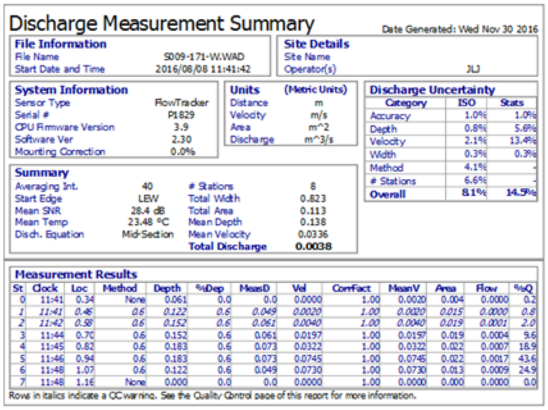


Figure 58. Site S009-171-E flow cross section



Discharge Measurement Summary

Date Generated: Wed Nov 30 2016

File Information

File Name	S009-171-W.WAD
Start Date and Time	2016/08/08 11:41:42

Site Details

Site Name	
Operator(s)	JLJ

System Information

Sensor Type	FlowTracker
Serial #	P1829
CPU Firmware Version	3.9
Software Ver	2.30
Mounting Correction	0.0%

Units	(Metric Units)
Distance	m
Velocity	m/s
Area	m^2
Discharge	m^3/s

Discharge Uncertainty

Category	ISO	Stats
Accuracy	1.0%	1.0%
Depth	0.8%	5.6%
Velocity	2.1%	13.4%
Width	0.3%	0.3%
Method	4.1%	-
# Stations	6.6%	-
Overall	**8.1%**	**14.5%**

Summary

Averaging Int.	40	# Stations	8
Start Edge	LEW	Total Width	0.823
Mean SNR	28.4 dB	Total Area	0.113
Mean Temp	23.48 °C	Mean Depth	0.138
Disch. Equation	Mid-Section	Mean Velocity	0.0336
		Total Discharge	**0.0038**

Measurement Results

St	Clock	Loc	Method	Depth	%Dep	MeasD	Vel	CorrFact	MeanV	Area	Flow	%Q
0	11:41	0.34	None	0.061	0.0	0.0	0.0000	1.00	0.0020	0.004	0.0000	0.2
1	*11:41*	*0.46*	*0.6*	*0.122*	*0.6*	*0.049*	*0.0020*	*1.00*	*0.0020*	*0.015*	*0.0000*	*0.8*
2	*11:42*	*0.58*	*0.6*	*0.152*	*0.6*	*0.061*	*0.0040*	*1.00*	*0.0040*	*0.019*	*0.0001*	*2.0*
3	11:44	0.70	0.6	0.152	0.6	0.061	0.0197	1.00	0.0197	0.019	0.0004	9.6
4	11:45	0.82	0.6	0.183	0.6	0.073	0.0322	1.00	0.0322	0.022	0.0007	18.9
5	11:46	0.94	0.6	0.183	0.6	0.073	0.0745	1.00	0.0745	0.022	0.0017	43.6
6	11:48	1.07	0.6	0.122	0.6	0.049	0.0730	1.00	0.0730	0.013	0.0009	24.9
7	11:48	1.16	None	0.000	0.0	0.0	0.0000	1.00	0.0000	0.000	0.0000	0.0

Rows in italics indicate a QC warning. See the Quality Control page of this report for more information.

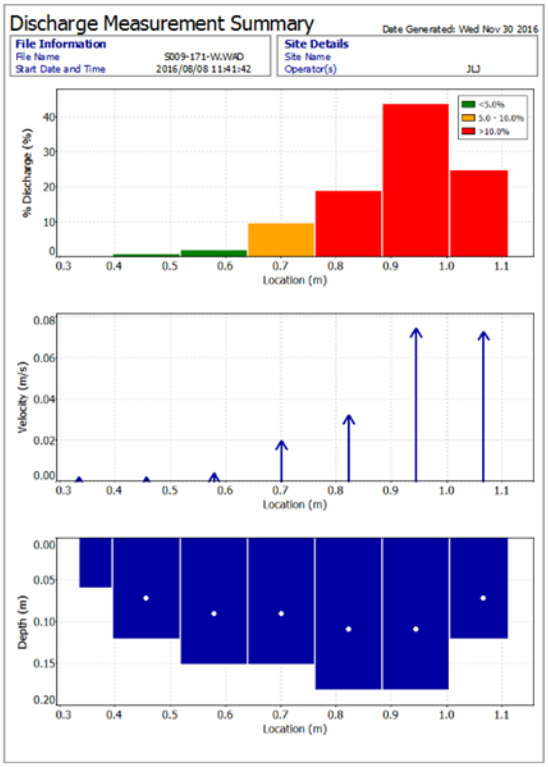
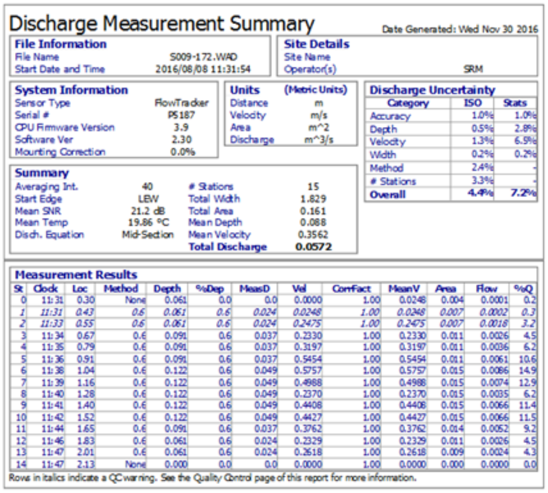


Figure 59. Site S009-171-W flow cross section



Discharge Measurement Summary

Date Generated: Wed Nov 30 2016

File Information

File Name	S009-172.WAD
Start Date and Time	2016/08/08 11:31:54

Site Details

Site Name	
Operator(s)	SRM

System Information

Sensor Type	FlowTracker
Serial #	P5187
CPU Firmware Version	3.9
Software Ver	2.30
Mounting Correction	0.0%

Units	(Metric Units)
Distance	m
Velocity	m/s
Area	m^2
Discharge	m^3/s

Discharge Uncertainty

Category	ISO	Stats
Accuracy	1.0%	1.0%
Depth	0.5%	2.8%
Velocity	1.3%	6.5%
Width	0.2%	0.2%
Method	2.4%	-
# Stations	3.3%	-
Overall	**4.4%**	**7.2%**

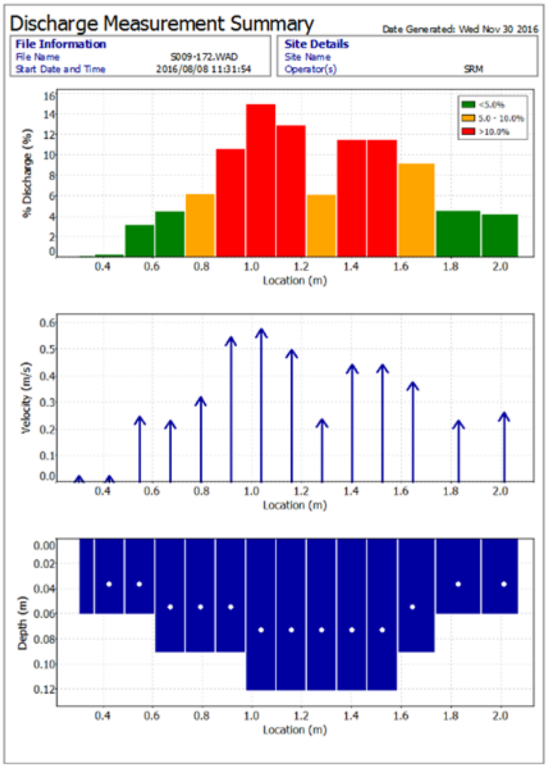
Summary

Averaging Int.	40	# Stations	15
Start Edge	LEW	Total Width	1.829
Mean SNR	21.2 dB	Total Area	0.161
Mean Temp	19.86 °C	Mean Depth	0.088
Disch. Equation	Mid-Section	Mean Velocity	0.3562
		Total Discharge	**0.0572**

Measurement Results

St	Clock	Loc	Method	Depth	%Dep	MeasD	Vel	CorrFact	MeanV	Area	Flow	%Q
0	11:31	0.30	None	0.061	0.0	0.0	0.0000	1.00	0.0248	0.004	0.0001	0.2
1	*11:31*	*0.43*	*0.6*	*0.061*	*0.6*	*0.024*	*0.0248*	*1.00*	*0.0248*	*0.007*	*0.0002*	*0.3*
2	*11:33*	*0.55*	*0.6*	*0.061*	*0.6*	*0.024*	*0.2475*	*1.00*	*0.2475*	*0.007*	*0.0018*	*3.2*
3	11:34	0.67	0.6	0.091	0.6	0.037	0.2330	1.00	0.2330	0.011	0.0026	4.5
4	11:35	0.79	0.6	0.091	0.6	0.037	0.3197	1.00	0.3197	0.011	0.0036	6.2
5	11:36	0.91	0.6	0.091	0.6	0.037	0.5454	1.00	0.5454	0.011	0.0061	10.6
6	11:38	1.04	0.6	0.122	0.6	0.049	0.5757	1.00	0.5757	0.015	0.0086	14.9
7	11:39	1.16	0.6	0.122	0.6	0.049	0.4988	1.00	0.4988	0.015	0.0074	12.9
8	11:40	1.28	0.6	0.122	0.6	0.049	0.2370	1.00	0.2370	0.015	0.0035	6.2
9	11:41	1.40	0.6	0.122	0.6	0.049	0.4408	1.00	0.4408	0.015	0.0066	11.4
10	11:42	1.52	0.6	0.122	0.6	0.049	0.4427	1.00	0.4427	0.015	0.0066	11.5
11	11:44	1.65	0.6	0.091	0.6	0.037	0.3762	1.00	0.3762	0.014	0.0052	9.2
12	11:46	1.83	0.6	0.061	0.6	0.024	0.2329	1.00	0.2329	0.011	0.0026	4.5
13	11:47	2.01	0.6	0.061	0.6	0.024	0.2618	1.00	0.2618	0.009	0.0024	4.3
14	11:47	2.13	None	0.000	0.0	0.0	0.0000	1.00	0.0000	0.000	0.0000	0.0

Rows in italics indicate a QC warning. See the Quality Control page of this report for more information.



Discharge Measurement Summary

Date Generated: Wed Nov 30 2016

File Information

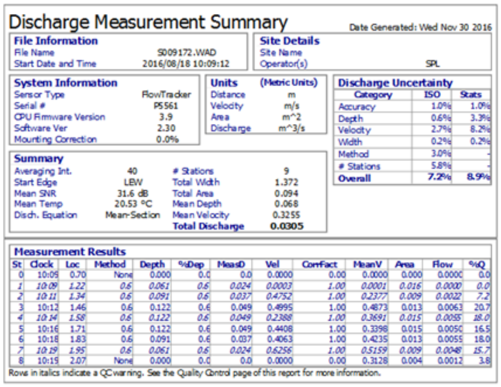
File Name	S009-172.WAD
Start Date and Time	2016/08/08 11:31:54

Site Details

Site Name	
Operator(s)	SRM

Figure 60. Site S009-172 flow cross section

Sample Date 8/18/2016



Discharge Measurement Summary

Date Generated: Wed Nov 30 2016

File Information

File Name	S009172.WAD
Start Date and Time	2016/08/18 10:09:12

Site Details

Site Name	
Operator(s)	SPL

System Information

Sensor Type	FlowTracker
Serial #	P5561
CPU Firmware Version	3.9
Software Ver	2.30
Mounting Correction	0.0%

Units	(Metric Units)
Distance	m
Velocity	m/s
Area	m^2
Discharge	m^3/s

Discharge Uncertainty

Category	ISO	Stats
Accuracy	1.0%	1.0%
Depth	0.6%	3.3%
Velocity	2.7%	8.2%
Width	0.2%	0.2%
Method	3.0%	-
# Stations	5.8%	-
Overall	**7.2%**	**8.9%**

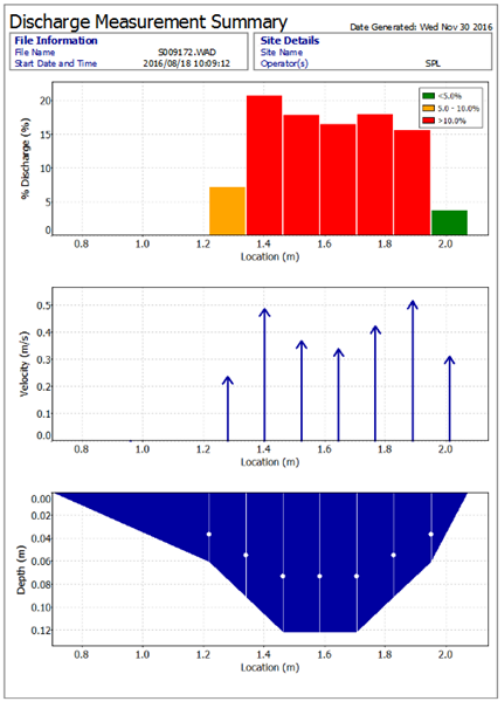
Summary

Averaging Int.	40	# Stations	9
Start Edge	LEW	Total Width	1.372
Mean SNR	31.6 dB	Total Area	0.094
Mean Temp	20.53 °C	Mean Depth	0.068
Disch. Equation	Mean-Section	Mean Velocity	0.3255
		Total Discharge	**0.0305**

Measurement Results

St	Clock	Loc	Method	Depth	%Dep	MeasD	Vel	CorrFact	MeanV	Area	Flow	%Q
0	10:09	0.70	None	0.000	0.0	0.0	0.0000	0.00	0.0000	0.000	0.0000	0.0
1	*10:09*	*1.22*	*0.6*	*0.061*	*0.6*	*0.024*	*0.0003*	*1.00*	*0.0001*	*0.016*	*0.0000*	*0.0*
2	*10:11*	*1.34*	*0.6*	*0.091*	*0.6*	*0.037*	*0.4752*	*1.00*	*0.2377*	*0.009*	*0.0022*	*7.2*
3	10:12	1.46	0.6	0.122	0.6	0.049	0.4995	1.00	0.4873	0.013	0.0063	20.7
4	*10:14*	*1.58*	*0.6*	*0.122*	*0.6*	*0.049*	*0.2388*	*1.00*	*0.3691*	*0.015*	*0.0055*	*18.0*
5	10:16	1.71	0.6	0.122	0.6	0.049	0.4408	1.00	0.3398	0.015	0.0050	16.5
6	10:18	1.83	0.6	0.091	0.6	0.037	0.4063	1.00	0.4235	0.013	0.0055	18.0
7	*10:19*	*1.95*	*0.6*	*0.061*	*0.6*	*0.024*	*0.6256*	*1.00*	*0.5159*	*0.009*	*0.0048*	*15.7*
8	10:19	2.07	None	0.000	0.0	0.0	0.0000	0.00	0.3128	0.004	0.0012	3.8

Rows in italics indicate a QC warning. See the Quality Control page of this report for more information.



Discharge Measurement Summary

Date Generated: Wed Nov 30 2016

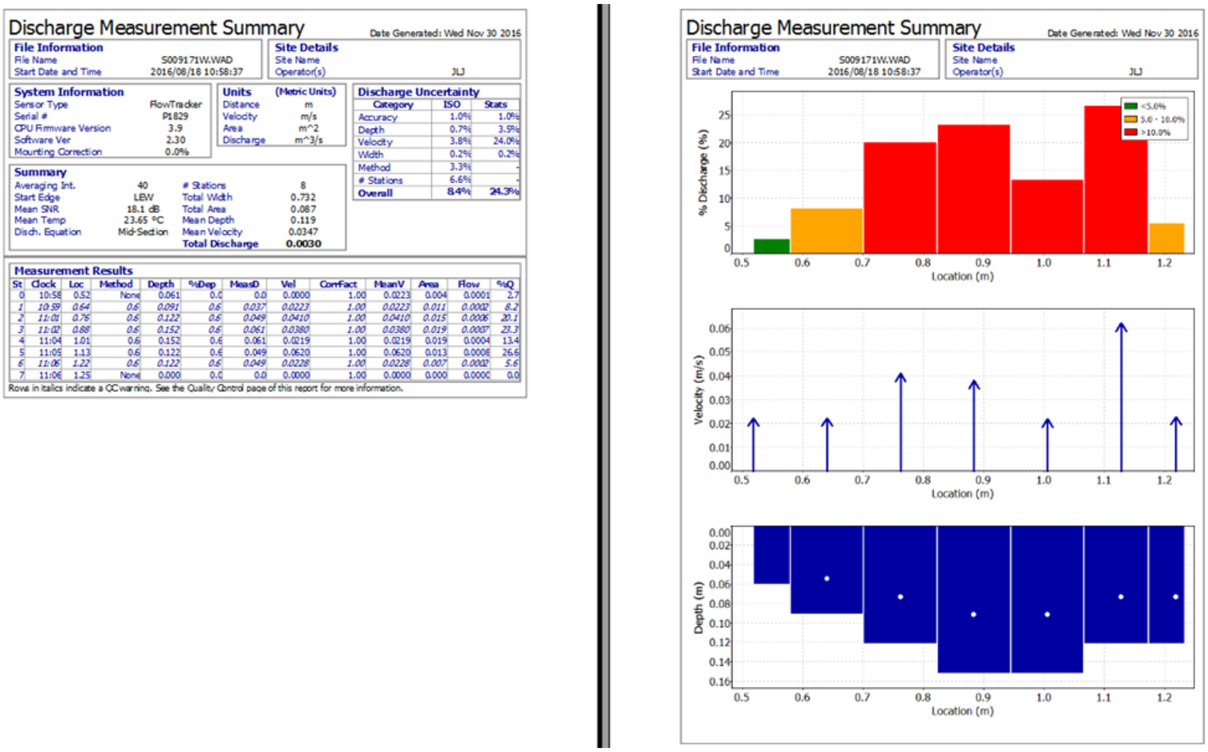
File Information

File Name	S009172.WAD
Start Date and Time	2016/08/18 10:09:12

Site Details

Site Name	
Operator(s)	SPL

Figure 61. Site S009-172 flow cross section



Discharge Measurement Summary

Date Generated: Wed Nov 30 2016

File Information	
File Name	S009171W.WAD
Start Date and Time	2016/08/18 10:58:37

Site Details	
Site Name	
Operator(s)	JLJ

System Information	
Sensor Type	FlowTracker
Serial #	P1829
CPU Firmware Version	3.9
Software Ver	2.30
Mounting Correction	0.0%

Units	(Metric Units)
Distance	m
Velocity	m/s
Area	m^2
Discharge	m^3/s

Discharge Uncertainty

Category	ISO	Stats
Accuracy	1.0%	1.0%
Depth	0.7%	3.5%
Velocity	3.8%	24.0%
Width	0.2%	0.2%
Method	3.3%	-
# Stations	6.6%	-
Overall	**8.4%**	**24.3%**

Summary			
Averaging Int.	40	# Stations	8
Start Edge	LEW	Total Width	0.732
Mean SNR	18.1 dB	Total Area	0.087
Mean Temp	23.65 °C	Mean Depth	0.119
Disch. Equation	Mid-Section	Mean Velocity	0.0347
		Total Discharge	**0.0030**

Measurement Results

St	Clock	Loc	Method	Depth	%Dep	MeasD	Vel	CorrFact	MeanV	Area	Flow	%Q
0	10:58	0.52	None	0.061	0.0	0.0	0.0000	1.00	0.0223	0.004	0.0001	2.7
1	*10:59*	*0.64*	*0.6*	*0.091*	*0.6*	*0.037*	*0.0223*	*1.00*	*0.0223*	*0.011*	*0.0002*	*8.2*
2	*11:01*	*0.76*	*0.6*	*0.122*	*0.6*	*0.049*	*0.0410*	*1.00*	*0.0410*	*0.015*	*0.0006*	*20.1*
3	*11:02*	*0.88*	*0.6*	*0.152*	*0.6*	*0.061*	*0.0380*	*1.00*	*0.0380*	*0.019*	*0.0007*	*23.3*
4	11:04	1.01	0.6	0.152	0.6	0.061	0.0219	1.00	0.0219	0.019	0.0004	13.4
5	11:05	1.13	0.6	0.122	0.6	0.049	0.0620	1.00	0.0620	0.013	0.0008	26.6
6	*11:06*	*1.22*	*0.6*	*0.122*	*0.6*	*0.049*	*0.0228*	*1.00*	*0.0228*	*0.007*	*0.0002*	*5.6*
7	11:06	1.25	None	0.000	0.0	0.0	0.0000	1.00	0.0000	0.000	0.0000	0.0

Rows in italics indicate a QC warning. See the Quality Control page of this report for more information.

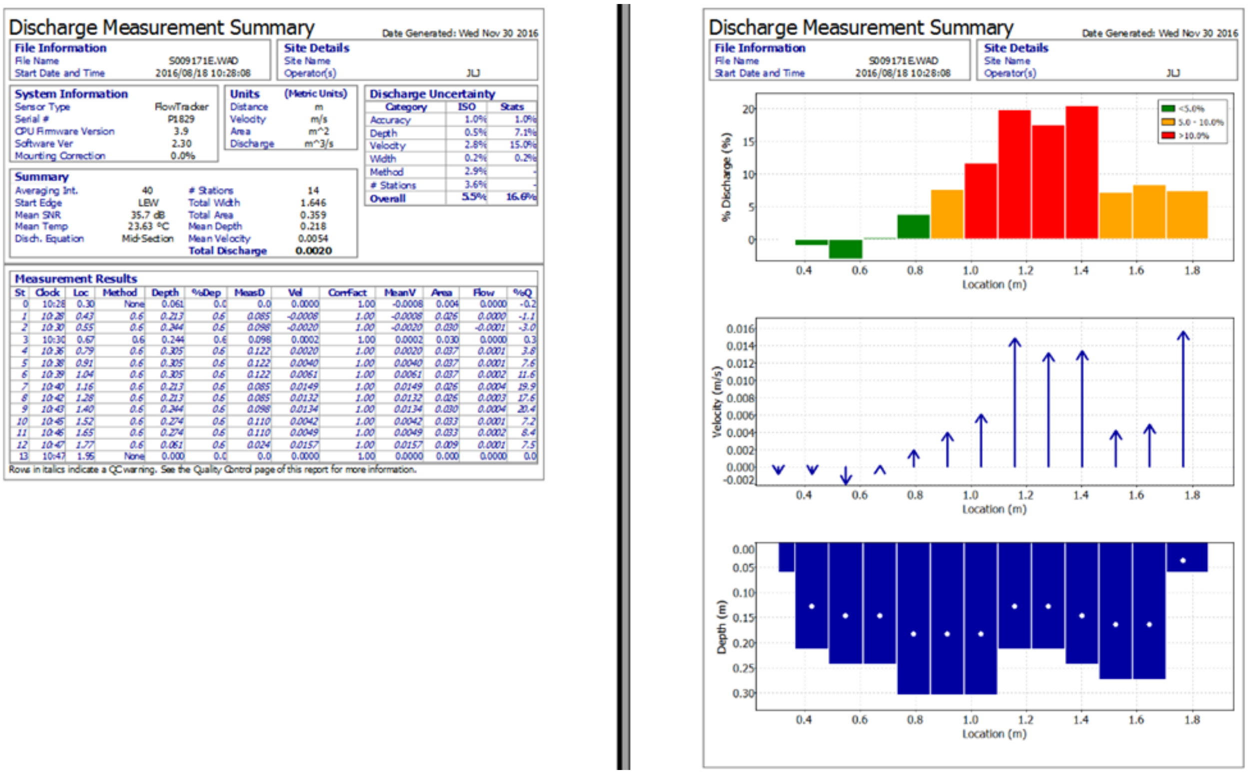
Discharge Measurement Summary

Date Generated: Wed Nov 30 2016

File Information	
File Name	S009171W.WAD
Start Date and Time	2016/08/18 10:58:37

Site Details	
Site Name	
Operator(s)	JLJ

Figure 62. Site S009-171-W flow cross section



Discharge Measurement Summary

Date Generated: Wed Nov 30 2016

File Information	
File Name	S009171E.WAD
Start Date and Time	2016/08/18 10:28:08

Site Details	
Site Name	
Operator(s)	JLJ

System Information	
Sensor Type	FlowTracker
Serial #	P1829
CPU Firmware Version	3.9
Software Ver	2.30
Mounting Correction	0.0%

Units	(Metric Units)
Distance	m
Velocity	m/s
Area	m^2
Discharge	m^3/s

Discharge Uncertainty

Category	ISO	Stats
Accuracy	1.0%	1.0%
Depth	0.5%	7.1%
Velocity	2.8%	15.0%
Width	0.2%	0.2%
Method	2.9%	-
# Stations	3.6%	-
Overall	**5.5%**	**16.6%**

Summary			
Averaging Int.	40	# Stations	14
Start Edge	LEW	Total Width	1.646
Mean SNR	35.7 dB	Total Area	0.359
Mean Temp	23.63 °C	Mean Depth	0.218
Disch. Equation	Mid-Section	Mean Velocity	0.0054
		Total Discharge	**0.0020**

Measurement Results

St	Clock	Loc	Method	Depth	%Dep	MeasD	Vel	CorrFact	MeanV	Area	Flow	%Q
0	10:28	0.30	None	0.061	0.0	0.0	0.0000	1.00	-0.0008	0.004	0.0000	-0.2
1	*10:28*	*0.43*	*0.6*	*0.213*	*0.6*	*0.085*	*-0.0008*	*1.00*	*-0.0008*	*0.026*	*0.0000*	*-1.1*
2	*10:30*	*0.55*	*0.6*	*0.244*	*0.6*	*0.098*	*-0.0020*	*1.00*	*-0.0020*	*0.030*	*-0.0001*	*-3.0*
3	10:30	0.67	0.6	0.244	0.6	0.098	0.0002	1.00	0.0002	0.030	0.0000	0.3
4	*10:36*	*0.79*	*0.6*	*0.305*	*0.6*	*0.122*	*0.0020*	*1.00*	*0.0020*	*0.037*	*0.0001*	*3.8*
5	*10:38*	*0.91*	*0.6*	*0.305*	*0.6*	*0.122*	*0.0040*	*1.00*	*0.0040*	*0.037*	*0.0001*	*7.6*
6	*10:39*	*1.04*	*0.6*	*0.305*	*0.6*	*0.122*	*0.0061*	*1.00*	*0.0061*	*0.037*	*0.0002*	*11.6*
7	*10:40*	*1.16*	*0.6*	*0.213*	*0.6*	*0.085*	*0.0149*	*1.00*	*0.0149*	*0.026*	*0.0004*	*19.9*
8	*10:42*	*1.28*	*0.6*	*0.213*	*0.6*	*0.085*	*0.0132*	*1.00*	*0.0132*	*0.026*	*0.0003*	*17.6*
9	*10:43*	*1.40*	*0.6*	*0.244*	*0.6*	*0.098*	*0.0134*	*1.00*	*0.0134*	*0.030*	*0.0004*	*20.4*
10	*10:45*	*1.52*	*0.6*	*0.274*	*0.6*	*0.110*	*0.0042*	*1.00*	*0.0042*	*0.033*	*0.0001*	*7.2*
11	*10:46*	*1.65*	*0.6*	*0.274*	*0.6*	*0.110*	*0.0049*	*1.00*	*0.0049*	*0.033*	*0.0002*	*8.4*
12	*10:47*	*1.77*	*0.6*	*0.061*	*0.6*	*0.024*	*0.0157*	*1.00*	*0.0157*	*0.009*	*0.0001*	*7.5*
13	10:47	1.95	None	0.000	0.0	0.0	0.0000	1.00	0.0000	0.000	0.0000	0.0

Rows in italics indicate a QC warning. See the Quality Control page of this report for more information.

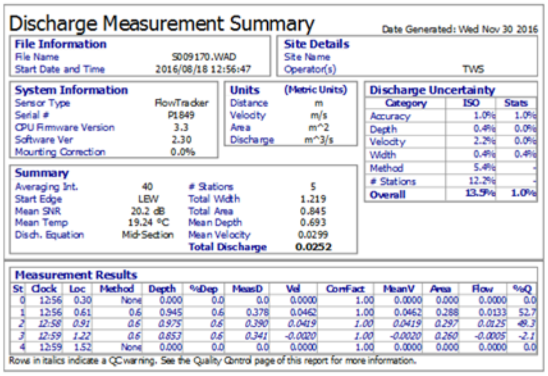
Discharge Measurement Summary

Date Generated: Wed Nov 30 2016

File Information	
File Name	S009171E.WAD
Start Date and Time	2016/08/18 10:28:08

Site Details	
Site Name	
Operator(s)	JLJ

Figure 63. Site S009-171-E flow cross section



Discharge Measurement Summary

Date Generated: Wed Nov 30 2016

File Information	
File Name	S009170.WAD
Start Date and Time	2016/08/18 12:56:47

Site Details	
Site Name	
Operator(s)	TWS

System Information	
Sensor Type	FlowTracker
Serial #	P1849
CPU Firmware Version	3.3
Software Ver	2.30
Mounting Correction	0.0%

Units	(Metric Units)
Distance	m
Velocity	m/s
Area	m^2
Discharge	m^3/s

Discharge Uncertainty

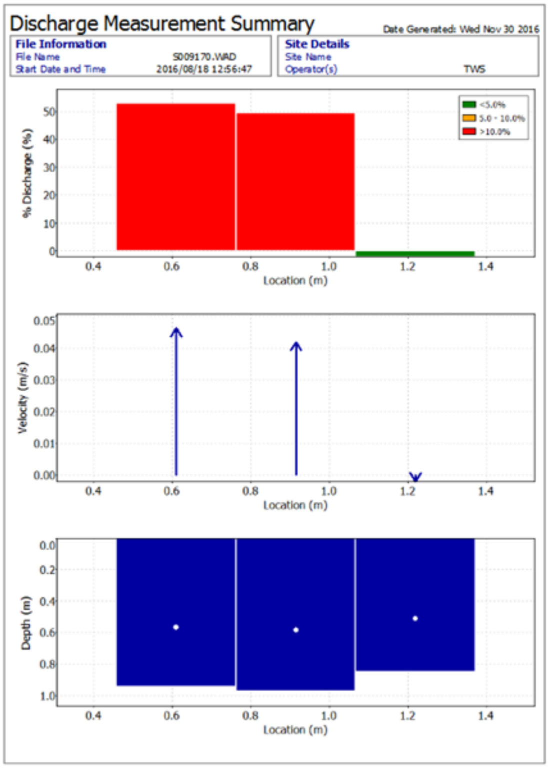
Category	ISO	Stats
Accuracy	1.0%	1.0%
Depth	0.4%	0.0%
Velocity	2.2%	0.0%
Width	0.4%	0.4%
Method	5.4%	-
# Stations	12.2%	-
Overall	**13.5%**	**1.0%**

Summary			
Averaging Int.	40	# Stations	5
Start Edge	LEW	Total Width	1.219
Mean SNR	20.2 dB	Total Area	0.845
Mean Temp	19.24 °C	Mean Depth	0.693
Disch. Equation	Mid-Section	Mean Velocity	0.0299
		Total Discharge	**0.0252**

Measurement Results

St	Clock	Loc	Method	Depth	%Dep	MeasD	Vel	CorrFact	MeanV	Area	Flow	%Q
0	12:56	0.30	None	0.000	0.0	0.0	0.0000	1.00	0.0000	0.000	0.0000	0.0
1	12:56	0.61	0.6	0.945	0.6	0.378	0.0462	1.00	0.0462	0.288	0.0133	52.7
2	*12:58*	*0.91*	*0.6*	*0.975*	*0.6*	*0.390*	*0.0419*	*1.00*	*0.0419*	*0.297*	*0.0125*	*49.3*
3	*12:59*	*1.22*	*0.6*	*0.853*	*0.6*	*0.341*	*-0.0020*	*1.00*	*-0.0020*	*0.260*	*-0.0005*	*-2.1*
4	12:59	1.52	None	0.000	0.0	0.0	0.0000	1.00	0.0000	0.000	0.0000	0.0

Rows in italics indicate a QC warning. See the Quality Control page of this report for more information.



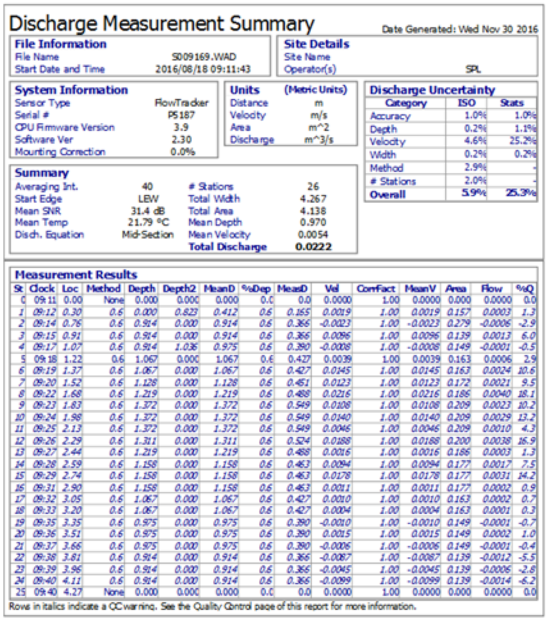
Discharge Measurement Summary

Date Generated: Wed Nov 30 2016

File Information	
File Name	S009170.WAD
Start Date and Time	2016/08/18 12:56:47

Site Details	
Site Name	
Operator(s)	TWS

Figure 64. Site S009-170 flow cross section



Discharge Measurement Summary

Date Generated: Wed Nov 30 2016

File Information	
File Name	S009169.WAD
Start Date and Time	2016/08/18 09:11:43

Site Details	
Site Name	
Operator(s)	SPL

System Information	
Sensor Type	FlowTracker
Serial #	P5187
CPU Firmware Version	3.9
Software Ver	2.30
Mounting Correction	0.0%

Units	(Metric Units)
Distance	m
Velocity	m/s
Area	m^2
Discharge	m^3/s

Discharge Uncertainty

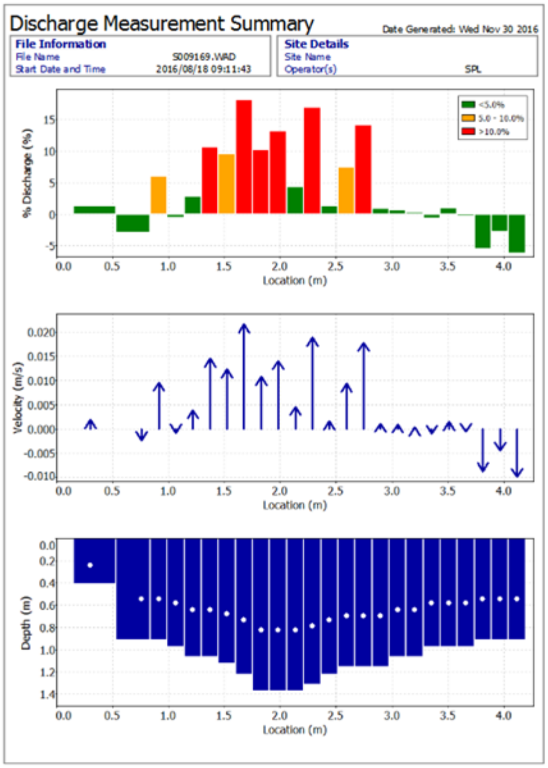
Category	ISO	Stats
Accuracy	1.0%	1.0%
Depth	0.2%	1.1%
Velocity	4.6%	25.2%
Width	0.2%	0.2%
Method	2.9%	-
# Stations	2.0%	-
Overall	**5.9%**	**25.3%**

Summary			
Averaging Int.	40	# Stations	26
Start Edge	LEW	Total Width	4.267
Mean SNR	31.4 dB	Total Area	4.138
Mean Temp	21.79 °C	Mean Depth	0.970
Disch. Equation	Mid-Section	Mean Velocity	0.0054
		Total Discharge	**0.0222**

Measurement Results

St	Clock	Loc	Method	Depth	Depth2	MeanD	%Dep	MeasD	Vel	CorrFact	MeanV	Area	Flow	%Q
0	09:11	0.00	None	0.000	0.000	0.000	0.0	0.0	0.0000	1.00	0.0000	0.000	0.0000	0.0
1	*09:12*	*0.30*	*0.6*	*0.000*	*0.823*	*0.412*	*0.6*	*0.165*	*0.0019*	*1.00*	*0.0019*	*0.157*	*0.0003*	*1.3*
2	*09:14*	*0.76*	*0.6*	*0.914*	*0.000*	*0.914*	*0.6*	*0.366*	*-0.0023*	*1.00*	*-0.0023*	*0.279*	*-0.0006*	*-2.9*
3	*09:15*	*0.91*	*0.6*	*0.914*	*0.000*	*0.914*	*0.6*	*0.366*	*0.0096*	*1.00*	*0.0096*	*0.139*	*0.0013*	*6.0*
4	*09:17*	*1.07*	*0.6*	*0.914*	*1.036*	*0.975*	*0.6*	*0.390*	*-0.0008*	*1.00*	*-0.0008*	*0.149*	*-0.0001*	*-0.5*
5	09:18	1.22	0.6	1.067	0.000	1.067	0.6	0.427	0.0039	1.00	0.0039	0.163	0.0006	2.9
6	*09:19*	*1.37*	*0.6*	*1.067*	*0.000*	*1.067*	*0.6*	*0.427*	*0.0145*	*1.00*	*0.0145*	*0.163*	*0.0024*	*10.6*
7	*09:20*	*1.52*	*0.6*	*1.128*	*0.000*	*1.128*	*0.6*	*0.451*	*0.0123*	*1.00*	*0.0123*	*0.172*	*0.0021*	*9.5*
8	*09:22*	*1.68*	*0.6*	*1.219*	*0.000*	*1.219*	*0.6*	*0.488*	*0.0216*	*1.00*	*0.0216*	*0.186*	*0.0040*	*18.1*
9	*09:23*	*1.83*	*0.6*	*1.372*	*0.000*	*1.372*	*0.6*	*0.549*	*0.0108*	*1.00*	*0.0108*	*0.209*	*0.0023*	*10.2*
10	*09:24*	*1.98*	*0.6*	*1.372*	*0.000*	*1.372*	*0.6*	*0.549*	*0.0140*	*1.00*	*0.0140*	*0.209*	*0.0029*	*13.2*
11	*09:25*	*2.13*	*0.6*	*1.372*	*0.000*	*1.372*	*0.6*	*0.549*	*0.0046*	*1.00*	*0.0046*	*0.209*	*0.0010*	*4.3*
12	*09:26*	*2.29*	*0.6*	*1.311*	*0.000*	*1.311*	*0.6*	*0.524*	*0.0188*	*1.00*	*0.0188*	*0.200*	*0.0038*	*16.9*
13	*09:27*	*2.44*	*0.6*	*1.219*	*0.000*	*1.219*	*0.6*	*0.488*	*0.0016*	*1.00*	*0.0016*	*0.186*	*0.0003*	*1.3*
14	*09:28*	*2.59*	*0.6*	*1.158*	*0.000*	*1.158*	*0.6*	*0.463*	*0.0094*	*1.00*	*0.0094*	*0.177*	*0.0017*	*7.5*
15	*09:29*	*2.74*	*0.6*	*1.158*	*0.000*	*1.158*	*0.6*	*0.463*	*0.0178*	*1.00*	*0.0178*	*0.177*	*0.0031*	*14.2*
16	*09:31*	*2.90*	*0.6*	*1.158*	*0.000*	*1.158*	*0.6*	*0.463*	*0.0011*	*1.00*	*0.0011*	*0.177*	*0.0002*	*0.9*
17	*09:32*	*3.05*	*0.6*	*1.067*	*0.000*	*1.067*	*0.6*	*0.427*	*0.0010*	*1.00*	*0.0010*	*0.163*	*0.0002*	*0.7*
18	*09:33*	*3.20*	*0.6*	*1.067*	*0.000*	*1.067*	*0.6*	*0.427*	*0.0004*	*1.00*	*0.0004*	*0.163*	*0.0001*	*0.3*
19	*09:35*	*3.35*	*0.6*	*0.975*	*0.000*	*0.975*	*0.6*	*0.390*	*-0.0010*	*1.00*	*-0.0010*	*0.149*	*-0.0001*	*-0.7*
20	*09:36*	*3.51*	*0.6*	*0.975*	*0.000*	*0.975*	*0.6*	*0.390*	*0.0015*	*1.00*	*0.0015*	*0.149*	*0.0002*	*1.0*
21	*09:37*	*3.66*	*0.6*	*0.975*	*0.000*	*0.975*	*0.6*	*0.390*	*-0.0006*	*1.00*	*-0.0006*	*0.149*	*-0.0001*	*-0.4*
22	*09:38*	*3.81*	*0.6*	*0.914*	*0.000*	*0.914*	*0.6*	*0.366*	*-0.0087*	*1.00*	*-0.0087*	*0.139*	*-0.0012*	*-5.5*
23	*09:39*	*3.96*	*0.6*	*0.914*	*0.000*	*0.914*	*0.6*	*0.366*	*-0.0045*	*1.00*	*-0.0045*	*0.139*	*-0.0006*	*-2.8*
24	*09:40*	*4.11*	*0.6*	*0.914*	*0.000*	*0.914*	*0.6*	*0.366*	*-0.0099*	*1.00*	*-0.0099*	*0.139*	*-0.0014*	*-6.2*
25	09:40	4.27	None	0.000	0.000	0.000	0.0	0.0	0.0000	1.00	0.0000	0.000	0.0000	0.0

Rows in italics indicate a QC warning. See the Quality Control page of this report for more information.



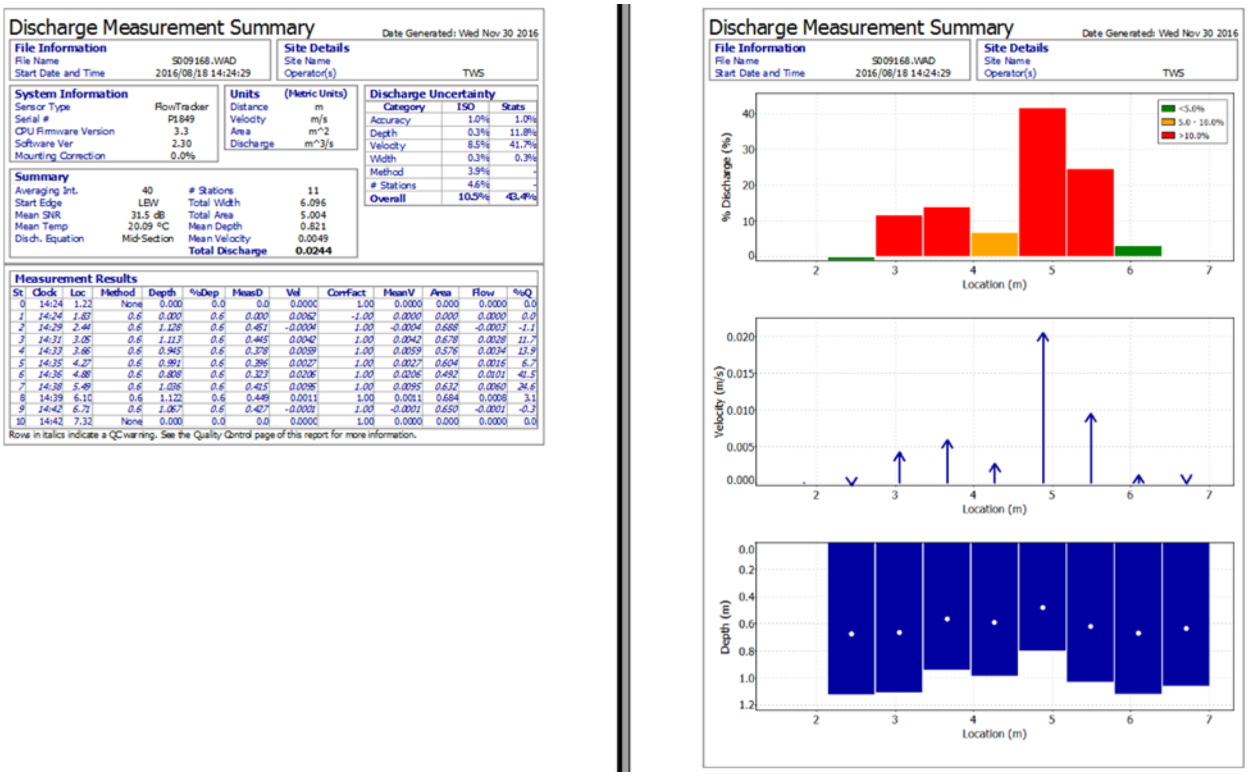
Discharge Measurement Summary

Date Generated: Wed Nov 30 2016

File Information	
File Name	S009169.WAD
Start Date and Time	2016/08/18 09:11:43

Site Details	
Site Name	
Operator(s)	SPL

Figure 65. Site S009-169 flow cross section



Discharge Measurement Summary

Date Generated: Wed Nov 30 2016

File Information

File Name	S009168.WAD
Start Date and Time	2016/08/18 14:24:29

Site Details

Site Name	
Operator(s)	TWS

System Information

Sensor Type	FlowTracker
Serial #	P1849
CPU Firmware Version	3.3
Software Ver	2.30
Mounting Correction	0.0%

Units	(Metric Units)
Distance	m
Velocity	m/s
Area	m^2
Discharge	m^3/s

Discharge Uncertainty

Category	ISO	Stats
Accuracy	1.0%	1.0%
Depth	0.3%	11.8%
Velocity	8.5%	41.7%
Width	0.3%	0.3%
Method	3.9%	-
# Stations	4.6%	-
Overall	**10.5%**	**43.4%**

Summary

Averaging Int.	40	# Stations	11
Start Edge	LEW	Total Width	6.096
Mean SNR	31.5 dB	Total Area	5.004
Mean Temp	20.09 °C	Mean Depth	0.821
Disch. Equation	Mid-Section	Mean Velocity	0.0049
		Total Discharge	**0.0244**

Measurement Results

St	Clock	Loc	Method	Depth	%Dep	MeasD	Vel	CorrFact	MeanV	Area	Flow	%Q
0	14:24	1.22	None	0.000	0.0	0.0	0.0000	1.00	0.0000	0.000	0.0000	0.0
1	*14:24*	*1.83*	*0.6*	*0.000*	*0.6*	*0.000*	*0.0062*	*-1.00*	*0.0000*	*0.000*	*0.0000*	*0.0*
2	*14:29*	*2.44*	*0.6*	*1.128*	*0.6*	*0.451*	*-0.0004*	*1.00*	*-0.0004*	*0.688*	*-0.0003*	*-1.1*
3	*14:31*	*3.05*	*0.6*	*1.113*	*0.6*	*0.445*	*0.0042*	*1.00*	*0.0042*	*0.678*	*0.0028*	*11.7*
4	*14:33*	*3.66*	*0.6*	*0.945*	*0.6*	*0.378*	*0.0059*	*1.00*	*0.0059*	*0.576*	*0.0034*	*13.9*
5	*14:35*	*4.27*	*0.6*	*0.991*	*0.6*	*0.396*	*0.0027*	*1.00*	*0.0027*	*0.604*	*0.0016*	*6.7*
6	*14:36*	*4.88*	*0.6*	*0.808*	*0.6*	*0.323*	*0.0206*	*1.00*	*0.0206*	*0.492*	*0.0101*	*41.5*
7	*14:38*	*5.49*	*0.6*	*1.036*	*0.6*	*0.415*	*0.0095*	*1.00*	*0.0095*	*0.632*	*0.0060*	*24.6*
8	14:39	6.10	0.6	1.122	0.6	0.449	0.0011	1.00	0.0011	0.684	0.0008	3.1
9	*14:42*	*6.71*	*0.6*	*1.067*	*0.6*	*0.427*	*-0.0001*	*1.00*	*-0.0001*	*0.650*	*-0.0001*	*-0.3*
10	14:42	7.32	None	0.000	0.0	0.0	0.0000	1.00	0.0000	0.000	0.0000	0.0

Rows in italics indicate a QC warning. See the Quality Control page of this report for more information.

Discharge Measurement Summary

Date Generated: Wed Nov 30 2016

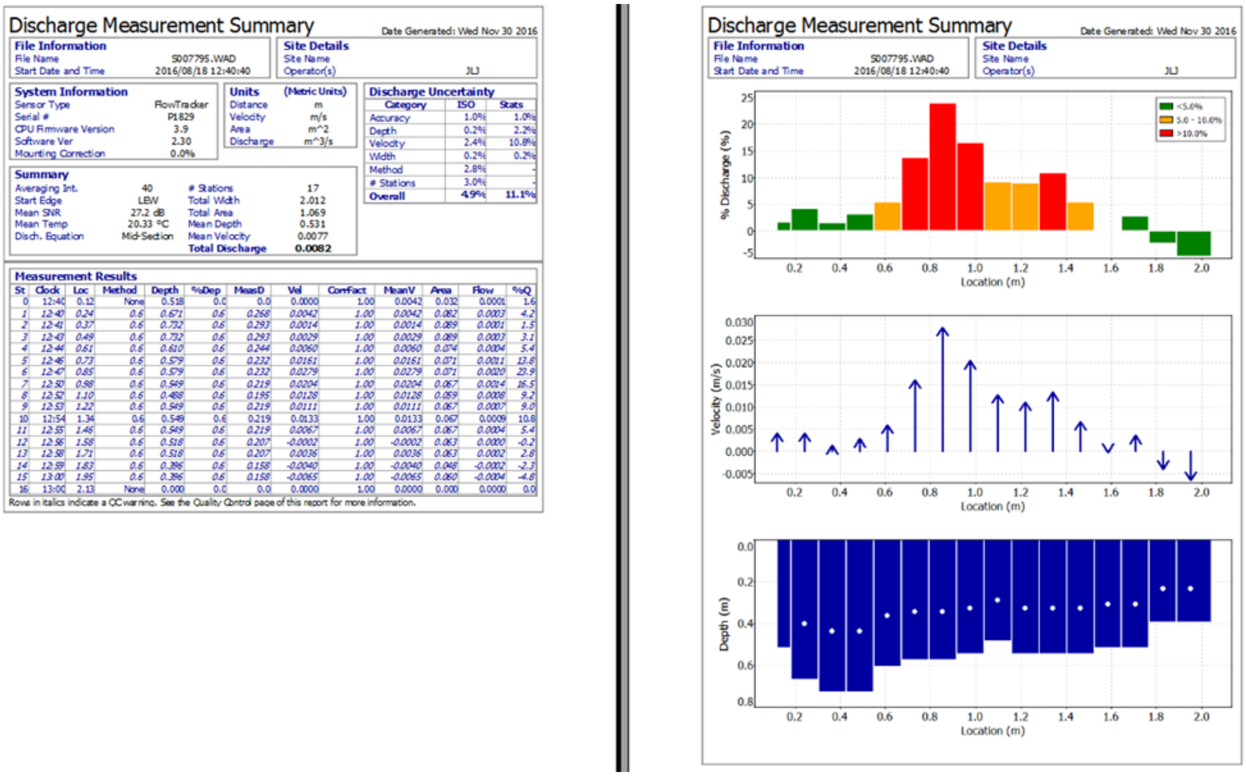
File Information

File Name	S009168.WAD
Start Date and Time	2016/08/18 14:24:29

Site Details

Site Name	
Operator(s)	TWS

Figure 66. Site S009-168 flow cross section



Discharge Measurement Summary

Date Generated: Wed Nov 30 2016

File Information

File Name	S007795.WAD
Start Date and Time	2016/08/18 12:40:40

Site Details

Site Name	
Operator(s)	JLJ

System Information

Sensor Type	FlowTracker
Serial #	P1829
CPU Firmware Version	3.9
Software Ver	2.30
Mounting Correction	0.0%

Units	(Metric Units)
Distance	m
Velocity	m/s
Area	m^2
Discharge	m^3/s

Discharge Uncertainty

Category	ISO	Stats
Accuracy	1.0%	1.0%
Depth	0.2%	2.2%
Velocity	2.4%	10.8%
Width	0.2%	0.2%
Method	2.8%	-
# Stations	3.0%	-
Overall	**4.9%**	**11.1%**

Summary

Averaging Int.	40	# Stations	17
Start Edge	LEW	Total Width	2.012
Mean SNR	27.2 dB	Total Area	1.069
Mean Temp	20.33 °C	Mean Depth	0.531
Disch. Equation	Mid-Section	Mean Velocity	0.0077
		Total Discharge	**0.0082**

Measurement Results

St	Clock	Loc	Method	Depth	%Dep	MeasD	Vel	CorrFact	MeanV	Area	Flow	%Q
0	12:40	0.12	None	0.518	0.0	0.0	0.0000	1.00	0.0042	0.032	0.0001	1.6
1	*12:40*	*0.24*	*0.6*	*0.671*	*0.6*	*0.268*	*0.0042*	*1.00*	*0.0042*	*0.082*	*0.0003*	*4.2*
2	*12:41*	*0.37*	*0.6*	*0.732*	*0.6*	*0.293*	*0.0014*	*1.00*	*0.0014*	*0.089*	*0.0001*	*1.5*
3	*12:43*	*0.49*	*0.6*	*0.732*	*0.6*	*0.293*	*0.0029*	*1.00*	*0.0029*	*0.089*	*0.0003*	*3.1*
4	*12:44*	*0.61*	*0.6*	*0.610*	*0.6*	*0.244*	*0.0060*	*1.00*	*0.0060*	*0.074*	*0.0004*	*5.4*
5	*12:46*	*0.73*	*0.6*	*0.579*	*0.6*	*0.232*	*0.0161*	*1.00*	*0.0161*	*0.071*	*0.0011*	*13.8*
6	*12:47*	*0.85*	*0.6*	*0.579*	*0.6*	*0.232*	*0.0279*	*1.00*	*0.0279*	*0.071*	*0.0020*	*23.9*
7	*12:50*	*0.98*	*0.6*	*0.549*	*0.6*	*0.219*	*0.0204*	*1.00*	*0.0204*	*0.067*	*0.0014*	*16.5*
8	*12:52*	*1.10*	*0.6*	*0.488*	*0.6*	*0.195*	*0.0128*	*1.00*	*0.0128*	*0.059*	*0.0008*	*9.2*
9	*12:53*	*1.22*	*0.6*	*0.549*	*0.6*	*0.219*	*0.0111*	*1.00*	*0.0111*	*0.067*	*0.0007*	*9.0*
10	12:54	1.34	0.6	0.549	0.6	0.219	0.0133	1.00	0.0133	0.067	0.0009	10.8
11	*12:55*	*1.46*	*0.6*	*0.549*	*0.6*	*0.219*	*0.0067*	*1.00*	*0.0067*	*0.067*	*0.0004*	*5.4*
12	*12:56*	*1.58*	*0.6*	*0.518*	*0.6*	*0.207*	*-0.0002*	*1.00*	*-0.0002*	*0.063*	*0.0000*	*-0.2*
13	*12:58*	*1.71*	*0.6*	*0.518*	*0.6*	*0.207*	*0.0036*	*1.00*	*0.0036*	*0.063*	*0.0002*	*2.8*
14	*12:59*	*1.83*	*0.6*	*0.396*	*0.6*	*0.158*	*-0.0040*	*1.00*	*-0.0040*	*0.048*	*-0.0002*	*-2.3*
15	*13:00*	*1.95*	*0.6*	*0.396*	*0.6*	*0.158*	*-0.0065*	*1.00*	*-0.0065*	*0.060*	*-0.0004*	*-4.8*
16	13:00	2.13	None	0.000	0.0	0.0	0.0000	1.00	0.0000	0.000	0.0000	0.0

Rows in italics indicate a QC warning. See the Quality Control page of this report for more information.

Discharge Measurement Summary

Date Generated: Wed Nov 30 2016

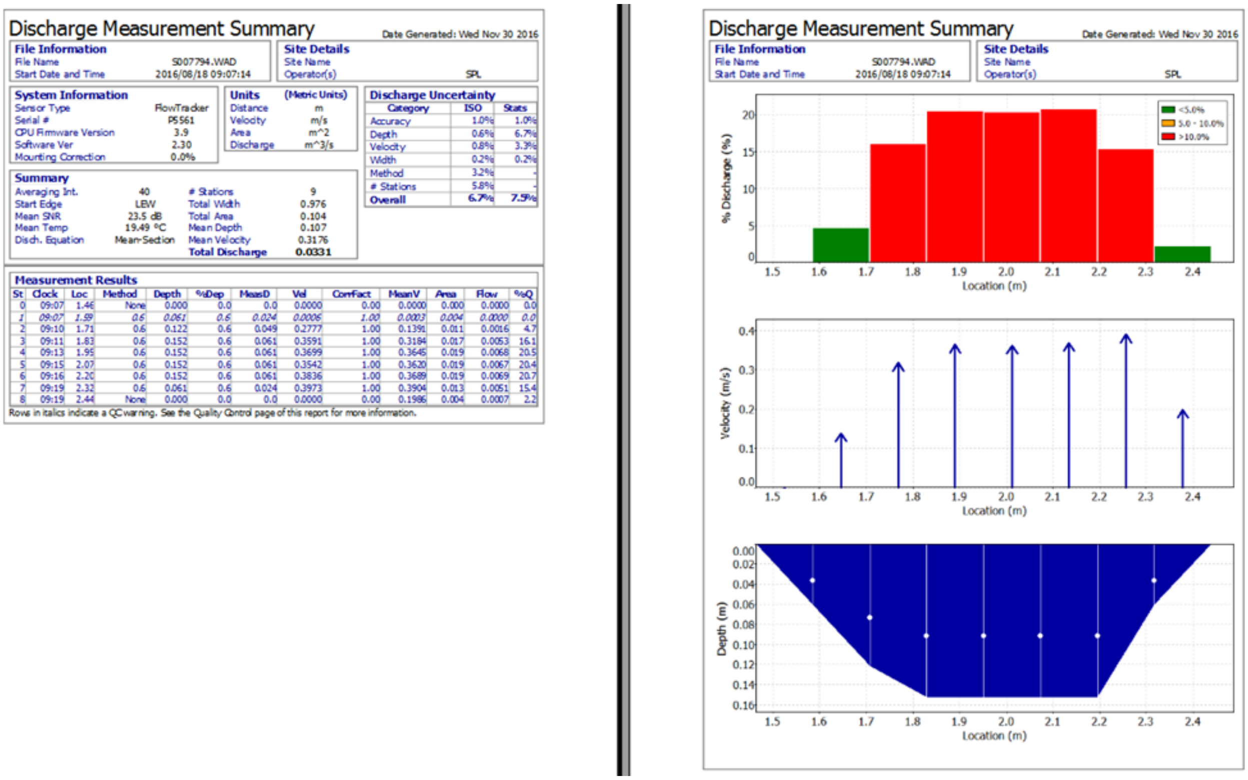
File Information

File Name	S007795.WAD
Start Date and Time	2016/08/18 12:40:40

Site Details

Site Name	
Operator(s)	JLJ

Figure 67. Site S007-795 flow cross section



Discharge Measurement Summary

Date Generated: Wed Nov 30 2016

File Information	
File Name	S007794.WAD
Start Date and Time	2016/08/18 09:07:14

Site Details	
Site Name	
Operator(s)	SPL

System Information	
Sensor Type	FlowTracker
Serial #	P5561
CPU Firmware Version	3.9
Software Ver	2.30
Mounting Correction	0.0%

Units	(Metric Units)
Distance	m
Velocity	m/s
Area	m^2
Discharge	m^3/s

Discharge Uncertainty

Category	ISO	Stats
Accuracy	1.0%	1.0%
Depth	0.6%	6.7%
Velocity	0.8%	3.3%
Width	0.2%	0.2%
Method	3.2%	-
# Stations	5.8%	-
Overall	**6.7%**	**7.5%**

Summary

Averaging Int.	40	# Stations	9
Start Edge	LEW	Total Width	0.976
Mean SNR	23.5 dB	Total Area	0.104
Mean Temp	19.49 °C	Mean Depth	0.107
Disch. Equation	Mean-Section	Mean Velocity	0.3176
		Total Discharge	**0.0331**

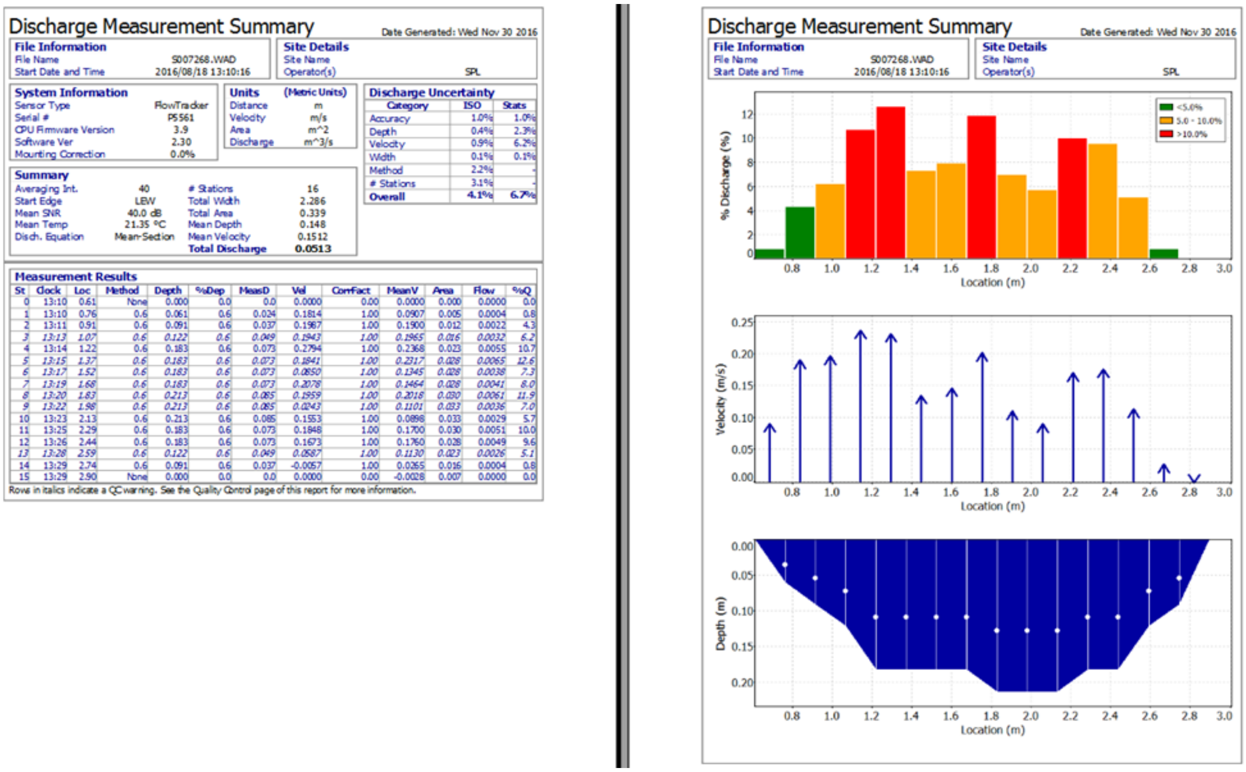
Measurement Results

St	Clock	Loc	Method	Depth	%Dep	MeasD	Vel	CorrFact	MeanV	Area	Flow	%Q
0	09:07	1.46	None	0.000	0.0	0.0	0.0000	0.00	0.0000	0.000	0.0000	0.0
1	*09:07*	*1.59*	*0.6*	*0.061*	*0.6*	*0.024*	*0.0006*	*1.00*	*0.0003*	*0.004*	*0.0000*	*0.0*
2	09:10	1.71	0.6	0.122	0.6	0.049	0.2777	1.00	0.1391	0.011	0.0016	4.7
3	09:11	1.83	0.6	0.152	0.6	0.061	0.3591	1.00	0.3184	0.017	0.0053	16.1
4	09:13	1.95	0.6	0.152	0.6	0.061	0.3699	1.00	0.3645	0.019	0.0068	20.5
5	09:15	2.07	0.6	0.152	0.6	0.061	0.3542	1.00	0.3620	0.019	0.0067	20.4
6	09:16	2.20	0.6	0.152	0.6	0.061	0.3836	1.00	0.3689	0.019	0.0069	20.7
7	09:19	2.32	0.6	0.061	0.6	0.024	0.3973	1.00	0.3904	0.013	0.0051	15.4
8	09:19	2.44	None	0.000	0.0	0.0	0.0000	0.00	0.1986	0.004	0.0007	2.2

Rows in italics indicate a QC warning. See the Quality Control page of this report for more information.

Discharge Measurement Summary
Date Generated: Wed Nov 30 2016
File Information
File Name S007794.WAD
Start Date and Time 2016/08/18 09:07:14
Site Details
Site Name
Operator(s) SPL

Figure 68. Site S007-794 flow cross section



Discharge Measurement Summary

Date Generated: Wed Nov 30 2016

File Information	
File Name	S007268.WAD
Start Date and Time	2016/08/18 13:10:16

Site Details	
Site Name	
Operator(s)	SPL

System Information	
Sensor Type	FlowTracker
Serial #	P5561
CPU Firmware Version	3.9
Software Ver	2.30
Mounting Correction	0.0%

Units	(Metric Units)
Distance	m
Velocity	m/s
Area	m^2
Discharge	m^3/s

Discharge Uncertainty

Category	ISO	Stats
Accuracy	1.0%	1.0%
Depth	0.4%	2.3%
Velocity	0.9%	6.2%
Width	0.1%	0.1%
Method	2.2%	-
# Stations	3.1%	-
Overall	**4.1%**	**6.7%**

Summary

Averaging Int.	40	# Stations	16
Start Edge	LEW	Total Width	2.286
Mean SNR	40.0 dB	Total Area	0.339
Mean Temp	21.35 °C	Mean Depth	0.148
Disch. Equation	Mean-Section	Mean Velocity	0.1512
		Total Discharge	**0.0513**

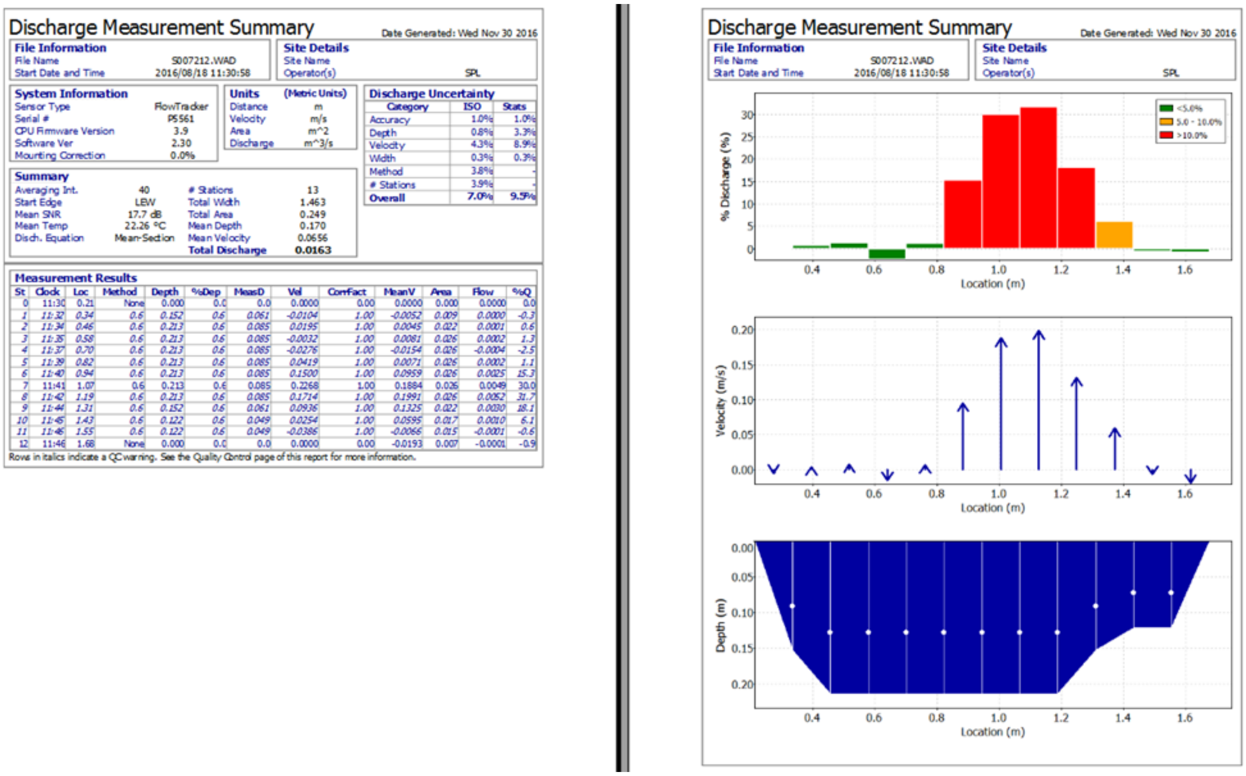
Measurement Results

St	Clock	Loc	Method	Depth	%Dep	MeasD	Vel	CorrFact	MeanV	Area	Flow	%Q
0	13:10	0.61	None	0.000	0.0	0.0	0.0000	0.00	0.0000	0.000	0.0000	0.0
1	13:10	0.76	0.6	0.061	0.6	0.024	0.1814	1.00	0.0907	0.005	0.0004	0.8
2	13:11	0.91	0.6	0.091	0.6	0.037	0.1987	1.00	0.1900	0.012	0.0022	4.3
3	*13:13*	*1.07*	*0.6*	*0.122*	*0.6*	*0.049*	*0.1943*	*1.00*	*0.1965*	*0.016*	*0.0032*	*6.2*
4	13:14	1.22	0.6	0.183	0.6	0.073	0.2794	1.00	0.2368	0.023	0.0055	10.7
5	*13:15*	*1.37*	*0.6*	*0.183*	*0.6*	*0.073*	*0.1841*	*1.00*	*0.2317*	*0.028*	*0.0065*	*12.6*
6	*13:17*	*1.52*	*0.6*	*0.183*	*0.6*	*0.073*	*0.0850*	*1.00*	*0.1345*	*0.028*	*0.0038*	*7.3*
7	*13:19*	*1.68*	*0.6*	*0.183*	*0.6*	*0.073*	*0.2078*	*1.00*	*0.1464*	*0.028*	*0.0041*	*8.0*
8	*13:20*	*1.83*	*0.6*	*0.213*	*0.6*	*0.085*	*0.1959*	*1.00*	*0.2018*	*0.030*	*0.0061*	*11.9*
9	*13:22*	*1.98*	*0.6*	*0.213*	*0.6*	*0.085*	*0.0243*	*1.00*	*0.1101*	*0.033*	*0.0036*	*7.0*
10	13:23	2.13	0.6	0.213	0.6	0.085	0.1553	1.00	0.0898	0.033	0.0029	5.7
11	13:25	2.29	0.6	0.183	0.6	0.073	0.1848	1.00	0.1700	0.030	0.0051	10.0
12	13:26	2.44	0.6	0.183	0.6	0.073	0.1673	1.00	0.1760	0.028	0.0049	9.6
13	*13:28*	*2.59*	*0.6*	*0.122*	*0.6*	*0.049*	*0.0587*	*1.00*	*0.1130*	*0.023*	*0.0026*	*5.1*
14	13:29	2.74	0.6	0.091	0.6	0.037	-0.0057	1.00	0.0265	0.016	0.0004	0.8
15	13:29	2.90	None	0.000	0.0	0.0	0.0000	0.00	-0.0028	0.007	0.0000	0.0

Rows in italics indicate a QC warning. See the Quality Control page of this report for more information.

Discharge Measurement Summary
Date Generated: Wed Nov 30 2016
File Information
File Name S007268.WAD
Start Date and Time 2016/08/18 13:10:16
Site Details
Site Name
Operator(s) SPL

Figure 69. Site S007-268 flow cross section



Discharge Measurement Summary

Date Generated: Wed Nov 30 2016

File Information	
File Name	S007212.WAD
Start Date and Time	2016/08/18 11:30:58

Site Details	
Site Name	
Operator(s)	SPL

System Information	
Sensor Type	FlowTracker
Serial #	P5561
CPU Firmware Version	3.9
Software Ver	2.30
Mounting Correction	0.0%

Units	(Metric Units)
Distance	m
Velocity	m/s
Area	m^2
Discharge	m^3/s

Summary			
Averaging Int.	40	# Stations	13
Start Edge	LEW	Total Width	1.463
Mean SNR	17.7 dB	Total Area	0.249
Mean Temp	22.26 °C	Mean Depth	0.170
Disch. Equation	Mean-Section	Mean Velocity	0.0656
		Total Discharge	**0.0163**

Discharge Uncertainty

Category	ISO	Stats
Accuracy	1.0%	1.0%
Depth	0.8%	3.3%
Velocity	4.3%	8.9%
Width	0.3%	0.3%
Method	3.8%	-
# Stations	3.9%	-
Overall	**7.0%**	**9.5%**

Measurement Results

St	Clock	Loc	Method	Depth	%Dep	MeasD	Vel	CorrFact	MeanV	Area	Flow	%Q
0	11:30	0.21	None	0.000	0.0	0.0	0.0000	0.00	0.0000	0.000	0.0000	0.0
1	*11:32*	*0.34*	*0.6*	*0.152*	*0.6*	*0.061*	*-0.0104*	*1.00*	*-0.0052*	*0.009*	*0.0000*	*-0.3*
2	*11:34*	*0.46*	*0.6*	*0.213*	*0.6*	*0.085*	*0.0195*	*1.00*	*0.0045*	*0.022*	*0.0001*	*0.6*
3	*11:35*	*0.58*	*0.6*	*0.213*	*0.6*	*0.085*	*-0.0032*	*1.00*	*0.0081*	*0.026*	*0.0002*	*1.3*
4	*11:37*	*0.70*	*0.6*	*0.213*	*0.6*	*0.085*	*-0.0276*	*1.00*	*-0.0154*	*0.026*	*-0.0004*	*-2.5*
5	*11:39*	*0.82*	*0.6*	*0.213*	*0.6*	*0.085*	*0.0419*	*1.00*	*0.0071*	*0.026*	*0.0002*	*1.1*
6	*11:40*	*0.94*	*0.6*	*0.213*	*0.6*	*0.085*	*0.1500*	*1.00*	*0.0959*	*0.026*	*0.0025*	*15.3*
7	11:41	1.07	0.6	0.213	0.6	0.085	0.2268	1.00	0.1884	0.026	0.0049	30.0
8	*11:42*	*1.19*	*0.6*	*0.213*	*0.6*	*0.085*	*0.1714*	*1.00*	*0.1991*	*0.026*	*0.0052*	*31.7*
9	*11:44*	*1.31*	*0.6*	*0.152*	*0.6*	*0.061*	*0.0936*	*1.00*	*0.1325*	*0.022*	*0.0030*	*18.1*
10	*11:45*	*1.43*	*0.6*	*0.122*	*0.6*	*0.049*	*0.0254*	*1.00*	*0.0595*	*0.017*	*0.0010*	*6.1*
11	*11:46*	*1.55*	*0.6*	*0.122*	*0.6*	*0.049*	*-0.0386*	*1.00*	*-0.0066*	*0.015*	*-0.0001*	*-0.6*
12	11:46	1.68	None	0.000	0.0	0.0	0.0000	0.00	-0.0193	0.007	-0.0001	-0.9

Rows in italics indicate a QC warning. See the Quality Control page of this report for more information.

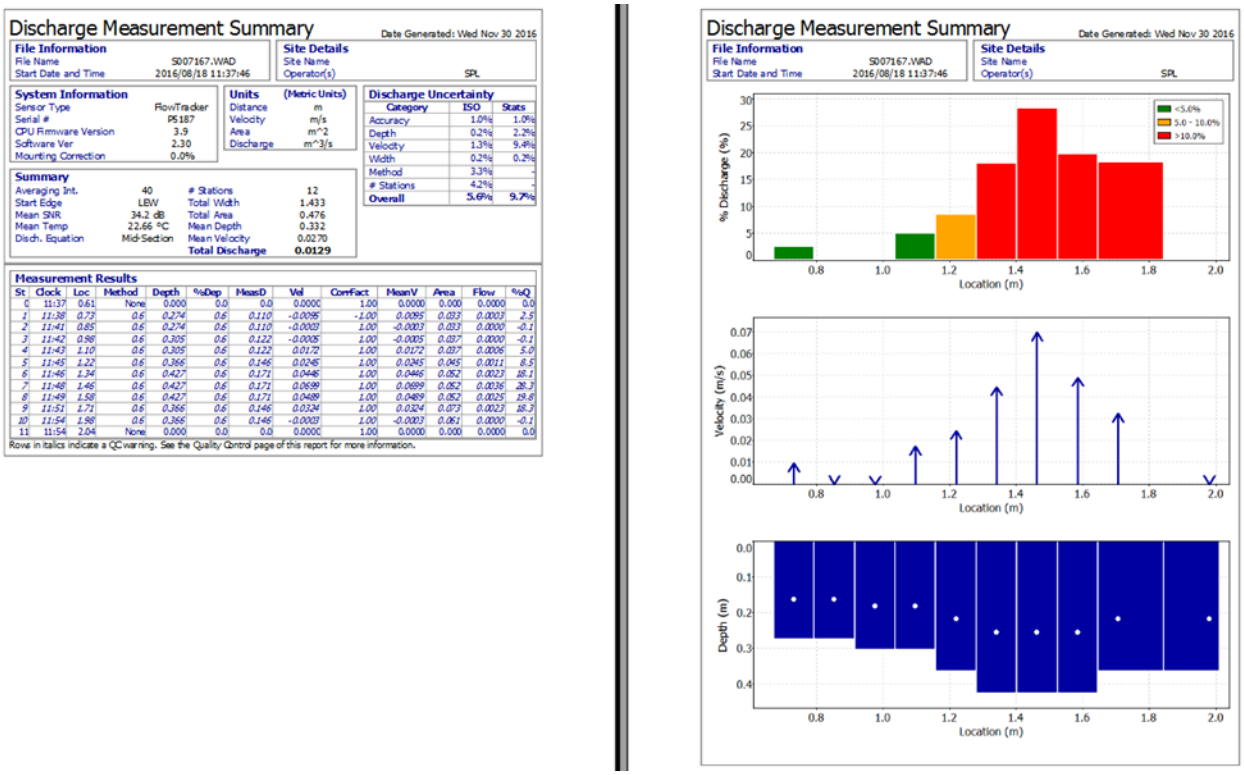
Discharge Measurement Summary

Date Generated: Wed Nov 30 2016

File Information
File Name S007212.WAD
Start Date and Time 2016/08/18 11:30:58

Site Details
Site Name
Operator(s) SPL

Figure 70. Site S007-212 flow cross section



Discharge Measurement Summary

Date Generated: Wed Nov 30 2016

File Information	
File Name	S007167.WAD
Start Date and Time	2016/08/18 11:37:46

Site Details	
Site Name	
Operator(s)	SPL

System Information	
Sensor Type	FlowTracker
Serial #	P5187
CPU Firmware Version	3.9
Software Ver	2.30
Mounting Correction	0.0%

Units	(Metric Units)
Distance	m
Velocity	m/s
Area	m^2
Discharge	m^3/s

Summary			
Averaging Int.	40	# Stations	12
Start Edge	LEW	Total Width	1.433
Mean SNR	34.2 dB	Total Area	0.476
Mean Temp	22.66 °C	Mean Depth	0.332
Disch. Equation	Mid-Section	Mean Velocity	0.0270
		Total Discharge	**0.0129**

Discharge Uncertainty

Category	ISO	Stats
Accuracy	1.0%	1.0%
Depth	0.2%	2.2%
Velocity	1.3%	9.4%
Width	0.2%	0.2%
Method	3.3%	-
# Stations	4.2%	-
Overall	**5.6%**	**9.7%**

Measurement Results

St	Clock	Loc	Method	Depth	%Dep	MeasD	Vel	CorrFact	MeanV	Area	Flow	%Q
0	11:37	0.61	None	0.000	0.0	0.0	0.0000	1.00	0.0000	0.000	0.0000	0.0
1	*11:38*	*0.73*	*0.6*	*0.274*	*0.6*	*0.110*	*-0.0095*	*-1.00*	*0.0095*	*0.033*	*0.0003*	*2.5*
2	*11:41*	*0.85*	*0.6*	*0.274*	*0.6*	*0.110*	*-0.0003*	*1.00*	*-0.0003*	*0.033*	*0.0000*	*-0.1*
3	*11:42*	*0.98*	*0.6*	*0.305*	*0.6*	*0.122*	*-0.0005*	*1.00*	*-0.0005*	*0.037*	*0.0000*	*-0.1*
4	*11:43*	*1.10*	*0.6*	*0.305*	*0.6*	*0.122*	*0.0172*	*1.00*	*0.0172*	*0.037*	*0.0006*	*5.0*
5	*11:45*	*1.22*	*0.6*	*0.366*	*0.6*	*0.146*	*0.0245*	*1.00*	*0.0245*	*0.045*	*0.0011*	*8.5*
6	*11:46*	*1.34*	*0.6*	*0.427*	*0.6*	*0.171*	*0.0446*	*1.00*	*0.0446*	*0.052*	*0.0023*	*18.1*
7	*11:48*	*1.46*	*0.6*	*0.427*	*0.6*	*0.171*	*0.0699*	*1.00*	*0.0699*	*0.052*	*0.0036*	*28.3*
8	*11:49*	*1.58*	*0.6*	*0.427*	*0.6*	*0.171*	*0.0489*	*1.00*	*0.0489*	*0.052*	*0.0025*	*19.8*
9	*11:51*	*1.71*	*0.6*	*0.366*	*0.6*	*0.146*	*0.0324*	*1.00*	*0.0324*	*0.073*	*0.0023*	*18.3*
10	*11:54*	*1.98*	*0.6*	*0.366*	*0.6*	*0.146*	*-0.0003*	*1.00*	*-0.0003*	*0.061*	*0.0000*	*-0.1*
11	11:54	2.04	None	0.000	0.0	0.0	0.0000	1.00	0.0000	0.000	0.0000	0.0

Rows in italics indicate a QC warning. See the Quality Control page of this report for more information.

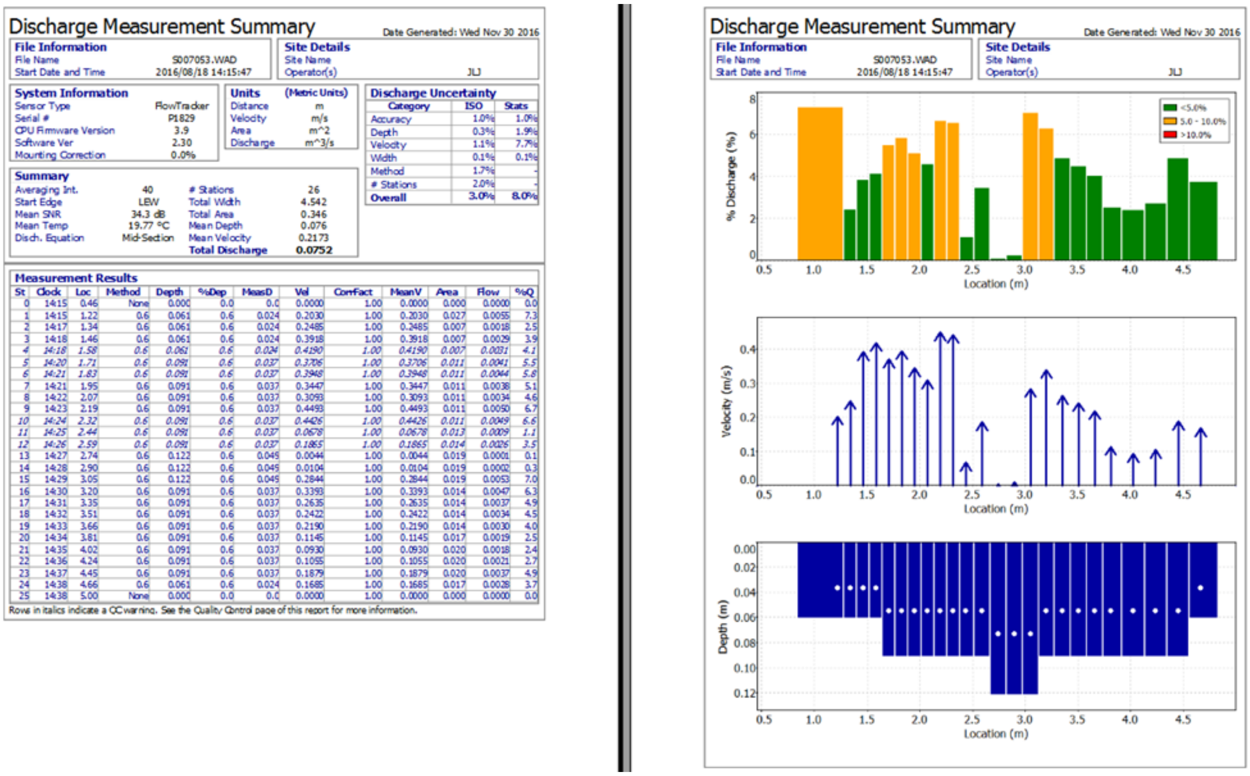
Discharge Measurement Summary

Date Generated: Wed Nov 30 2016

File Information
File Name S007167.WAD
Start Date and Time 2016/08/18 11:37:46

Site Details
Site Name
Operator(s) SPL

Figure 71. Site S007-167 flow cross section



Discharge Measurement Summary

Date Generated: Wed Nov 30 2016

File Information

File Name	S007053.WAD
Start Date and Time	2016/08/18 14:15:47

Site Details

Site Name	
Operator(s)	JLJ

System Information

Sensor Type	FlowTracker
Serial #	P1829
CPU Firmware Version	3.9
Software Ver	2.30
Mounting Correction	0.0%

Units	**(Metric Units)**
Distance	m
Velocity	m/s
Area	m^2
Discharge	m^3/s

Discharge Uncertainty

Category	ISO	Stats
Accuracy	1.0%	1.0%
Depth	0.3%	1.9%
Velocity	1.1%	7.7%
Width	0.1%	0.1%
Method	1.7%	-
# Stations	2.0%	-
Overall	**3.0%**	**8.0%**

Summary

Averaging Int.	40	# Stations	26
Start Edge	LEW	Total Width	4.542
Mean SNR	34.3 dB	Total Area	0.346
Mean Temp	19.77 °C	Mean Depth	0.076
Disch. Equation	Mid-Section	Mean Velocity	0.2173
		Total Discharge	**0.0752**

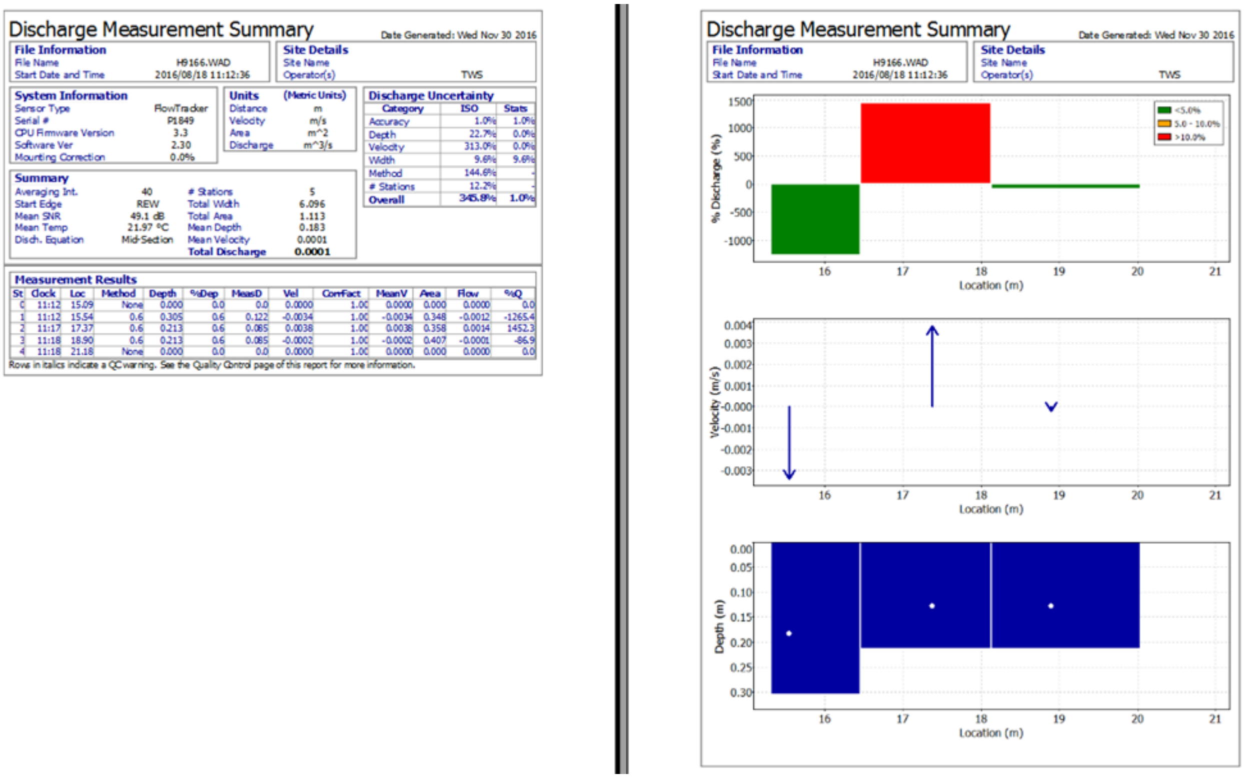
Measurement Results

St	Clock	Loc	Method	Depth	%Dep	MeasD	Vel	CorrFact	MeanV	Area	Flow	%Q
0	14:15	0.46	None	0.000	0.0	0.0	0.0000	1.00	0.0000	0.000	0.0000	0.0
1	14:15	1.22	0.6	0.061	0.6	0.024	0.2030	1.00	0.2030	0.027	0.0055	7.3
2	14:17	1.34	0.6	0.061	0.6	0.024	0.2485	1.00	0.2485	0.007	0.0018	2.5
3	14:18	1.46	0.6	0.061	0.6	0.024	0.3918	1.00	0.3918	0.007	0.0029	3.9
4	*14:18*	*1.58*	*0.6*	*0.061*	*0.6*	*0.024*	*0.4190*	*1.00*	*0.4190*	*0.007*	*0.0031*	*4.1*
5	*14:20*	*1.71*	*0.6*	*0.091*	*0.6*	*0.037*	*0.3706*	*1.00*	*0.3706*	*0.011*	*0.0041*	*5.5*
6	*14:21*	*1.83*	*0.6*	*0.091*	*0.6*	*0.037*	*0.3948*	*1.00*	*0.3948*	*0.011*	*0.0044*	*5.8*
7	14:21	1.95	0.6	0.091	0.6	0.037	0.3447	1.00	0.3447	0.011	0.0038	5.1
8	14:22	2.07	0.6	0.091	0.6	0.037	0.3093	1.00	0.3093	0.011	0.0034	4.6
9	14:23	2.19	0.6	0.091	0.6	0.037	0.4493	1.00	0.4493	0.011	0.0050	6.7
10	*14:24*	*2.32*	*0.6*	*0.091*	*0.6*	*0.037*	*0.4426*	*1.00*	*0.4426*	*0.011*	*0.0049*	*6.6*
11	*14:25*	*2.44*	*0.6*	*0.091*	*0.6*	*0.037*	*0.0678*	*1.00*	*0.0678*	*0.013*	*0.0009*	*1.1*
12	*14:26*	*2.59*	*0.6*	*0.091*	*0.6*	*0.037*	*0.1865*	*1.00*	*0.1865*	*0.014*	*0.0026*	*3.5*
13	14:27	2.74	0.6	0.122	0.6	0.049	0.0044	1.00	0.0044	0.019	0.0001	0.1
14	14:28	2.90	0.6	0.122	0.6	0.049	0.0104	1.00	0.0104	0.019	0.0002	0.3
15	14:29	3.05	0.6	0.122	0.6	0.049	0.2844	1.00	0.2844	0.019	0.0053	7.0
16	14:30	3.20	0.6	0.091	0.6	0.037	0.3393	1.00	0.3393	0.014	0.0047	6.3
17	14:31	3.35	0.6	0.091	0.6	0.037	0.2635	1.00	0.2635	0.014	0.0037	4.9
18	14:32	3.51	0.6	0.091	0.6	0.037	0.2422	1.00	0.2422	0.014	0.0034	4.5
19	14:33	3.66	0.6	0.091	0.6	0.037	0.2190	1.00	0.2190	0.014	0.0030	4.0
20	14:34	3.81	0.6	0.091	0.6	0.037	0.1145	1.00	0.1145	0.017	0.0019	2.5
21	14:35	4.02	0.6	0.091	0.6	0.037	0.0930	1.00	0.0930	0.020	0.0018	2.4
22	14:36	4.24	0.6	0.091	0.6	0.037	0.1055	1.00	0.1055	0.020	0.0021	2.7
23	14:37	4.45	0.6	0.091	0.6	0.037	0.1879	1.00	0.1879	0.020	0.0037	4.9
24	14:38	4.66	0.6	0.061	0.6	0.024	0.1685	1.00	0.1685	0.017	0.0028	3.7
25	14:38	5.00	None	0.000	0.0	0.0	0.0000	1.00	0.0000	0.000	0.0000	0.0

Rows in italics indicate a QC warning. See the Quality Control page of this report for more information.

Discharge Measurement Summary
Date Generated: Wed Nov 30 2016
File Information
File Name S007053.WAD
Start Date and Time 2016/08/18 14:15:47
Site Details
Site Name
Operator(s) JLJ

Figure 72. Site S007-053 flow cross section



Discharge Measurement Summary

Date Generated: Wed Nov 30 2016

File Information

File Name	H9166.WAD
Start Date and Time	2016/08/18 11:12:36

Site Details

Site Name	
Operator(s)	TWS

System Information

Sensor Type	FlowTracker
Serial #	P1849
CPU Firmware Version	3.3
Software Ver	2.30
Mounting Correction	0.0%

Units	**(Metric Units)**
Distance	m
Velocity	m/s
Area	m^2
Discharge	m^3/s

Discharge Uncertainty

Category	ISO	Stats
Accuracy	1.0%	1.0%
Depth	22.7%	0.0%
Velocity	313.0%	0.0%
Width	9.6%	9.6%
Method	144.6%	-
# Stations	12.2%	-
Overall	**345.8%**	**1.0%**

Summary

Averaging Int.	40	# Stations	5
Start Edge	REW	Total Width	6.096
Mean SNR	49.1 dB	Total Area	1.113
Mean Temp	21.97 °C	Mean Depth	0.183
Disch. Equation	Mid-Section	Mean Velocity	0.0001
		Total Discharge	**0.0001**

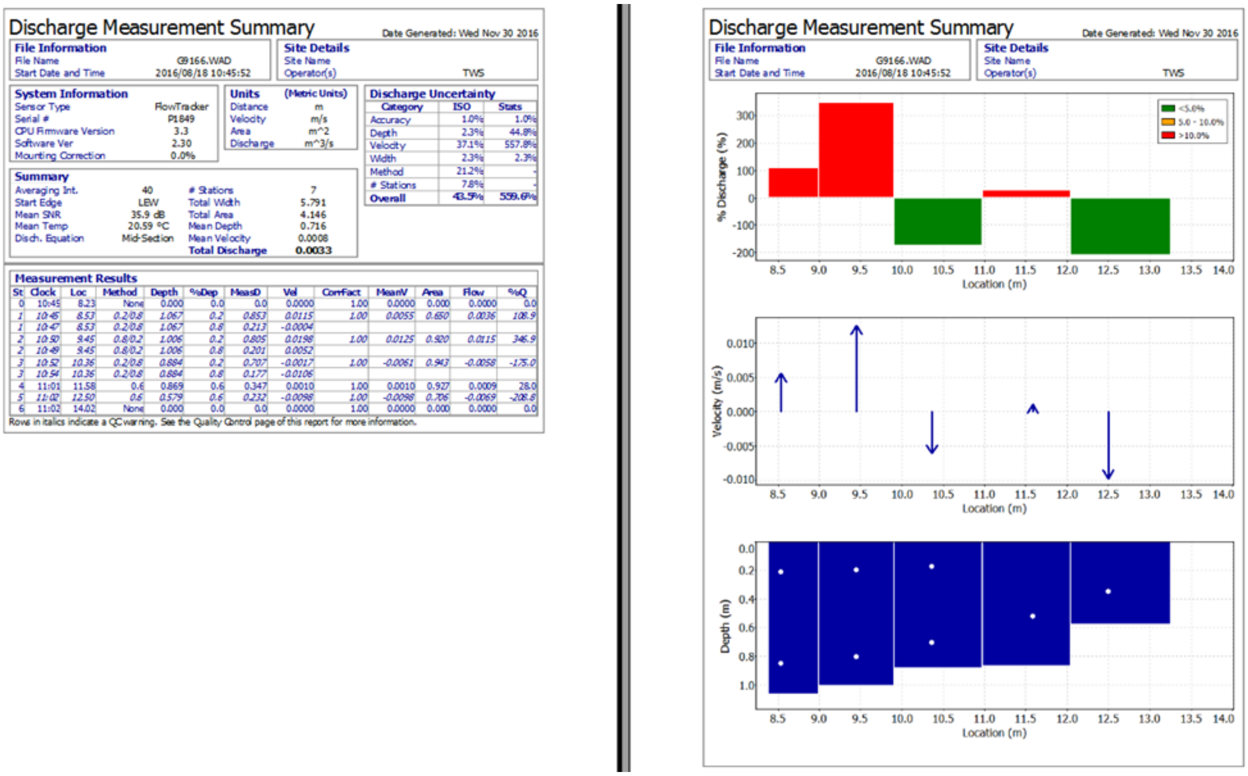
Measurement Results

St	Clock	Loc	Method	Depth	%Dep	MeasD	Vel	CorrFact	MeanV	Area	Flow	%Q
0	11:12	15.09	None	0.000	0.0	0.0	0.0000	1.00	0.0000	0.000	0.0000	0.0
1	11:12	15.54	0.6	0.305	0.6	0.122	-0.0034	1.00	-0.0034	0.348	-0.0012	-1265.4
2	11:17	17.37	0.6	0.213	0.6	0.085	0.0038	1.00	0.0038	0.358	0.0014	1452.3
3	11:18	18.90	0.6	0.213	0.6	0.085	-0.0002	1.00	-0.0002	0.407	-0.0001	-86.9
4	11:18	21.18	None	0.000	0.0	0.0	0.0000	1.00	0.0000	0.000	0.0000	0.0

Rows in italics indicate a QC warning. See the Quality Control page of this report for more information.

Discharge Measurement Summary
Date Generated: Wed Nov 30 2016
File Information
File Name H9166.WAD
Start Date and Time 2016/08/18 11:12:36
Site Details
Site Name
Operator(s) TWS

Figure 73. Site H9166 flow cross section



Discharge Measurement Summary

Date Generated: Wed Nov 30 2016

File Information	
File Name	G9166.WAD
Start Date and Time	2016/08/18 10:45:52

Site Details	
Site Name	
Operator(s)	TWS

System Information	
Sensor Type	FlowTracker
Serial #	P1849
CPU Firmware Version	3.3
Software Ver	2.30
Mounting Correction	0.0%

Units	(Metric Units)
Distance	m
Velocity	m/s
Area	m^2
Discharge	m^3/s

Category	ISO	Stats
Accuracy	1.0%	1.0%
Depth	2.3%	44.8%
Velocity	37.1%	557.8%
Width	2.3%	2.3%
Method	21.2%	-
# Stations	7.8%	-
Overall	**43.5%**	**559.6%**

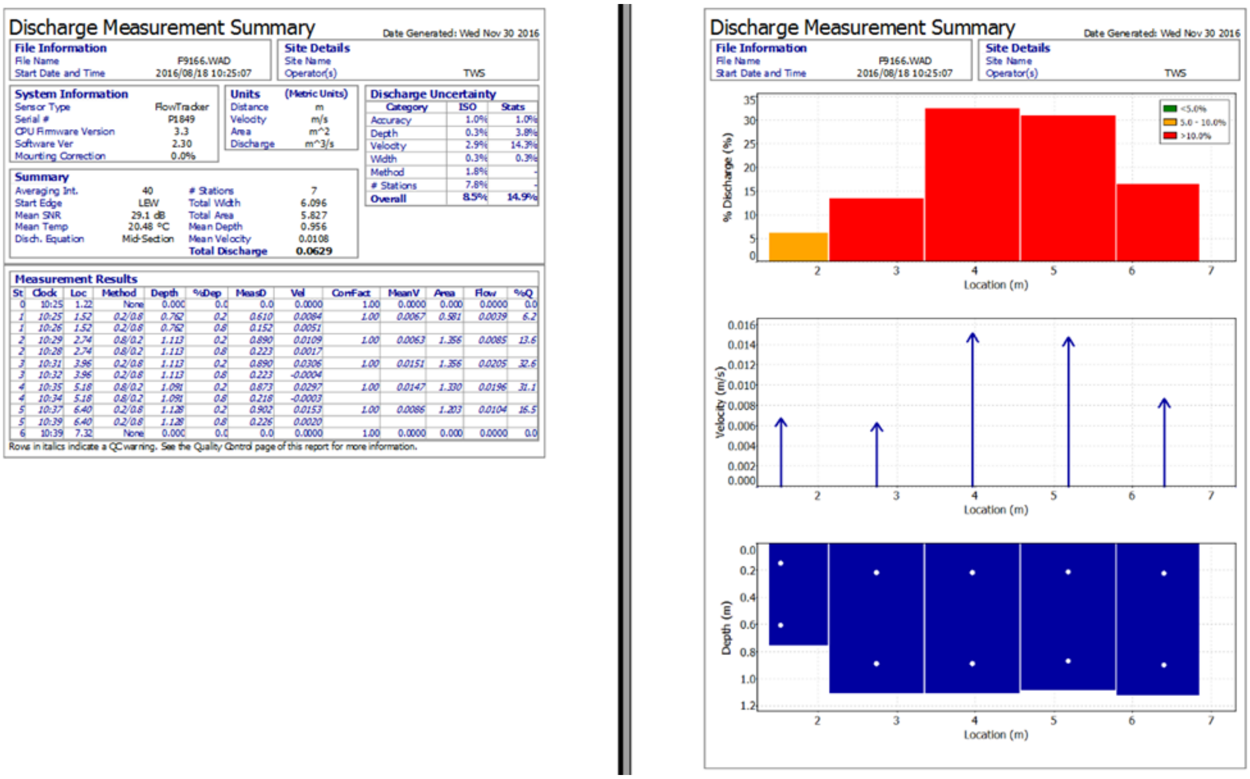
Summary			
Averaging Int.	40	# Stations	7
Start Edge	LEW	Total Width	5.791
Mean SNR	35.9 dB	Total Area	4.146
Mean Temp	20.59 °C	Mean Depth	0.716
Disch. Equation	Mid-Section	Mean Velocity	0.0008
		Total Discharge	**0.0033**

Measurement Results

St	Clock	Loc	Method	Depth	%Dep	MeasD	Vel	CorrFact	MeanV	Area	Flow	%Q
0	10:45	8.23	None	0.000	0.0	0.0	0.0000	1.00	0.0000	0.000	0.0000	0.0
1	*10:45*	*8.53*	*0.2/0.8*	*1.067*	*0.2*	*0.853*	*0.0115*	*1.00*	*0.0055*	*0.650*	*0.0036*	*108.9*
1	*10:47*	*8.53*	*0.2/0.8*	*1.067*	*0.8*	*0.213*	*-0.0004*					
2	*10:50*	*9.45*	*0.8/0.2*	*1.006*	*0.2*	*0.805*	*0.0198*	*1.00*	*0.0125*	*0.920*	*0.0115*	*346.9*
2	*10:49*	*9.45*	*0.8/0.2*	*1.006*	*0.8*	*0.201*	*0.0052*					
3	*10:52*	*10.36*	*0.2/0.8*	*0.884*	*0.2*	*0.707*	*-0.0017*	*1.00*	*-0.0061*	*0.943*	*-0.0058*	*-175.0*
3	*10:54*	*10.36*	*0.2/0.8*	*0.884*	*0.8*	*0.177*	*-0.0106*					
4	11:01	11.58	0.6	0.869	0.6	0.347	0.0010	1.00	0.0010	0.927	0.0009	28.0
5	*11:02*	*12.50*	*0.6*	*0.579*	*0.6*	*0.232*	*-0.0098*	*1.00*	*-0.0098*	*0.706*	*-0.0069*	*-208.8*
6	11:02	14.02	None	0.000	0.0	0.0	0.0000	1.00	0.0000	0.000	0.0000	0.0

Rows in italics indicate a QC warning. See the Quality Control page of this report for more information.

Figure 74. Site G9166 flow cross section



Discharge Measurement Summary

Date Generated: Wed Nov 30 2016

File Information	
File Name	F9166.WAD
Start Date and Time	2016/08/18 10:25:07

Site Details	
Site Name	
Operator(s)	TWS

System Information	
Sensor Type	FlowTracker
Serial #	P1849
CPU Firmware Version	3.3
Software Ver	2.30
Mounting Correction	0.0%

Units	(Metric Units)
Distance	m
Velocity	m/s
Area	m^2
Discharge	m^3/s

Category	ISO	Stats
Accuracy	1.0%	1.0%
Depth	0.3%	3.8%
Velocity	2.9%	14.3%
Width	0.3%	0.3%
Method	1.8%	-
# Stations	7.8%	-
Overall	**8.5%**	**14.9%**

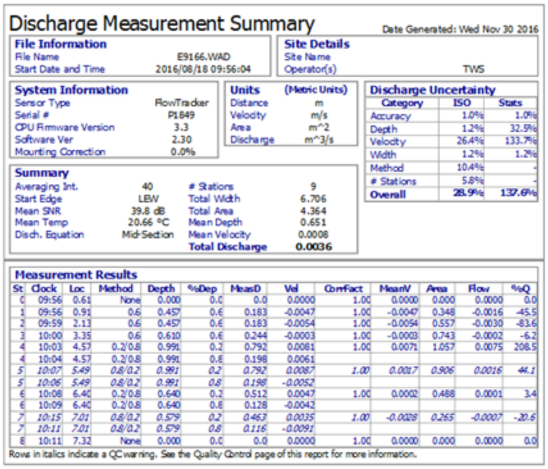
Summary			
Averaging Int.	40	# Stations	7
Start Edge	LEW	Total Width	6.096
Mean SNR	29.1 dB	Total Area	5.827
Mean Temp	20.48 °C	Mean Depth	0.956
Disch. Equation	Mid-Section	Mean Velocity	0.0108
		Total Discharge	**0.0629**

Measurement Results

St	Clock	Loc	Method	Depth	%Dep	MeasD	Vel	CorrFact	MeanV	Area	Flow	%Q
0	10:25	1.22	None	0.000	0.0	0.0	0.0000	1.00	0.0000	0.000	0.0000	0.0
1	*10:25*	*1.52*	*0.2/0.8*	*0.762*	*0.2*	*0.610*	*0.0084*	*1.00*	*0.0067*	*0.581*	*0.0039*	*6.2*
1	*10:26*	*1.52*	*0.2/0.8*	*0.762*	*0.8*	*0.152*	*0.0051*					
2	*10:29*	*2.74*	*0.8/0.2*	*1.113*	*0.2*	*0.890*	*0.0109*	*1.00*	*0.0063*	*1.356*	*0.0085*	*13.6*
2	*10:28*	*2.74*	*0.8/0.2*	*1.113*	*0.8*	*0.223*	*0.0017*					
3	*10:31*	*3.96*	*0.2/0.8*	*1.113*	*0.2*	*0.890*	*0.0306*	*1.00*	*0.0151*	*1.356*	*0.0205*	*32.6*
3	*10:32*	*3.96*	*0.2/0.8*	*1.113*	*0.8*	*0.223*	*-0.0004*					
4	*10:35*	*5.18*	*0.8/0.2*	*1.091*	*0.2*	*0.873*	*0.0297*	*1.00*	*0.0147*	*1.330*	*0.0196*	*31.1*
4	*10:34*	*5.18*	*0.8/0.2*	*1.091*	*0.8*	*0.218*	*-0.0003*					
5	*10:37*	*6.40*	*0.2/0.8*	*1.128*	*0.2*	*0.902*	*0.0153*	*1.00*	*0.0086*	*1.203*	*0.0104*	*16.5*
5	*10:39*	*6.40*	*0.2/0.8*	*1.128*	*0.8*	*0.226*	*0.0020*					
6	10:39	7.32	None	0.000	0.0	0.0	0.0000	1.00	0.0000	0.000	0.0000	0.0

Rows in italics indicate a QC warning. See the Quality Control page of this report for more information.

Figure 75. Site F9166 flow cross section



Discharge Measurement Summary

Date Generated: Wed Nov 30 2016

File Information

File Name	E9166.WAD
Start Date and Time	2016/08/18 09:56:04

Site Details

Site Name	
Operator(s)	TWS

System Information

Sensor Type	FlowTracker
Serial #	P1849
CPU Firmware Version	3.3
Software Ver	2.30
Mounting Correction	0.0%

Units	(Metric Units)
Distance	m
Velocity	m/s
Area	m^2
Discharge	m^3/s

Discharge Uncertainty

Category	ISO	Stats
Accuracy	1.0%	1.0%
Depth	1.2%	32.5%
Velocity	26.4%	133.7%
Width	1.2%	1.2%
Method	10.4%	-
# Stations	5.8%	-
Overall	**28.9%**	**137.6%**

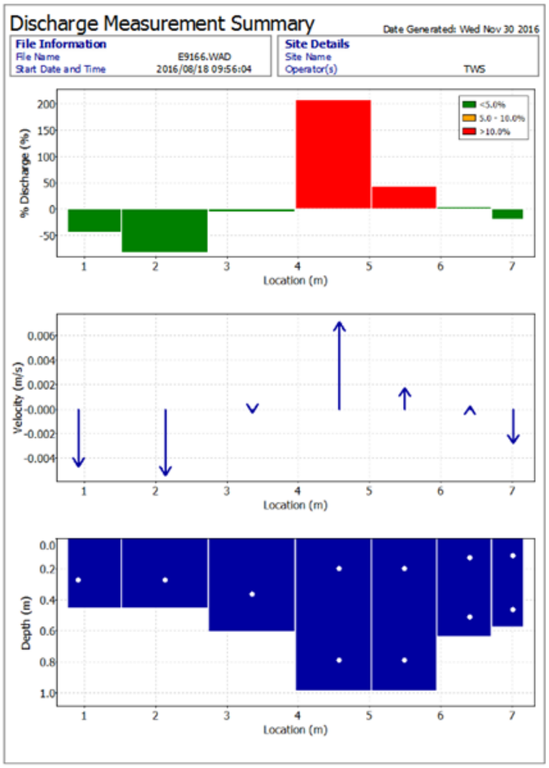
Summary

Averaging Int.	40	# Stations	9
Start Edge	LEW	Total Width	6.706
Mean SNR	39.8 dB	Total Area	4.364
Mean Temp	20.66 °C	Mean Depth	0.651
Disch. Equation	Mid-Section	Mean Velocity	0.0008
		Total Discharge	**0.0036**

Measurement Results

St	Clock	Loc	Method	Depth	%Dep	MeasD	Vel	CorrFact	MeanV	Area	Flow	%Q
0	09:56	0.61	None	0.000	0.0	0.0	0.0000	1.00	0.0000	0.000	0.0000	0.0
1	09:56	0.91	0.6	0.457	0.6	0.183	-0.0047	1.00	-0.0047	0.348	-0.0016	-45.5
2	09:59	2.13	0.6	0.457	0.6	0.183	-0.0054	1.00	-0.0054	0.557	-0.0030	-83.6
3	10:00	3.35	0.6	0.610	0.6	0.244	-0.0003	1.00	-0.0003	0.743	-0.0002	-6.2
4	10:03	4.57	0.2/0.8	0.991	0.2	0.792	0.0081	1.00	0.0071	1.057	0.0075	208.5
4	10:04	4.57	0.2/0.8	0.991	0.8	0.198	0.0061					
5	*10:07*	*5.49*	*0.8/0.2*	*0.991*	*0.2*	*0.792*	*0.0087*	*1.00*	*0.0017*	*0.906*	*0.0016*	*44.1*
5	*10:06*	*5.49*	*0.8/0.2*	*0.991*	*0.8*	*0.198*	*-0.0052*					
6	10:08	6.40	0.2/0.8	0.640	0.2	0.512	0.0047	1.00	0.0002	0.488	0.0001	3.4
6	10:09	6.40	0.2/0.8	0.640	0.8	0.128	-0.0042					
7	*10:15*	*7.01*	*0.8/0.2*	*0.579*	*0.2*	*0.463*	*0.0035*	*1.00*	*-0.0028*	*0.265*	*-0.0007*	*-20.6*
7	*10:11*	*7.01*	*0.8/0.2*	*0.579*	*0.8*	*0.116*	*-0.0091*					
8	10:11	7.32	None	0.000	0.0	0.0	0.0000	1.00	0.0000	0.000	0.0000	0.0

Rows in italics indicate a QC warning. See the Quality Control page of this report for more information.



Discharge Measurement Summary

Date Generated: Wed Nov 30 2016

File Information

File Name	E9166.WAD
Start Date and Time	2016/08/18 09:56:04

Site Details

Site Name	
Operator(s)	TWS

Figure 76. Site E9166 flow cross section

APPENDIX B: HISTORICAL IMAGERY

Historical aerial imagery of Wyman Creek is available periodically from 1939 to present from a variety of sources such as DNR Landview, Google Earth, and the MN Geospatial Office WMS image server.

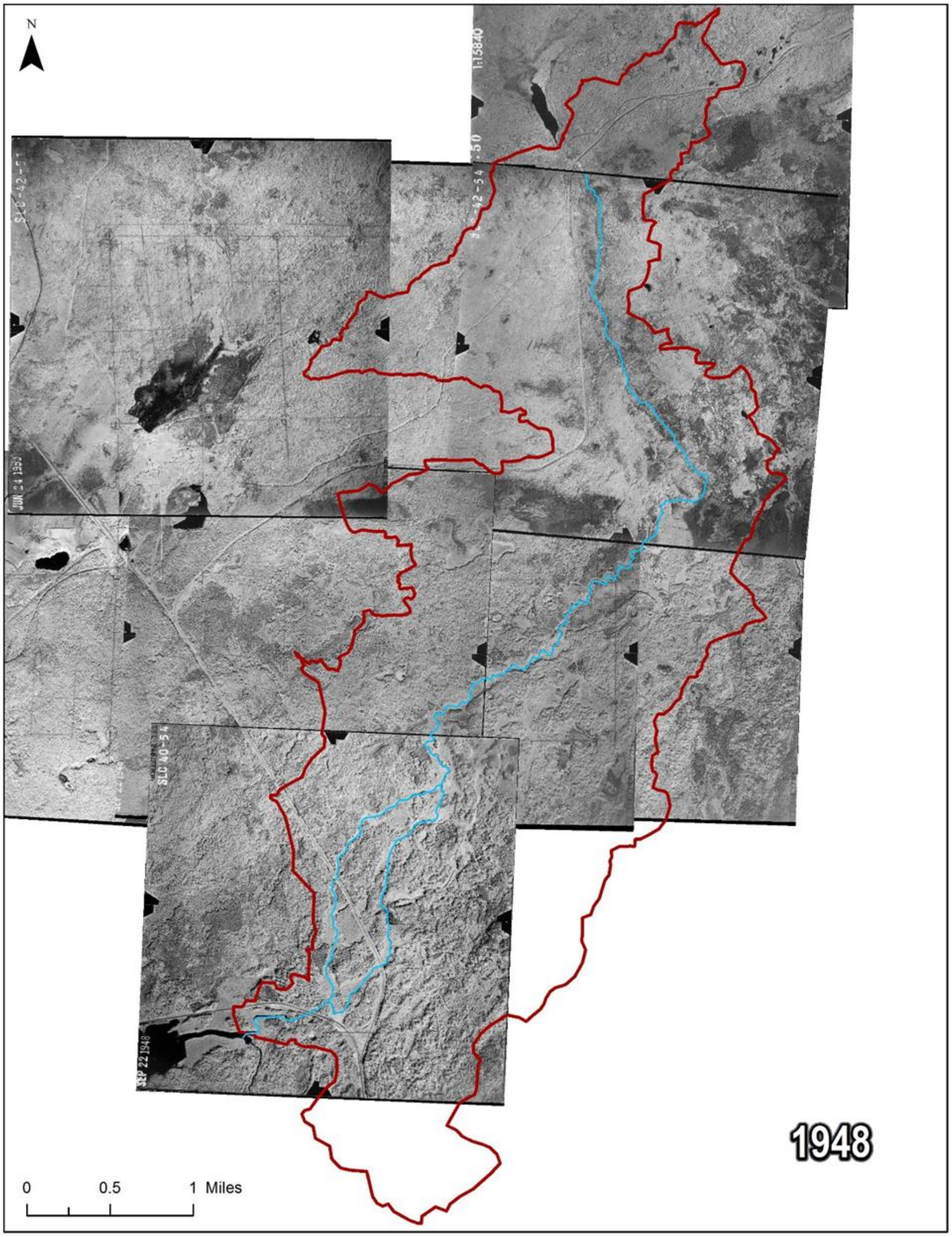


Figure 77. Aerial imagery of Wyman Creek Watershed: 1948 (DNR Landview)

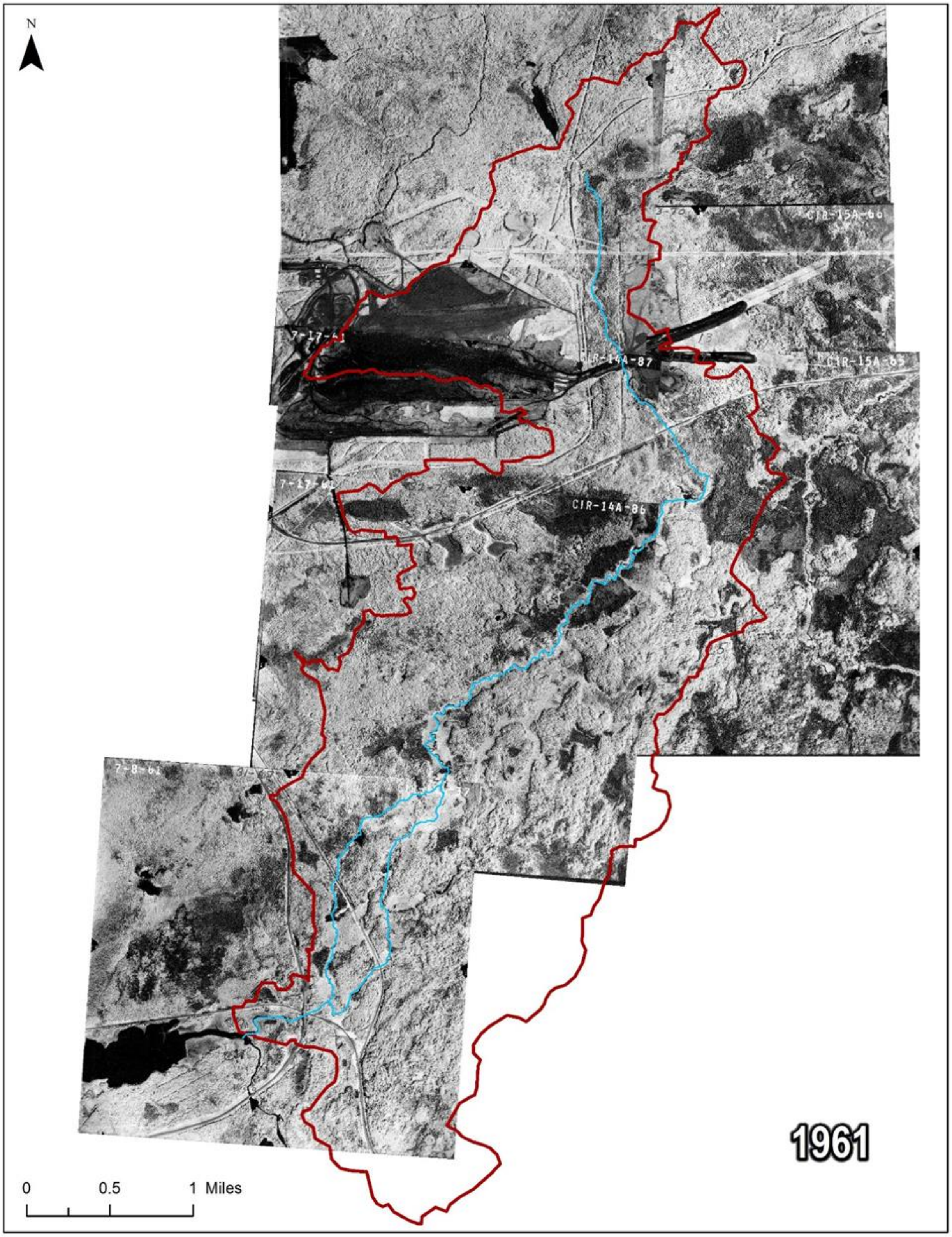


Figure 78. Aerial imagery of Wyman Creek Watershed: 1961 (DNR Landview)

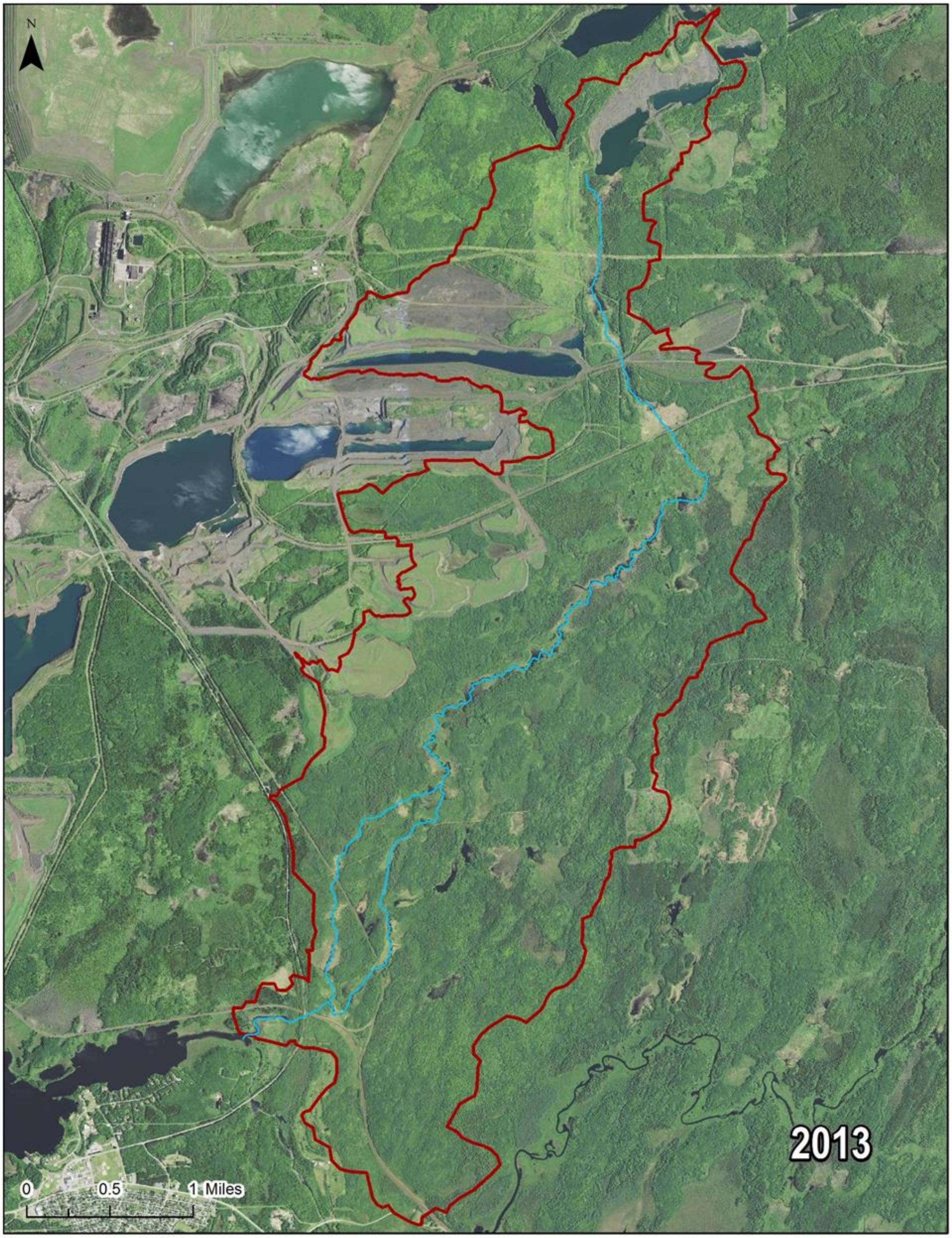


Figure 79. Aerial imagery of Wyman Creek Watershed: 2013 (MN Geospatial Office WMS image server)

APPENDIX C: QUAL2K “RATES” INPUTS

The following details include the model rates used in the Wyman Creek QUAL2K model.

Table 29. QUAL2K “Rates” tab inputs

Parameter	***Value***	***Units***	***Symbol***
Stoichiometry:			
Carbon	40	gC	gC
Nitrogen	7.2	gN	gN
Phosphorus	1	gP	gP
Dry weight	100	gD	gD
Chlorophyll	1	gA	gA
Inorganic suspended solids:			
Settling velocity	0.01	m/d	v_i
Oxygen:			
Reaeration model	Tsivoglou-Neal		
User reaeration coefficient α	3.93		α
User reaeration coefficient β	0.5		β
User reaeration coefficient γ	1.5		γ
Temp correction	1.024		θ_a
Reaeration wind effect	None		
O2 for carbon oxidation	2.69	gO_2/gC	r_{oc}
O2 for NH4 nitrification	4.57	gO_2/gN	r_{on}
Oxygen inhib model CBOD oxidation	Exponential		
Oxygen inhib parameter CBOD oxidation	0.60	L/mgO2	K_{socf}
Oxygen inhib model nitrification	Exponential		
Oxygen inhib parameter nitrification	0.60	L/mgO2	K_{sona}
Oxygen enhance model denitrification	Exponential		
Oxygen enhance parameter denitrification	0.60	L/mgO2	K_{sodn}
Oxygen inhib model phyto resp	Exponential		
Oxygen inhib parameter phyto resp	0.60	L/mgO2	K_{sop}
Oxygen enhance model bot alg resp	Exponential		
Oxygen enhance parameter bot alg resp	0.60	L/mgO2	K_{sob}
Slow CBOD:			
Hydrolysis rate	0.05	/d	k_{hc}
Temp correction	1.07		θ_{hc}
Oxidation rate	0	/d	k_{dcs}
Temp correction	1.047		θ_{dcs}
Fast CBOD:			
Oxidation rate	0.3	/d	k_{dc}
Temp correction	1.047		θ_{dc}
Organic N:			
Hydrolysis	0.015	/d	k_{hn}

Parameter	***Value***	***Units***	***Symbol***
Temp correction	1.07		θ_{hn}
Settling velocity	0.0005	m/d	v_{on}
Ammonium:			
Nitrification	0.08	/d	k_{na}
Temp correction	1.07		θ_{na}
Nitrate:			
Denitrification	0.1	/d	k_{dn}
Temp correction	1.07		θ_{dn}
Sed denitrification transfer coeff	0.8	m/d	v_{di}
Temp correction	1.07		θ_{di}
Organic P:			
Hydrolysis	0.03	/d	k_{hp}
Temp correction	1.07		θ_{hp}
Settling velocity	0.001	m/d	v_{op}
Inorganic P:			
Settling velocity	0.8	m/d	v_{ip}
Inorganic P sorption coefficient	1000	L/mgD	K_{dpi}
Sed P oxygen attenuation half sat constant	1	mgO_2/L	k_{spi}
Phytoplankton:			
Max Growth rate	3.8	/d	k_{gp}
Temp correction	1.07		θ_{gp}
Respiration rate	0.1	/d	k_{rp}
Temp correction	1.07		θ_{rp}
Excretion rate	0.1	/d	k_{ep}
Temp correction	1.07		θ_{dp}
Death rate	0.1	/d	k_{dp}
Temp correction	1.07		θ_{dp}
External Nitrogen half sat constant	100	ugN/L	k_{sPp}
External Phosphorus half sat constant	10	ugP/L	k_{sNp}
Inorganic carbon half sat constant	1.30E-05	moles/L	k_{sCp}
Light model	Half saturation		
Light constant	250	langleys/d	K_{Lp}
Ammonia preference	25	ugN/L	k_{hnxp}
Subsistence quota for nitrogen	0	mgN/mgA	q_{0Np}
Subsistence quota for phosphorus	0	mgP/mgA	q_{0Pp}
Maximum uptake rate for nitrogen	0	mgN/mgA/d	ρ_{mNp}
Maximum uptake rate for phosphorus	0	mgP/mgA/d	ρ_{mPp}
Internal nitrogen half sat constant	0	mgN/mgA	K_{qNp}
Internal phosphorus half sat constant	0	mgP/mgA	K_{qPp}
Settling velocity	0	m/d	v_a

Parameter	***Value***	***Units***	***Symbol***
Bottom Algae:			
Growth model	First-order		
Max Growth rate	50	mgA/m^2/d or /d	C_{gb}
Temp correction	1.07		θ_{gb}
First-order model carrying capacity	1000	mgA/m^2	$a_{b,max}$
Respiration rate	0.2	/d	k_{rb}
Temp correction	1.07		θ_{rb}
Excretion rate	0.12	/d	k_{eb}
Temp correction	1.07		θ_{db}
Death rate	0.1	/d	k_{db}
Temp correction	1.07		θ_{db}
External nitrogen half sat constant	3	ugN/L	k_{sPb}
External phosphorus half sat constant	1	ugP/L	k_{sNb}
Inorganic carbon half sat constant	1.30E-05	moles/L	k_{sCb}
Light model	Half saturation		
Light constant	100	langleys/d	K_{Lb}
Ammonia preference	25	ugN/L	k_{hnxb}
Subsistence quota for nitrogen	0.72	mgN/mgA	q_{0N}
Subsistence quota for phosphorus	0.1	mgP/mgA	q_{0P}
Maximum uptake rate for nitrogen	72	mgN/mgA/d	ρ_{mN}
Maximum uptake rate for phosphorus	5	mgP/mgA/d	ρ_{mP}
Internal nitrogen half sat constant	0.9	mgN/mgA	K_{qN}
Internal phosphorus half sat constant	0.13	mgP/mgA	K_{qP}
Detritus (POM):			
Dissolution rate	0.23	/d	k_{dt}
Temp correction	1.07		θ_{dt}
Fraction of dissolution to fast CBOD	1.00		F_f
Settling velocity	0.008	m/d	v_{dt}
Pathogens:			
Decay rate	0.8	/d	k_{dx}
Temp correction	1.07		θ_{dx}
Settling velocity	1	m/d	v_x
Light efficiency factor	1.00		α_{path}
pH:			
Partial pressure of carbon dioxide	347	ppm	p_{CO2}
Constituent i:			
First-order reaction rate	0	/d	
Temp correction	1		θ_{dx}
Settling velocity	0	m/d	v_{dt}
Constituent ii:			

Parameter	***Value***	***Units***	***Symbol***
First-order reaction rate	0	/d	
Temp correction	1		θ_{dx}
Settling velocity	0	m/d	v_{dt}
Constituent iii:			
First-order reaction rate	0	/d	
Temp correction	1		θ_{dx}
Settling velocity	0	m/d	v_{dt}