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Engineers • Scientists
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Snake River Watershed TMDL

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CLEAN WATER LAND & LEGACY AMENDMENT

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TMDL Summary Table		
EPA/MPCA Required Elements	**Summary**	**TMDL Page #**
Loading Capacity (expressed as daily load)	Bacteria: *See Section 3.4.1* Lake Nutrients: *See Section 4.6.1* Biotic Integrity: *See Section 5.3.4*	Pp. 3-3 – 3-6 P. 4-14 Pp. 5-12 – 5-13
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Reasonable Assurance	TMDL implementation will be carried out on an iterative basis so that implementation course corrections based on periodic monitoring and reevaluation can adjust the strategy to meet the standard. *See Section 8.0*	P. 8-1 – 8-4
Monitoring	Progress of TMDL implementation will be measured through regular monitoring efforts of water quality and total BMPs completed. This will be accomplished through the efforts of several cooperating agencies and groups. *See Section 9.0*	P. 9-1 – 9-2
Implementation	This report sets forth an implementation framework to achieve the TMDL. (A separate more detailed implementation plan will be developed within one year after of EPA's approval of this TMDL report.) *See Section 7.0*	P. 7-1 – 7-5
Public Participation	*See Section 10.0* Public Comment Period: Comments received:	P. 10-1

Acronyms

AUID	Assessment Unit ID
BMP	Best Management Practice
BWSR	Board of Water and Soil Resources
CADDIS	Causal Analysis/Diagnosis Decision Information System
CAFO	Concentrated Animal Feeding Operation
cfu	colony-forming unit
CHF	Central Hardwoods Forest
Chl-a	Chlorophyll-a
CLWP	Comprehensive Local Water Plan
CR	County Road
CWP	Clean Water Partnership
DNR	Department of Natural Resources
DO	Dissolved oxygen
DOQ	Digital Ortho Quadrangle
EQuIS	Environmental Quality Information System
F-IBI	Index of Biotic Integrity for Fish
FSA	Farm Service Agency
ft^3	cubic foot
ft/s^2	Foot per second squared
GIS	Geographical Information System
GSM	Growing Season Mean
HRU	Hydrologic Response Unit
IBI	Index of Biotic Integrity
IRG	intensive rotation grazing
kg/km^2-year	kilograms per square kilometer per year
kg/m^3	kilogram per cubic meter
LA	Load Allocation
lb/ft^2	pounds per square foot
m	meter

m^2/day	meters squared per day
m^2/mg	meters squared per milligram
m/s^2	meter per second squared
MDA	Minnesota Department of Agriculture
MDH	Minnesota Department of Health
mg/L	milligrams per liter
mg/m^2-day	milligram per square meter per day
M-IBI	Index of Biotic Integrity for Macroinvertebrates
ml	milliliter
mm	millimeter
mm/ft	millimeter per foot
mm/m	millimeter per meter
MN DNR	Minnesota Department of Natural Resources
MOS	Margin of Safety
MPCA	Minnesota Pollution Control Agency
MR	Minnesota Rules
MS4	Municipal Separate Storm Sewer Systems
MSHA	Minnesota Stream Habitat Assessment
NASS	National Agricultural Statistics Service
NAWQA	National Water Quality Assessment Program
NCHF	North Central Hardwood Forest
NH_3-N	Total Ammonia-Nitrogen
NLF	Northern Lakes and Forests
NO_2/ NO_3-N	Nitrite/ Nitrate- Nitrogen
NPDES	National Pollutant Discharge Elimination System
NPS	Nonpoint Source
NRCS	Natural Resource Conservation Service
NTU	Nephelometric Turbidity Units
NWI	National Wetland Inventory
ppb	parts per billion
RC&D	Resource Conservation and Development (Council)
SCS	Soil Conservation Service
SDS	State Disposal System

SONAR	Statement of Need and Reasonableness
SRWMB	Snake River Watershed Management Board
SSTS	Subsurface Sewage Treatment Systems
SSURGO	Soil Survey Geographic
SWCD	Soil and Water Conservation District
TDLC	Total Daily Loading Capacity
TKN	Total Kjeldahl Nitrogen
TMDL	Total Maximum Daily Load
TP	Total phosphorus
TSA	Technical Service Area
TSS	Total Suspended Solids
UAL	Unit-area Load
µg/L	microgram per liter
USDA	United States Department of Agriculture
USEPA	United States Environmental Protection Agency
USGS	United States Geological Survey
WCA	Wetland Conservation Act
WMA	Wildlife Management Areas
WLA	Wasteload Allocation

Executive Summary

This Total Maximum Daily Load (TMDL) study addresses eight impairments in the Snake River watershed, which is an 8 digit Hydrologic Unit (HUC) located in the St Croix River Basin. It includes nutrient impairments in Knife, Quamba, Pokegama and Cross Lakes; *E. coli* impairments for Upper and Lower Mud Creek and Bear Creek; and fish and macroinvertebrate biotic integrity impairments for Upper Mud Creek. The Snake River Watershed covers approximately 1,006 square miles or 643,534 acres and overlies six counties including Aitkin, Kanabec, Mille Lacs, Pine, Chisago and Isanti. The headwaters of the Snake River are located in southeastern Aitkin County. The Snake River flows south to east to its confluence with the St. Croix River in Pine County, MN. The goal of this TMDL is to quantify the pollutant reductions needed to meet state water quality standards for nutrients in the lakes, *E. coli* standards for the three impaired stream reaches, and State Index of Biotic Integrity standards in Upper Mud Creek. This TMDL is established in accordance with Section 303(d) of the Clean Water Act and provides wasteload allocations (WLAs) and load allocations (LAs) for the Snake River Watershed.

Lakes

Pokegama and Cross Lakes are defined as deep lakes for which the North Central Hardwood Forest ecoregion numeric water quality standards are: a summer average total phosphorus concentration of 40 µg/L or less; 14 µg/L chlorophyll-a or less;, and greater than 1.4 meter Secchi depth. Knife and Quamba Lakes are shallow, for which the numeric water quality standards are: a summer average total phosphorus concentration of 60 µg/L or less; 20 µg/L chlorophyll-a or less; and greater than one meter Secchi depth.

Nutrient budgets were developed for all four lakes along with lake response models to set the TMDL and LAs and WLAs. A robust lake and stream monitoring dataset was available and was the basis of the nutrient budget calculations. Total nutrient reductions ranging from 25% to 73% will be necessary to meet state water quality standards. Nutrient reduction implementation strategies for the four lakes should focus on watershed and internal nutrient load reductions and failing septic system upgrades.

Bacteria

Flow and bacteria monitoring data recorded in Upper Mud Creek, Lower Mud Creek and Bear Creek were used to establish load duration curves meeting the *E. coli* numeric standard of no more than 126 organisms per 100 ml as a geometric mean of not less than five samples representative of conditions within any calendar month, nor more than 10% of all samples taken during any calendar month individually exceed 1,260 organisms per 100 ml. A TMDL, WLAs, and LAs were established for five flow categories: very high flow, high flow, mid-range flow, low flow and dry flow conditions. Bacteria reductions ranging from no reduction to 72% during certain flow regimes will be necessary to meet *E. coli* concentration standards. Implementation activities for the *E. coli* impaired watersheds should focus on manure and pasture management initiatives and limiting cattle access to streams and septic system upgrades.

Fish and Macroinvertebrates

The MPCA has developed an Index of Biotic Integrity (IBI) to evaluate the biological health of streams in the State. Currently, an IBI has been developed for two biological communities, fish and macroinvertebrates. Upper Mud Creek is impaired based on both fish IBI (F-IBI) and the macroinvertebrate IBI (M-IBI). The fish impairment is not severe, with sites scoring at the fish IBI standard for Northern Headwaters Streams, however the fish assemblage is somewhat degraded compared to other, higher quality sites. One of two sites assessed on Upper Mud Creek scored well below the Northern Forest Streams Glide-Pool macroinvertebrate IBI standard, exhibiting an abundance of tolerant species and species that are indicative of nutrient enrichment.

A Stressor Identification Report was completed by the MPCA in 2012 using the USEPA's Causal Analysis/Diagnosis Decision Information System (CADDIS), which is a methodology for conducting a stepwise analysis of candidate causes of impairment using a "strength of evidence" approach to evaluate candidate causes affecting biotic integrity. Five candidate causes were identified in the Stressor ID – bedded sediment, low dissolved oxygen, riparian habitat degradation, loss of connectivity due to ditching and altered flow due to ditching. The evidence is strongest that lack of benthic habitat due to sedimentation is the primary stressor to aquatic life in Upper Mud Creek. Impacts from riparian degradation and persistent low dissolved oxygen are important co-stressors. The loss of connectivity and altered hydrology due to extensive ditching in the watershed and on the creek itself are plausible stressors and are likely contributing to the impairment, however there is less direct or conflicting evidence of their role.

Further assessment identified stream bank erosion as a primary source of excess sediment. Streambank instability is affected by the type of vegetation maintained in the degraded riparian zone – primarily short pasture grasses. Animals generally enjoy unrestricted access to the stream, which has resulted in stream bank failures and bare or sparsely vegetated banks and riparian area. Occasions of low dissolved oxygen concentrations are likely the result of excessive stream warming due to a lack of tree canopy, lack of reaeration capacity, and nutrient enrichment.

Restoration of eroded streambanks to reduce sediment contribution and restoring native streambank vegetation to stabilize banks would have the greatest impact on improving benthic habitat. Planting wide native buffers and reestablishing a canopy cover should also be completed to reduce nutrient enrichment, decrease stream temperature, and increase dissolved oxygen.

1.0 Introduction

1.1 PURPOSE

This Total Maximum Daily Load (TMDL) study addresses four lake nutrient impairments, three *E. coli* impairments and one fish and macroinvertebrate biotic integrity in the Snake River watershed. The impaired water bodies are located throughout the Snake River watershed as shown in Figure 1.1. The goal of this TMDL is to quantify the pollutant reductions needed to meet State water quality standards for nutrients, *E. coli* and State Index of Biotic Integrity standards for Northern Headwaters Streams. These TMDLs are established in accordance with Section 303(d) of the Clean Water Act and provides wasteload allocations (WLAs) and load allocations (LAs) for the Snake River Watershed impairments.

1.2 PROBLEM IDENTIFICATION

The lakes addressed in this study were first placed on the State of Minnesota's 303(d) list of impaired waters for nutrient (total phosphorus) impairment in 2010 (Table 1-1). The *E. coli* impaired reaches and the fish and macroinvertebrate reach were also placed on the 303(d) list in 2010.

Table 1-1. MPCA 2012 303(d) list of impaired waters covered in this TMDL.

Water Body	Yr Listed	Assessment Unit ID	Affected Use	Pollutant or Stressor	Target Start // Completion
Mud Creek – Headwaters to Quamba Lake	2010	07030004-566	Aquatic life	Fish Bio-assessment	2010//2015
Mud Creek – Headwaters to Quamba Lake	2010	07030004-566	Aquatic life	Macroinvertebrate Bio-assessment	2010//2015
Mud Creek – Headwaters to Quamba Lake	NA	07030004-566	Aquatic recreation	*E. coli*	2010//2015
Mud Creek – Quamba Lake to Snake River	2010	07030004-567	Aquatic recreation	*E. coli*	2010//2015
Bear Creek – Headwaters to Snake River	2010	07030004-514	Aquatic recreation	*E. coli*	2010//2015
Knife Lake	2004	33-0028	Aquatic recreation	Excess Nutrients	2010//2015
Quamba Lake	2004	33-0015	Aquatic recreation	Excess Nutrients	2010//2015
Pokegama Lake	2004	58-0142	Aquatic Recreation	Excess Nutrients	2010//2015
Cross Lake	2004	58-0119	Aquatic Recreation	Excess Nutrients	2010//2015

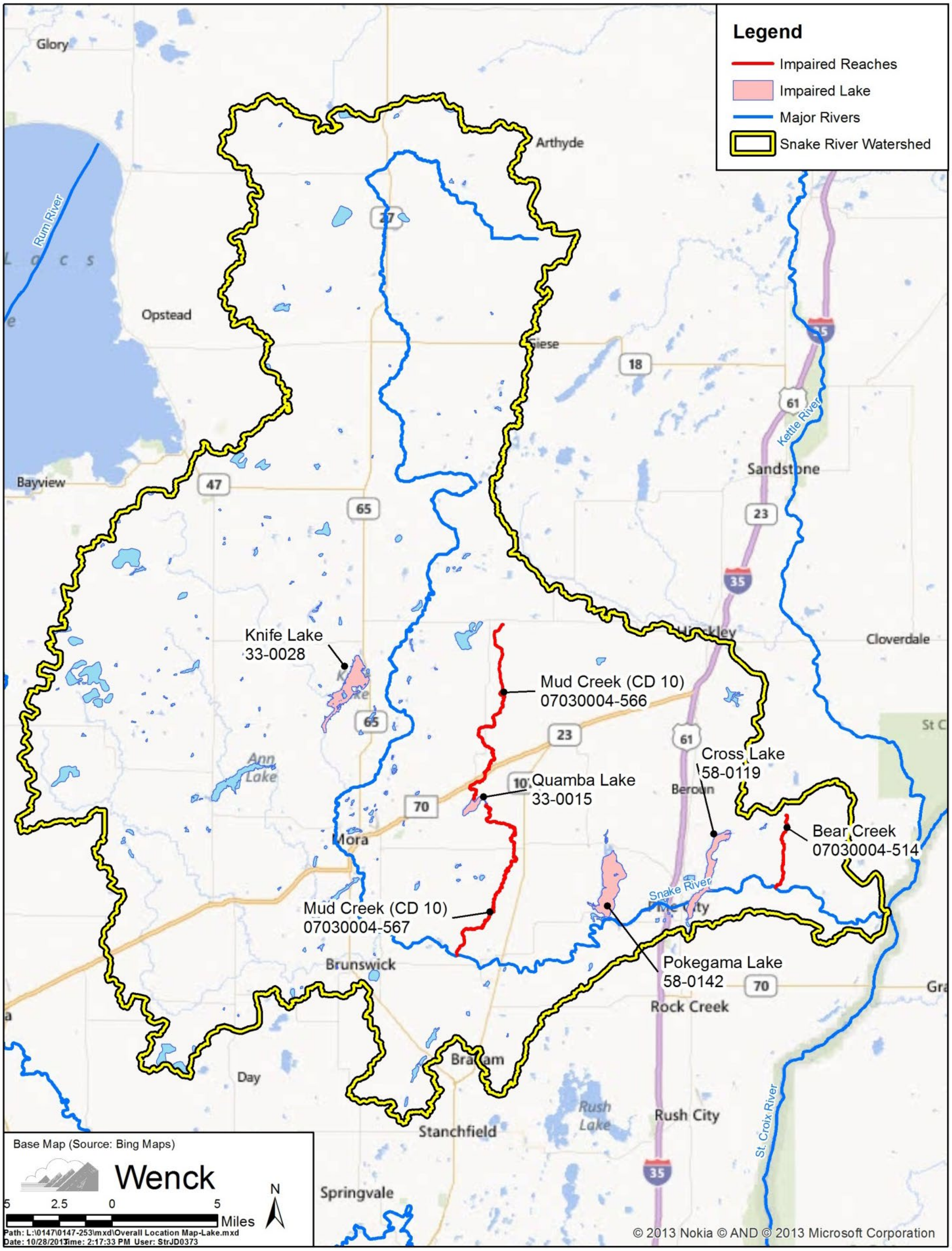


Figure 1.1. Impaired Waters in the Snake River Watershed.

1.3 IMPAIRED WATERS AND MINNESOTA WATER QUALITY STANDARDS

1.3.1 State of Minnesota Designated Uses

Knife Lake, Quamba Lake, Pokegama Lake, Cross Lake, Bear Creek and Upper and Lower Mud Creeks are all classified as class 2B waters for which aquatic life and recreation are the protected beneficial uses. The MPCA's projected schedule for TMDL completions on the 303(d) impaired waters list implicitly reflects Minnesota's priority ranking of this TMDL, which was scheduled to be initiated in 2010 and completed by 2015. Ranking criteria for scheduling TMDL projects include, but are not limited to: impairment impacts on public health and aquatic life; public value of the impaired water resource; likelihood of completing the TMDL in an expedient manner, including a strong base of existing data and restorability of the water body; technical capability and willingness locally to assist with the TMDL; and appropriate sequencing of TMDLs within a watershed or basin.

1.3.2 State of Minnesota Standards and Criteria for Listing

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

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

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

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

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

E coli concentration (equivalents) = 1.80 x (Fecal Coliform Concentration)$^{0.81}$

Nutrients. Minnesota's standards for nutrients limit the quantity of nutrients which may enter surface waters. Minnesota's standards at the time of listing (MR 7050.0150(3)) stated that in all Class 2 waters of the State "…there shall be no material increase in undesirable slime growths or aquatic plants including algae." In accordance with MR 7050.0150(5), to evaluate whether a water body is in an impaired condition the MPCA developed "numeric translators" for the narrative standard for purposes of determining which lakes should be included in the section 303(d) list as being impaired for nutrients. The numeric standards for shallow and deep lakes, adopted in 2008, established numeric thresholds for phosphorus and response variables chlorophyll-a and clarity as measured by Secchi depth (Table 1-2). Regression equations developed by the MPCA (2005) suggest that the two response variables, Secchi depth and chlorophyll-a, should also meet state standards when the necessary phosphorus reductions are made.

Table 1-2. Trophic status thresholds for determination of use support for lakes.

Ecoregion – Lake Type	Numeric Standards		
	303(d) Designation		
	TP (ppb)	Chl-a (ppb)	Secchi (m)
North Central Hardwood Forests (Deep Lake)	< 40	< 14	> 1.4
North Central Hardwood Forests (Shallow Lake[1])	≤60	≤20	≥1.0

[1] Shallow lakes are defined as lakes with a maximum depth of 15 feet or less, or with 80% or more of the lake area shallow enough to support emergent and submerged rooted aquatic plants (littoral zone).

1.4 ANALYSIS OF IMPAIRMENT

The criteria used for determining impairments are outlined in the MPCA document Guidance Manual for Assessing the Quality of Minnesota Surface Waters for Determination of Impairment – 305(b) Report and 303(d) List, January 2010. The applicable water body classifications and water quality standards are specified in MR Chapter 7050. MR 7050.0407 lists water body classifications and MR 7050.2222 (5) lists applicable water quality standards.

Biotic Impairment. Table 1-3 shows the Index of Biotic Integrity scores used to evaluate Upper Mud Creek for biotic impairment. The fish impairment is not severe, with sites scoring at the fish IBI standard for Northern Headwaters Streams, however the fish assemblage is somewhat degraded compared to other, higher quality sites. Macroinvertebrate scores were impaired at one site (Site 7) in Upper Mud Creek.

Table 1-3. Index of Biotic Integrity standards and relevant Mud Creek data.

Station ID	Location	Fish IBI		Macroinvertebrate IBI	
		Standard	Score	Standard*	Score
06SC110	Site 3: CR 5	40	40	52.4	40.7
98SC018	Site 7: 225th Street	40	40	52.4	59.2

Note: Fish-IBI used is Northern Headwaters Streams. Invert-IBI is Northern Forest Glide-Pool.

Nutrients. In 2010, Knife, Quamba, Pokegama and Cross Lake were listed for nutrient impairments due to excess total phosphorus. The lakes also did not meet either chlorophyll-a or Secchi depth standards.

E. coli. In 2010, Bear and Lower Mud Creek were listed as impaired for bacteria. Upper Mud Creek is not currently on the 303(d) list. However, recent samplings in Upper Mud Creek in 2010-2011 indicate this reach will likely be listed as impaired for *E. coli* during the next listing cycle.

2.0 Watershed and Stream Characterization

2.1 SNAKE RIVER WATERSHED DESCRIPTION

The Snake River watershed is an 8 digit Hydrologic Unit (HUC) located in the St. Croix River Basin. The watershed is approximately 1,006 square miles, or 643,534 acres, in extent and overlies six counties including Aitkin, Kanabec, Mille Lacs, Pine, Chisago and Isanti. The headwaters of the Snake River are located in the southeastern Aitkin County. The Snake River watershed can be broken down into 8 sub-watersheds (Figure 2.1), which include: Upper Snake, Middle Snake, Knife River, Mud Creek, Groundhouse River, Pokegama Creek, Ann River and Lower Snake River. The Snake River flows south to east to its confluence with the St. Croix River in Pine County, MN.

2.2 LAND COVER

Land use and land cover in the Snake River watershed has a large variation of cover ranging from agricultural and urban in the south, to largely forest and wetland in the north (Figure 2.2). Land use for the impaired reach watersheds are presented in Tables 2-1 and 2-2 and were calculated using the 2010 National Agricultural Statistics Service (NASS).

Table 2-1. 2010 land cover for the *E. coli* impaired reach watersheds.

Land Cover	Percent of Total		
	[1] Upper Mud Creek	[1] Lower Mud Creek	[1]Bear Creek
Watershed area (acres)	20,353	26,389	6,156
Hay/Pasture	35%	36%	38%
Cropland	2%	8%	16%
Forest	31%	24%	28%
Wetland	27%	28%	15%
Urban/Roads	3%	4%	3%
Open Water	2%	1%	0%

[1] Includes only subwatersheds that drain to impaired reach.

Table 2-2. 2010 land cover for the nutrient impaired lake watersheds.

Land Cover	Percent of Total				
	Knife Lake	Quamba Lake	Pokegama Lake	Cross Lake (Snake)	Cross Lake (Direct)
Watershed area (acres)	59,777	24,350	52,146	428,025	8,027
Hay/Pasture	17%	37%	33%	22%	35%
Cropland	1%	2%	2%	6%	8%
Forest	47%	29%	29%	36%	20%
Wetland	28%	26%	30%	31%	16%
Urban/Roads	2%	3%	3%	3%	8%
Open Water	4%	3%	3%	2%	13%

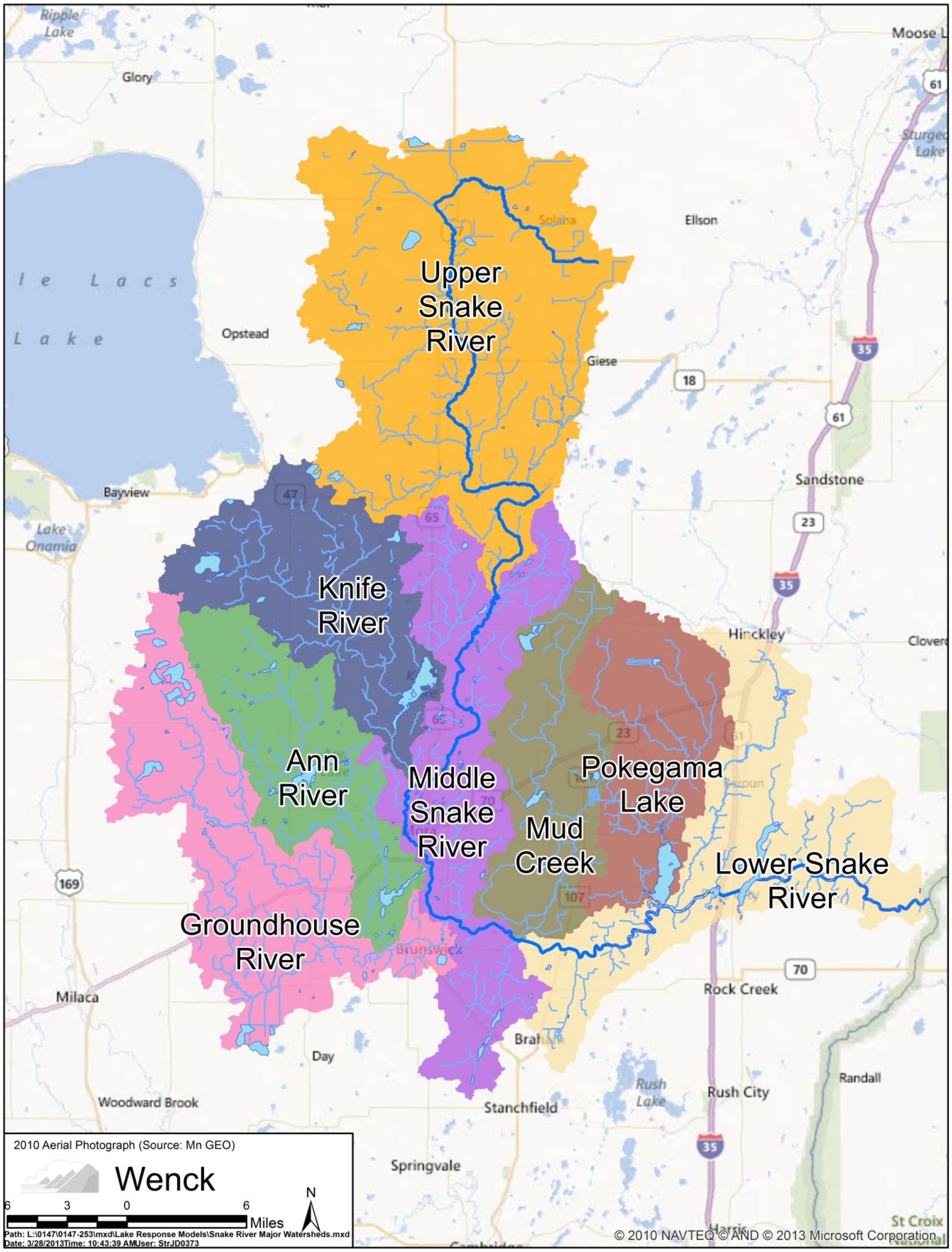


Figure 2.1. Major Subwatersheds and Drainage Pattern in the Snake River Watershed.

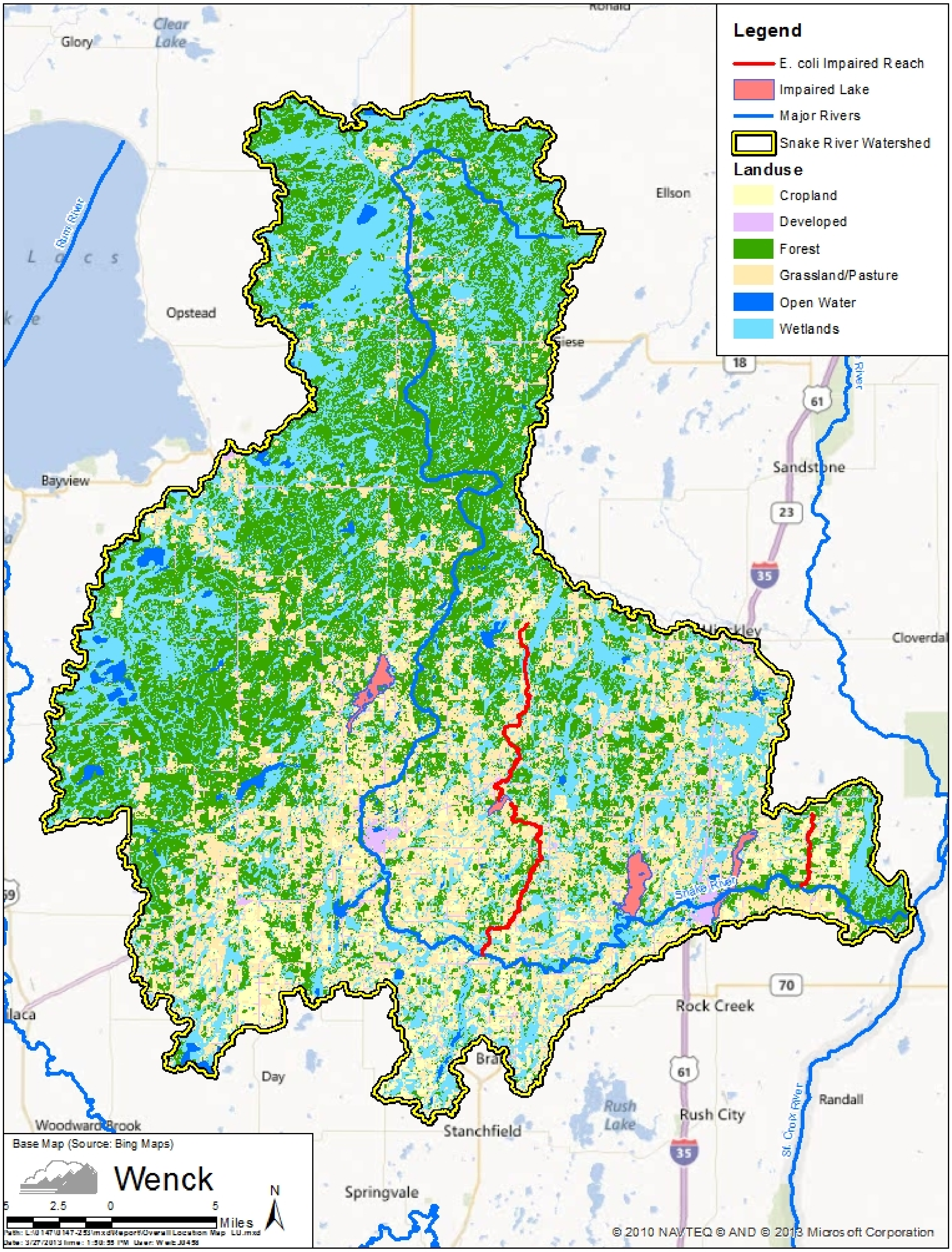


Figure 2.2. Snake River Watershed 2010 NASS Land Cover.

2.3 PREVIOUS TMDLS IN THE SNAKE RIVER WATERSHED

There have been three bacteria, three biotic and two lake nutrient TMDLs completed in the Snake River watershed prior to this study. The Groundhouse River TMDL was completed in 2009 and covered three bacteria impairments and two biotic impairments (fish and invertebrate IBIs) in the South Fork Groundhouse River and main-stem Groundhouse River (Tetra Tech, 2009). The Ann River Watershed TMDL study was completed in 2013 and included lake nutrient TMDLs for Ann and Fish Lake and one bacteria and biotic (fish and invertebrate IBIs) TMDL for the Ann River main-stem reach between Ann and Fish Lake (Wenck Associates, 2013). In 2012, a TMDL study was completed for Lake St. Croix near Stillwater, MN downstream of the Snake River watershed (MPCA and Wisconsin DNR, 2012). This study determined outflow from the Snake River accounts for approximately 10% of the Lake St. Croix phosphorus budget and TMDL allocations were assigned to the St. Croix River and its tributaries, which includes the Snake River.

2.4 BIOTIC INTEGRITY IN SNAKE RIVER

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

The impairments were listed on the basis of monitoring conducted in 1996 and 1998 (see Figure 2.3 for monitoring locations.) The fish impairment was designated in 2002 and the macroinvertebrate in 2004. Additional monitoring conducted in 2006-2009 was used to confirm the impairments and prepare a Stressor Identification Study (Stressor ID) in 2012 (Jasperson 2012) for both the fish and macroinvertebrate communities. This TMDL report summarizes the biologic data and IBI results that were evaluated in more detail in that Stressor ID.

While the fish-IBI scores at the two bio monitoring sites on Upper Mud (Site 3 and Site 7, Figure 2.3) were equal to the listing standard for Northern Headwaters Streams, more detailed evaluation found that the sites lacked a balanced community and Upper Mud was designated as impaired. The fish community was found to be dominated by species with high tolerance to habitat degradation and environmental stress. Both sites also scored low on metrics pertaining to lithophilic (gravel-spawning) species and benthic insectivores.

Upper Mud Creek is classified for macroinvertebrate monitoring purposes as a Northern Forest Glide-Pool stream, which typically exhibits a low gradient. Only one of the two biomonitoring sites did not meet the state M-IBI standard – Site 3. The individual metrics indicate the community is dominated by pollution tolerant species with a distinct lack of intolerant species found at other locations on Upper and Lower Mud Creek. The site also was abundant in filter feeders, a trophic trait that often indicates nutrient enrichment and excessive algal production.

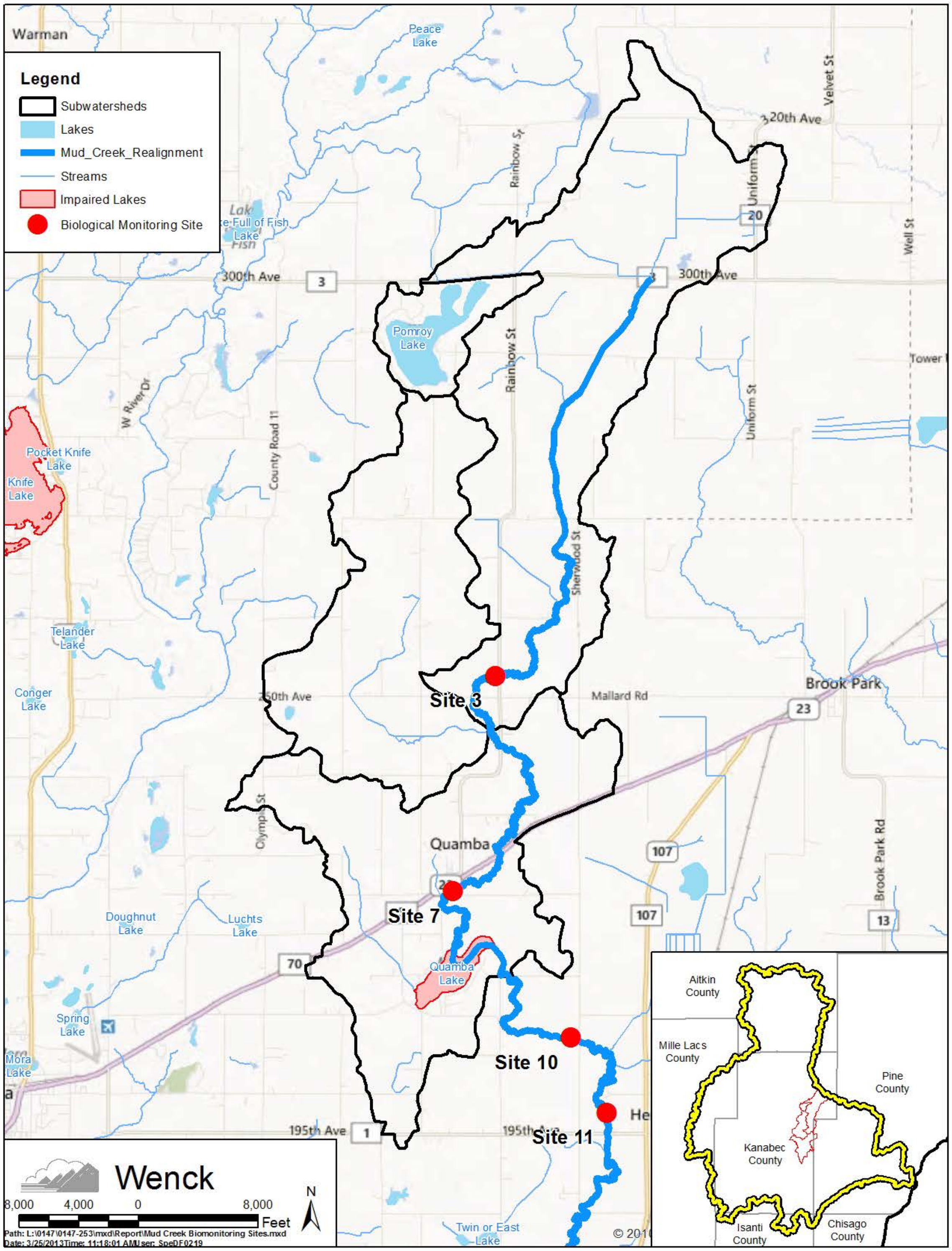


Figure 2.3 Biomonitoring locations from the Stressor Identification Study.

2.5 FACTORS INFLUENCING BIOTIC INTEGRITY IN THE SNAKE RIVER

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

Potential candidate causes of the impairments that were ruled out based on a review of available data include: pH; turbidity/TSS; stream temperature; chloride toxicity; pesticides; and heavy metals toxicity. Five stressors that are potential candidate causes were examined in more detail: loss of habitat due to excess deposited and bedded sediment; low dissolved oxygen concentrations; degraded riparian habitat; loss of connectivity and altered flow, both due to ditching in the watershed and on the stream itself. The Mud Creek Stressor Identification Report (Jasperson 2012) is incorporated into this report by reference.

2.5.1 Excess Deposited and Bedded Sediments

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

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

As described in the Stressor ID Report, pebble counts and stream condition assessments found that the stream bottom sediments in Upper Mud Creek were dominated by sand and fine sediments, especially Sites 3 and 6. The Pfankuch Stability Index was used to assess condition and stability of the stream channel. Sites 2, 3, and 6 were rated poor stability, specifically in the metrics relating to scouring and sediment deposition. Agricultural land uses, primarily cattle grazing, are a significant source of sediment delivery in the watershed. Destabilization of stream banks from animal grazing is resulting in segments of destabilized streambanks, which has contributed to sediment loss and delivery downstream. Channel widening, gully formation, and other erosional processes within the stream corridor appear to be contributing higher than normal sediment loads to the river. Excess sediment deposition can reduce pool and riffle habitat quality, and result in a lack of fish and macroinvertebrate species that depend on coarse substrates for feeding and reproduction.

2.5.2 Low Dissolved Oxygen

Living aquatic organisms such as fish and macroinvertebrates require oxygen to sustain life. Decreases in dissolved oxygen (DO) in the water column can cause changes in the types and numbers of fish and aquatic macroinvertebrates in surface waters, and shift the community composition to species that are tolerant of lower levels or wider diurnal swings in DO. Instantaneous, longitudinal and continuous (diurnal) measurements for dissolved oxygen were conducted at monitoring stations on Upper and Lower Mud Creek during the summers of 2007, 2008 and 2009. Instantaneous data indicates that dissolved oxygen concentrations in both reaches of the creek occasionally drop below the standard of 5 mg/L during mid to late summer months.

Longitudinal surveys in the late summer months found early-morning concentrations less than the 5.0 mg/L standard, but continuous sampling over multiple days in early summer months found concentrations staying consistently above the 5.0 mg/L standard, and an acceptable daily flux. More data is necessary to better establish the extent of potential low DO in both reaches. There is some uncertainty regarding the processes driving this stressor, which may be related to in-line and riparian wetland flushing or possibly to nutrient enrichment from mid-stream Quamba Lake, which is impaired by excess nutrients.

2.5.3 Habitat Loss from Riparian Corridor Disturbance

The riparian zone of a stream is generally defined as the transition area between aquatic ecosystems and adjacent upland terrestrial ecosystem. High quality undisturbed riparian corridors provide shading from solar radiation, filtration of overland runoff, mitigation of bank erosion, and inputs of detritus and organic matter that are critical to supporting aquatic life.

Land cover alterations have reduced the quality of the riparian corridor. Cattle grazing and activity near the stream and removal of natural riparian vegetation have led to destabilized streambanks and reduced overhanging vegetation that provides fish cover, filtering, and habitat.

2.5.4 Loss of Watershed Connectivity Due to Ditching

Connectivity can refer to a number of different pathways that move organisms, energy, and matter. Connectivity can be longitudinal or linear; lateral, or with the floodplain; vertical, to the hyporrheic zone below the stream bed and banks; or temporal. Much of Upper Mud Creek and its tributaries have been channelized, or excavated and straightened to serve as drainage ditches. This can have an immediate effect on biotic integrity by reducing or eliminating natural in-stream habitat structures such as pools, riffles, and backwaters, and it can change how the stream and organisms access the floodplain and other locations upstream and downstream. Limited information is available, but literature suggests ditching in the watershed and on Upper Mud Creek has a negative impact on biotic integrity.

2.5.5 Altered Hydrology

Ditching can also impact hydrology. Ditches are often constructed to control or reduce water levels in wetlands, reducing storage in the watershed and increasing discharge downstream. Limited information is available, but literature suggests ditching in the watershed and on Upper Mud Creek has a negative impact on biotic integrity.

2.6 BACTERIA IN THE SNAKE RIVER

E. coli bacteria are an indicator organism, meaning that not all the species of bacteria of this category are harmful but are usually associated with harmful organisms transmitted by fecal contamination. They are found in the intestines of warm-blooded animals, including humans. The presence of *E. coli* in water suggests the presence of fecal matter and associated bacteria, viruses, and protozoa (i.e. *Giardia* and *Cryptosporidium*) that are pathogenic to humans when ingested (USEPA 2001). The primary bacterium present in the Snake River is *E. coli*. Monitoring data were used to determine the extent to which factors are influencing bacteria levels in the watershed and to determine the potential sources of that bacterium.

2.7 FACTORS INFLUENCING BACTERIA IN SNAKE RIVER WATERSHED

The main factors influencing bacteria in the Snake River watershed are potential for loading from point and non-point sources and stream flow. Understanding these factors and what contributes to their current conditions is important to addressing the bacteria TMDL.

2.7.1 Bacteria Loading

Bacteria loading can occur from both point and non-point sources, thus the potential sources of bacteria need to be identified as well as the linkages between those sources and the receiving water. Initial review of the Bear Creek and the Mud Creek impaired reach watersheds suggests that there are no current point sources (such as wastewater treatment plant discharges) in the watershed. This indicates that the bacteria exceedance is likely the result of loading from non-point sources. Available bacteria monitoring data was used to assess bacteria loading and develop the TMDL.

2.7.2 Streamflow

Stream flow data was examined to search for linkages between exceedances of the bacteria standard and to develop bacteria allocations for the TMDL. For example, exceedances during high flow events suggest that bacteria load may be related to wash off from the watershed (i.e., stormwater inputs). Exceedances during low flow suggest that animals in streams and septic system sources might be contributors. Flow regime, defined by selected flow levels ranging from dry to very high, when paired with bacteria data provides insights on potential sources.

2.8 FACTORS INFLUENCING NUTRIENTS IN SNAKE RIVER WATERSHED

Factors influencing total phosphorus and other nutrient levels in the Snake River watershed impaired lakes are atmospheric nutrient loading, watershed nutrient loading, internal phosphorus loading and loading from failing septic systems and wastewater treatment facilities. These sources are described in detail in Section 4.

3.0 *E. coli* Impairments

3.1 OVERVIEW OF *E. COLI* IMPAIRED REACHES IN THE WATERSHED

This TMDL applies to the *E. coli* bacteria impairment for three reaches in the Snake River Watershed (Figure 1.1). Data from main-stem monitoring stations in the watersheds served as the basis of the impairment determination and were used to support development of the TMDL.

3.2 WATERSHED LAND USE/LAND COVER

Land use for the *E. coli* impaired reach watersheds was calculated using the 2010 National Agricultural Statistics Service (NASS) GIS land cover file (Table 2-1). Land use in these watersheds is primarily a mixture of hay/pasture, forest and wetland with some urban and cropland.

3.3 DATA SOURCES

3.3.1 Water Quality Data

The *E. coli* data used for the development of this TMDL are grab samples collected by the Snake River Watershed Management Board (SRWMB), Kanabec SWCD, Pine SWCD, and the MPCA in 2004 through 2006 and 2008 through 2010 (Table 3-1). Although data prior to this period exists, the more recent data better represent current conditions in the watershed. Mud Creek samples were analyzed for fecal coliform prior to 2006 and since then for *E. coli*. All Bear Creek samples were analyzed for *E. coli*. Fecal coliform data was converted to *E. coli* "equivalents" using the equation discussed in section 1.3.2. Appendices A-C show the location of the monitoring stations at which samples were collected. All data were obtained through MPCA's EQuIS online database.

Table 3-1. Snake River *E. coli* monitoring sites.

EQuIS ID	Reach ID	Location	Parameter	Number of Samples	Years
S003-533	07030004-567	Lower Mud Creek @ CSAH-5	Fecal Coliform	None	-
			E. coli	2	2009
S005-597	07030004-566	Upper Mud Creek @ 225th Ave	Fecal Coliform	None	-
			E. coli	26	2010 - 2011
S003-533	07030004-566	Upper Mud Creek @ 290th Ave	Fecal Coliform	22	2004 - 2006
			E. coli	40	2008 - 2010
S005-286	07030004-514	Bear Creek @ Crooked River Rd	Fecal Coliform	None	-
			E. coli	63	2005 - 2011
S005-293	07030004-514	Bear Creek @ CSAH 10	Fecal Coliform	None	-
			E. coli	10	2006
S005-292	07030004-514	Tributary to Bear Creek @ Cedar Creek Rd	Fecal Coliform	None	-
			E. coli	11	2006

3.3.2 Streamflow Data

The Upper and Lower Mud Creek impaired reaches have recent continuous flow data (Appendices A-C). These MPCA stations operated during the 2010 to 2011 sampling seasons from April/March through the middle of November. There is also one long-term USGS flow monitoring station located on the Snake River near Pine City (S000-198). This station began operating in 1906 and has operated year around since the early 1990s. Regression relationships between the Mud Creek impaired reach stations and the Snake River USGS station show good correlation (R^2 of 0.65-0.71) and the regression equations were used to fill data gaps and predict all winter and non-monitored flows from 2001-2011.

The Bear Creek impaired reach (S005-286) had three instantaneous flow measurements collected during the 2010 sampling season. A regression relationship (R^2 of 0.97) for Bear Creek was established with a nearby station, S002-542 (Pokegama Creek at CSAH-14), which was used to simulate a continuous flow record from 2001-2011.

3.3.3 Impairment Criteria for the Snake River

To determine *E. coli* impairment, the MPCA used data collected by the MPCA and other agencies that satisfy QA/QC requirements, meet EPA guidelines, are analyzed by an EPA-approved method and entered into the MPCA's EQuIS/STORET online database. If multiple *E. coli* samples were collected on the same assessment unit (reach), then the geometric mean of all measurements is used in the assessment analysis for that day. Then, data over the full 10-year period are aggregated by individual month (i.e. all April values for all 10 years). A minimum of five values for each month is ideal, but is not always necessary to make an impairment determination. If the geometric mean of the aggregated monthly *E. coli* concentrations for one or more months exceeds 126 organisms per 100 mL, that reach is placed on the 303(d) impaired list. Also, a water body is considered impaired if more than 10% of individual values over the 10-year period (independent of month) exceed 1,260 organisms per 100 mL (cfu/100 mL).

E. coli and *E. coli* "equivalent" data from each main-stem impaired reach monitoring station were combined into one dataset and analyzed according to the aforementioned MPCA assessment methodology to demonstrate the level of impairment in the impaired reach. Figure 3.2 shows monthly geometric means for each impaired reach during the bacteria index period (April-October). Table 3-2 lists the acute standard exceedances for each impaired reach and months in which exceedances occurred.

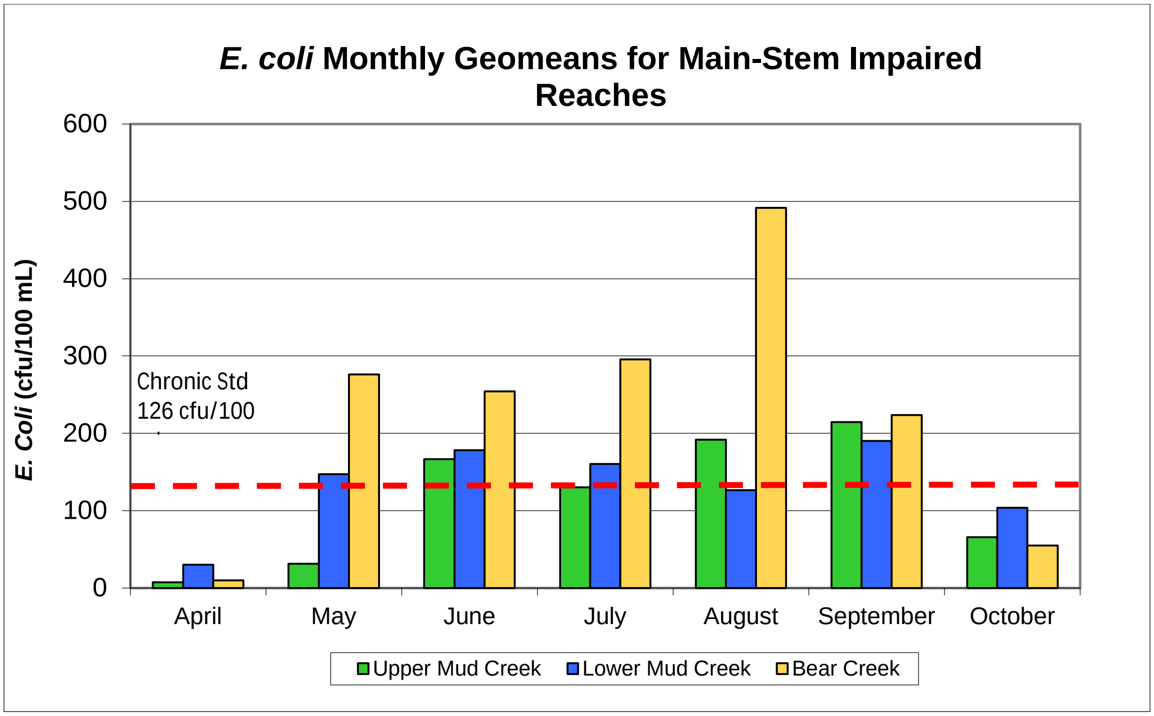


Figure 3.1. Monthly *E. coli* geometric means for each impaired reach for 2004-2006 and 2008-2011.
Note: The dotted red lines indicate the *E. coli* chronic (126 cfu/100 ml) state standards.

Table 3-2. Individual *E. coli* acute exceedances in 2004-2006 and 2008-2011 for the impaired reach monitoring stations.

Site	Total Samples	Acute Exceedances	Percent	Months with Acute Exceedances
Upper Mud Creek S003-533	62	4	6%	August (1); September (1); October (2)
Lower Mud Creek S005-597 S005-596	28	0	0%	None
Bear Creek S002-286 S002-293	71	12	17%	June (2); July (3); August (4); September (3)

3.4 ALLOCATION METHODOLOGY

3.4.1 Overview of Load Duration Curve Approach

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

A flow duration curve was developed using 10 years of continuous flow records at the furthest downstream flow station in each impaired reach. The curved line relates mean daily flow to the percent of time those values have been met or exceeded (Figure 3.3). For example, at the 50% exceedance value for Lower Mud Creek (S003-533), the river was at 10 cubic feet per second or greater 50% of the time.

The 50% exceedance is also the midpoint or median flow value. The curve is then divided into flow zones including very high (0-10%), high (10-40%), mid (40-60%), low (60-90%) and dry (90 to 100%) flow conditions. Subdividing all flow data over the past 10-years into these five categories ensures high-flow and low-flow critical conditions are accounted for in this TMDL study.

To develop a load duration curve, all average daily flow values were multiplied by the 126 cfu/100 ml standard and converted to a daily bacteria load to create a "continuous" load duration curve. Now the line represents the assimilative capacity of the stream for each daily flow. To develop the TMDL, the median load of each flow zone is used to represent the Total Daily Loading Capacity (TDLC) for that flow zone. The TDLC can also be compared to current conditions by plotting the measured load by exceedance for each water quality sampling event (Figures 3.3-3.5). Each value that is above the TDLC line represents an exceedance of the water quality standard while those below the line are below the water quality standard.

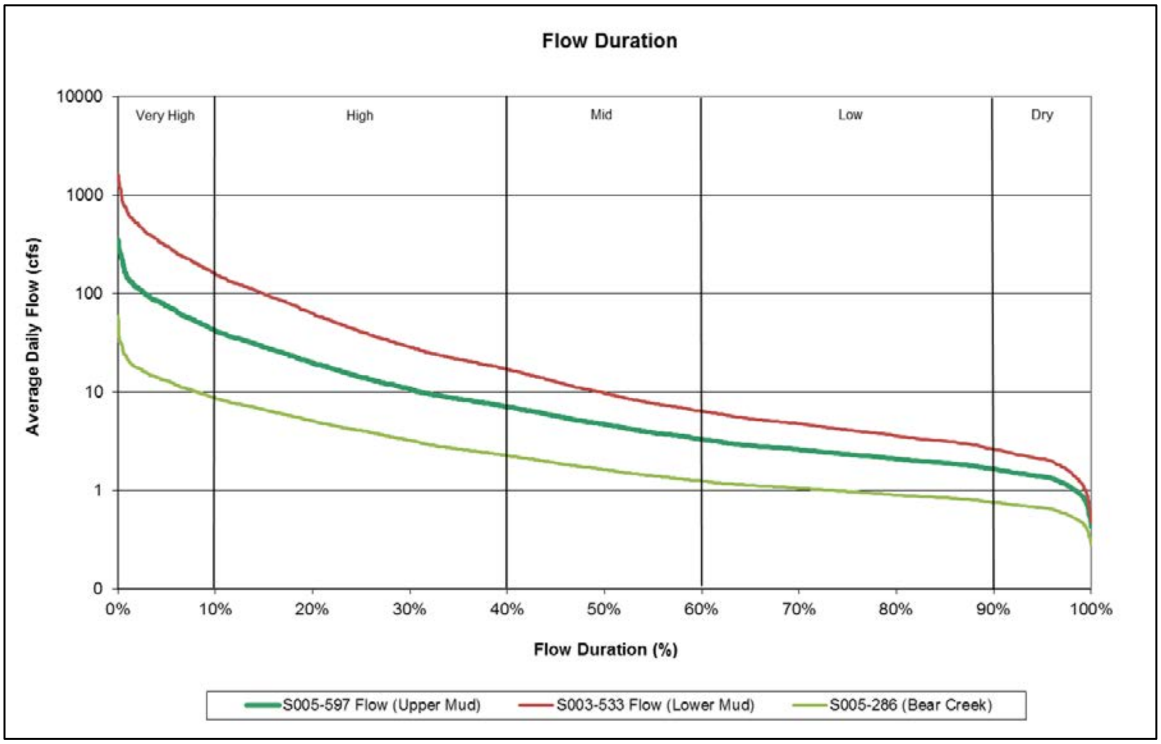


Figure 3.2. Flow duration curve for each impaired reach.

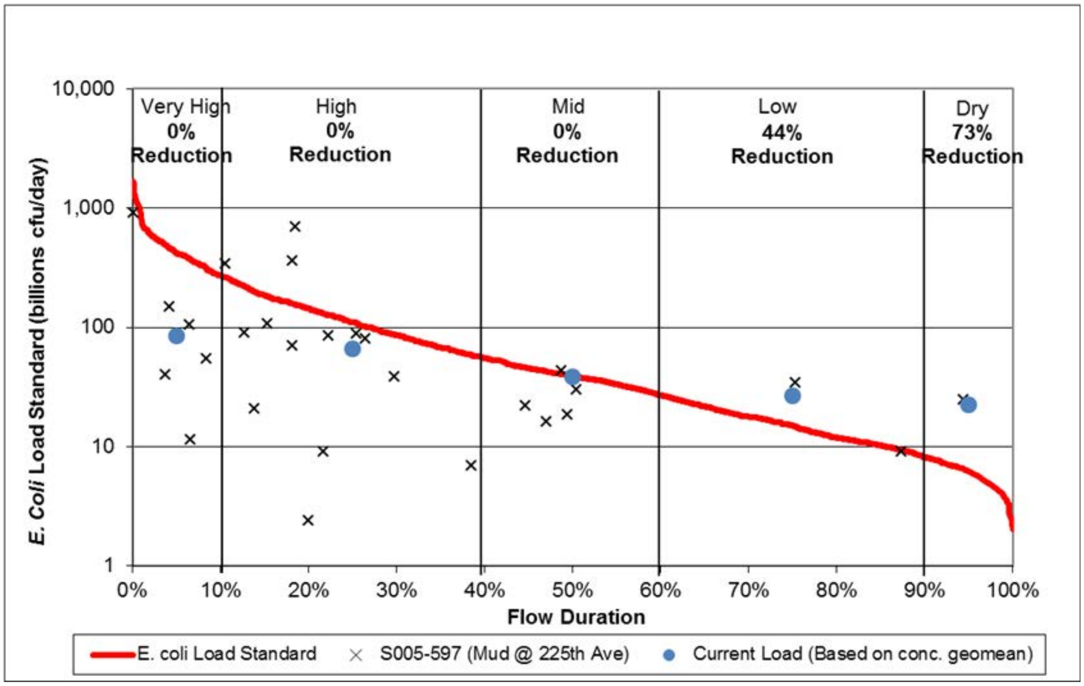


Figure 3.3. Upper Mud Creek *E. coli* load duration curve and required load reductions by flow category.

Note: The red line represents the maximum allowable daily *E. coli* load.

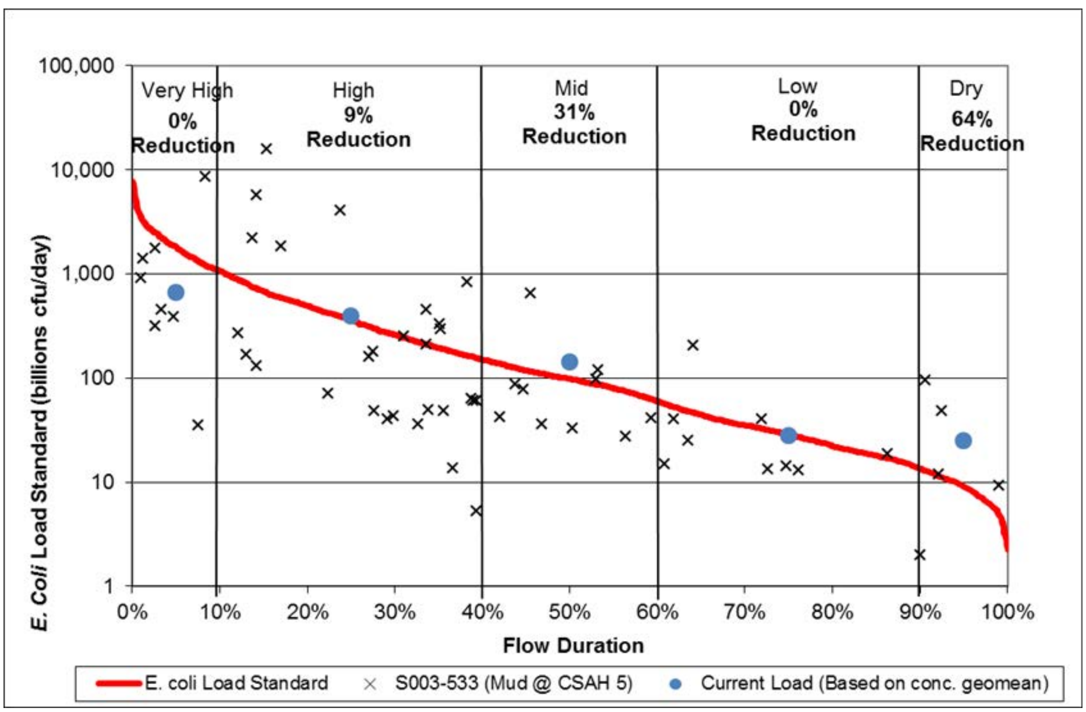


Figure 3.4. Lower Mud Creek *E. coli* load duration curve and required load reductions by flow category.

Note: The red line represents the maximum allowable daily *E. coli* load.

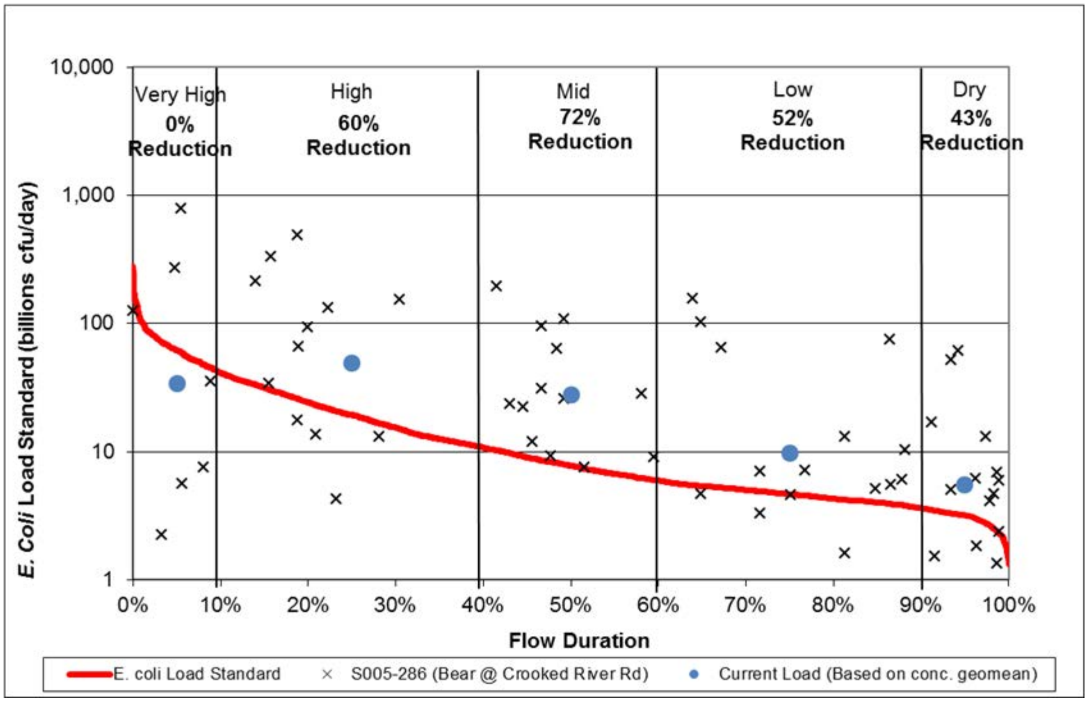


Figure 3.5. Bear Creek *E. coli* load duration curve and required load reductions by flow category.
Note: The red line represents the maximum allowable daily *E. coli* load.

3.4.2 Margin of Safety

The Margin of Safety (MOS) accounts for uncertainties in both characterizing current conditions and the relationship between the load, wasteload, monitored flows and in-stream water quality. The purpose of the MOS is to account for uncertainty so the TMDL allocations result in attainment of water quality standards. An explicit MOS equal to 5 percent of the total load was applied whereby 5 percent of the loading capacity for each flow regime was subtracted before allocations were made among wasteload and non-point sources. Five percent was considered an appropriate MOS since the load duration curve approach minimizes a great deal of uncertainty associated with the development of TMDLs since the calculation of the loading capacity is simply a function of flow multiplied by the target value. Most of the uncertainty is associated with the estimated flows in each assessed segment which were based on simulating a portion of the 10 year flow record at the most down-stream monitoring station. A similar MOS approach was applied in the Groundhouse River Bacteria TMDL (Tetra Tech 2009).

3.4.3 Wasteload Allocations

Wasteload allocations for bacteria TMDLs are typically divided into three categories: permitted wastewater dischargers, Municipal Separate Storm Sewer Systems (MS4s), and construction and industrial storm water. At the time of this study, the MPCA confirmed there were no active permitted NPDES surface wastewater dischargers or MS4s in the impaired reaches watersheds. Thus, these wasteload categories were given a zero value in each of the impaired reaches *E. coli* allocation tables (Tables 3-3 to 3-5). However, should a WWTF or regulated MS4 community be proposed; Section 6.0 describes the process or steps necessary to obtain a permit to discharge.

Industrial facilities and construction sites with storm water permits through the MPCA are not believed to discharge the pollutant of concern and were not given *E. coli* allocations for this TMDL.

3.4.4 Watershed Load Allocations

The non-point source load allocation, also referred to as the watershed load allocation, is the remaining load after the MOS and wasteload allocations are subtracted from the total load capacity of each flow zone. The watershed load includes all non-permitted sources such as outflow from lakes and wetlands in the watershed and runoff from agricultural land, forested land, and non- regulated MS4 residential areas. For this TMDL, non-point sources were allocated all of the available load capacity (minus the MOS) since there are no wasteload allocations in the impaired reach watersheds.

3.5 TOTAL MAXIMUM DAILY LOADS

Tables 3-3 through 3-5 present the total loading capacity, margin of safety, wasteload allocations and the remaining watershed load allocations for the impaired reaches. The table also presents all load allocations in terms of the percent of total loading capacity in each flow category.

Table 3-3. Upper Mud Creek *E. coli* impaired reach TMDL for each flow zone.

Mud Creek 07030004-566		Flow Zones				
		Very High	High	Mid-Range	Low	Dry
		E. coli Load (billions of organisms/day)				
Total Daily Loading Capacity		353.2	66.8	22.4	11.0	6.5
Margin of Safety (MOS)		17.7	3.3	1.1	0.6	0.3
Wasteload Allocations	Permitted Point Source Dischargers	0.0	0.0	0.0	0.0	0.0
	ITPHS Septics	0.0	0.0	0.0	0.0	0.0
Load Allocation	[1]Watershed Load	335.5	63.5	21.3	10.4	6.2
Value expressed as percentage of total daily loading capacity						
Total Daily Loading Capacity		100%	100%	100%	100%	100%
Margin of Safety (MOS)		5%	5%	5%	5%	5%
Wasteload Allocation	Permitted Point Source Dischargers	0%	0%	0%	0%	0%
	ITPHS Septics	0%	0%	0%	0%	0%
Load Allocation	[1]Watershed Load	95%	95%	95%	95%	95%

[1]Watershed load consists of all non-regulated runoff from forest land, wetlands, rural land, agricultural land and non-regulated MS4 stormwater

Table 3-4. Lower Mud Creek *E. coli* impaired reach TMDL for each flow zone.

Mud Creek 07030004-567		Flow Zones				
		Very High	High	Mid-Range	Low	Dry
		E. Coli Load (billions of organisms/day)				
Total Daily Loading Capacity		1,438.3	193.7	46.0	19.5	9.8
Margin of Safety (MOS)		71.9	9.7	2.3	1.0	0.5
Wasteload Allocations	Permitted Point Source Dischargers	0.0	0.0	0.0	0.0	0.0
	ITPHS Septics	0.0	0.0	0.0	0.0	0.0
Load Allocation	[1]Watershed Load	1,366.4	184.0	43.7	18.5	9.3
Value expressed as percentage of total daily loading capacity						
Total Daily Loading Capacity		100%	100%	100%	100%	100%
Margin of Safety (MOS)		5%	5%	5%	5%	5%
Wasteload Allocation	Permitted Point Source Dischargers	0%	0%	0%	0%	0%
	ITPHS Septics	0%	0%	0%	0%	0%
Load Allocation	[1]Watershed Load	95%	95%	95%	95%	95%

[1]Watershed load consists of all non-regulated runoff from forest land, wetlands, rural land, agricultural land and non-regulated MS4 stormwater

Table 3-5. Bear Creek *E. coli* impaired reach TMDL for each flow zone.

Bear Creek 07030004-514		Flow Zones				
		Very High	High	Mid-Range	Low	Dry
		E. Coli Load (billions of organisms/day)				
Total Daily Loading Capacity		61.5	19.3	7.7	4.6	3.1
Margin of Safety (MOS)		3.1	1.0	0.4	0.2	0.2
Wasteload Allocations	Permitted Point Source Dischargers	0.0	0.0	0.0	0.0	0.0
	ITPHS Septics	0.0	0.0	0.0	0.0	0.0
Load Allocation	[1]Watershed Load	58.4	18.3	7.3	4.4	2.9
Value expressed as percentage of total daily loading capacity						
Total Daily Loading Capacity		100%	100%	100%	100%	100%
Margin of Safety (MOS)		5%	5%	5%	5%	5%
Wasteload Allocation	Permitted Point Source Dischargers	0%	0%	0%	0%	0%
	ITPHS Septics	0%	0%	0%	0%	0%
Load Allocation	[1]Watershed Load	95%	95%	95%	95%	95%

[1]Watershed load consists of all non-regulated runoff from forest land, wetlands, rural land, agricultural land and non-regulated MS4 stormwater

3.6 POLLUTANT SOURCE ASSESSMENT

The pollutant source assessment is intended to present information that is helpful in identifying the potential sources of elevated bacteria concentrations in the impaired reach watersheds. The first section of the source assessment is a discussion of background levels of bacteria in streams. The next section addresses seasonal influences and looks at the relationships between elevated bacteria concentrations and flow. The final section contains estimates of the potential sources of bacteria available for transport by source category for the *E. coli* impaired reach watersheds.

3.6.1 *E. coli* Background Conditions

It has been suggested that *E. coli* bacteria has the capability to reproduce naturally in water and sediment and therefore should be taken into account when identifying bacteria sources. Two Minnesota studies describe the presence and growth of “naturalized” or “indigenous” strains of *E. coli* in watershed soils (Ishii et al. 2006), and ditch sediment and water (Sadowsky et al. 2010). The latter study, supported with Clean Water Land and Legacy funding, was conducted in the Seven Mile Creek watershed, an agricultural landscape in southwest Minnesota. DNA fingerprinting of *E. coli* from sediment and water samples collected in Seven Mile Creek from 2008-2010 resulted in the identification of 1568 isolates comprised of 452 different *E. coli* strains. Of these strains, 63.5% were represented by a single isolate, suggesting new or transient sources of *E. coli*. The remaining 36.5% of strains were represented by multiple isolates, suggesting persistence of specific *E. coli*. Discussions with the primary author of the Seven Mile Creek study suggest that while 36% might be used as a rough indicator of “background” levels of bacteria at this site during the study period, this percentage is not directly transferable to the concentration and count data of *E. coli* used in water quality standards and TMDLs. Additionally, because the study is not definitive as to the ultimate origins of this bacteria, it would not be appropriate to consider it as “natural” background. Finally, the author cautioned about extrapolating results from the Seven Mile Creek watershed to other watersheds without further studies.

The outlet of Quamba Lake represents the upstream boundary of the Lower Mud Creek *E. coli* impaired reach. Even if bacteria inputs to Quamba Lake are high, the lake’s volume should provide significant dilution. Thus, it is assumed a majority of the bacteria observed in the Lower Mud Creek impaired reach is produced within the Lower Mud Creek watershed.

3.6.2 Exceedances by Season and Flow Regime

Individual *E. coli* measurements show exceedances during summer and fall and occasionally in the spring (Tables 3-6 to 3-8). April was the month with the lowest bacteria concentrations even though there is little crop canopy cover and there is often significant manure application during this time. This suggests seasonality of bacteria concentrations may be influenced by stream water temperature. More samples should be gathered in April to confirm this. Fecal bacteria are most productive at temperatures similar to their origination environment in animal digestive tracts. Thus, these organisms are expected to be at their highest concentrations during the warmer summer months when stream temperature are highest. High *E. coli* concentrations continue into the late summer and fall which may be attributed to cattle access to stream/tributaries and/or reapplication of manure.

Table 3-6. Chronic *E. coli* exceedances in the Upper Mud Creek impaired reach by season and flow regime.

Season	Very High/High Flow	Mid Flow	Low/Dry Flow
Spring	0%	NA[1]	NA[1]
Summer	71%	67% (3 samples)	100% (1 sample)
Fall	100%	0% (2 samples)	100% (2 samples)

[1] No samples collected during season and flow regime.
Note: Number of samples only listed if less than 4 samples were taken during season/flow regime.

Table 3-7. Chronic *E. coli* exceedances in the Lower Mud Creek impaired reach by season and flow regime.

Season	Very High/High Flow	Mid Flow	Low/Dry Flow
Spring	20%	0% (1 sample)	NA[1]
Summer	58%	60%	50%
Fall	23%	75%	100% (2 samples)

[1] No samples taken during season and flow regime.
Note: Number of samples only listed if less than 4 samples were taken during season/flow regime.

Table 3-8. Chronic *E. coli* exceedances in the Bear Creek impaired reach by season and flow regime.

Season	Very High/High Flow	Mid Flow	Low/Dry Flow
Spring	20%	NA[1]	NA[1]
Summer	100%	100%	78%
Fall	0%	100% (2 samples)	64%

[1] No samples taken during season and flow regime.
Note: Number of samples only listed if less than 4 samples were taken during season/flow regime.

The relationship between flow and bacteria concentrations aids in identifying potential sources of elevated bacteria concentrations. Table 3-9 shows the conceptual relationship between flow and loading sources under various flow conditions. Under low flows, runoff processes are minimal as bacteria concentrations are primarily driven by wastewater treatment plants (if present), failing subsurface sewage treatment systems (SSTS) and animals in or near the receiving water. Conversely, at high flows, runoff from land with bacteria concentrations such as feedlots and pastures, urban areas and cropland often dominate. Exceedances appear to occur across all flow regimes in the bacteria-listed reaches. This suggests that, at times, all of the aforementioned flow-driven sources may contribute to high bacteria concentrations observed throughout each reach.

Table 3-9. Conceptual relationship between flow regime and potential pollutant sources.

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

Point Source Contributing Source Area	Flow Regime				
	Very High	High	Mid	Low	Dry
Bank Erosion	H	H	M		

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

3.6.3 Potential Bacteria Source Inventory

The purpose of the bacteria source assessment is to develop a comparison of the number of bacteria generated by the major known sources in the project area as an aid in focusing source identification activities. Only subwatersheds that drain directly to the *E. coli* impaired reaches were included in the source inventory. The source assessment is not directly linked to the total maximum loading capacities and allocations, which are a function of the water quality standards and stream flow (i.e., dilution capacity). Further, the inventory itself uses fecal coliform concentrations as the metric, not *E coli*. This is because the inventory assessment is intended to evaluate the relative magnitude of bacteria loads being generated within the major source categories. The relative source comparisons are expected to be the same, regardless of whether fecal coliform or *E coli* units are used.

3.6.3.1 Livestock Sources

Animal units are the standardized measurement of livestock for various agricultural purposes. A livestock animal that consumes, on average, 26 pounds of dry matter forage per day is the standard metric for one animal unit. This number is based on the feeding requirements for a 1,000 pound beef cow. Owners of an animal feedlot or manure storage area with 50 or more animal units (10 animal units in shore land areas) are required to register with the MPCA. Owners with fewer than 300 animal units are not required to have a permit for the construction of a new facility or expansion of an existing facility as long as construction is in accordance with the technical standards. For owners with 300 animal units or more, and less than 1,000 animal units, a streamlined construction short form permit is required for construction/expansion activities. Feedlots greater than 1,000 animal units or a significant amount of confined animals are considered large concentrated animal feedlot operations (CAFOs) and are required to apply for a National Pollutant Discharge Elimination System (NPDES) or State Disposal System (SDS) permit. These operations, by law, are not allowed to discharge to waters of the state (MR 7020.2003).

Table 3-10 lists the number of feedlots present in the impaired reach watersheds according to the 2012 MPCA database and county surveys. Maps showing the approximate location (as points) and size (total animal units) of each feedlot are shown in Appendices A-C.

Table 3-10. Inventory of Agricultural Animals in the Impaired Reaches Watersheds.

Impaired Reach	# of Feedlots	# of CAFOs Permit #	Total Animal Units	Total Dairy Units	Total Beef Units	Total Swine Units	Total Poultry Units	Total Other Units
Upper Mud Creek 07030004-566	49	0	1,789	0	1,658	13	1	117
Lower Mud Creek 07030004-567	61	0	1,146	72	712	172	0	257
Bear Creek 07030004-514	23	0	1,198	54	1,042	59	0	43

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

3.6.3.1.1 Manure Application

A significant proportion of the cropland throughout Minnesota and the upper Midwest receives some sort of manure application during different times of the year. Most beef manure is applied as a solid while dairy manure is applied as both liquid and solid manure. In most cases, the larger dairy operations have liquid manure pits, while the smaller dairies haul manure as a solid. Most liquid manure is injected into the soil or incorporated within 24 hours. Solid manure is spread on the soil surface where it is not immediately incorporated into the ground. A large portion of manure applications occur in the fall when animal waste pits are emptied out. However, some farmers (especially small dairy farmers) will spread this manure year round. In general, manure that is not incorporated has a higher potential for runoff. Land application of manure within 300 feet of intermittent and perennial streams and all Minnesota DNR protected lakes and wetlands are required to meet MPCA setback requirements (MPCA, 2005).

Beef and dairy cattle and horses, all three of which are considered grazers, are the only agricultural animals in the impaired reach watersheds. For the purposes of this TMDL, it is assumed these animals spend about eight months of the year grazing in pastureland throughout the impaired reaches watersheds. For the other four months, the animals are housed in barns or other confined spaces where their manure is stockpiled. Thus, approximately 33% of the animal manure produced in the watershed is available for spreading on cropland. However, since less than 20% of the total land in each of the watersheds is currently used to grow crops, it is assumed only half (16%) of the stockpiled manure is spread on cropland while the other half is spread on pastureland. It is also assumed that all of the manure spreading in the watershed is surface applied.

3.6.3.1.2 Feedlots and Pastures near Streams

GIS processing suggests that approximately 16% of the pastureland in the Upper and Lower Mud Creek impaired reach watersheds and 20% in the Bear Creek watershed is located within 500 feet of the main-stem or a major tributary. As a result, this TMDL will assume that 16% and 20% of the fecal coliform produced by the agricultural animals in the Mud Creek and Bear Creek watersheds during the eight month grazing period is deposited within 500 feet of streams while the rest is deposited on upstream pastureland. As discussed in the previous section, this TMDL also assumes approximately 50% of the manure stockpile is spread on pastureland when stockpiles are emptied. Pastures, feedlots and open lot cattle and dairy facilities near streams or waterways have a higher likelihood of animal access to the stream and therefore higher likelihood of delivering bacteria to the receiving water.

3.6.3.2 Septic Systems

Failing sub-surface sewage treatment systems (SSTS) can be an important source of bacteria to surface waters. Currently, the exact number and status of SSTSs in the Snake River watershed is unknown. MPCA's 2012 SSTS Annual Report includes some general information regarding the performance of SSTSs in the Snake River watershed (MPCA, 2013). This study provides county annual reports from 2012 that include estimated failure rates for each county in the state of Minnesota. The report differentiates between systems that are generally failing and those that are an imminent threat to public health and safety (ITPHS). Generally failing systems are those that do not provide adequate treatment and may contaminate groundwater. For example a generally failing system may have a functioning, intact tank and soil absorption system, but fails to protect ground water by providing a less than sufficient amount of unsaturated soil between where the sewage is discharged and the ground water or bedrock. Systems considered ITPHS are severely failing or were never designed to provide adequate raw sewage treatment. Examples include SSTSs that discharge directly to surface water bodies such as ditches, streams or lakes.

Total number of generally failing and ITPHS systems in each of the three impaired reach watersheds was estimated in GIS using 2010 Census population data. Rural population that falls outside the boundaries of municipalities with wastewater treatment facilities (WWTFs) was calculated and divided by 3 people per household to estimate the total number of SSTSs in each watershed. Next, failing and ITPHS systems were estimated by multiplying the total number of SSTSs by the county failure rates from the 2013 MPCA report (Table 3-11). Finally, annual bacteria load from failing SSTSs was calculated using the University of Minnesota Water Resource Center's 2012 version of the Septic System Improvement Estimator (SSIE). The SSIE is a spreadsheet-based model that uses published literature rates to calculate annual pollutant loads from problematic septic system. This model was setup to assume that even though generally failing systems often discharge bacteria and other pollutants to groundwater, it is unlikely that any of the bacteria from these systems makes it to surface waters. ITPHS systems, on the other hand, often discharge directly to surface waters and have extremely high delivery potentials. Thus it was assumed that none of the bacteria in ITPHS systems is removed and 100% is transported to surface waters in the impaired reach watersheds. A complete SSTS bacteria load summary for each impaired reach watershed is provided in Appendices A-C.

Table 3-11. SSTS failure rates by County (MPCA, 2013).

County	Generally Failing SSTSs	ITPHS SSTSs
Aitkin	6%	1%
Isanti	16%	1%
Kanabec	15%	0%
Mille Lacs	30%	7%
Pine	38%	26%
Chisago	18%	0%

3.6.3.3 Wildlife

Wildlife in the impaired reach watersheds encompasses a broad group of animals. For this assessment, deer and waterfowl were assumed to be the main contributors while all other wildlife was grouped into one separate category. The Minnesota DNR estimated there are approximately 10-12 deer per square mile in the watersheds and surrounding areas (Doug Welinski, MN DNR Cambridge Office Wildlife technician, personal communication). This report assumes an average deer density of 11 deer per square mile for the entire watershed. There are currently no waterfowl surveys or data available for watersheds or the surrounding area. A 2011 Waterfowl Breeding Population Survey by the MN DNR and U.S. Fish & Wildlife Service estimated that there are approximately 10 waterfowl (includes both geese and ducks) per square mile throughout the state (Minnesota DNR 2011).

3.6.3.4 Urban Storm Water Runoff

Untreated urban storm water has demonstrated bacteria concentrations high as or higher than grazed pasture runoff, cropland runoff, and feedlot runoff (USEPA 2001, Bannerman et al. 1993, 1996). There is very little urban area in impaired reach watersheds. This TMDL source assessment assumes urban bacteria contributions come from improperly managed waste from dogs and cats. Deer and waterfowl densities in urban areas were assumed to be the same as those discussed in the previous section. Consistent with the methodology outlined in the Southeast Minnesota Regional Bacteria TMDL (MPCA 2002), it was assumed that there were 0.58 dogs/household and 0.73 cats/household in the urban areas.

3.6.4 Snake River Watershed Bacteria Available for Transport

Each bacteria source was assigned a percentage to predict the likelihood of that animal's bacteria reaching the impaired reaches and their tributaries. A summary of these percentages is presented in Appendices A-C. It is important to note that this process assumes that all bacteria produced in the watershed remain in the watershed. The assumptions are approximations that were first developed as part of the Southeast Regional TMDL (MPCA, 2002), then altered to reflect GIS calculations and current conditions within the watershed.

Next, potential fecal coliform runoff loads were estimated for the impaired reaches watersheds (Figures 3.6 to 3.8 and Appendices A-C). Daily fecal coliform production estimates for each agricultural animal unit, cat/dog and wildlife animal were derived from the Southeast Regional TMDL (MPCA 2002).

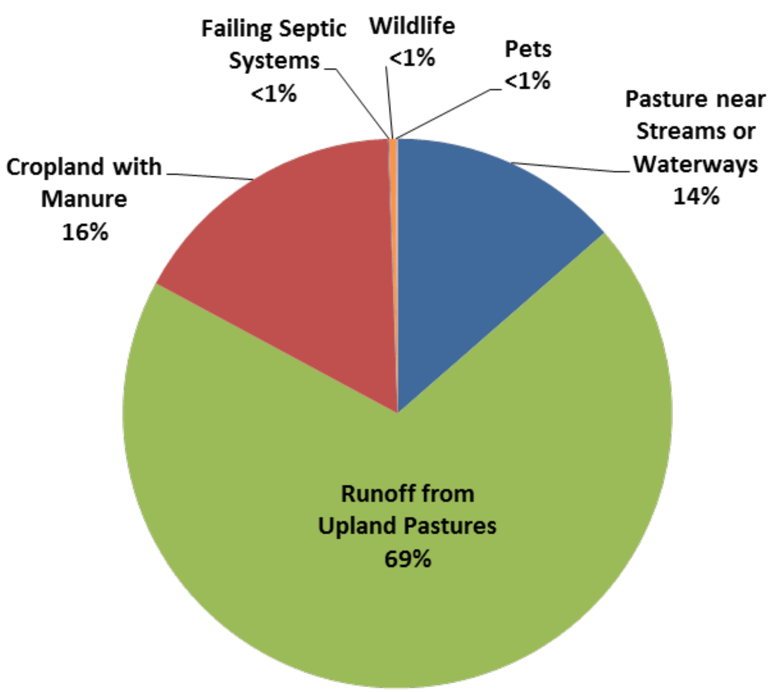


Figure 3.6. Fecal coliform available (by source) for delivery in the Upper Mud Creek impaired reach watershed.

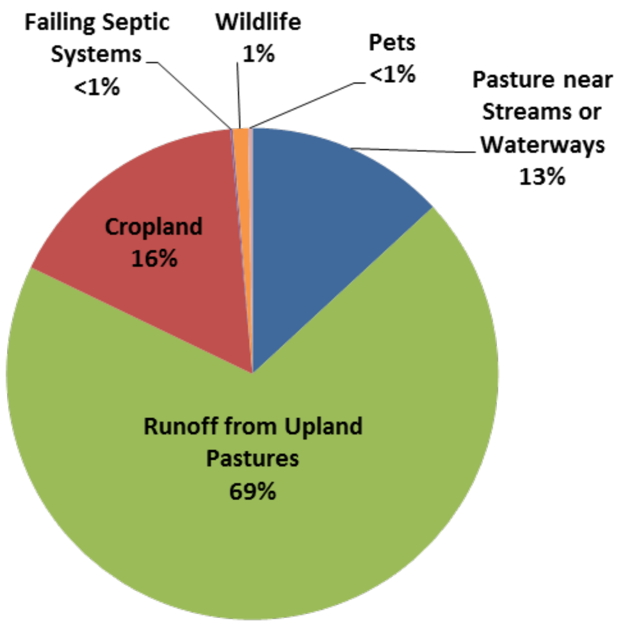


Figure 3.7. Fecal coliform available (by source) for delivery in the Lower Mud Creek impaired reach watershed.

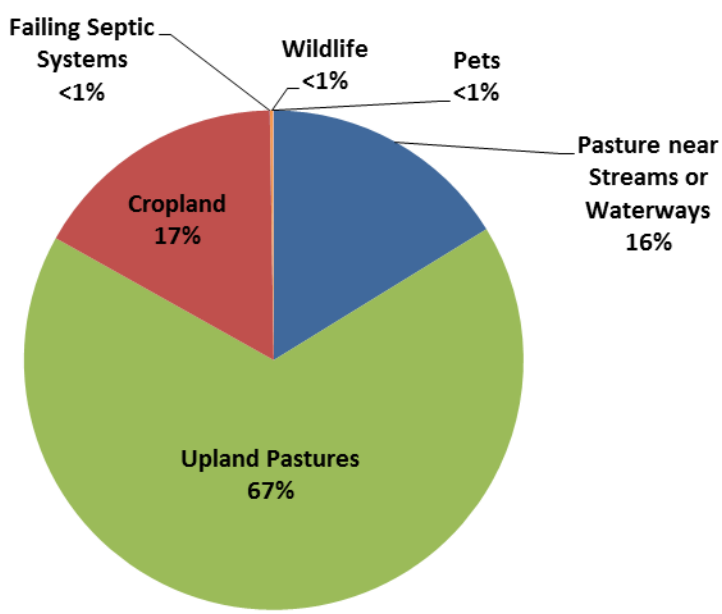


Figure 3.8. Fecal coliform available (by source) for delivery in the Bear Creek impaired reach watershed.

3.6.5 Pollutant Source Assessment Summary

- Livestock are by far the biggest producer of bacteria in the impaired reach watersheds.
- The largest potential sources are those activities associated with pasture management. Implementation activities should focus on limiting cattle access to the impaired reaches and their tributaries, and buffering runoff from pastures near streams and waterways. Secondarily, BMPs for upland pasture land should also be implemented.
- Cropland manure application does not appear to be a top source of bacteria to the impaired reaches since cropland represents only 2-16 percent of the land use throughout the watershed. That said, cropland with high runoff potential, heavy drain tiling and fields located near streams/waterways should be targeted for BMPs.
- Collectively, failing SSTSs appear to be a relatively small source compared to livestock. However, all three reaches, especially Bear Creek, displayed significant *E. coli* violations during dry and low-flow conditions. Thus, depending on their location and level of failure, these systems have the potential to be significant bacteria contributors during these flow conditions.

4.0 Lake Nutrient Impairments

4.1 WATERSHED AND LAKE CHARACTERIZATION

Knife Lake (DNR # 33-0028), Quamba Lake (DNR # 33-0015), Pokegama Lake (DNR # 58-0142) and Cross Lake (DNR # 58-0119) are located in east-central Minnesota in the Snake River watershed (Figure 4.1). Knife and Quamba Lakes are impoundments that discharge to tributaries of the Snake River. Pokegama Lake discharges directly to the Snake River west of Pine City, MN. Cross Lake is located downstream of Knife, Quamba and Pokegama Lakes near the outlet of the Snake River watershed. The south basin of Cross Lake acts as a flow-through basin for the Snake River near Pine City before the river eventually discharges to the St. Croix River.

Knife Lake is a 1,259 acre impoundment on the Knife River in Kanabec County approximately 7 miles north of Mora, MN. Outflow from Knife Lake eventually flows to the Snake River via the Knife River. Knife Lake is a shallow (maximum depth of 15 feet) lake with a short residence time (77 days) meaning the lake flushes about once every two and a half months (Table 4-1). Knife Lake has a relatively large drainage area (58,518 acres). The Knife River enters the lake on the southwest end of the lake drains approximately 53,000 acres and accounts for a majority of the lake's total watershed. The remainder of the Knife Lake watershed is made up of direct drainage to the lake.

Quamba Lake is a shallow (maximum depth of 11 feet) 226 acre impoundment of Mud Creek about 6 miles northeast of Mora, MN (Table 4-1). Mud Creek enters the lake from the north and outflows through a dam on the east end of the lake. The Mud Creek watershed above Quamba is about 20,354 acres and accounts for a majority of the lake's inflow. Direct drainage to Quamba accounts for about 17% (3,771 acres) of the lake's total watershed. Quamba Lake has very short residence time (22 days). Because it is shallow, Quamba Lake should be expected to have 100% coverage of submerged aquatic vegetation.

Pokegama Lake is a 1,515 acre lake located about three miles east of Pine City, MN. Pokegama Lake is a shallow basin with a maximum depth of 25 feet; however 60% of the lake is 15 feet or less in depth. The lake is connected to the Snake River via a constructed outlet and is subject to extreme water level fluctuations. A large portion of Pokegama Lake's inflow comes from Pokegama Creek which drains approximately 42,811 acres and enters the lake through a wide channel on the north end of the lake. Direct drainage to Pokegama Lake accounts for approximately 15% (7,819 acres) of the lake's total watershed and is made up of several small tributaries that drain directly to the lake.

Table 4-1. Lake morphometry and watershed characteristics.

Parameter	Knife Lake	Quamba Lake	Pokegama Lake
Surface Area (acres)	1,259	226	1,515
Average Depth (ft)	8.5	5.6	11.8
Maximum Depth (ft)	15	11	25
Volume (ac-ft)	10,740	1,264	17,868
Residence Time (years)	0.21	0.06	0.35
Littoral Area (acres)	1,259	226	903
Littoral Area (%)	100%	100%	60%
Watershed (acres)	58,518	24,125	50,630

Cross Lake is a 925 acre lake located on the northeast edge of Pine City, MN. Cross Lake has a long narrow shape, generally running north-south. Cross Lake has three primary basins that display very different physical and limnological characteristics (Table 4-2). Direct drainage to Cross Lake is approximately 7,102 acres and includes Cross Creek, which enters the lake on the north side of the north basin, and several smaller tributaries and intermittent streams. The Snake River, which enters and exits the lake through the south basin, drains approximately 611,704 acres including five upstream nutrient impaired lakes: Knife Lake, Ann Lake, Fish Lake, Quamba Lake and Pokegama Lake. The south basin has a maximum depth of 30 feet and an average depth of 10 feet.

Minnesota Rules Chapter 7050.0150(4)states that in order to be considered a lake/reservoir, a water body must have a hydraulic residence time of at least 14 days which is to be determined using a flow equal to the 122-day ten-year low flow (122Q10) measured June 1st through September 30th. The south basin of Cross Lake has a calculated residence time of 9.4 days during 122Q10 flow conditions. Thus, for the purpose of this study, the south basin of Cross Lake is considered a wide spot in the river and not a lake/reservoir. The north and central basins, on the other hand have significantly longer residence times (0.8-1.45 years) and function as typical lake systems. The general flow pattern for Cross Lake is from the north basin to the central basin and eventually to the lake's outlet between the central and south basins. Residence times for the north and central basins indicate flow from the north basin to the outlet is slow and takes at least 1-2 years.

Table 4-2. Cross Lake morphometry and watershed characteristics.

Parameter	Cross – All Basins	South Basin	Central Basin	North Basin
Surface Area (acres)	924	311	269	344
Average Depth (ft)	13.8	10.4	15.5	15.7
Maximum Depth (ft)	30	30	22	27
Volume (ac-ft)	12,807	3,238	4,171	5,398
Residence Time (years)	0.02	<0.01	0.80	1.45
Littoral Area (acres)	472	57	198	217
Littoral Area (%)	51%	18%	73%	63%
Watershed (acres)	618,806	613,563	1,470	3,773

4.2 LAKE WATER QUALITY

4.2.1 Introduction

Water quality in Minnesota lakes is often evaluated using three associated parameters: total phosphorus, chlorophyll-a, and Secchi depth. Total phosphorus is typically the limiting nutrient in Minnesota's lakes meaning algal growth will increase with increases in phosphorus. However, there are cases where phosphorus is widely abundant and the lake becomes limited by nitrogen or light availability. Chlorophyll-a is the primary pigment in aquatic algae and has been shown to have a direct correlation with algal biomass. Since chlorophyll-a is a simple measurement and is often used to evaluate algal abundance rather than expensive cell counts. Secchi depth is a physical measurement of water clarity, measured by lowering a black and white disk until it can no longer be seen from the surface. Higher Secchi depths indicate less light refracting particulates in the water column and better water quality. Conversely, high total phosphorus and chlorophyll-a concentrations point to poorer water quality and thus lower water clarity. Measurements of these three parameters are interrelated and can be combined into an index that describes water quality.

Lake water quality samples have been collected at various locations on Knife, Quamba, Pokegama and Cross Lake (Appendices D-G). Lake sampling conducted in 2010 and 2011 was specifically intended to support this TMDL study. The data collected these years represent the most complete and robust dataset for all four lakes since 2000. In general, lake monitoring was conducted bi-weekly from May through September for Secchi depth, total phosphorus (TP) and chlorophyll-a, and temperature and dissolved oxygen measurements. Collection efforts were coordinated and carried out by lake association groups, the Kanabec SWCD, Pine SWCD, and the Minnesota Pollution Control Agency (MPCA).

4.2.2 Temperature and Dissolved Oxygen

Dissolved oxygen (DO) profiles for all four lakes were collected at least once per month 2010 and 2011. These profiles show slight stratification and temperature gradients between the surface and bottom waters during the mid-summer months (Appendices D-G). The DO profiles demonstrate anoxia (DO ≤ 2 mg/L) occasionally occurs in the bottom 1-2 meters of the water column during the warm summer months (July to early September) which suggests the potential for internal loading of phosphorus. It should be noted that Knife and Quamba Lakes are shallow systems with relatively high surface area to depth ratios causing the lakes to be more susceptible to wind-driven mixing events. Pokegama and Cross Lakes are considered deep lakes; however their fetch is long causing their thermoclines to develop relatively deep which minimizes the depth at which anoxic conditions develop. Thus, none of the lakes sustain strong thermoclines and large anoxic areas for the entire summer period.

4.2.3 Total Phosphorus

Summer average total phosphorus (TP) concentrations for Knife Lake and Quamba Lake consistently exceeded the 60 µg/L standard for shallow lakes in the North Central Hardwood Forest (NCHF) Ecoregion (Appendices D-G). Similarly, summer average TP concentrations for Pokegama and Cross Lake exceeded the 40 µg/L NCHF deep lake standard in every year monitored since 2001. Total phosphorus was monitored at multiple locations/basins in Knife, Pokegama and Cross Lake in 2010 and 2011. For Knife and Pokegama Lakes, average TP was nearly identical between the two monitored basins, suggesting little spatial variability in TP. For Cross Lake, TP in the north and central basins showed little variability, while the south basin was noticeably higher. The higher concentrations in the south basin reflect TP loading from the Snake River which enters and exits Cross Lake through the south basin.

4.2.4 Chlorophyll-*a*

Since 2001, average chlorophyll-a concentrations in Knife, Quamba and Pokegama have consistently exceeded state standards. Average summer chlorophyll-a concentrations for Knife Lake's central basin have ranged from 11-27 µg, and has exceeded the deep lake standard in 4 of the 5 years sampled since 2001 (Appendices D-G). Chlorophyll-a concentrations that exceed state water quality standards indicate a high incidence of nuisance algae blooms. Chlorophyll-a concentrations were similar between the two

Knife Lake and Pokegama Lake basins sampled in 2010 and 2011. For Cross Lake, chlorophyll-a was consistently higher in the north and central basins compared to the south basin, likely due to the south basin's river influence and short residence time.

4.2.5 Secchi Depth

Water clarity (Secchi depth) in general follows the same trend as TP and chlorophyll-a. Since 2001, mean summer Secchi depth in all four lakes has not met state water quality standards (Appendices D-G). The Secchi data for Knife and Pokegama Lake show little variability between basins. Cross Lake Secchi data also indicates little spatial variability between the north, central and south basins. Non-algal turbidity and TSS from the Snake River are likely driving the poor transparency in south basin since chlorophyll-a concentrations are consistently low in this basin.

4.2.6 Lake Water Quality Conclusions

Overall, Knife, Quamba, Pokegama and Cross Lake do not meet current Minnesota lake water quality standards for shallow and deep lakes in the NCHF ecoregion. While there is some variability in the monitoring data from year to year, trends over the past 10 years show that water quality in these lakes is relatively stable in its current state. There has not appeared to be a significant decline or improvement in the water quality of these lakes over this time period. However, it is important to note that these observations are based on a few years of data and a rigorous trend analysis has not been conducted on the data set.

4.3 LAKE ECOLOGY

4.3.1 Fish Populations and Fish Health

Fish survey reports for Knife, Quamba, Pokegama and Cross Lake were provided by the DNR Area Fisheries Office in Hinckley, Minnesota. The first DNR fish surveys for these lakes were conducted in 1979 (Knife) and 1981 (Quamba, Pokegama and Cross). Standard survey methods used by the DNR include gill net and trap nets. These sampling methods do have some sampling bias, including focusing on game management species (i.e., northern pike and walleye), under representing small minnow and darter species presence/abundance, and under representing certain management species such as largemouth bass. The current methods also likely under represent carp populations in the lakes. However, in our experience, when carp are present in the lakes, the sampling methods do capture some of the population. So, although carp density is likely under represented, the methods do provide a reasonable year to year comparison.

There have been 34 species collected during the Knife, Quamba, Pokegama and Cross Lake DNR surveys:

- black bullhead
- black crappie
- bluegill
- bowfin
- brown bullhead
- channel catfish
- chestnut lamprey
- common carp
- common shiner
- creek chub
- largemouth bass
- muskellunge
- northern pike
- pumpkinseed
- quillback
- river redhorse
- rock bass
- shorthead redhorse
- shovelnose sturgeon
- silver redhorse

- freshwater drum
- golden redhorse
- golden shiner
- greater redhorse
- hog sucker
- hybrid sunfish (Ann Lake only)
- lake sturgeon
- smallmouth bass
- walleye
- white bass
- white crappie
- white sucker
- yellow bullhead
- yellow perch

Fish community data for each lake was summarized by trophic groups. Appendices D-G provide a complete trophic summary for each survey year both in terms total fish caught and biomass. Species within a trophic group serve the same ecological process in the lake (i.e., panfish species feed on zooplankton and invertebrates; may serve as prey for predators). Analyzing all the species as a group is often a more accurate summary of the fish community then analyzing individual species trends.

Rough fish, particularly common carp, have both direct and indirect effects on aquatic environments. Carp uproot aquatic macrophytes during feeding and spawning and re-suspend bottom sediments and nutrients. These activities can lead to increased nutrients in the water column ultimately resulting in increased nuisance algal blooms. Carp and other rough fish have been sampled in all four lakes, however rough fish size and numbers have declined significantly since the early surveys in the 1980s. Rough fish management in Knife Lake has been particularly effective since common carp entered the lake in 1972 when flooding caused the lake's outlet structure to wash out. Knife Lake was treated with rotenone in 1989 and no carp have been noted in the DNR surveys since 1988. At least one common carp was captured in the recent DNR surveys for Quamba, Pokegama and Cross Lakes. However, common carp and other rough fish currently account for only a small portion each lake's total fish population and total biomass.

4.3.2 Aquatic Plants

The littoral zone is defined as that portion of the lake that is less than 15 feet in depth and is where the majority of the aquatic plants are found. The littoral zone of the lake also provides the essential spawning habitat for most warm water fishes (e.g. bass, walleye, and panfish). Knife Lake and Quamba Lake are both shallow lakes with maximum depths less than 15 feet meaning both lakes should support a healthy rooted aquatic plant community. Though they are considered deep lakes, Pokegama Lake and Cross Lake have large littoral areas which should also support a healthy rooted aquatic plant community. The key for these lakes is fostering a diverse population of rooted aquatic plants that is dominated by native (non-invasive) species.

Aquatic plants are beneficial to lake ecosystems, providing spawning and cover for fish, habitat for macroinvertebrates, refuge for prey, and stabilization of sediments. However, in high abundance and density they limit recreation activities, such as boating and swimming, and may reduce aesthetic value. Excess nutrients in lakes can lead to non-native, invasive aquatic plants taking over a lake. Some exotics can lead to special problems in lakes. For example, under the right conditions, Eurasian water milfoil can reduce plant biodiversity in a lake because it grows in great densities and out-competes all the other plants. Ultimately, this can lead to a shift in the fish community because these high densities favor panfish over larger game fish.

Another non-native plant species, curly-leaf pondweed, can cause very specific problems by changing the dynamics of internal phosphorus loading. Curly-leaf pondweed is a perennial submersed aquatic plant that was first noted in Minnesota around 1910 (Moyle and Hotchkiss, 1945). Curly-leaf pondweed sprouts in the fall from vegetative structures called turions, and can grow slowly throughout the winter, even under thick ice and snow cover. Thus by the time other species start growing in the spring, curly-leaf plants are large enough to block light penetration to the bottom. By late spring, curly-leaf pondweed can form dense surface mats which interfere with recreation activities. By mid-summer these dense mats senesce and die back, releasing nutrients that can contribute to undesirable algae blooms. Before curly-leaf pondweed plants die back, they form hardened stem tips called turions, which serve the function of vegetative reproduction. These turions sprout in the fall and begin the plant's cycle again.

The DNR has conducted qualitative plant surveys during most of the fish surveys since the late 1970's and early 1980's. These surveys indicate all four lakes support moderately diverse aquatic plant communities that include a mixture of emergent, floating leaf and submerged plant species. These surveys also revealed all four lakes contain undesirable species such curly-leaf pondweed. Recently, the DNR has begun conducting more quantitative plant surveys for Knife, Quamba, Pokegama and Cross Lakes in May and June to assess the early season plant community and map curly-leaf pondweed problem areas (Table 4-3). These surveys indicate curly-leaf pondweed currently has a stronghold in all four lakes and is the most common species during the early summer months. Chemical and mechanical treatments to control curly-leaf pondweed in Knife Lake and Pokegama Lake have taken place since the 1990s; however the DNR has begun issuing more individual and multi-party permits in recent years. More point-intercept plant survey data should be collected on these lakes to continue to monitor curly-leaf pondweed abundance and analyze the effectiveness of chemical treatments.

Table 4-3. Curly-leaf Pondweed abundance Knife, Quamba, Pokegama and Cross Lakes.

Lake	Recent Survey Month-Year	Curly-leaf Pondweed % of points sampled	Other Submerged Species % of points sampled
Knife	[1]May-2009	17%	10%
Quamba	[2]June-2003	30%	19%
Pokegama	[3]May-2009	93%	28%
Cross	[4]June-2006	Present	Present

[1]Only points less than 7 feet deep surveyed
[2]All depths surveyed (11 foot maximum depth)
[3]Only points less than 5 feet deep surveyed
[4]Curly-leaf pondweed mapped, but not surveyed using point-intercept methodology

4.4 NUTRIENT SOURCES

Understanding the sources of nutrients to a lake is a key component in developing an excess nutrient TMDL for lakes. To that end, a phosphorus budget that sets forth the current phosphorus load contributions from each potential source was developed using the modeling and collected data described below. Additionally, lake response models can be developed to understand how different lake variables respond to changes in nutrient loads.

4.4.1 Watershed Load

Kanabec, Mille Lacs and Pine SWCDs and MPCA staff and various lake association personnel have collected total and ortho-phosphorus grab samples at various main-stem river and tributary monitoring stations upstream of the four impaired lakes over the past 10 years. Continuous flow has been measured by the MPCA at several monitoring stations throughout the Snake River watershed in recent years. Total phosphorus data shows TP concentrations from certain sites are relatively high and occasionally exceed the proposed state stream TP standard of 100 µg/L. Total phosphorus loads for four continuous flow monitoring stations were estimated using the Flux32 Load Estimation Software supplied by the U.S. Army Corps of Engineers (Walker, 1999). FLUX uses TP sample concentration data and continuous flow measurements to calculate mass discharges (loadings) using five estimation methods. Average daily flow data gaps for each station were filled using regression equations with the Snake River USGS station (S000-198) which has operated year around since1992. Phosphorus loading for subwatersheds with TP data but no continuous flow data was calculated by multiplying the flow weighted mean TP concentration by the runoff depth of the closest continuous flow monitoring station. A complete summary of the continuous flow and phosphorus monitoring data and FLUX load estimates, methods and assumptions is presented in Appendices D-G.

In order to assess TP loading between different land uses and subwatersheds, a Generalized Watershed Loading Function (GWLF) model was developed for the Knife, Quamba, Pokegama, and Cross Lake drainage areas. GWLF is a GIS-based continuous simulation model which uses daily weather data to calculate water balance and simulate runoff, sediment and nutrient loading (Evans et al. 2008). The GWLF models were established using the following GIS layers: daily temperatures and rainfall, subwatershed boundaries, DNR ditch/stream network, 30 meter digital elevation model (DEM), the Soil Survey Geographic (SSURGO) database and 2010 National Agricultural Statistics Service (NASS) land-use. Once the models were setup in GIS, runoff curve numbers and phosphorus runoff rates were adjusted to match observed annual water yields and FLUX calculated TP loads. Appendices D-G provides a complete summary of GWLF model performance and model predicted TP loading rates for each subwatershed in the Knife, Quamba, Pokegama and Cross Lake watersheds. Table 4-4 summarizes watershed TP loading by land use for each lake watershed modeled using GWLF. The models indicate a majority of the watershed TP runoff for each lake comes from land uses associated with animal agricultural. Thus, implementing pasture and manure management BMPs will be critical in meeting the watershed load reductions required in this TMDL.

Table 4-4. GWLF predicted TP load as a percent of the total watershed runoff load.

Loading Source	Knife Lake Watershed	Quamba Lake Watershed	Pokegama Lake Watershed	Cross Lake Watershed (Snake)	Cross Lake Watershed (Direct)
Hay/Pasture	80%	89%	80%	65%	79%
Cropland	7%	6%	9%	30%	19%
Forest	4%	1%	1%	1%	<1%
Wetland	8%	3%	9%	3%	<1%
Urban/Roads	1%	1%	1%	1%	1%

4.4.2 Upstream Lakes

There are five major upstream impaired lakes that contribute flow and TP load to the Snake River, which eventually flows to Cross Lake's south basin: Ann Lake (DNR Lake # 33-0040), Fish Lake (DNR Lake # 33-0036), Knife Lake, Quamba Lake and Pokegama Lake. These upstream lakes drain approximately 191,700 acres and account for about 31% of the south basin's total drainage area. Discharge volume from these lakes was calculated using annual runoff depths from the continuous flow station located in each impaired lake watershed (Appendices D-G). Phosphorus loads from each upstream lake were calculated by multiplying each lake's flow weighted mean TP concentration by the estimated outflow volume. Knife, Quamba and Pokegama Lakes have no major upstream lakes located in their drainage basin.

4.4.3 Failing Septic Systems

Failing subsurface sewage treatment systems (SSTS) can be an important source of phosphorus to surface waters. Currently, the exact number and status of SSTSs in the Snake River watershed is unknown. MPCA's 2012 SSTS Annual Report includes some general information regarding the performance of SSTSs in the Snake River watershed (MPCA, 2013). This study provides county annual reports from 2012 that include estimated failure rates for each county in the state of Minnesota. The report differentiates between systems that are generally failing and those that are an imminent threat to public health and safety (ITPHS). Generally failing systems are those that do not provide adequate treatment and may contaminate groundwater. For example a generally failing system may have a functioning, intact tank and soil absorption system, but fails to protect ground water by providing a less than sufficient amount of unsaturated soil between where the sewage is discharged and the ground water or bedrock. Systems considered ITPHS are severely failing or were never designed to provide adequate raw sewage treatment. Examples include SSTSs that discharge directly to surface water bodies such as ditches, streams or lakes.

Total number of generally failing and ITPHS systems in each of the impaired lake watersheds was estimated in GIS using 2010 Census population data. Rural population that falls outside the boundaries of municipalities with wastewater treatment facilities (WWTFs) was calculated and divided by 3 people per household to estimate the total number of SSTSs in each watershed. Next, failing and ITPHS systems were estimated by multiplying the total number of SSTSs by the county failure rates from the 2013 MPCA report (Table 3-11). Finally, annual phosphorus load from failing SSTSs was calculated using the University of Minnesota Water Resource Center's 2012 version of the Septic System Improvement Estimator (SSIE). The SSIE is a spreadsheet-based model that uses published literature rates to calculate annual pollutant loads from problematic septic system. This model was setup to assume that even though generally failing systems often discharge phosphorus and other pollutants to groundwater, it is unlikely that phosphorus from systems in the upland areas make it to surface waters. However, those failing systems within the shoreland area can have a hydraulic connection through local groundwater to nearby waterbodies; which can make these shoreland SSTS's a source of phosphorus to the nearby waterbody. This source of phosphorus is included in the Watershed Load allocation portion of the Knife Lake (59 lbs/yr at 50% delivery rate) and Quamba Lake (28 lbs/yr at 50% delivery rate) TMDLs in section 4.6.6. Cross Lake and Pokegama Lake were not included since the shoreland owners around each lake are connected to sanitary sewer.

ITPHS systems, on the other hand, often discharge directly to surface waters and have extremely high delivery potentials. Thus it was assumed that none of the phosphorus in ITPHS systems is removed and 100% is transported to surface waters in the impaired lake watersheds. A complete SSTS phosphorus load summary for each impaired reach watershed is provided in Appendices D-G.

Table 4-5. SSTS failure rates by county (MPCA, 2013)

County	Generally Failing SSTSs	ITPHS SSTSs
Aitkin	6%	1%
Isanti	16%	1%
Kanabec	15%	0%
Mille Lacs	30%	7%
Pine	38%	26%
Chisago	18%	0%

4.4.4 Wastewater Treatment Facilities/Regulated MS4 Communities

There are five active point sources in the Knife Lake and Cross Lake watersheds: Wahkon WWTF (MN0047066), Isle WWTF (MN0023809), Ogilvie WWTF (MN0021997), Mora WWTF (MN0021156) and Grasston WWTF (MN0025691). Wahkon WWTF and Isle WWTF are located in the Knife Lake watershed and discharge to tributaries and wetlands near the headwaters of the Knife River (Appendix D). Ogilvie WWTF, Mora WWTF and Grasston WWTF are located in the Snake River watershed and discharge directly to the Snake River or a major tributary of the Snake River upstream of Cross Lake's south basin. Table 4-6 summarizes current permit limits and effluent flow and TP loads based on discharge monitoring reports (DMRs) supplied by the MPCA. It should be noted that Grasston WWTF does not currently discharge effluent to surface waters through its surface discharge control structure. The only water that leaves this facility is to evaporation and groundwater recharge from the facility's primary cell. At this time, all facilities are currently permitted for wet weather design flow and several water quality parameters, however not TP.

Table 4-6. Current WWTF effluent in the Knife and Cross Lake watersheds.

Facility	Lake Watershed	Receiving Water	Permitted Wet Weather Design Flow (mgd)	Current Effluent Flow (mgd)[1]	Current Effluent TP Load (lbs/year)[1]	Current Effluent TP Conc. (µg/L)[1]
Wahkon WWTF	Knife	Unnamed dry run	0.121	0.075	100	434
Isle WWTF	Knife	Unnamed wetland	0.200	0.123	204	546
Ogilvie WWTF	Cross	Groundhouse River	0.230	0.139	701	1,660
Mora WWTF	Cross	Snake River	0.800	0.511	4,489	3,144
Grasston WWTF[2]	Cross	Snake River	0.038	NA	NA	NA

[1] Effluent flow and TP calculated based on annual average of the 2010-2011 MPCA discharge monitoring reports
[2] Grasston WWTF does not currently discharge to surface water

4.4.5 Internal Load

Internal phosphorus loading from lake sediments has been demonstrated to be an important part of the phosphorus budgets of lakes. However, measuring or estimating internal loads can be difficult, especially in shallow lakes and lakes with long fetch that periodically or constantly mix throughout the year.

To estimate internal loading, an anoxic factor (Nürnberg 2004), which estimates the period where anoxic conditions exist over the sediments, is estimated from dissolved oxygen profile data. The anoxic factor is expressed in days but is normalized over the area of the lake. The anoxic factor is then used along with a sediment release rate to estimate the total phosphorus load from the sediments. Oxic and anoxic phosphorus release rates were estimated individually for all four lakes by collecting sediment cores and incubating them in the lab under oxic and anoxic conditions (James, 2012; Appendix H).

For all four lakes, dissolved oxygen and temperature profiles were collected at least once per month in 2010 and 2011. However; little anoxia (DO less than 2.0 mg/L) was observed in all four lakes. Even in lakes considered "deep" basins, Pokegama and Cross, anoxia was recorded only in the bottom 1-3 meters during one or two of the site visits each summer. It is important to note that shallow lakes (Knife and Quamba) and medium depth lakes with long fetch (Pokegama and Cross) can often demonstrate short periods of anoxia due to instability of stratification which is often missed by periodic measurements. So, for all four lakes, an equation was used (Nürnberg 2005) to estimate the anoxic factor. Once the anoxic factor was estimated, the next step is to identify the rate at which sediments release phosphorus under both anoxic and oxic conditions. The laboratory measured rate of phosphorus release from anoxic and oxic sediments for each lake are presented in Table 4-7. These rates were then multiplied by the total area of each lake to estimate gross internal loading in each system (Nürnburg 2004).

Table 4-7. Internal load estimates.

Lake	Oxic Release (mg/m^2/day)	Anoxic Release (mg/m^2/day)	Anoxic Factor (days)	Total Internal Load (lbs/year)
Knife	0.7	9.5	54	6,764
Quamba	0.4	11.1	56	1,347
Pokegama	0.5	16.3	56	13,203
Cross - North	0.5	17.8	50	3,212
Cross – Central	1.8	31.1	51	5,196
Cross – South	NA	18.8	56	3,612

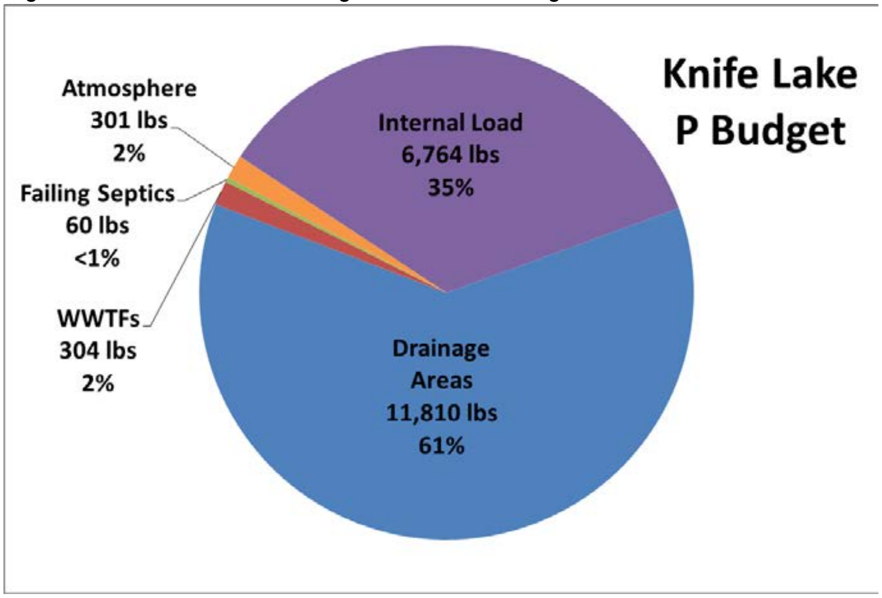
4.4.6 Atmospheric Load

The atmospheric load refers to the load applied directly to the surface of the lake through atmospheric deposition. Atmospheric inputs of phosphorus from wet and dry deposition are estimated using rates set forth in the MPCA report “Detailed Assessment of Phosphorus Sources to Minnesota Watersheds” (Barr Engineering 2004), and are based on annual precipitation. The values used for dry (< 25 inches), average, and wet precipitation years (>38 inches) for atmospheric deposition are 24.9, 26.8, and 29.0 kg/km2-year, respectively. These values are equivalent to 0.22, 0.24, and 0.26 pounds/acre-year for dry, average, and wet years, respectively.

4.4.7 Lake Nutrient Budgets

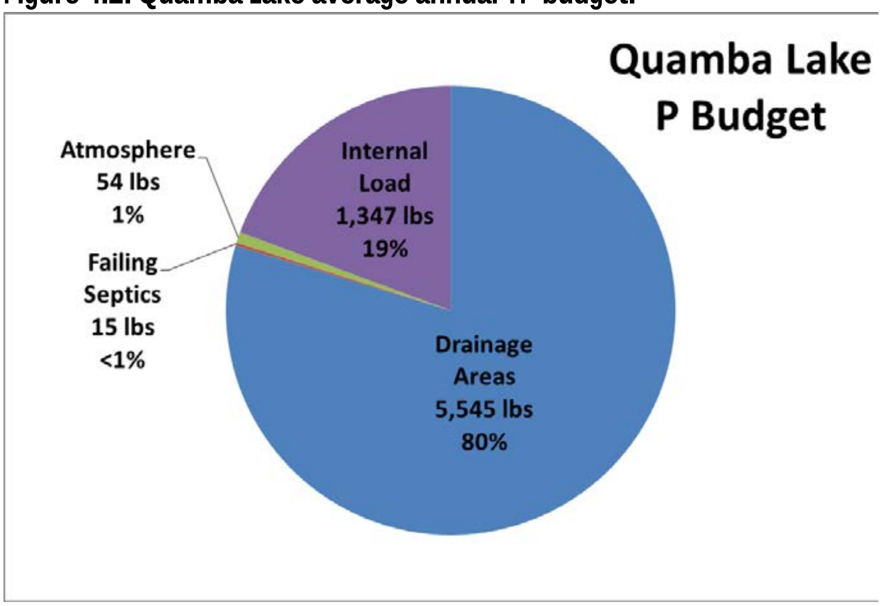
Knife Lake’s phosphorus budget for model years 2010 and 2011 is presented in Figure 4.1. Loading from Knife Lake’s drainage area, particularly Knife River, represents a majority of the annual TP load to the lake. Internal load from Knife Lake sediments represents the second largest source of TP. Internal load can play a significant role during the warm summer months when TP load from the watershed is low and primary production is high. The Wahkon and Isle WWTFs currently only account for about 2% of the annual TP budget while failing septics and atmospheric inputs account for less than 1% and 2%, respectively.

Figure 4.1. Knife Lake average annual TP budget.



Phosphorus loading to Quamba Lake is dominated by inputs from Upper Mud Creek and the lake's direct watershed (Figure 4.2). Similar to Knife Lake, the internal loading from Quamba Lake's sediment represent the next largest source of TP to the lake and plays an important role during the warm, dry summer months. Failing septics and atmospheric loading are not major nutrient sources to Quamba Lake compared to watershed and internal sources.

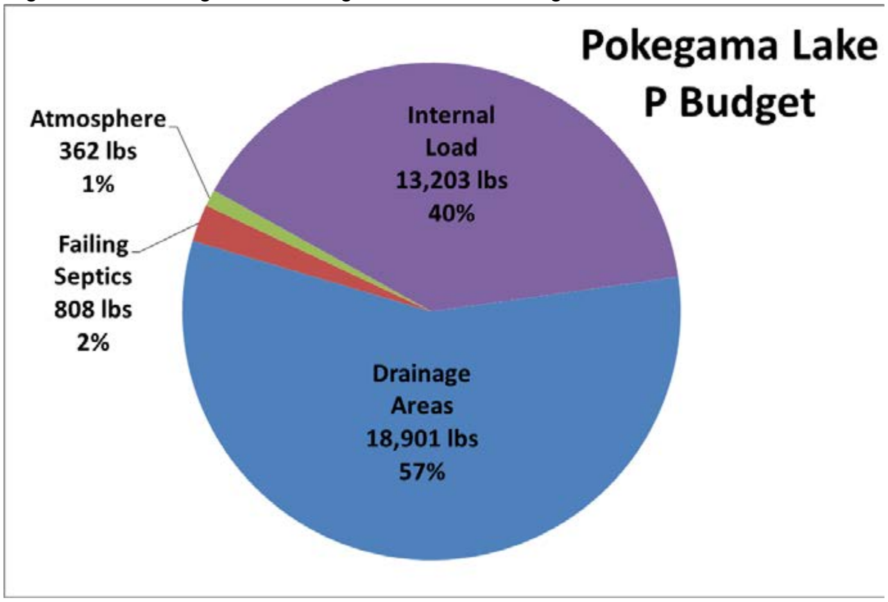
Figure 4.2. Quamba Lake average annual TP budget.



Compared to Quamba Lake, TP loading to Pokegama Lake is split more evenly between watershed runoff and internal loading. Phosphorus loading from Pokegama's direct watershed accounts for about half of the watershed TP runoff. Monitored TP runoff concentrations for the direct watershed were extremely high (336-499 µg/L) and above the proposed TP standard of 100 µg/L. Pokegama Creek accounts for more than half of the drainage area water budget for Pokegama Lake, however monitored

TP concentrations for Pokegama Creek were significantly lower (89 µg/L average TP) than the direct watershed. Pokegama Lake has a very high measured internal P release rate (16.3 $mg/m^2/day$) and internal load is responsible for approximately 40% of the lake's P budget. Only about 2% of the TP load to Pokegama Lake comes from failing SSTSs. Atmospheric deposition also accounts for only 1% of Pokegama Lake's TP budget.

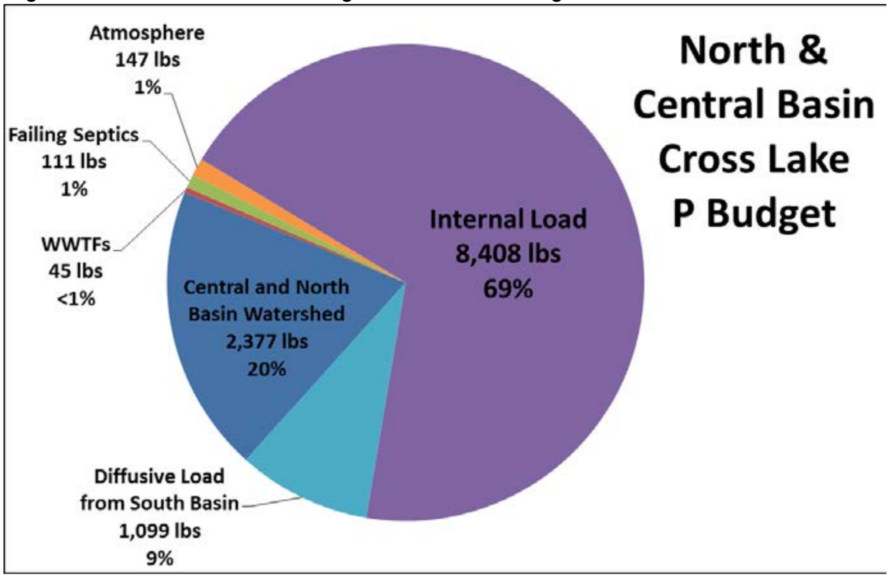
Figure 4.3. Pokegama average annual TP budget.



As discussed in section 4.1, Cross Lake's south basin has a hydraulic residence time of less than 14 days and is therefore considered a wide spot in the Snake River according to Minnesota Rules, Chapter 7050, Part 0150 Subp. 4(S). The Snake River inflow to the lake's south basin currently meets the State of Minnesota's 100 µg/L proposed river and stream TP eutrophication standard. As a result, this study will only focus on TMDL allocations for Cross Lake's central and north basins. Figure 4.4 shows average annual loading to the north and central basins. Appendix G contains a complete summary of annual TP loading to each individual basin, including the south basin. Results indicate the diffusive flux of phosphorus from the south basin to the central and north basins is relatively small (9%) compared to other loading sources. Direct runoff from the central and north basin watersheds also accounts for a relatively small portion of the overall phosphorus budget, however monitored TP runoff concentrations are very high (120-321 µg/L average TP) and are consistently above the proposed 100 µg/L river and stream TP standard. Internal load accounts for about 69% of the total phosphorus load to Cross Lake's central and north basins and plays a significant role in the growing season phosphorus budget due to these basin's long residence times and high internal P release rates.

There are no wastewater treatment facilities in the central and north basin watersheds. The facilities discussed in section 4.4.4 discharge to the Snake River upstream of the south basin and do not directly impact the central and north basin. These facilities do have the potential to contribute phosphorus indirectly via the south basin diffusive flux. Wastewater treatment facility diffusive input was estimated by calculating the WWTFs percent of the total phosphorus load to the south basin and then multiplying this percentage by the total diffusive flux from the south basin. This analysis demonstrates that while the WWTFs collectively discharge 5,190 pounds of phosphorus to the Snake River annually, only about 45 pounds makes it to the central and north basins from the south basin each year. Atmospheric inputs and failing septics in the central and north basin are small and individually account for less than 2% of the TP load.

Figure 4.4. Cross Lake average annual TP budget.



4.5 LAKE RESPONSE MODELS

Once the nutrient budget for a lake has been developed, the response of the lake to those nutrient loads must be established. Lake response to nutrient loading was modeled using the BATHTUB suite of models and the monitored data available for the impaired lakes. BATHTUB is a series of empirical eutrophication models that predict the response to phosphorus inputs for morphologically complex lakes and reservoirs (Walker 1999). Several models (subroutines) are available for use within the BATHTUB model, and the Canfield-Bachmann model was used to predict the lake response to total phosphorus loads. The Canfield-Bachmann model estimates the lake phosphorus sedimentation rate, which is needed to predict the relationship between in-lake phosphorus concentrations and phosphorus load inputs. The phosphorus sedimentation rate is an estimate of net phosphorus loss from the water column through sedimentation to the lake bottom, and is used in concert with lake-specific characteristics such as annual phosphorus loading, mean depth, and hydraulic flushing rate to predict in-lake phosphorus concentrations. These model predictions are compared to measured data to evaluate how well the model describes the lake system. Once a model is well calibrated, the resulting relationship between phosphorus load and in-lake water quality is used to determine the assimilative capacity. Lake response model inputs, performance and results for all four impaired lakes are included in Appendices D-G.

4.6 TMDL ALLOCATIONS

The numerical TMDL for Knife, Quamba, Pokegama and Cross Lakes was calculated as the sum of the wasteload allocation (WLA), load allocation (LA) and the margin of safety (MOS) expressed as phosphorus mass per unit time. Nutrient loads in this TMDL are set for phosphorus, since this is typically the limiting nutrient for nuisance aquatic algae. These TMDLs are written to solve the TMDL equation for a numeric target of 60 µg/L (Knife and Quamba) and 40 µg/L (Pokegama and Cross) of TP as a summer growing season average.

4.6.1 Total Loading Capacity

The first step in developing an excess nutrient TMDL for lakes is to determine the total nutrient loading capacity for the lake. To determine the total loading capacity, the average annual nutrient budgets and lake response models for each lake were used as the starting point. WLAs for the municipal wastewater facilities (WWTFs) were derived from the WLAs in the Lake St. Croix TMDL (the Wahkon WLA required adjustment, however, because Wahkon's NPDES permit was reissued with a more restrictive limit during the Lake St. Croix TMDL approval process) (Table 4-8). After specifying the WWTF WLAs, other nutrient inputs were systematically reduced until the model predicted that the lakes met the appropriate total phosphorus standard as a growing season mean. The reductions were applied first to the internal load and then the watershed sources. The TMDL loading capacities for each lake are presented in Tables 4-9 to 4-12.

4.6.2 Wasteload Allocations

Wasteload allocations for lakes are typically divided into four categories: NPDES surface wastewater discharges, construction and industrial storm water, Municipal Separate Storm Sewer Systems (MS4s), and ITPHS's. Currently, there are no MS4s located anywhere in the Snake River watershed. At the time of this study, the MPCA confirmed there were no active permitted NPDES surface wastewater dischargers in the Quamba and Pokegama Lake watersheds. However, should a Regulated MS4 community be proposed; Section 6.0 describes the process or steps necessary to obtain a permit to discharge in the watershed(s).

As discussed in Section 4.4.4 there are currently five permitted NPDES wastewater dischargers in the Knife and Cross Lake watershed: Wahkon WWTF, Isle WWTF, Ogilvie WWTF, Mora WWTF and Grasston WWTF.

4.6.2.1 Wastewater Treatment Facilities

Load allocations for NPDES wastewater dischargers are set by multiplying the facility's wet whether design flow by their permitted pollutant (in this case TP) concentration limit. While all five of the permitted WWTFs in this study monitor effluent TP concentrations, none of the facilities currently have TP concentration or loading limits in their disposal system (SDS) permits. While these facilities account for a relatively small portion of the Knife and Cross Lake TP budgets, some of the facilities discharge at concentrations well over 1,000 µg/L (Table 4-6). The recently approved Lake St. Croix Nutrient Total Maximum Daily Load assigned individual and aggregate load cap WLAs to all municipal WWTFs in the Snake River watershed (MPCA and Wisconsin DNR, 2012). This study assigned annual WLAs based on a 1,000 µg/L TP concentration for all facilities whose wet weather design flow is between 0.2-1.0 mgd. Facilities with wet whether design flows below 0.2 mgd were assigned WLAs based on a 2,000 µg/L TP concentration. It was determined these WLAs were reasonable for inclusion in this TMDL since the Knife and Cross Lake BATHTUB models responded favorably when these loads were applied. The Wahkon and Isle WWTFs currently discharge below their Lake St. Croix TMDL WLAs and will not require reductions for the Knife Lake TMDL. The Ogilvie and Mora WWTFs consistently discharge above their Lake St. Croix TMDL WLAs and thus a reduction based on that TMDL (Table 4-8).

The St. Croix TMDL WLAs described above require overall phosphorus load reductions of approximately 0.2% for Ogilvie WWTF and 50% for Mora WWTF. Grasston WWTF will not provide any load reduction since this facility does not currently discharge its effluent to surface waters. Implementing the Lake St Croix TMDL aggregate load cap WLAs to the WWTFs in the Snake River watershed should have a direct benefit on water quality in Cross Lake's south basin and indirect benefits on water quality for Cross Lake's central and north basins. Current condition WWTF loading estimates to Cross Lake's central and north basin is described in section 4.4.7. Model analysis showed that the Ogilvie, Mora and Grasston WWTFs collectively discharge 5,190 pounds of phosphorus to the Snake River each year but only 45 pounds makes it to Cross Lake's central and north basins through diffusion from the south basin each year (Table 4-8). It is estimated that the WWTF reductions required in the St. Croix TMDL will result in a diffusive load reduction of approximately 16 pounds to Cross Lake's north and central basins (Tables 4-8 and 4-12).

Table 4-8. Current effluent conditions and Lake St. Croix TMDL allocations for all Snake River Watershed WWTFs.

Facility	Lake Watershed	Current Effluent TP Load (TP lb/year)[1]		Current Effluent TP Conc. (µg/L)[1]	Lake St Croix TMDL TP Load (TP lb/year)		Basis For Lake St. Croix TMDL TP Conc. (µg/L)
		Total	Diffusive[2]		Total	Diffusive[2]	
Wahkon WWTF	Knife	100	NA	434	736[4]	NA	2,000
Isle WWTF	Knife	204	NA	546	609	NA	1,000
Ogilvie WWTF	Cross	701	6	1,660	701	6	1,000
Mora WWTF	Cross	4,489	39	3,144	2,436	19	1,000
Grasston WWTF[3]	Cross	NA	NA	NA	231	4	2,000

[1] Current effluent TP calculated based on annual average of the 2010-2011 MPCA discharge monitoring reports
[2] Estimated proportion of WWTF TP load that reaches Cross Lake's north and central basins via diffusive flux from the south basin
[3] Grasston's WWTF does not currently discharge to surface water
[4] The NPDES Permit was revised with a 1 mg/L concentration limit; which equates to a 369 lb/yr annual load. For the sake of the Knife Lake TMDL the 369 lb/yr load value will be used.

4.6.2.2 Construction and Industrial Stormwater

At the time of this study, there were 53 active NPDES construction permits in the four impaired reach watersheds. To account for these facilities and future growth in the watershed (reserve capacity), construction storm water allocations in each TMDL are set to one percent of the watershed TMDL load allocation before the MOS and LA are subtracted. Also at the time of this study, there were 3 active industrial storm water permits in the impaired reach watersheds. To account for these permits and future growth (reserve capacity), allocations for industrial storm water in the TMDL are set at a half percent of the watershed TMDL load allocation before the MOS and LA are subtracted.

For Cross Lake, construction and industrial stormwater from the south basin's direct watershed and Snake River via diffusive flux from the south basin was estimated similar to WWTF allocations using the following equation:

$$C\&I\ WLA = (WAL_{total} * 0.015) / South_{total} * Diff_{total}$$

Where:

C&I WLA = construction and industrial stormwater WLA from the south basin via diffusion

WAL_{total} = Total watershed phosphorus load to the south basin
$South_{total}$ = Total phosphorus load to the south basin
$Diff_{total}$ = Total diffusive phosphorus flux from the south basin to the north and central basins

4.6.3 Load Allocation

The Load Allocation includes all non-permitted watershed loads such as inflow from upstream wetlands and lakes, runoff from forest land, rural agricultural land, SSTS and storm water runoff not covered by a state or federal permit. The Load Allocation also includes atmospheric deposition and internal loading. One of the first steps in determining the allowable phosphorus loads to the lakes is setting the appropriate internal load release rate. Measured release rates in Knife, Quamba, Pokegama and Cross were compared to expected release rates for mesotrophic lakes (Nürnberg 1997). Mesotrophic lakes demonstrate internal phosphorus release rates ranging from 0 to 12 mg/m^2-day with a median release rate around 4 mg/m^2-day. Although the median is 4 mg/m^2-day, there is a broad range of internal loads in mesotrophic lakes which makes selecting an appropriate number difficult. Furthermore, all of these lakes are considered shallow or are over 50% littoral and should be expected to release little or no phosphorus when maintained in a healthy state. For example, anoxic release rates in Oneka Lake, a shallow, submerged aquatic vegetation dominated lake located in Anoka County, were below detection. Oneka Lake is the only healthy shallow lake with release measurements near the Snake River watershed. Therefore, release rates in healthy, plant dominated lakes could arguably be zero.

Internal release rates for all four lakes were high and considered eutrophic to hyper-eutrophic. The lake response models for each lake indicated achieving state standards would be impossible without significant internal load reductions. To meet state standards, internal release rates for Knife, Quamba, Pokegama and Cross need to be reduced to 1.0 mg/m^2/day or below. Oxic release of phosphorus was also measured in all four lakes. These rates were not adjusted assuming that the release is a result of the natural breakdown of sediment in the lakes.

It is also important to note that the selected Canfield-Bachmann lake response model implicitly accounts for some internal loading because the response is predicted from external loads from a database that includes lakes with internal loading. Therefore, the assigned internal load in these models is included above and beyond the implicitly included internal load. Therefore, the lake can likely demonstrate an internal load greater than what is explicitly identified in the TMDL and still meet state water quality standards.

To determine the allowable watershed phosphorus load, the lake response models were updated with the selected allowable internal load as determined in the previous section. Next, current estimated watershed loading in the lake response models was reduced until the models predicted in-lake phosphorus concentration to meet state standards. Significant watershed load reductions (35%-88%) will be needed for each lake to meet state standards. No changes were expected for atmospheric deposition because this source is impossible to control.

4.6.4 Margin of Safety

The MOS is intended to ensure achievement of the water quality goals in the face of inevitable scientific uncertainties. This TMDL has a robust dataset that includes lake water quality monitoring over multiple years and basins, extensive tributary flow and TP monitoring and lab measured internal phosphorus release rates. An explicit margin of safety of 5% of the load has been set aside for the Knife, Quamba, Pokegama and Cross Lake TMDLs. The 5% MOS was considered reasonable given each lake's robust dataset and lake response model performance.

4.6.5 Reserve Capacity

In the Snake River watershed and the St. Croix River basin, reserve capacity (RC) is only available to establish wasteload allocations for the conversion of existing phosphorus loads; it is not intended to provide wasteload allocations for new and expanding industrial or municipal discharges. In Minnesota, RC is established for projects that address failing or nonconforming septic systems and "unsewered" communities and will be made available only to new WWTPs or existing WWTPs that provide service to existing populations with failing or nonconforming systems. The determination of the RC for lakes with WWTPs located in their watersheds, Knife and Cross Lake, was done according to methodology set forth in the Lake St. Croix TMDL (MPCA 2012) and is described below.

The reserve capacities for SSTSs were estimated based on the septic system populations provided in Appendices D-G. MPCA staff experience indicates around 10 percent of all SSTS systems in a given area ultimately convert to surface discharge. A per capita phosphorus rate of 0.16 kg phosphorus/cap-yr was applied to 10 percent of the septic population in each impaired lake watershed to calculate the reserve capacity. This per capita rate was estimated by applying an assumed 80 percent reduction through wastewater treatment to an MPCA raw-wastewater loading guideline of 0.80 kg phosphorus/cap-yr (or 1.76 lb phosphorus/cap-yr). The allotting of reserve capacity for future SSTS conversions will be made on the basis of this 0.16-kg phosphorus/cap-yr rate. For Cross Lake's north and central basins, the RC only includes the estimated RC for the Snake River watershed that flows to the south basin and was therefore removed from the south basin diffusive flux load allocation.

4.6.6 Summary of TMDL Allocations

The numerical TMDL for each lake was calculated as the sum of the WLA, LA, and the MOS expressed as phosphorus mass per unit time. Tables 4-9 to 4-12 present the TMDL equations for each lake. Annual load allocations were rounded to the nearest whole number. Daily load allocations were rounded to the nearest tenth of a pound.

Table 4-9. Knife Lake Total Maximum Daily Load allocations.

Allocation	Source	Existing TP Load [1]	TP Allocations		Load Reduction	
		(lbs/year)	(lbs/year)	(lbs/day)[2]	(lbs/year)[3]	%
Wasteload Allocation	Construction & Industrial Stormwater	121	121	0.3	0	0%
	Wahkon WWTF[4]	100	369	8.0	+(269)	0%
	Isle WWTF[4]	204	609	10.1	+(405)	0%
	ITPHS Septics	60	0	0.0	60	100%
Load Allocation	Watershed Load[5]	11,689	7,639	20.9	4,050	35%
	Internal	6,764	1,297	3.6	5,467	81%
	Atmosphere	301	301	0.8	0	0%
Reserve Capacity		--	47	0.1	--	
MOS		--	547	1.5	--	--
TOTAL		**19,239**	**10,930**	**45.3**	**9,577**	**50%**

[1] Existing load is the average for the years 2010 and 2011 based on monitored data and Discharge Monitoring Reports from the WWTF's.
[2] Annual loads converted to daily by dividing by 365.25 days per year accounting for leap years
[3] Net reduction from current load to TMDL is 8,309 lbs/yr; but gross load reduction from all sources must accommodate WWTF permitted conditions and the Reserve Capacity and MOS as well, and hence is 8,309 + 269 + 405 + 47 + 547 = 8,903 lbs/yr.
[4] The Wahkon and Isle WWTFs are controlled (pond) discharge facilities and daily effluent allocations were calculated using the 1,000 µg/L concentration assumption and the maximum permitted effluent flow rate of 6 inches/day over the area of each facility's discharging cell (MPCA and Wisconsin DNR, 2012). Controlled discharge facilities are designed to store 180 days' worth of influent flow and discharge during spring and fall during periods of relatively high stream flow and/or low receiving water temperature. Since this facility discharges intermittently, daily wasteload allocations do not represent their annual wasteload divided by 365.25 days. Rather they reflect the permitted daily effluent loads as described above.
[5] Watershed load consists of all non-regulated runoff from forest land, wetlands, rural land, agricultural land, failing septics within the shoreland area (59 lbs/yr), and non-regulated MS4 stormwater.

Table 4-10. Quamba Lake Total Maximum Daily Load allocations.

Allocation	Source	Existing TP Load [1]	TP Allocations		Load Reduction	
		(lbs/year)	(lbs/year)	(lbs/day)[2]	(lbs/year)[3]	%
Wasteload Allocation	Construction & Industrial Storm water	55	55	0.2	0	0%
	ITPHS Septics	15	0	0.0	15	100%
Load Allocation	Watershed Load[4]	5,490	3,516	9.6	1,974	36%
	Internal	1,347	113	0.3	1,234	92%
	Atmosphere	54	54	0.1	0	0%
MOS		--	197	0.5	--	--
TOTAL		**6,961**	**3,935**	**10.7**	**3,223**	**46%**

[1] Existing load is the average for the years 2010 and 2011.
[2] Annual loads converted to daily by dividing by 365.25 days per year accounting for leap years.
[3] Net reduction from current load to TMDL is 3,026 lbs/yr; but gross load reduction from all sources must accommodate the MOS as well, and hence is 3,026 + 197 = 3,223 lbs/yr.
[4] Watershed load consists of all non-regulated runoff from forest land, wetlands, rural land, agricultural land, failing septics within the shoreland area (28 lbs/yr), and non-regulated MS4 stormwater.

Table 4-11. Pokegama Lake Total Maximum Daily Load allocations.

Allocation	Source	Existing TP Load [1]	TP Allocations		Load Reduction	
		(lbs/year)	(lbs/year)	(lbs/day)[2]	(lbs/year)[3]	%
Wasteload Allocation	Construction & Industrial Storm water	108	108	0.3	0	0%
	ITPHS Septics	808	0	0.0	808	100%
Load Allocation	Pokegama Brook Watershed Load[4]	9,631	5,777	15.8	3,854	40%
	Direct Watershed Load[4]	9,163	1,055	2.9	8,108	88%
	Internal	13,203	1,356	3.7	11,847	90%
	Atmosphere	362	362	1.0	0	0%
MOS		--	456	1.2	--	--
TOTAL		**33,275**	**9,114**	**24.9**	**24,617**	**74%**

[1] Existing load is the average for the years 2001, 2002, 2008 and 2010.
[2] Annual loads converted to daily by dividing by 365.25 days per year accounting for leap years.
[3] Net reduction from current load to TMDL is 24,161 lbs/yr; but gross load reduction from all sources must accommodate the MOS as well, and hence is 24,161 + 456 = 24,617 lbs/yr.
[4] Watershed loads consist of all non-regulated runoff from forest land, wetlands, rural land, agricultural land and non-regulated MS4 stormwater.

Table 4-12. Cross Lake North and Central Basin Total Maximum Daily Load allocations.

Allocation	Source	Existing TP Load[1]	TP Allocations		Load Reduction	
		(lbs/year)	(lbs/year)	(lbs/day)[2]	(lbs/year)[3]	%
Wasteload Allocation	North & Central Basin Watershed Construction & Industrial Stormwater	21	21	<0.1	0	0%
	South Basin Diffusive Flux Construction & Industrial Stormwater[4]	21	21	<0.1	0	0%
	South Basin Diffusive Flux WWTFs[5]	45	29	<0.1	16	36%
	ITPHS Septics	111	0	0.0	111	100%
Load Allocation	South Basin Diffusive Flux	1,078	1,947	5.3	(+)869	--
	Direct Watershed Load[6]	2,356	1,220	3.3	1,136	48%
	Internal	8,408	3,053	8.4	5,355	64%
	Atmosphere	147	147	0.4	0	0%
Reserve Capacity		--	7	<0.1	--	--
MOS		--	339	0.9	--	--
TOTAL		**12,187**	**6,784**	**18.6**	**5,749**	**47%**

[1] Existing load is the average for the years 2010 and 2011 based on monitored data and Discharge Monitoring Reports from the WWTF's.
[2] Annual loads converted to daily by dividing by 365.25 days per year accounting for leap years.
[3] Net reduction from current load to TMDL is 5,403 lbs/yr; but gross load reduction from all sources must accommodate the Reserve Capacity and MOS as well, and hence is 5,403 + 7 + 339 = 5,749 lbs/yr.
[4] Construction and industrial stormwater allocation from the south basin includes construction and industrial stormwater for the entire Snake River watershed downstream of the other impaired lakes in the Snake River watershed (Ann, Fish, Knife,

Quamba and Pokegama). This value was calculated based on diffusive flux from the south basin to the central and north basins as described in section 4.6.2.2.
[5] WWTF allocation from the south basin includes effluent from Ogilvie, Mora and Grasston WWTFs. This value was calculated based on diffusive flux from the south basin to the central and north basins as described in section 4.6.2.1.
[6] Watershed loads consist of all non-regulated runoff from forest land, wetlands, rural land, agricultural land and non-regulated MS4 stormwater.

4.6.7 Lake Response Variables

In developing the lake nutrient standards for Minnesota lakes (Minn. Rule 7050), the MPCA evaluated data from a large cross-section of lakes within each of the state's Eco regions (Heiskary and Lindon, 2005). Clear relationships were established between the causal factor total phosphorus and the response variables chlorophyll-a and Secchi disk. Based on these relationships it is expected that the allocations set forth in this TMDL to meet the phosphorus targets of 60 µg/L and 40 µg/ for shallow and deep lakes, the chlorophyll-a and Secchi standards will likewise be met.

4.6.8 Seasonal and Annual Variation

The daily load reduction targets in this TMDL are calculated from the current annual phosphorus budgets for Knife, Quamba, Pokegama and Cross Lakes. The TP budget is an average of at least two years of recent monitoring data. BMPs designed to address excess loads to the lakes will be designed for these average conditions; however, the performance will be protective of all conditions. For example, a storm water pond designed for average conditions may not perform at design standards for wet years; however the assimilative capacity of the lake will increase due to increased flushing. Additionally, in dry years the watershed load will be naturally down allowing for a larger proportion of the load to come from internal loading. Consequently, averaging across several modeled years addresses annual variability in lake loading.

5.0 Biotic Impairment

5.1 EVALUATING BIOTIC INTEGRITY

The CADDIS Stressor Identification analysis uses a "strength of evidence" approach to evaluate candidate causes affecting biotic integrity. The five candidate causes identified in the Mud Creek Stressor Identification (ID) Report – excess embedded sediment, low dissolved oxygen, degraded riparian habitat, loss of connectedness, and altered flow – were evaluated and the results summarized in Table 5-1.

Data are analyzed in terms of associations that might support, weaken or refute the case for a candidate cause. This strength of evidence analysis is a systematic approach that sorts through the available data to determine the most probable cause or causes based on weight of evidence. Each of the types of evidence is scored based on the degree to which it supports or weakens the case using pluses (++) or minuses (--). The number of pluses or minuses depends on the likelihood that an association might be observed by chance rather than because of the true cause. A score of 0 indicates that the evidence neither supports nor weakens the case for the cause, a D is diagnostic of the cause and an R refutes the case for the cause.

The evidence for lack of benthic habitat due to excess bedded sediment and is strongest. Low dissolved oxygen and impacts from riparian degradation are plausible co-stressors. Loss of connectivity and flow alteration from ditching in the watershed and on the stream are identified as potential stressors but there is not enough evidence available to evaluate their strength.

Table 5-1. Stressor identification strength of evidence table.

Types of Evidence	Sediment Score	Riparian Degradation Score	Low DO Score	Connectivity Score	Altered Hydrology Score
Evidence using data from Mud Creek					
Spatial/temporal co-occurrence	+	+	+	0	+
Temporal sequence	0	0	0	NE	NE
Field evidence of stressor-response	+	++	+	0	0
Causal pathway	++	++	++	0	0
Evidence of exposure, biological mechanism	+	+	+	0	0
Field experiments /manipulation of exposure	NE	NE	NE	NE	NE
Laboratory analysis of site media	NE	NE	NE	NE	NE
Verified or tested predictions	+	+	+	NE	NE
Symptoms	+	+	+	0	0

Types of Evidence	Sediment Score	Riparian Degradation Score	Low DO Score	Connectivity Score	Altered Hydrology Score
Evidence using data from other systems					
Mechanistically plausible cause	+	+	+	+	+
Stressor-response in other lab studies	NE	NE	++	0	NE
Stressor-response in other field studies	++	+	+	+	+
Stressor-response in ecological models	NE	NE	NE	+	+
Manipulation experiments at other sites	NE	NE	NE	NE	NE
Analogous stressors	++	+	+	+	+
Multiple lines of evidence					
Consistency of evidence	+	+	+	0	0
Explanatory power of evidence	0	++	0	0	0

Note: "+" symbols indicate support for that cause, and "–" symbols indicate evidence weakens the cause, with the number of symbols indicating strength of evidence. A "0" indicates evidence neither supports nor weakens the cause. "NE" indicates there is no evidence available for analysis.

5.2 SEDIMENT SOURCES

Excess sedimentation and embeddedness was identified as being a primary stressor on aquatic life in Upper Mud Creek. The primary sources of sediment in streams are sediment conveyed from the landscape and soil particles detached from the stream bank. The amount of sediment conveyed from the landscape will vary based on general soil erodibility, land cover, slope, and conveyances to the stream. Streambank erosion is a natural process that can be accelerated significantly as a result of change in the watershed or to the stream itself. Field data was collected to better understand the source of excess sedimentation so that the most effective mitigation actions could be identified.

5.2.1 Sediment Conveyed from the Landscape

Alterations to the landscape that might result in excessive sediment delivery to streams include row crop agriculture, deforestation, high-density pasturage, and removal or lack of vegetative buffers adjacent to ditches, channels and streams. About 40 percent of land in the Upper Mud Creek watershed is in pasture or cultivated row crops, and there is a network of ditches and small channels that convey drainage to Upper Mud Creek. There are a number of small feedlots in the direct drainage area of Upper Mud Creek, including several that are immediately riparian.

These changes in land cover from forest to grass and shrublands can increase sediment delivery if the watershed is ditched or tiled, or if there is a lack of intervening buffer vegetation to filter sediment from overland flow. While neither the Stressor ID nor this TMDL modeled sediment from the watershed, the Stressor ID Study evaluated Total Suspended Solids (TSS), turbidity, and transparency data for Upper Mud Creek and found values were well below the State of Minnesota turbidity and draft TSS standards.

The Universal Soil Loss Equation (USLE) was used to estimate the potential amount of sediment delivered to Upper Mud Creek from watershed sources. USLE is a widely-used model developed by the Natural Resources Conservation Service (NRCS), and uses factors such as soil erodibility, topography, and cropping practices to estimate potential soil loss. Since not all soil loss will be delivered downstream, the potential soil loss is corrected by applying a Sediment Delivery Ratio (SDR) (Vanoni 1975) to estimate how much soil loss from a drainage area will be delivered downstream.

$$SDR = 0.451(b)^{-0.298}$$

Where b = watershed size in square kilometers

USLE predicts that the annual potential soil loss in the 20,366 acres watershed is 405 tons per year. The sediment delivery ratio is 0.121, and the annual estimated mass of sediment delivered from the watershed to the river is (405 tons/year * 0.121) or 49.05 tons/year.

5.2.2 Sediment Contributed from Streambank Erosion

Streambank erosion may be a source of excess bedded sediment. Landcover changes in the riparian zone may weaken streambanks by reducing or eliminating long-rooted native vegetation that strengthens and stabilizes the banks. Changes in flow regime may also destabilize streambanks that are exposed to prolonged periods of wetting or wet-dry cycles. Animals grazing on the stream bank may denude the riparian area, and may physically break down the banks as they access the stream.

To evaluate whether soil loss from stream bank erosion may be contributing significantly to sediment load, representative stream reaches on both Upper and Lower Mud Creek were evaluated for stability and amount of observed soil loss by severity. The annual soil loss by mile by riparian land use type was estimated, and the results extrapolated to the whole stream.

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

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

The Direct Volume Method is summarized in the following equation:

$$\frac{\text{(eroding area) (lateral recession rate) (density)}}{\text{2,000 lbs/ton}} = \text{erosion in tons/year}$$

5.2.2.1 Streambank Conditions

The following sections describe how each of the parameters in the Direct Volume equation was estimated for Mud Creek.

Eroding Area. The eroding area is defined as that part of the stream bank that is bare, rilled, or gullied, and showing signs of active erosion such as sloughed soil at the base. The length and width of the eroding face of the stream bank is multiplied to get an eroded area. As each of the evaluated reaches was walked, each area of significant erosion on either side of the stream bank was measured and recorded on a field sheet. Professional judgment was used to determine which areas were significant.

Lateral Recession Rate. The lateral recession rate is the thickness of soil eroded from a stream bank face in a given year. Soil loss may occur at an even rate every year, but more often occurs unevenly as a result of large storm events, or significant land cover change in the upstream watershed. Historic aerial or other photographs, maps, construction records, or other information sources may be available to estimate the total recession over a known period of time, which can be converted into an average rate per year. However, these records are often not available, so the recession rate is estimated based on stream bank characteristics that evaluate risk potential and through professional judgment. Table 5-2 presents the categories of bank condition that are evaluated and the varying levels of condition and associated risk severity score.

Density. Soil texture was field evaluated at each location and noted on the field sheet

Table 5-2. Bank condition severity rating.

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

A Cumulative Rating score of 0-4 indicates a stream bank at slight risk of erosion. A score of 5-8 indicates a moderate risk, and 9 or greater a severe risk. The Wisconsin NRCS used its field data from streams in Wisconsin to assign a lateral recession rate for each category (Table 5-3). Professional judgment is necessary to select a reasonable rate within the category.

At each of the measured erosion areas, evaluators performed the above severity assessment, recorded on the field sheet the score for each of the condition categories above and the total score, and selected an appropriate recession rate.

Table 5-3. Estimated annual lateral recession rates per severity risk category.

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

5.2.2.2 Annual Streambank Soil Loss

Data were compiled into a spreadsheet database that summarized stream length, total eroding area, Bank Condition Severity Rating, and soil texture. The estimated recession rate was multiplied by the total eroding area to obtain the estimated total annual volume of soil loss (Table 5-4). To convert this soil loss to mass, soil texture was used to establish a volume weight for the soil. The total estimated volume of soil was multiplied by the assumed volume weight and converted into annual tons.

Field surveys and reviews of aerial photography and ortho photography show that conditions on the stream to be similar depending on the land use and vegetative cover through which the stream flows. For example, most of the wetland segments reviewed displayed similar erosional features and characteristics, as did pastures and grasslands with limited animal access, lands with animal access, and woodland areas.

To estimate the total annual soil lost from streambank erosion on Upper Mud Creek, the surveyed annual soil loss rates were assumed to be representative of rates for all the segments of Upper Mud Creek that were similar in land use and land cover. The stream centerline was segmented and categorized by land use/land cover (Figure 5.1). An annual soil loss rate was estimated for each land use category based on the erosion observations taken in both Upper and Lower Mud Creeks. Again, based on the field work at various locations, each land use type was assigned a percent of streambank experiencing excess erosion. It was assumed that the balance of each classification is experiencing minor erosion and a literature value for annual stream recession was used to develop an annual rate of soil loss from the stable banks. Table 5-5 below shows the estimated annual mass of sediment from streambank soil loss, applying those representative loss rates to both banks of the stream

Table 5-4. Estimated annual stream bank soil loss in surveyed locations.

Description	Reach	Eroding Bank			Lateral Recession Rate (Ft / Year)	Volume (Ft^3) Eroded Annually	Soil Texture	Approximate Pounds of Soil per Ft^3	Estimated Soil Loss (Tons/Year)
		Length (Ft)	Height (Ft)	Area (Ft^2)					
Lower: Pasture With animal access: 1,700 lineal feet	Lower Mud Creek	100	6	600	0.025	15.0	Sandy Loam	100	0.8
		50	4.5	225	.05	11.3	Sandy Loam	100	0.6
		100	4	400	.025	10.0	Sandy Loam	100	0.5
		45	3	135	.15	20.3	Sandy Loam	100	1.0
		100	3.5	350	.15	52.5	Sandy Loam	100	2.6
		45	2.5	113	.15	16.9	Sandy Loam	100	0.8
		440						**Total**	**6.3**
							Per linear bank-foot		**0.0143**
Upper: Grassland Limited animal access 1,500 lineal feet	2	30	3.5	105	.05	5.3	Silt Loam	85	0.2
		25	4	100	.05	5.0	Silt Loam	85	0.2
		40	6	240	.025	6.0	Silt Loam	85	0.3
		30	1	210	.06	12.6	Silt Loam	85	0.5
		125						**Total**	**1.2**
							Per linear bank-foot		**0.0098**
Lower: Wetland 1,200 lineal feet	Lower Mud Creek	50	3	150	0.1	15.0	Silt Loam	85	0.6
		78	4.5	351	0.1	35.1	Silt Loam	85	1.5
		128						**Total**	**2.1**
							Per linear bank-foot		**0.0166**
Turf grass 800 lineal feet	1	45	6	270	0.1	27.0	Sandy Loam	100	1.4
		49	3	147	0.1	14.7	Sandy Loam	100	0.7
		50	2	100	0.05	5.0	Sandy Loam	100	0.3
		34	3.5	119	0.05	6.0	Sandy Loam	100	0.3
		178						**Total**	**2.6**
							Per linear bank-foot		**0.0148**
Lower: Wooded 10,600 lineal feet	Lower Mud Creek	100	2	200	0.01	2.0	Silt Loam	85	0.1
		69	8	552	0.3	165.6	Silt Loam	85	7.0
		75	4	300	0.1	30.0	Silt Loam	85	1.3
		15	3	45	0.2	9.0	Silt Loam	85	0.4
		259						**Total**	**8.8**
							Per linear bank-foot		**.0339**

Note: Based on field surveys conducted April 2011.

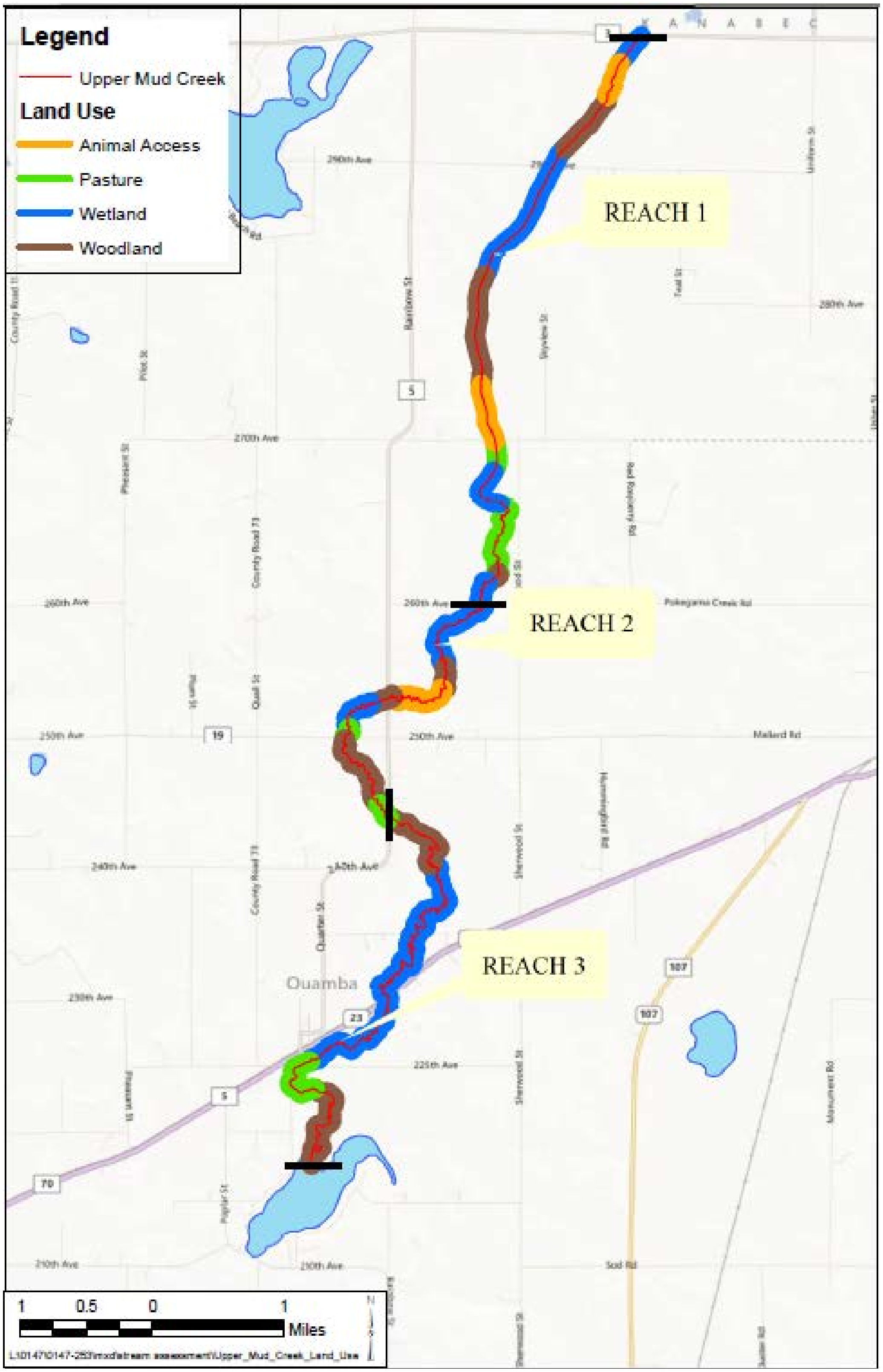


Figure 5.1. Reaches and corridor types in Upper Mud Creek.

Table 5-5. Estimated annual stream bank soil loss, Upper Mud Creek.

Reach	Land Use	Stream Length (ft)	% With Excess Erosion	Excess Eroding Bank		Stable Bank		Soil Loss (Tons/Year)
				Bank Length (ft)	Soil Loss Rate (Tons/Yr/bank-ft)	Bank Length (ft)	Soil Loss Rate (Tons/Yr/bank-ft)	
1	Animal Access	3,724	15%	1,117	0.0143	6,331	0.000375	18.3
	Pasture	0	5%		0.0098	0	0.000375	0.0
	Wetland	7,529	5%	753	0.0166	14,306	0.000211	15.5
	Woodland	7,266	5%	727	0.0339	13,805	0.000375	29.8
2	Animal Access	3,767	15%	1,130	0.0143	6,404	0.000375	18.6
	Pasture	7,146	5%	715	0.0098	13,576	0.000375	12.1
	Wetland	8,595	5%	859	0.0166	16,330	0.000211	17.7
	Woodland	7,594	5%	759	0.0339	14,428	0.000375	31.1
3	Animal Access	0	15%	-	0.0143	0	0.000375	0.0
	Pasture	2,725	5%	272	0.0098	5,178	0.000375	4.6
	Wetland	18,124	5%	1,812	0.0166	34,436	0.000211	37.4
	Woodland	9,748	5%	975	0.0339	18,522	0.000375	40.0
	Total	**76,217**		**9,119**		**143,316**		**225.2**

5.2.3 Sediment Delivery and Transport

The total annual soil lost from watershed and stream bank sources and delivered to Upper Mud Creek as calculated in the previous sections is:

Watershed Sources	49.05 tons/year
Streambank Sources	225.2 tons/year
TOTAL	274.25 tons/year

In undisturbed watersheds there is still some minor soil lost every year and delivered to nearby streams. Sediment loss from stream bank erosion also occurs in undisturbed streams as channels undergo natural evolution and as the stream meanders within its meander belt. Channels are made and unmade; streams in equilibrium will neither on average aggrade, or experience deposition, nor degrade, or scour. Changes in sediment delivery, particle size, stream flow, or stream slope (Lane 1955) may cause the stream to aggrade or degrade, impacting channel type and morphology. An aggrading stream does not have the power to effectively mobilize and flush streambed particles either by bed load or suspended load. Embeddedness such as that found in Upper Mud Creek is often a characteristic of an aggrading stream

The Shields Threshold of Motion Equation (Shields 1936) can be used to determine D_s, the particle size at the threshold of motion, when individual particles on a stream bed are on the verge of motion by stream flow. For a sand-gravel stream in equilibrium at bankfull flow the D_s value is close to the D_{50} value, which is the median particle size.

$$D_s = \tau / ((\rho_s - \rho)\, g\, 0.06)(304.8)$$

D_s=diameter sediment particle (mm)
τ=shear stress=(ρg)(depth)(slope) (lb/ft^2) (N/m^2)
ρ_s=density of sediment (5.15 slugs/ft^3) (2560 kg/m^3)
ρ=density of water (1.94 slugs/ft^3) (1000 kg/m^3)
g=gravitational acceleration (32.2 ft/s^2) (9.81 m/s^2)
0.06 = Shield's parameter typically in the range of 0.04 to 0.07
Conversion constant 304.8 mm/ft or 1000 mm/m

Einstein (1950) developed a method of using the Shields Equation to estimate bedload transport in a way that accounts for the probability that any sediment particle would be mobilized by flow. This method assumes that the streambed material is not uniformly sized and uses channel depth, slope, and sediment size characteristics to estimate the particle size at the threshold of motion. These equations can be used to estimate the rate of bedload transport per unit channel width.

MPCA staff evaluated conditions and morphology at four sites on Upper and Lower Mud Creek using Rosgen's Level II methodology (Rosgen 1996). A stream profile and riffle and pool cross sections were undertaken at one site each on Upper and Lower Mud. That data was used in the Ohio DNR STREAM Sediment Equations Model (Ohio DNR 2011) to calculate shear stress, particle size at threshold of motion, and rate of bedload transport per unit channel width (Table 5-6).

Table 5-6. Threshold of motion parameters for four sites on Mud Creek.

Parameter	Site 3	Site 6	Site 7	Site 10- Lower Mud Creek
Depth (m)	0.5	0.7	0.82	0.727
Slope (m/m)	0.0007	0.0003	0.0005	.0016
Sediment D_{50} (mm)	0.06	0.13	0.5	23
Shear Stress (lb/ft^2)	0.072	0.045	0.084	0.237
Particle at Threshold of Motion (mm)	3.54	2.21	4.14	11.7
% Particles Smaller	95%	96%	74%	43%
Unit Bedload Transport (m^2/s unit width)	<0.000001	<0.000001	0.000004	<0.000001

At the three Upper Mud Creek sites, the size of particle at the threshold of motion is larger than the D_{50} particle size, which is the median particle size. At those sites, the channel morphology and sediment composition is such that the stream should be able to effectively mobilize particles on the streambed. At Site 10, the opposite is true, which typically results in aggradation.

While it appears the stream has the capability to mobilize the sediment on the stream bottom, that sediment is composed primarily of fine sands and silt. Native soils in the direct watershed are generally Fernander, Mora and Plover fine sandy loam and Milaca-Brennyville complex, which is a silt loam-fine sandy loam complex.

Almost all the locations that were evaluated on both Upper and Lower Mud Creek are dominated by fine sand and silt, except for the subreach just downstream of Quamba Lake where Site 10 is located. Pebble counts taken as part of the assessment of geomorphology found very few particles larger than 2 mm at Site 3 and Site 6, and about 30 percent larger than 2 mm at Site 7. Most of the larger particles were smaller than 45 mm, or about 1.7 inches. Site 10 was unusually rocky, with particles up to 362 mm (14 inches) in diameter. If cobble and larger bed material is present in Upper Mud Creek, it may be well below a layer of fine sands and silts that may be mobilized but which is constantly being replenished from the banks and watershed.

The Stressor ID found that significant characteristics of the fish impairment were lack of simple lithophils, or fish that lay their eggs in the interstices of gravel and coarse sand, and to a lesser extent lack of benthic insectivores, which feed on organisms that live in the bottom substrate. The impact of streambed quality was less conclusive for macroinvertebrates. Scores for the metric representing abundance of clinger species, which attach themselves to the stream bottom or to rocks and cobble or other substrates in the stream, would generally be depressed when excess sedimentation limits their habitat. However, scores on Upper Mud Creek did not appear to be sensitive to this. However, Site 3, which had the highest percentage of fine sediment on the stream bottom, did score poorly on taxa richness of Plecoptera, Odonata, Ephemeroptera, and Tricoptera compared to the other sites. These orders are more sensitive to sediment accumulation.

5.2.4 Causes of Streambank Erosion

Field data measured at sites on Upper and Lower Mud Creek and the estimates of sediment delivered from the watershed and from the non-surveyed streambanks indicate that stream bank erosion is likely the primary source of excess sediment contributed to Upper Mud Creek. The stream flows through wetlands, grass/pastureland, and wooded areas. Many of the eroded banks are outside bends, with deposition creating point bars and channel braids. There are also several instances of moderate to severe erosion downstream of culvert crossings. Streambank vegetation is variable, either wetland grasses such as reed canary grass or short grasses with sparse trees that do not provide adequate stream bank stability. Animals have free access to the stream in several locations, and in those areas streambanks are denuded of vegetation and physically disturbed.

It is likely that natural fluvial stream migration processes in Upper Mud Creek are accelerated by the disturbed riparian conditions. The less stable streambanks are more likely to experience erosion and mass wasting, delivering more sediment to the stream than it can effectively flush. Streambank loss may also be widening the stream, reducing effective stream depth, power, and velocity. Thus riparian disturbance is the likely source of excess sediment in Upper Mud Creek.

5.3 BIOTIC INTEGRITY TMDL

The Stressor ID identified five stressors affecting biotic integrity in Upper Mud Creek. Two of these stressors are associated with a specific pollutant – dissolved oxygen (DO) and bedded sediment. The water quality monitoring performed for the Stressor ID recorded some periods of low DO and concluded that occasional low levels of DO may be contributing to the biotic impairment. The data was not sufficient to determine whether the impairment listing criteria were violated. Occasional low DO concentrations appear to be related to nutrient enrichment from the watershed, and potentially from discharges from disturbed wetlands that may be exporting phosphorus instead of sinking phosphorus.

Minnesota does not currently have a standard for bedded sediment. The Stressor ID concluded that suspended sediment Upper Mud Creek falls within the lower percentile of ecoregion reference streams, and that the source of excess bedded sediment is excess sediment delivered from the streambanks and channel itself. That load is used as a surrogate for bedded sediment.

The three other stressors – loss of degraded riparian habitat, loss of connectivity due to ditching, and flow alteration - are not associated with a specific pollutant for which a TMDL can be developed. However, based on the Stressor ID, the goals for those stressors are established in Section 5.4 below. Achieving these goals will also address common causes of low DO concentration.

5.3.1 Wasteload Allocation

Wasteload allocations typically include three sources: permitted wastewater dischargers, Municipal Separate Storm Sewer Systems (MS4s), and construction and industrial storm water. There are currently no permitted wastewater dischargers or MS4s located in the Upper Mud Creek watershed. However, should a WWTF or regulated MS4 community be proposed; Section 6.0 describes the process or steps necessary to obtain a permit to discharge.

There is a limited amount of construction activity within the impaired reach watershed each year, so a wasteload allocation of 0.1% has been set aside for that purpose.

5.3.2 Load Allocation

The Load Allocation includes all sources not covered by a state or federal permit. As noted in Section 5.2 above, the primary sources of bedded sediment are watershed load delivered directly from the landscape or conveyed by channels, tiles, or pipes; and stream bank load resulting from erosion and mass wasting. Potential sediment delivery for each of these sources was estimated above for current conditions.

Based on the soil erodibility, topography, and cropping practices within the watershed, and the size of the watershed tributary to the impaired reach, the annual volume of sediment contributed from the watershed is estimated to be small compared to the volume estimated to be contributed from the streambanks each year. The Wisconsin NRCS found a range of 0.01 to 0.05 feet of soil loss per year on undisturbed streams, with 0.01 being the most pristine in a minimally altered watershed and 0.05 stable but in a more disturbed watershed.

Because the Upper Mud Creek watershed contains areas that have been impacted and areas that have been minimally impacted, a stable recession rate of 0.025 feet per year was selected to establish the TMDL. For fine loamy sand banks, assuming an average three foot bank that rate equates to an annual soil loss of .000375 tons per year per bank-foot. Where the banks are silty loam, such as those found in the wetland sub-reaches of Upper Mud Creek, that equates to an annual soil loss of 0.0002125 tons per year per bank-foot. Table 5-7 calculates a reduction of 179.2 tons per year as the difference between estimated current conditions and that stable lateral recession rate of 0.025 feet per year, a reduction of 80 percent.

Table 5-7. Streambank soil loss calculation.

Reach	Land Use	Stream Length (ft)	Current Conditions Soil Loss (Tons/Year)	TMDL Conditions Soil Loss (Tons/Year)	Reduction (Tons/Year)
1	Animal Access	3,724	18.3	2.8	15.6
	Pasture	0	0.0	0.0	0.0
	Wetland	7,529	15.5	3.2	12.3
	Woodland	7,266	29.8	5.4	24.4
2	Animal Access	3,767	18.6	2.8	15.7
	Pasture	7,146	12.1	5.4	6.7
	Wetland	8,595	17.7	3.6	14.1
	Woodland	7,594	31.1	5.7	25.4
3	Animal Access	0	0.0	0.0	0.0
	Pasture	2,725	4.6	2.0	2.6
	Wetland	18,124	37.4	7.7	29.7
	Woodland	9,748	40.0	7.3	32.7
	Total	**76,217**	**225.2**	**45.9**	**179.2**

5.3.3 Margin of Safety

An explicit MOS was used to compute the TMDL. The estimates of stream bank erosion and recession rates were based on a limited review of field conditions and aerial photos as well as local knowledge and professional judgment. A MOS of 10% of the stream bank load was included in the TMDL to account for uncertainties in the estimates used in the model.

5.3.4 Summary of TMDL Allocations

A 67% reduction in sediment loading to Upper Mud Creek is necessary to achieve the bedded sediment TMDL (Table 5-8). Streambank sources would need to be reduced by 82% to meet the TMDL.

Table 5-8. Upper Mud Creek Bedded Sediment Total Maximum Daily Load allocations.

Allocation	Source	Existing Bedded Sediment Load		Bedded Sediment TMDL (WLA & LA)		Load Reduction[3]	
		(tons/year)[1]	(tons/day)[2]	(tons/year)[1]	(tons/day)[2]	(tons/year)	%
Wasteload Allocation	Construction & Industrial Stormwater	3	<0.10	3	<0.10	0	0
Load Allocation	Watershed	49	0.13	49	0.13	0	0
	Streambank	225	0.62	41	0.11	184	82
MOS (10%)		--	--	5	0.01	--	--
TOTAL		**277**	**0.76**	**98**	**0.27**	**184**	**67**

[1] All fractional loads rounded up to the next whole number to provide a conservative estimate
[2] Annual loads converted to daily by dividing by 365.
[3] Net reduction from current load to TMDL is 179 tons/yr; but gross load reduction from all sources must accommodate the MOS as well, and hence is 179 + 5 = 184 tons/yr.

5.3.5 Seasonal and Annual Variation

The daily load reduction targets in this TMDL are calculated from annual rescission rates observed by the Wisconsin NRCS on a variety of streams over numerous years and reflect a wide variety of seasonal and annual variation in conditions. Consequently, using these average rates addresses both seasonal and annual variability.

5.3.6 Reserve Capacity

The amount of land in agricultural use in the Upper Mud Creek watersheds is likely to remain fairly constant over the next several decades. The watershed is comprised mainly of wetlands and pasture and hay with some land used for row crops (corn and soybeans). While the majority of the landscape is likely to remain in an agricultural land use, it is possible a modest shift between pasture/hay and row crops may occur. Slight shifts in land use should not appreciably change the magnitude of the land use runoff variability that the period of record assumed in the NRCS rescission rates already reflects.

5.4 BIOTIC INTEGRITY AND NON-TMDL PARAMETER TARGETS

5.4.1 Low Dissolved Oxygen Concentrations

Limited analysis of DO data was completed in the Stressor ID. Low DO concentrations were recorded during the summer months at some locations; however, the cause(s) of those low readings was not determined. Likely causes include excess nutrient delivery and enrichment from the watershed and for Lower Mud Creek, from Quamba Lake; low-oxygen outflow from riparian and in-line wetlands; and lack of reaeration opportunities.

While more data is necessary to better diagnose the cause(s) of periods of low dissolved oxygen, some general goals to increase reaeration can be established for Upper Mud Creek. Many of the goals to reduce excess sedimentation and improve riparian conditions would also positively impact DO conditions.

- The Creek passes through some wooded reaches, but the tree canopy is often sparse. There is limited temperature data, but in the summer months, the stream temperature often rises above 20°

C. Stream warming decreases the saturation capacity of streamflow. Increased warming can also enhance primary production, which in turn consumes DO. Manage riparian trees and vegetation so that the stream surface is at least 25 percent shaded.

- Reduce sediment and nutrient enrichment from overland flow and streambank erosion by stabilizing streambanks with native buffers. Establish a goal of 100% native vegetation coverage except where stabilized animal access to the stream must be maintained.

5.4.2 Degraded Riparian Habitat

Logging and land conversion to pasture and hay has altered the Upper Mud Creek riparian zone. The Stressor ID Study performed a Pfankuch Stability Index assessment at the monitoring sites along both Upper and Lower Mud Creek. Three of the five sites on Upper Mud scored "Poor" for bank and stream bottom stability, scoring poorly on vegetative bank protection and low bank rock content.

- An aerial photo analysis shows areas of Upper Mud Creek with little or no buffer on either side of the stream. There are also areas of very dense tree canopy where shading may be inhibiting the growth of stabilizing understory vegetation. Restore native vegetation on the streambanks and riparian zone to stabilize streambanks, filter runoff, and provide overhanging vegetation, with a goal of providing a buffer at least 50 feet wide on both sides of the stream.

- Unrestricted animal access to the stream has resulted in bare and eroded streambanks as well as sparse vegetative cover in overgrazed areas. Limit animal access to stabilized access points.

5.4.3 Loss of Watershed Connectivity and Flow Alteration Due to Ditching

Ditching has reduced the connectivity of the stream to its floodplain as well as physically altered the stream. In ditched segments, dredging and straightening have reduced pool frequency and depth and channel roughness has been reduced by eliminating riffles. These ditched segments with limited habitat may limit the colonization of species from one segment of the stream to another. It is unlikely that the stream could be restored to a more natural form and function along its entire length, however, ditched segments could be evaluated to assess whether it is possible to enhance habitat and restore some connectivity.

Ditching in the watershed to drain wetlands and to provide for more arable land has likely changed the hydrology of the stream from its pre-settlement conditions. Segments that are ditched my experience higher velocities and more bank instability than the segments that are more naturally meandering. As above, ditched segments could be evaluated to assess whether stream stabilization may be necessary to protect the banks from increased flows and durations.

6.0 Impact of Growth on TMDL Allocations

6.1 MS4

There are currently no MS4 communities in the impaired reaches watersheds and there are no plans to develop MS4 communities in the watersheds for the foreseeable future. However, future transfer of loads in this TMDL may be necessary if any of the following scenarios occur within the impaired reaches watershed boundaries:

1. New development occurs within a regulated MS4. Newly developed areas that are not already included in the WLA must be given additional WLA to accommodate the growth.
2. One regulated MS4 acquires land from another regulated MS4. Examples include annexation or highway expansions. In these cases, the transfer is WLA to WLA.
3. One or more non-regulated MS4s become regulated. If this has not been accounted for in the WLA, then a transfer must occur from the LA.
4. Expansion of an urban area encompasses new regulated areas for existing permittees. An example is existing state highways that were outside an Urban Area at the time the TMDL was completed, but are now inside a newly expanded urban area. This will require either a WLA to WLA transfer or a LA to WLA transfer.
5. A new MS4 or other storm water-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 other TMDLs. WLAs for new MS4s will be transferred from the LA and calculated by multiplying the municipalities' percent watershed area by the total watershed loading capacity after the MOS has been subtracted (MPCA, 2006). In cases where WLA is transferred from or to a regulated MS4, the permittees will be notified of the transfer. Ultimately, increases in urban storm water also increase the loading capacity of the receiving water thereby supplying their own increases in receiving water assimilative capacity.

6.2 WASTEWATER TREATMENT FACILITIES

The MPCA, in agreement with the US EPA Region 5, has developed a streamlined process for wasteload allocations (WLAs) for new and expanding wastewater discharges to waterbodies with EPA approved TMDLs. This procedure will be used to update WLAs in approved TMDLs for new or expanding wastewater dischargers whose permitted effluent limits are sufficiently restrictive to ensure that the effluent concentrations will not exceed applicable water quality standards or surrogate measures. The process for modifying any and all WLAs after TMDL approval will be handled by the MPCA, with input and involvement of the US 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 US EPA to comment on the changes and recommendations based on the proposed WLA modification(s). Once any comments or concerns are addressed, and the MPCA determines that new or expanded WWTF is consistent with the applicable water quality standards, the permit will be issued and any updates to the TMDL WLA(s) will be made.

7.0 Implementation

7.1 IMPLEMENTATION FRAMEWORK

The Aitkin, Kanabec, Mille Lacs and Pine County SWCDs and County Environmental Services will coordinate implementation of actions identified in this TMDL and the Snake River Watershed Restoration and Protect Strategies (WRAPS) in partnership with the Snake River Watershed Management Board (SRWMB). All actions will be incorporated into each county's Comprehensive Local Water Plan.

7.2 *E. COLI* AND NUTRIENT LOAD REDUCTION STRATEGIES

The following is a description of potential actions for bacterial and nutrient loading to Mud Creek, Bear Creek, Knife Lake, Quamba Lake, Pokegama Lake and Cross Lake. These actions will be further developed in the TMDL Implementation Plan.

Lakes. Implementation activities for Knife, Quamba, Pokegama and Cross Lakes should focus primarily on watershed and internal phosphorus load reductions. All four lake TMDLs require load reductions including upgrading all noncompliant SSTSs. Reductions specific for Cross Lake will include WWTF load reductions and upstream nutrient impaired lake restoration to meet water quality criteria. Reductions in watershed loading will need to come from land practices including manure and livestock management. Another important factor in restoring all four lakes will be vegetation management.

E. coli. During higher flow events, the majority of *E. coli* appears to be coming from pastures near the streams and ditches in the watershed. During low flows, cattle access to streams and failing septic systems are major sources. Therefore, BMPs should focus on livestock exclusions, buffers, and manure management.

The estimated total cost of implementing these and other potential BMPs ranges from $500,000 to $1,500,000.

7.2.1 Installation or Enhancement of Buffers

The largest potential sources of *E. coli* and other bacteria are those activities associated with pasture management. In many locations along the river, cattle grazing have denuded stream banks of stabilizing native vegetation that would otherwise filter runoff from pastures near streams and waterways. Secondarily, BMPs for upland pasture land should also be implemented.

7.2.2 Pasture Management

Overgrazed pastures, reduction of pastureland and direct access of livestock to streams may contribute a significant amount of nutrients to surface waters throughout all flow conditions. The following livestock grazing practices are for the most part economically feasible and are extremely effective measures in reducing nutrient runoff from feedlots:

- Livestock exclusion from public waters through setback implementation and fencing
- Creating alternate livestock watering systems
- Rotational grazing
- Vegetated buffer strips between grazing land and surface water bodies

7.2.3 Manure Management

Manure Application. Minnesota feedlot rules (MR 7020) now require manure management plans for feedlots greater than 300 animal units that do not employ a certified manure applicator. These plans require manure accounting and record-keeping as well as manure application risk assessment based on method, time and place of application. The following BMPs will be considered in all manure management plans, including animal operations with less than 300 animal units, to reduce potential nutrient delivery to surface waters:

- Immediate incorporation of manure into topsoil
- Reduction of winter spreading, especially on slopes
- Eliminate spreading near open inlets and sensitive areas
- Apply at agronomic rates
- Follow setbacks in feedlot rules for spreading manure
- Erosion control through conservation tillage and vegetated buffers

Additional technologies will be evaluated including chemical addition to manure prior to field application to reduce phosphorus availability and mobility.

Manure Stockpile Runoff Controls. There are a variety of options for controlling manure stockpile runoff that reduce nonpoint source nutrient loading, including:

- Move fences or altering layout of feedlot
- Eliminate open tile intakes and/or feedlot runoff to direct intakes
- Install clean water diversions and rain gutters
- Install grass buffers
- Maintain buffer areas
- Construct solid settling area(s)
- Prevent manure accumulations
- Manage feed storage
- Manage watering devices
- Total runoff control and storage
- Install roofs
- Runoff containment with irrigation onto cropland/grassland
- Vegetated infiltration areas or tile-drained vegetated infiltration area with secondary filter strips

These practices should be applied where appropriate.

Soil Phosphorus Testing. Because the amount of manure applied in the Snake River watersheds is high, soil testing would help manage where manure can be applied with little or no loss to surface waters. A soil phosphorus testing program will allow managers to make better decisions about where TP from manure is needed and where it may be applied in excess.

7.2.4 Septic System Inspections and Upgrades

Aitkin County, Kanabec County, Mille Lacs County, and Pine County should continue to inspect and order SSTS upgrades, with priority given to systems that are imminent threats to public health and safety and failing systems near streams and waterways. The counties should continue to identify and address systems that are not meeting adopted septic ordinances. Special attention shall be given to systems with high nutrient loading potential based on proximity to the lake, streams and systems that may discharge directly to surface water.

7.2.5 Implement Construction and Industrial Stormwater Regulations

The wasteload allocation for storm water discharges from sites where there is construction activities reflects the number of construction sites > 1 acre expected to be active in the watershed at any one time, and the Best Management Practices (BMPs) and other storm water control measures that should be implemented at the sites to limit the discharge of pollutants of concern. The BMPs and other storm water control measures that should be implemented at construction sites are defined in the State's NPDES/SDS General Storm water Permit for Construction Activity (MNR100001). If a construction site owner/operator obtains coverage under the NPDES/SDS General Storm water 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 storm water discharges would be expected to be consistent with the WLA in this TMDL. It should be noted that all local construction storm water requirements must also be met.

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

7.2.6 Internal Nutrient Load Reductions

Internal nutrient loads will need to be reduced to meet the TMDL allocations for all four lakes presented in this document. There are numerous options for reducing internal nutrient loads ranging from simple chemical inactivation of sediment phosphorus to complex infrastructure techniques including hypolimnetic aeration.

Internal load reduction technical review. Prior to implementation of any strategy to reduce internal loading in each lake, a technical review needs to be completed to evaluate the cost and feasibility of the lake management techniques available to reduce or eliminate internal loading. Several options could be considered to manage internal sources of nutrients including hypolimnetic withdrawal, alum treatment, vegetation management and hypolimnetic aeration. A technical review should be completed to provide recommendations for controlling internal loading in each lake. This review will also include the potential impacts of each management option to wild rice beds and other sensitive aquatic vegetation.

7.2.7 Studies and Biological Management Plans

Vegetation management. Curly-leaf pondweed is present in all four lakes, and in some cases at extremely high concentrations. Senescence of curly-leaf pondweed in summer can be a source of internal phosphorus load that often results in a late summer nuisance algal bloom. Vegetation management, such as several successive years of chemical treatment, may be required to keep this exotic invasive species at non-nuisance levels.

Conduct periodic aquatic plant surveys and prepare and implement vegetation management plans. As BMPs are implemented and water clarity improves, the aquatic vegetation community will change. Surveys should be updated periodically and vegetation management plans amended to take into account appropriate management activities for that changing community.

Carp Management. One activity should be to partner with the DNR to monitor and manage the fish population to maintain a beneficial fish community. Options to reduce rough fish populations should be evaluated, and the possibility of fish barriers explored to reduce rough fish access to spawning areas and to minimize rough fish migration between lakes.

Encourage shoreline restoration. Many property owners maintain a turfed edge to the shoreline. Property owners should be encouraged to restore their shoreline with native plants to reduce erosion and capture direct runoff. Shoreline restoration can cost $30-$65 per linear foot, depending on the width of the buffer installed. The Aitkin County SWCD, Kanabec County SWCD, Mille Lacs County SWCD, Pine County SWCD and Snake River Watershed Management Board will continue to work with all willing landowners to naturalize their shorelines.

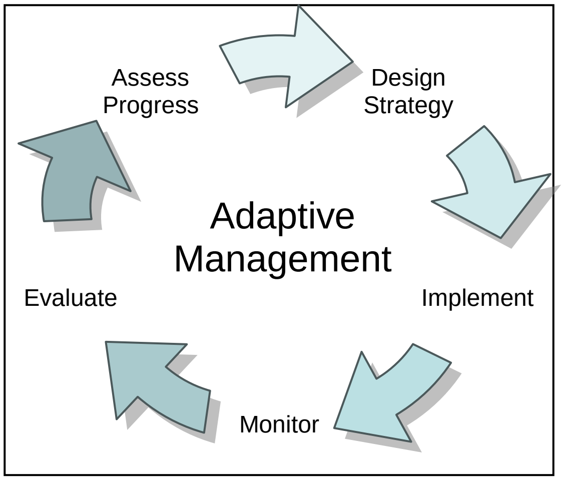
7.2.8 Education

Provide educational and outreach opportunities in the watershed about proper fertilizer use, manure management, grazing management, low-impact lawn care practices, and other topics to increase awareness of sources of pollutant loadings to the lakes and encourage the adoption of good individual property management practices. Opportunities to better understand aquatic vegetation management practices and how they relate to beneficial biological communities and water quality should also be developed.

7.3 BIOTIC INTEGRITY IMPROVEMENT STRATEGIES

Many of the bacteria load reduction activities identified above such as installation of native buffers and controlling animal access to the streams will also benefit biotic integrity. Implementation should also include physically assessing ditched segments to determine if additional streambank stabilization is required, or whether habitat enhancements can be made.

7.4 ADAPTIVE MANAGEMENT



This list of implementation elements and the more detailed implementation plan that will be prepared following this TMDL assessment focuses on adaptive management. As the bacteria, nutrient, sediment dynamics and other stressors throughout the Snake River watershed are better understood, management activities both to reduce the pollutants of concern and to address the other biotic stressors will be changed or refined to efficiently meet the TMDL and lay the groundwork for de-listing the impaired lakes and reaches.

7.5 COST

As part of all TMDLs a cost estimate for implementing the necessary actions to restore the impaired waters included is required. Based on a review of the impairments, and the scale at which restoration needs to happen in the watershed it is estimated that a dollar range of $10 - $15 Million might be necessary. However, this is an estimate and many aspects can cause the costs to rise and fall as implementation takes place across the watershed.

8.0 Reasonable Assurance

8.1 INTRODUCTION

As part of an implementation strategy, reasonable assurances provide a level of confidence that the TMDL allocations will be implemented by federal, state, or local authorities. Implementation of these TMDLs will be accomplished by both state and local action on many fronts, both regulatory and non-regulatory. Multiple entities in the watershed already work towards improving local water quality. Water quality restoration efforts will be led by the Aitkin SWCD, Kanabec SWCD, Mille Lacs SWCD, Pine SWCD, Counties, Townships, and the Snake River Watershed Management Board; along with assistance from the local communities, and lake and watershed organizations.

8.2 NON-REGULATORY

At the local level, Aitkin County SWCD, Kanabec County SWCD, Mille Lacs County SWCD, Pine County SWCD, and SRWMB currently implement programs targeted at water quality improvement and have been actively involved in projects to improve water quality in the past. It is anticipated that their involvement will continue. Potential funding of TMDL implementation projects includes:

- Conservation Reserve Program,
- Federal Section 319 program for watershed improvements,
- Funds ear-marked to support TMDL implementation from the Clean Water, Land, and Legacy constitutional amendment, approved by the Minnesota's citizens in November 2008,
- Local government cost-share funds,
- CWP Grants, and
- CWP (SRF Loan Funds).

The implementation strategies described in this TMDL have demonstrated to be effective in reducing loadings to lakes and streams. The Aitkin County SWCD, Kanabec SWCD, Mille Lacs SWCD, Pine County SWCD and SRWMB have programs in place to continue many of the recommended activities; however much of it is dependent upon funding. Monitoring will continue as local and state funding allows, and adaptive management will be in place to evaluate progress made towards achieving the beneficial use of each impaired lake and stream in the Snake River watershed.

8.3 REGULATORY

State implementation of the TMDL will be through action on NPDES permits for regulated construction storm water. To meet the WLA for construction storm water, construction storm water activities are required to meet the conditions of the Construction General Permit under the NPDES program and properly select, install, and maintain all BMPs required under the permit, including any applicable additional BMPs required in Appendix A of the Construction General Permit for discharges to impaired waters, or meet local construction storm water requirements if they are more restrictive than requirements of the State General Permit.

To meet the WLA for industrial storm water, industrial storm water activities are required to meet the conditions of the industrial storm water general permit or Nonmetallic Mining & Associated Activities general permit (MNG49) under the NPDES program and properly select, install and maintain all BMPs required under the permit.

Kanabec, Mille Lacs, Aitkin and Pine County's current septic system ordinance is based on septic system inspection at the time of property transfer or installation of any new or replacement on-site sewage disposal system. From 2007 – 2012, Kanabec County has been successful and receiving and implementing Clean Water Partnership SRF Loan Funds to replace failing and non-compliant systems. This is a program that Kanabec County looks to continue into the future, should funding be available.

Kanabec, Mille Lacs, Aitkin and Pine County are not MPCA delegated partner with the State Feedlot Program and does not employ a County Feedlot Officer; MPCA provides field staff for feedlot permitting and compliance checks on all registered animal operations.

Through other local, state, and federal regulatory programs such as shore land ordinances, SSTS rules, Wetland Conservation Act, Farm Bill, and other County Ordinances potential sources of phosphorus, sediment, and E. coli are being addressed.

The following is a discussion of the key agencies at the local level that will help assure that implementation activities proposed under this TMDL report will be executed.

8.4 SOIL AND WATER CONSERVATION DISTRICTS

The Snake River watershed is located within the jurisdiction of four Soil and Water Conservation Districts (SWCD): Aitkin County SWCD, Kanabec County SWCD, Milles Lacs County SWCD and Pine County SWCD. In general, the SWCDs plan and execute policies, programs, and projects that conserve soil and water resources within their jurisdictions. The SWCDs are involved in implementation of practices that reduce or prevent erosion, sedimentation, siltation, and other pollution in order to protect water and soil resources. The SWCDs frequently provide education, outreach and cost share for many types of projects, such as erosion control structures.

The SWCD is the first step for landowners wanting to implement BMPs or other conservation projects. The SWCD provides technical assistance through the planning, engineering, and funding process. The Area III-SWCD Technical Service Area (TSA) provides engineering and project oversight assistance. Through the SWCD, the TSA provides a licensed engineering, engineering technician, and vegetation specialist for work on BMPs. The local SWCD works with the landowner on project planning, coordination, and funding assistance.

Each SWCD develops an annual work plan that identifies actions for the year that address specific objectives from the Long Range District Comprehensive Plan. District staff and board members have established working relationships with a number of different agencies and groups. These include County Environmental Services, the SRWMB, and the NRCS, for example. The SWCD staff and board also maintain regular communication with the County commissioners and State legislators regarding progress, accomplishments, budgets, and services.

The SWCD assists with carrying out the goals and objectives of the Kanabec County Comprehensive Local Water Plan (CLWP), Wetland Conservation Act (WCA), Board of Water and Soil Resources (BWSR) related programs, NRCS, SRWMB, and the East Central Landscape Committee. Coordinating the TMDL for the Ann River subwatershed and Snake River Watershed area is identified in the 2011 annual work plan. SWCD staff and funding have been identified for this task. Additionally, the SWCD outlines a number of other action steps for maintaining and improving surface and groundwater quality, including technical assistance to landowners, implementation of BMPs, and state and local agency partnerships.

All of the SWCD's have been very successful in the past in implementation BMPs in the past. During the development of this TMDL, the Kanabec SWCD continues to work with landowners on Knife Lake and Quamba Lake to implement lakeshore BMP's to control erosion, sedimentation and reduce nutrient runoff. Examples of past BMP's on these lakes include the establishment of native vegetative buffers and bank stabilization projects, using rock rip – rap. The SWCD is promoting more bioengineering as the technology improves. In order for a landowner to receive state cost share funds to protect and stabilize their lakeshore property, the SWCD requires the installation of a twenty five foot (depth) vegetative buffer strip.

The Aitkin County SWCD, Kanabec County SWCD, Mille Lacs County SWCD, and Pine County SWCD will continue to coordinate the implementation of the TMDL and work with partnering agencies to meet the goals and standards recommended in these TMDLs.

8.5 SNAKE RIVER WATERSHED MANAGEMENT BOARD

Each of the impaired reach watersheds are part of the larger Snake River Watershed. The Snake River Watershed Management Board (SRWMB), through a joint powers agreement with Aitkin, Kanabec, Mille Lacs, and Pine Counties, coordinates the counties' comprehensive water plans as they pertain to the area within the Snake River Watershed. This cooperative management allows for more comprehensive protection and enhancement of water and land resources within the watershed.

The SRWMB also has a Citizen's Advisory Committee (CAC) whose membership includes a SWCD supervisor from each county, two citizens, lake association member, and any individual looking to attend the meetings. The CAC meets to address policy issues and specific topics, such as land use management, proposed BMP project requests, water quality monitoring, and education/stewardship, then advises the SRWMB on these issues.

The SRWMB will play a role in the implementation of all TMDLs presented in this report by providing a level of coordination across local governments. The SRWMB will also work closely with the SWCDs to identify BMP projects and administer grant funding for those projects.

The SRWMB successfully completed a Snake River Watershed CWP Diagnostic and Implementation, and recently completed a Phase II Clean Water Partnership program in the Snake River Watershed. These programs have successfully implemented on the ground management practices to reduce sediment, nutrient, bacteria, as well as other issues, and the intent of the SRWMB is to continue the work it has been doing for the Snake River Watershed.

8.6 COMPREHENSIVE LOCAL WATER MANAGEMENT PLAN

Each county within the Snake River Watersheds currently develops a Comprehensive Local Water Plan (CLWP). The purpose of these plans is to identify existing and potential problems or opportunities for protection, management, and development of water resources and related land resources in each county, including the Snake River Watershed, on a 10 year cycle. Other purposes of the CLWP are to develop and implement an action plan to promote sound water management decisions, and to achieve effective environmental protection of each County's water and land resources.

The CLWP's outline several priority concerns identified during the planning process and goals to address those concerns. Each County's CLWP is slightly different, but all contain the same message about concerns like: protecting and restoring water resources, implementing BMP's, septic systems, shoreland regulations, etc. A link to each Count's CLWP is provided below.

- Aitkin County
- Kanabec County
- Mille Lacs County
- Pine County
- Isanti County
- Chisago County

8.7 SUSTAINED STATE- AND FEDERAL-LOCAL COOPERATION

There are many conservation partners and cooperating agencies that work within the Snake River Watershed to protect and enhance land and water resources. These partnerships were built over time and will be important during the development and implementation of these TMDLs. The list of partners includes, but are not limited to, the Soil and Water Conservation Districts (SWCD), Snake River Watershed Management Board (SRWMB), Board of Soil and Water Resources (BWSR), Natural Resources Conservation Service (NRCS), Farm Service Agency (FSA), Resource Conservation and Development (RC&D) Council, MN DNR, MPCA, Minnesota Department of Agriculture (MDA), Minnesota Department of Health (MDH), St. Croix River Association (SCRA), The Nature Conservancy (TNC), and local lake and watershed associations.

The NRCS agency is federally funded and works with landowners on projects similar to those that local SWCD's works on. The two agencies serve a similar purpose to assist landowners with BMP projects, while finding funding and cost share opportunities. This role will be important for the implementation of the TMDL.

9.0 Monitoring

Progress of TMDL implementation will be measured through regular monitoring efforts of water quality and total BMPs completed. This will be accomplished through the efforts of the cooperating agencies and groups discussed above. As long as sufficient funding exists, the following monitoring efforts below will be targeted. Since funding is limited for effectiveness monitoring, one avenue that could and may be used in this watershed is the Intensive Watershed Monitoring being conducted by the MPCA. This monitoring was conducted in the Snake River Watershed in 2007 and is expected to be monitored again in 2017 as part of the 10 year cycle. At a minimum this effort will help provide data at a larger scale that may not be available otherwise.

However, all efforts will be made locally to conduct and target monitor should funds and staff time be available.

9.1 LAKE MONITORING

Cross Lake, Knife Lake, Pokegama Lake, and Quamba Lake have been periodically monitored by volunteers and staff over the years. This monitoring is planned to continue to keep a record of the changing water quality as funding allows. Lakes are generally monitored for chlorophyll-*a*, total phosphorus, and Secchi disk transparency.

In-lake monitoring will continue as implementation activities are installed across the watersheds. These monitoring activities should continue until water quality goals are met. Some tributary monitoring has been completed on the inlets to the lakes and may be important to continue as implementation activities take place throughout the sub-watersheds.

The MN DNR will continue to conduct macrophyte and fish surveys as allowed by their regular schedule. Currently fish surveys are conducted every 5 years and macrophyte surveys are conducted as staffing and funding allow on a 10-year rotation, unless there are special situations.

9.2 BACTERIA MONITORING

River and stream monitoring in the Snake River Watershed, which includes Mud Creek and Bear Creek, has been coordinated largely by the Snake River Watershed Management Board over the last 10 years as part of two Clean Water Partnership Grants, and other available local funds. Monitoring is being conducted on a smaller scale due to county water plans and limited funding.

Stream monitoring in the Upper Mud, Lower Mud and Bear Creeks should at a minimum continue at the most downstream site to continue to build on the current dataset and track changes based implementation progress. At a minimum it is recommended that two *E. coli* samples be collected each month from May through September. As BMP practices are implemented throughout the watershed it is also suggested that monitoring take place in those subwatersheds to track progress towards the TMDL.

9.3 BIOLOGICAL MONITORING

Continuing to monitor water quality and biota scores in the listed segments will determine whether or not stream habitat restoration measures are required to bring the watershed into compliance. At a minimum, fish and macroinvertebrate sampling should be conducted by the MPCA, MN DNR, or other agencies every five to ten years during the summer season at each established location until compliance is observed for at least two consecutive assessments. It will also be important to continue to conduct streambank assessments before and after any major stabilization BMP is implemented to track if in-stream erosion is improving, or if more work is needed.

Tracking the implementation of BMPs while continuing to monitor the biological conditions in the watershed will assist local stakeholders and the public agencies in determining the effectiveness of the WRAPS document. If biota scores remain below the confidence intervals, further encouragement of the use of BMPs across the watershed through education and incentives will be a priority. It may also be necessary to begin funding efforts for localized BMPs such as riparian buffer and stream restoration.

10.0 Public Participation

A stakeholder and public engagement and participation process was undertaken for this TMDL to obtain input from, review results with, and take comments from the public and interested and affected agencies regarding the development of and conclusions of this TMDL.

10.1 TECHNICAL ADVISORY COMMITTEE

A Technical Advisory Committee was established so that interested stakeholders could be involved in key decisions during development of the TMDL. Stakeholders represented on the Technical Advisory Committee or asked to comment on drafts of the TMDL and/or Stressor Identification included county and SWCD representatives, MN DNR, Board of Water and Soil Resources, NRCS, Lake Association Representatives, MPCA, local non-profits, and other local and city officials. Technical Advisory Committee meetings where this TMDL was discussed were held on the following dates:

- March 26, 2012
- October 22, 2012
- January 28, 2013
- March 30, 2013
- June 5, 2013

10.2 STAKEHOLDER MEETINGS

The general public and lake associations were invited to a series of stakeholder meetings on these TMDLs. These were held on the following dates:

- December 22, 2010
- February 22, 2011
- October 22, 2012
- January 28, 2013
- March 30, 2013
- June 5, 2013
- June 24, 2013 (SRWMB Meeting)

The official TMDL public comment period was held from September 3rd through October 3rd of 2013.

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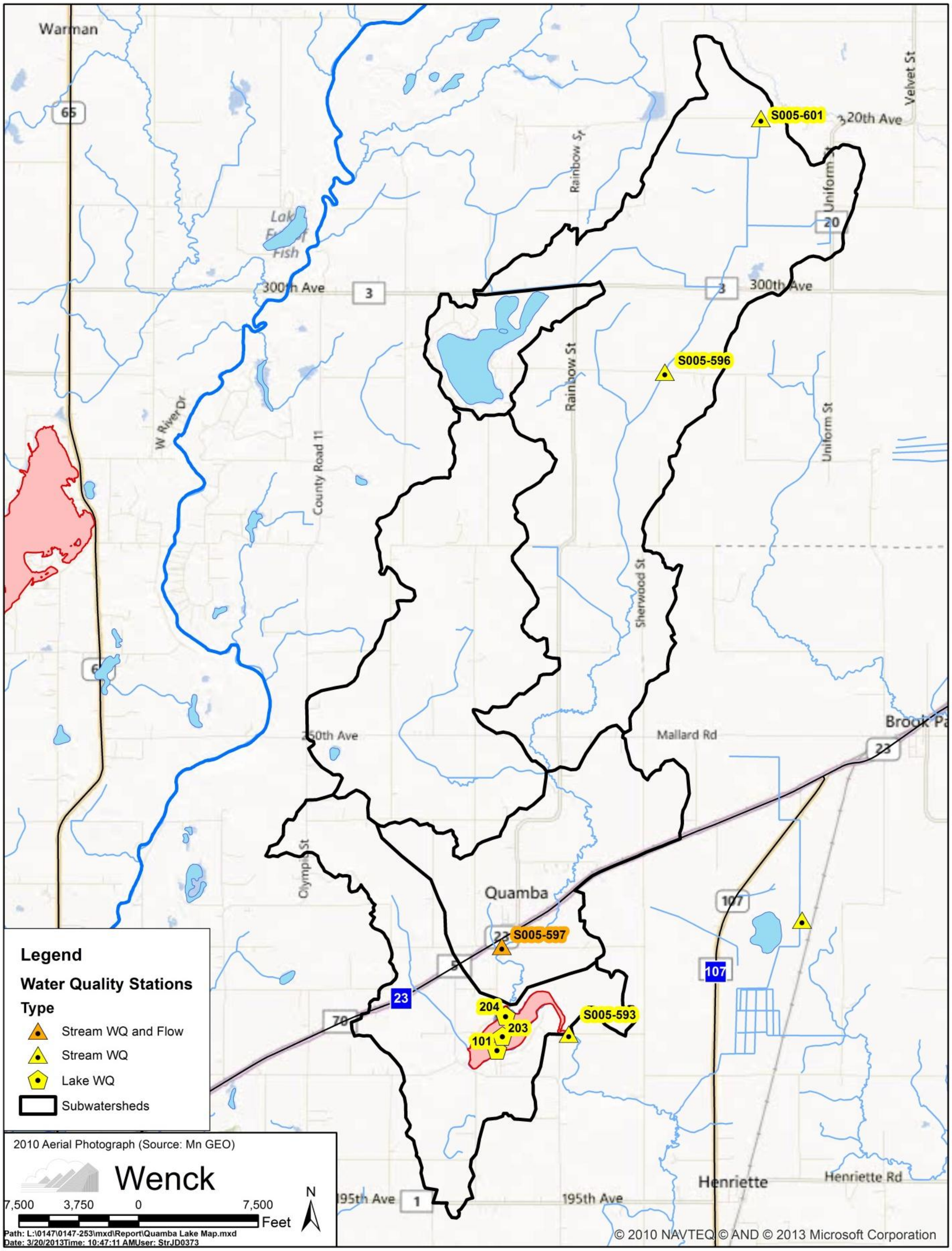
12.0 Appendices

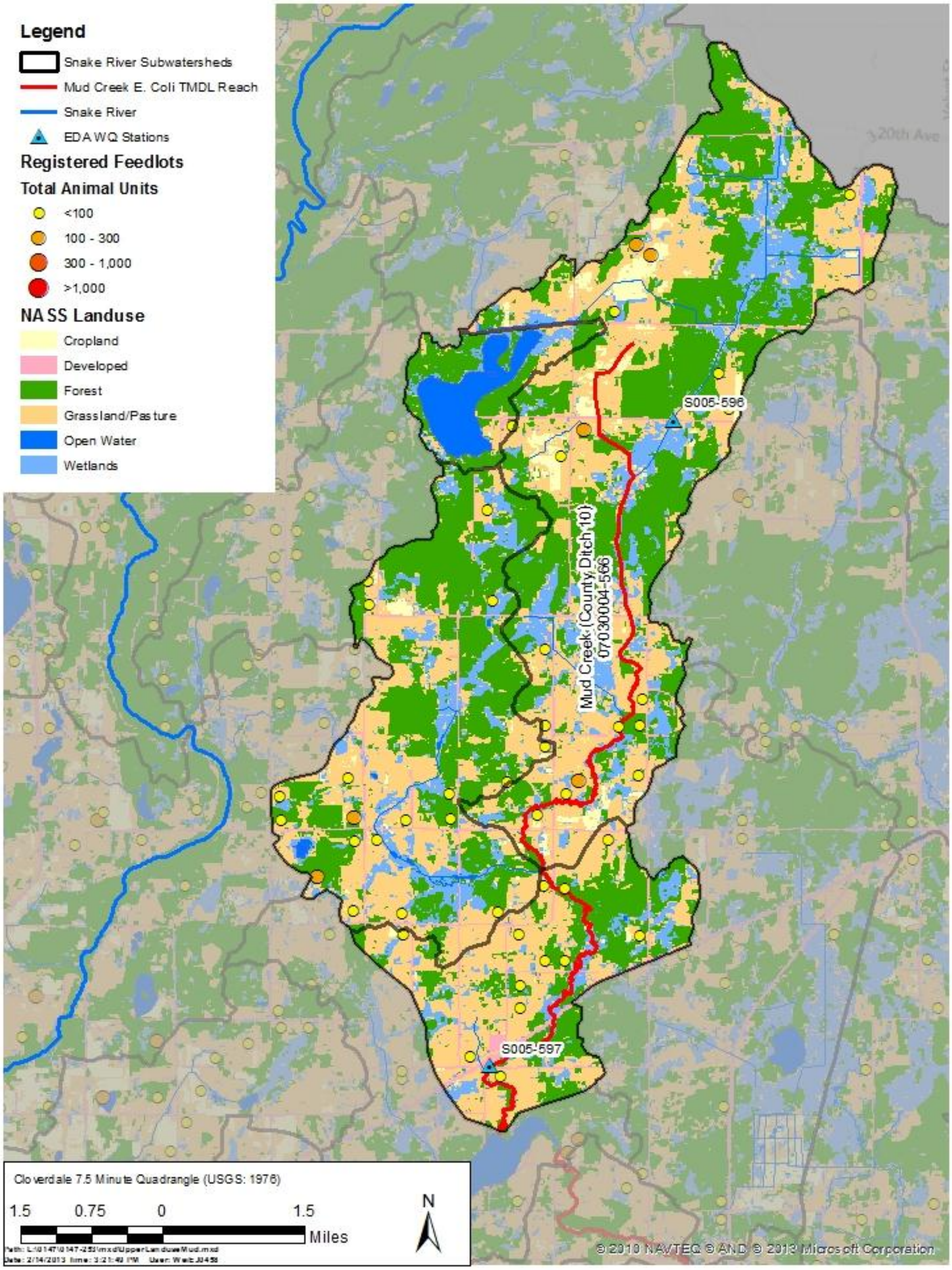
Appendix A

Upper Mud Creek Supporting Documents

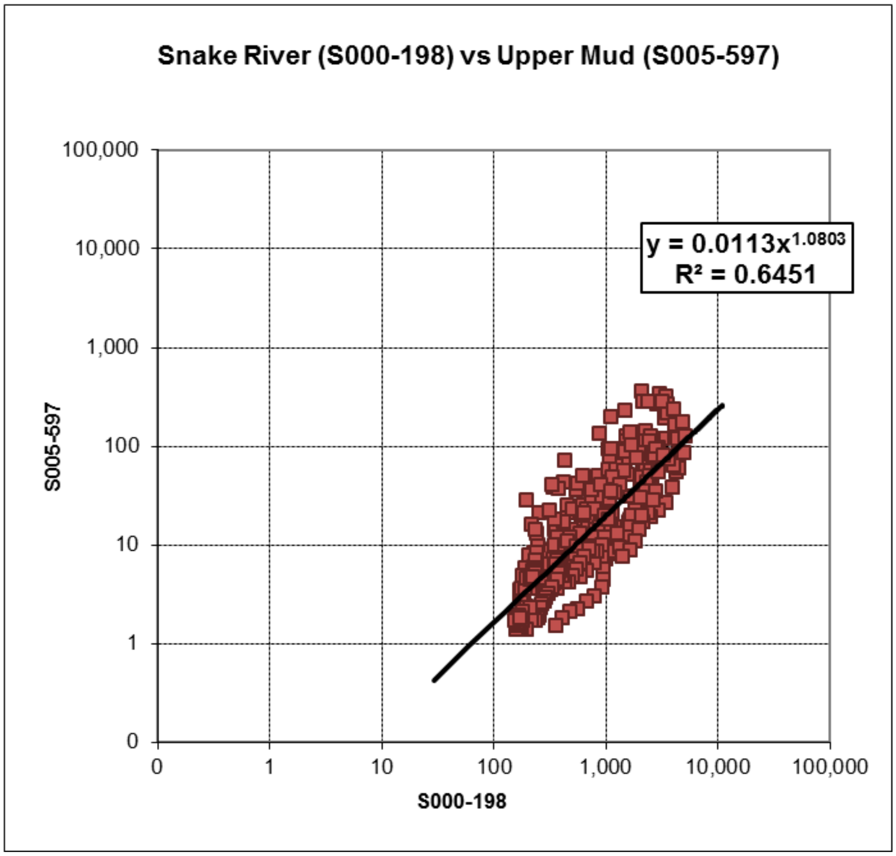
Upper Mud Creek Monitoring Sites



Upper Mud Creek Landuse



Upper Mud Creek and Snake River Flow Regression



Failing Septic System Bacteria Loading Summary

System Type	Count	Bacteria Contribution (10^9 organisms/year)
Non-Failing	146	0
Failure to protect groundwater	28	0
Imminent threat to public health	2	5
Total	176	5

Upper Mud Creek Fecal Coliform Production Inventory

Category	Sub-Category		Animal Units or Individuals
Livestock	The Basin contains an estimated 49 registered livestock facilities ranging in size from less than 50 animal units to several hundred	Dairy	0 animal units
		Beef	1,658 animal units
		Swine	13 animal units
		Poultry	1 animal units
		Other (Horses)	117 animal units
Human[1]	Total systems with inadequate wastewater treatment[2]		2 systems
	Total systems that do not discharge to surface water		174 systems
	Municipal Wastewater Treatment Facilities[4]		123 people
Wildlife[3]	Deer (average 11 per square mile)		350 deer
	Waterfowl (average 10 per square mile)		318 geese/ducks
	Other		Other wildlife was assumed to be the equivalent of deer and waterfowl combined in the watershed.
Pets	Dogs and Cats in Urban Areas[3]		389 dogs and cats

[1] Based on Kanabec County SSTS inventory
[2] Assumes 3.0 people per household (USEPA 2002) and ITPHS failure rate based on Kanebec County SSTS inventory
[3] Calculated based on # of households in watershed (SSTS inventory) multiplied by 0.58 dogs/household and 0.73 cats/household according to the Southeast Minnesota Regional TMDL (MPCA 2002).
[4] City of Quamba started using sanitary sewer in 2012. The discharge is pumped to Mora, outside the watershed.

Upper Mud Creek Bacteria Delivery Assumptions

Category	Source	Assumption
Livestock	Pastures near streams or waterways	13.7% of beef, dairy and horse manure
	Upland pastures	69.6% of beef, dairy and horse manure
	Cropland surface applied manure	16.7% of beef, dairy and horse manure
Human	ITPHS septic systems and unsewered communities	All waste from failing septic systems and unsewered communities
	Municipal wastewater treatment facilities	None
Wildlife	Deer	All fecal matter produced by deer in basin
	Waterfowl	All fecal matter produced by geese and ducks in basin
	Other wildlife	The equivalent of all fecal matter produced by deer and waterfowl in basin
Urban Stormwater Runoff	Improperly managed waste from dogs and cats	10% of waste produced by estimated number of dogs and cats in basin

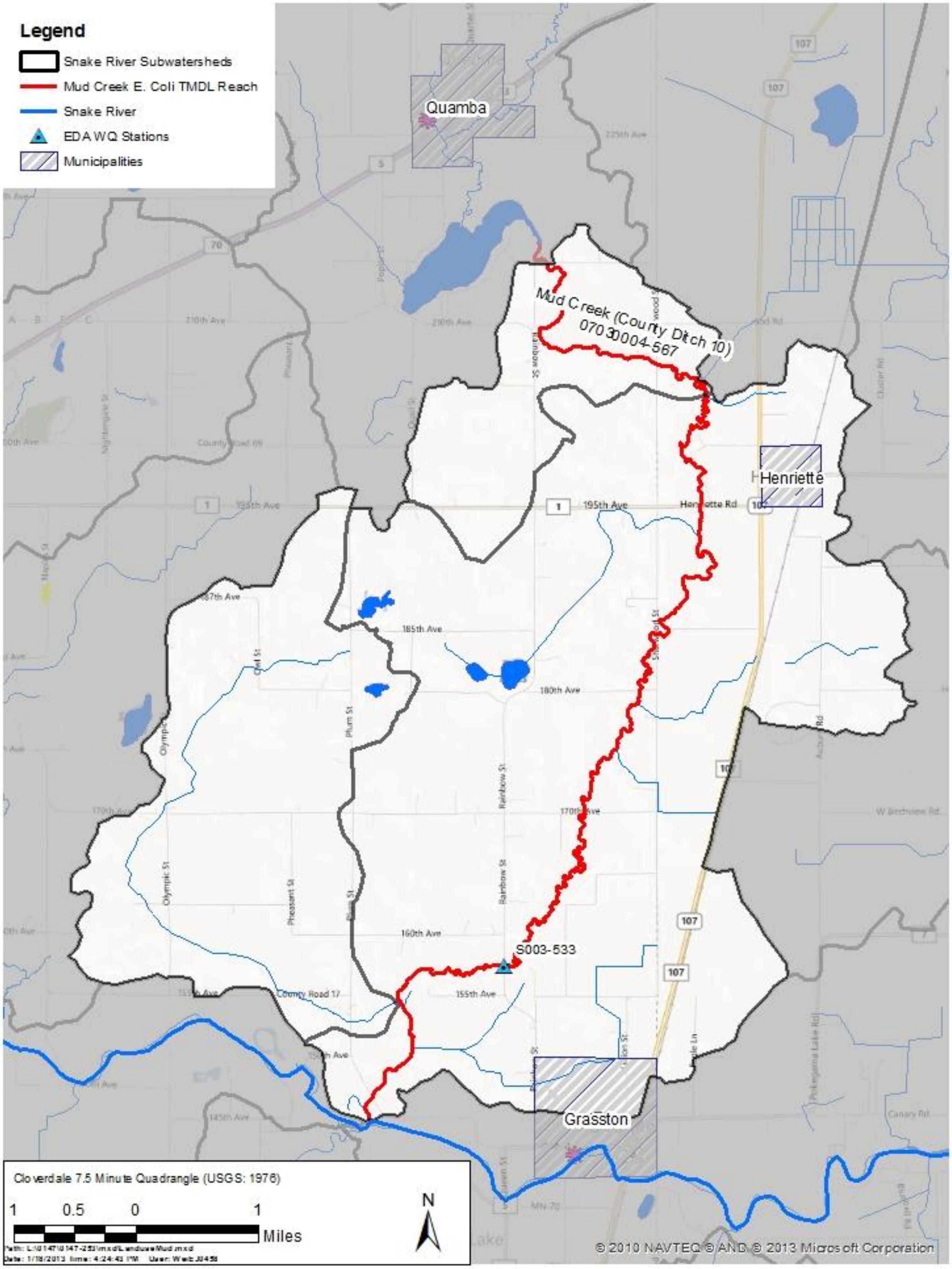
Upper Mud Creek Fecal Coliform Available for Delivery

Category	Source	Animal Type	Total Fecal Coliform Available(10^9)	Total Fecal Coliform Available by Source(10^9) (% of total watershed bacteria production)
Livestock	Pastures near streams or waterways	Dairy Animal Units	0	21,602 (14%)
		Beef Animal Units	20,672	
		Horse Animal Units	930	
	Upland pastures	Dairy Animal Units	0	110,149 (69%)
		Beef Animal Units	105,405	
		Horse Animal Units	4,744	
	Cropland surface applied manure	Dairy Animal Units	0	26,350 (17%)
		Beef Animal Units	25,215	
		Horse Animal Units	1,135	
Human	ITPHS septic systems and unsewered communities	Systems	5	5 (<1%)
	Municipal wastewater treatment facilities	People	0	
Wildlife	Deer	Deer	350	604 (<1%)
	Waterfowl	Geese and ducks	254	
Urban Stormwater Runoff	Improperly managed waste from dogs and cats	Dogs and cats	175	175 (<1%)
Total				**158,885**

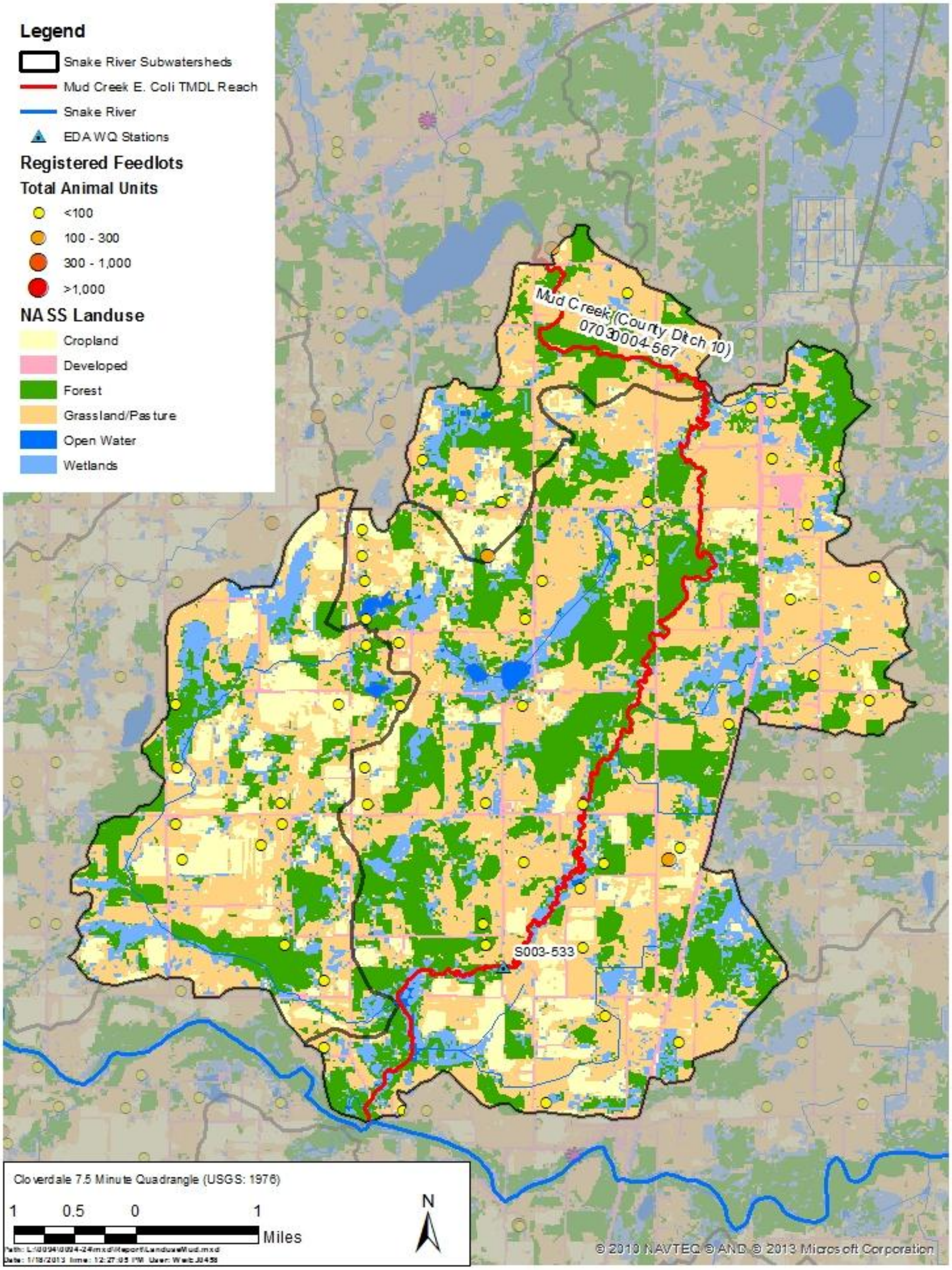
Appendix B

Lower Mud Creek Supporting Documents

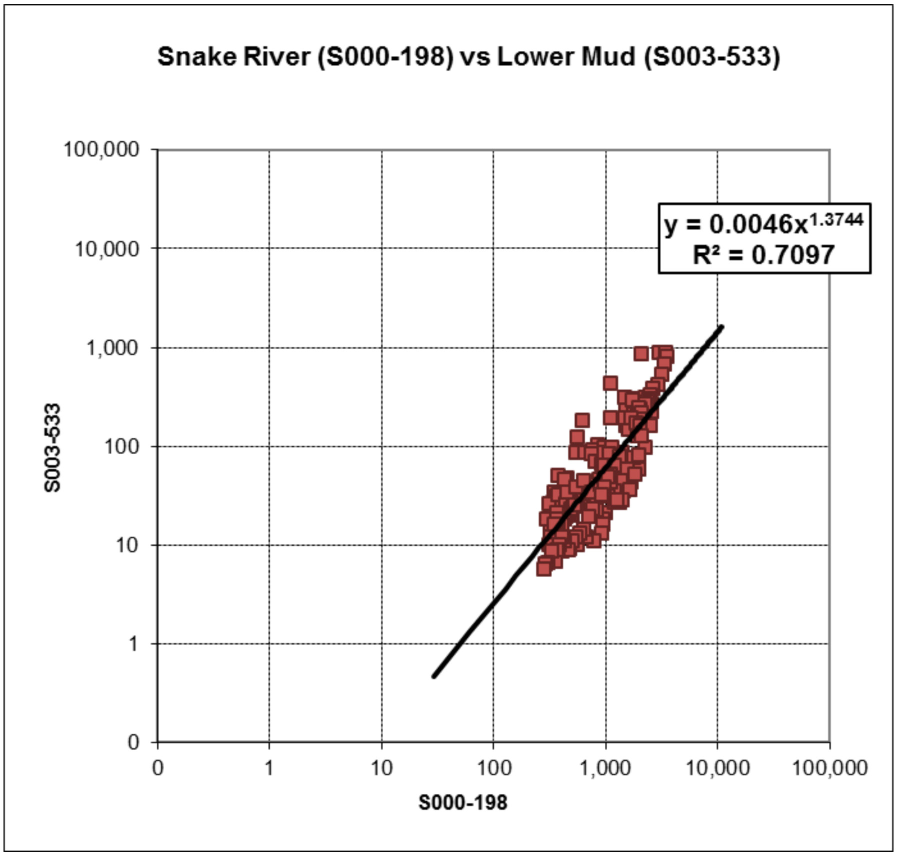
Lower Mud Creek Monitoring Sites



Lower Mud Creek Landuse and Feedlots



Lower Mud Creek and Snake River Flow Regression



Lower Mud Creek Failing Septic System Bacteria Loading Summary

System Type	Count	Bacteria Contribution (10^9 organisms/year)
Non-Failing	135	0
Failure to protect groundwater	48	0
Imminent threat to public health	20	50
Total	203	50

Lower Mud Creek Fecal Coliform Production Inventory

Category	Sub-Category		Animal Units or Individuals
Livestock	The Basin contains an estimated 61 registered livestock facilities ranging in size from less than 50 animal units to several hundred	Dairy	72 animal units
		Beef	712 animal units
		Swine	172 animal units
		Poultry	0 animal units
		Other (Horses, Sheep)	175 animal units
Human[1]	Total systems with inadequate wastewater treatment[2]		20 systems
	Total systems that do not discharge to surface water		183 systems
	Municipal Wastewater Treatment Facilities		67 people
Wildlife[3]	Deer (average 11 per square mile)		454 deer
	Waterfowl (average 10 per square mile)		412 geese/ducks
	Other		Other wildlife was assumed to be the equivalent of deer and waterfowl combined in the watershed.
Pets	Dogs and Cats in Urban Areas[3]		488 dogs and cats

[1] Based on Kanabec County SSTS inventory

[2] Assumes 3.0 people per household (USEPA 2002) and ITPHS failure rates based on Kanebec and Pine County SSTS inventory

[3] Calculated based on # of households in watershed (SSTS inventory) multiplied by 0.58 dogs/household and 0.73 cats/household according to the Southeast Minnesota Regional TMDL (MPCA 2002).

Lower Mud Creek Bacteria Delivery Assumptions

Category	Source	Assumption
Livestock	Pastures near streams or waterways	13.3% of beef, dairy and horse manure
	Upland pastures	70.0% of beef, dairy and horse manure
	Cropland surface applied manure	16.7% of beef, dairy and horse manure
Human	ITPHS septic systems and unsewered communities	All waste from failing septic systems and unsewered communities
	Municipal wastewater treatment facilities	None
Wildlife	Deer	All fecal matter produced by deer in basin
	Waterfowl	All fecal matter produced by geese and ducks in basin
	Other wildlife	The equivalent of all fecal matter produced by deer and waterfowl in basin
Urban Stormwater Runoff	Improperly managed waste from dogs and cats	10% of waste produced by estimated number of dogs and cats in basin

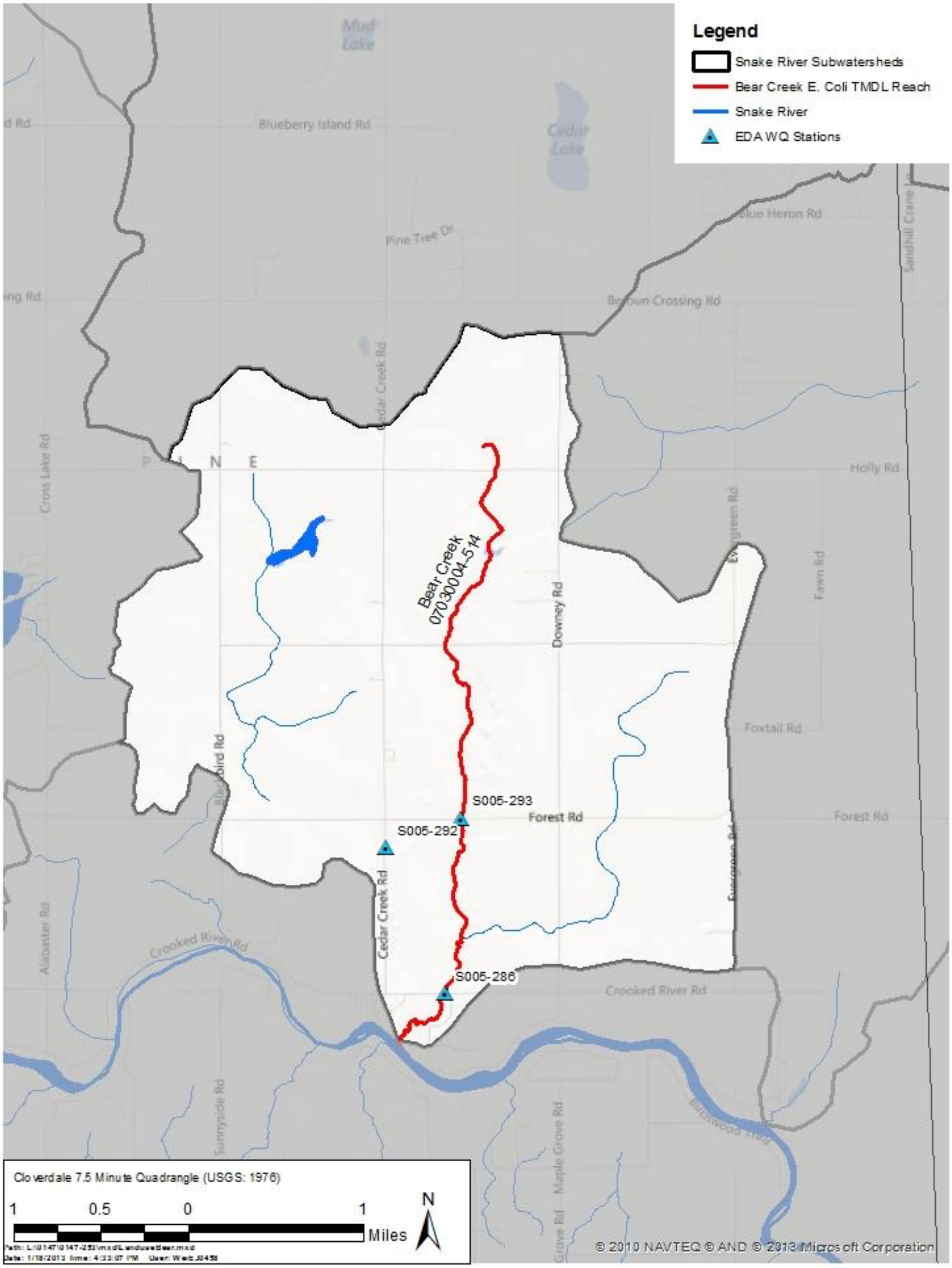
Lower Mud Creek Fecal Coliform Available for Delivery

Category	Source	Animal Type	Total Fecal Coliform Available(10^9)	Total Fecal Coliform Available by Source(10^9) (% of total watershed bacteria production)
Livestock	Pastures near streams or waterways	Dairy Animal Units	558	10,334 (13%)
		Beef Animal Units	8,444	
		Horse Animal Units	1,332	
	Upland pastures	Dairy Animal Units	2,934	54,366 (69%)
		Beef Animal Units	44,422	
		Horse Animal Units	7,010	
	Cropland surface applied manure	Dairy Animal Units	698	12,940 (16%)
		Beef Animal Units	10,573	
		Horse Animal Units	1,667	
Human	ITPHS septic systems and unsewered communities	Systems	50	50 (<1%)
	Municipal wastewater treatment facilities	People	0	
Wildlife	Deer	Deer	453	783 (1%)
	Waterfowl	Geese and ducks	330	
Urban Stormwater Runoff	Improperly managed waste from dogs and cats	Dogs and cats	220	220 (<1%)
Total				**78,693**

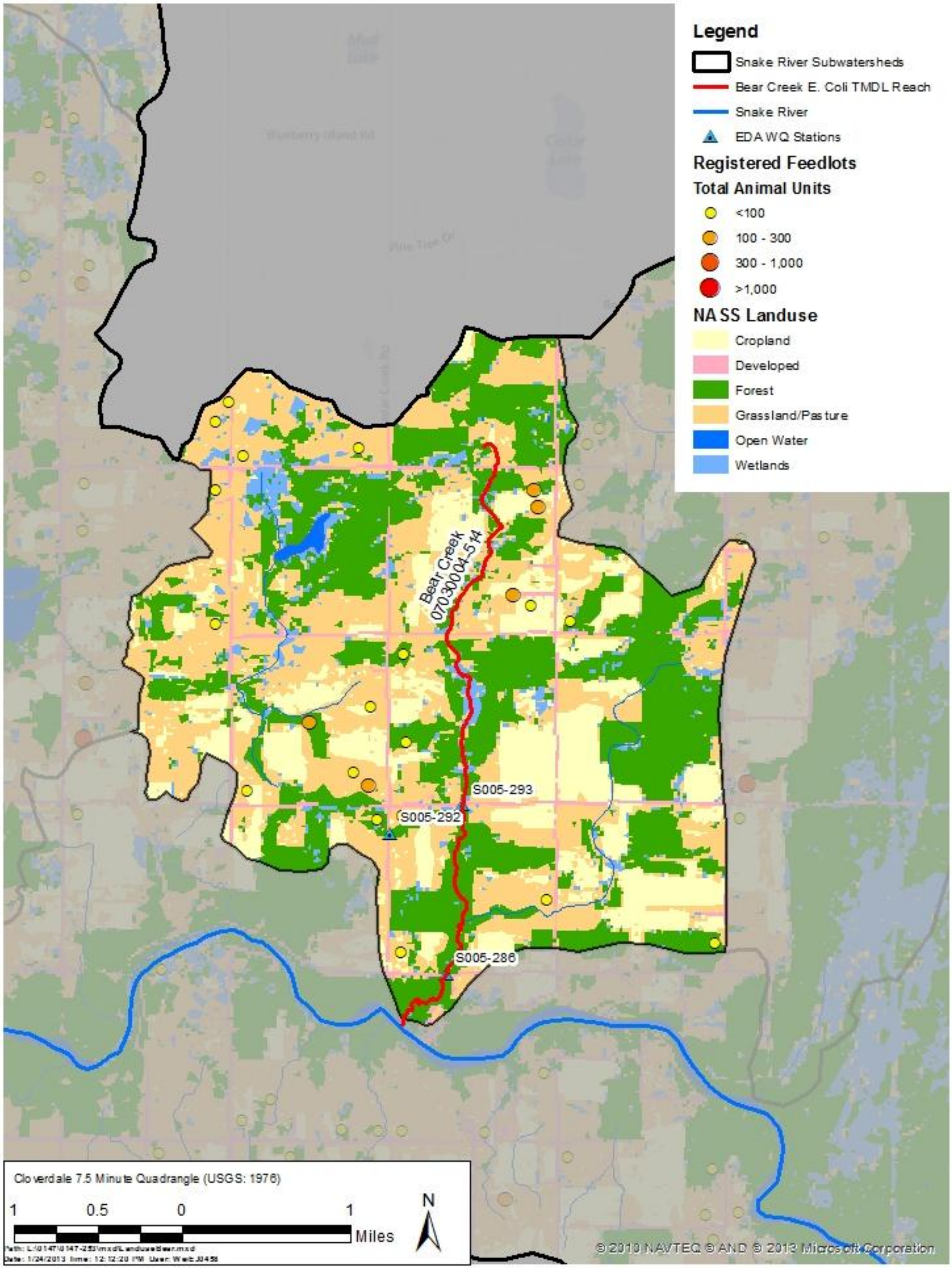
Appendix C

Bear Creek Supporting Documents

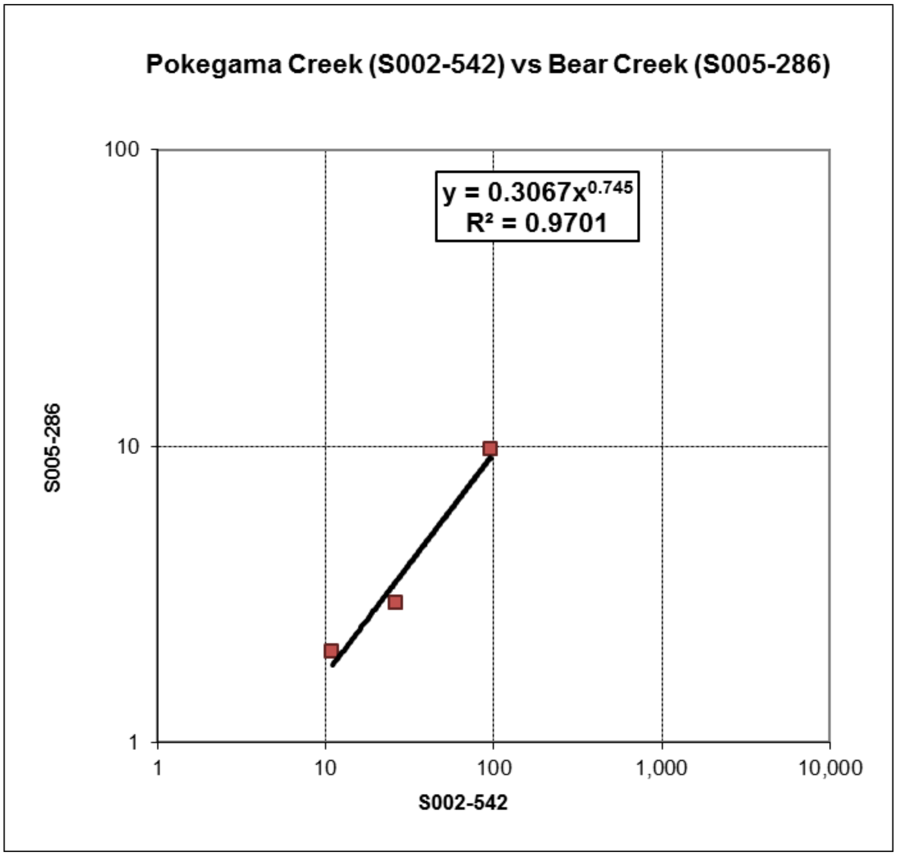
Bear Creek Monitoring Sites



Bear Creek Landuse and Feedlots



Bear Creek and Pokegama Creek Flow Regression



Bear Creek Failing Septic System Bacteria Loading Summary

System Type	Count	Bacteria Contribution (10^9 organisms/day)
Non-Failing	62	0
Failure to protect groundwater	29	0
Imminent threat to public health	20	50
Total	28	50

Bear Creek Fecal Coliform Production Inventory

Category	Sub-Category		Animal Units or Individuals
Livestock	The Basin contains an estimated 23 registered livestock facilities ranging in size from less than 50 animal units to several hundred	Dairy	54 animal units
		Beef	1,042 animal units
		Swine	59 animal units
		Poultry	0 animal units
		Other (Horses)	43 animal units
Human[1]	Total systems with inadequate wastewater treatment[2]		20 systems
	Total systems that do not discharge to surface water		57 systems
	Municipal Wastewater Treatment Facilities		0 people
Wildlife[3]	Deer (average 11 per square mile)		106 deer
	Waterfowl (average 10 per square mile)		96 geese/ducks
	Other		Other wildlife was assumed to be the equivalent of deer and waterfowl combined in the watershed.
Pets	Dogs and Cats in Urban Areas[3]		108 dogs and cats

[1] Based on Pine County SSTS inventory
[2] Assumes 3.0 people per household (USEPA 2002) and ITPHS failure rate based on Pine County SSTS inventory
[3] Calculated based on # of households in watershed (SSTS inventory) multiplied by 0.58 dogs/household and 0.73 cats/household according to the Southeast Minnesota Regional TMDL (MPCA 2002).

Bear Creek Bacteria Delivery Assumptions

Category	Source	Assumption
Livestock	Pastures near streams or waterways	16.3% of beef, dairy and horse manure
	Upland pastures	67.0% of beef, dairy and horse manure
	Cropland surface applied manure	16.7% of beef, dairy and horse manure
Human	ITPHS septic systems and unsewered communities	All waste from failing septic systems and unsewered communities
	Municipal wastewater treatment facilities	None
Wildlife	Deer	All fecal matter produced by deer in basin
	Waterfowl	All fecal matter produced by geese and ducks in basin
	Other wildlife	The equivalent of all fecal matter produced by deer and waterfowl in basin
Urban Stormwater Runoff	Improperly managed waste from dogs and cats	10% of waste produced by estimated number of dogs and cats in basin

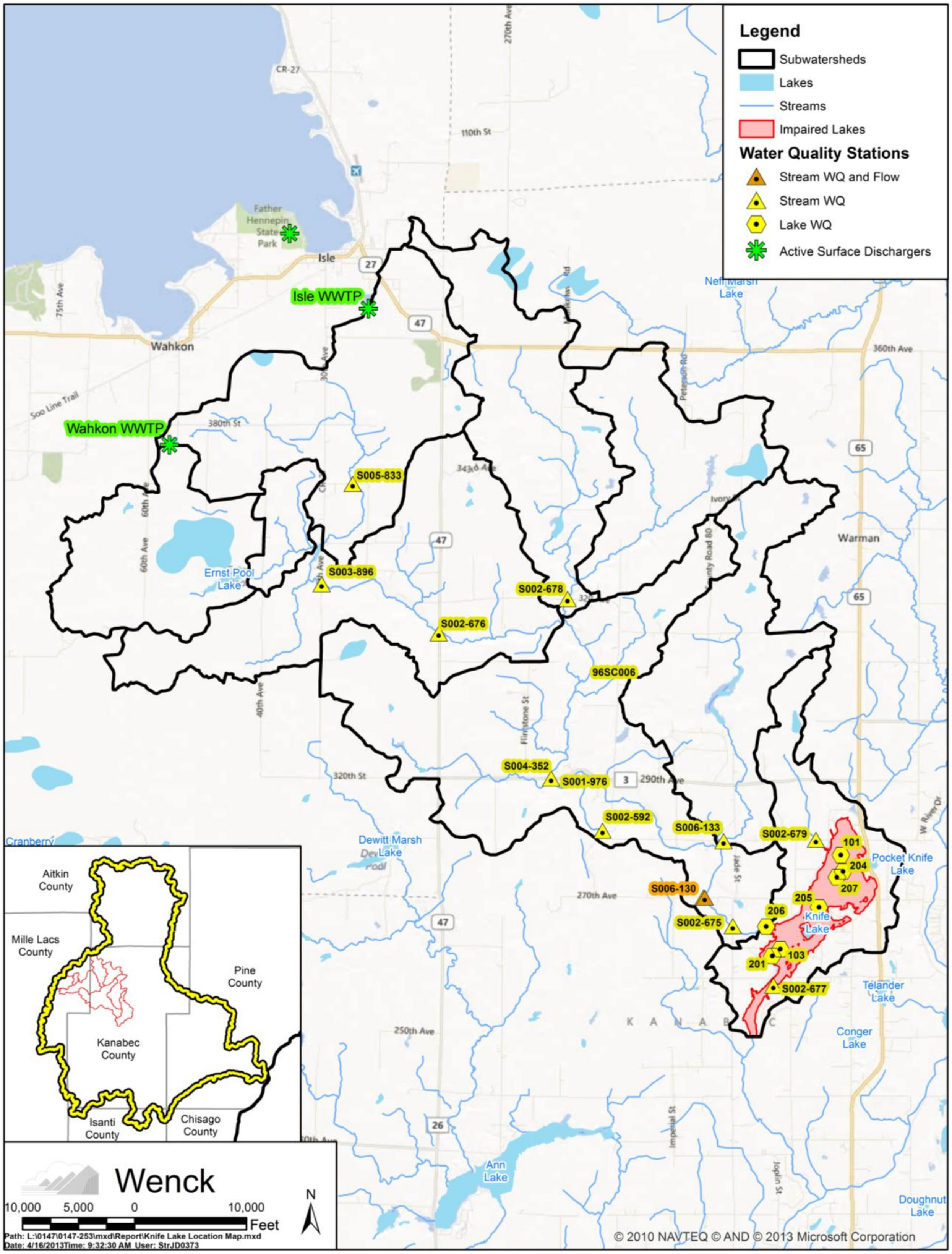
Bear Creek Fecal Coliform Available for Delivery

Category	Source	Animal Type	Total Fecal Coliform Available(10^9)	Total Fecal Coliform Available by Source(10^9 per day) (% of total watershed bacteria production)
Livestock	Pastures near streams or waterways	Dairy Animal Units	511	16,053 (16%)
		Beef Animal Units	15,097	
		Horse Animal Units	445	
	Upland pastures	Dairy Animal Units	2,108	66,214 (67%)
		Beef Animal Units	62,271	
		Horse Animal Units	1,835	
	Cropland surface applied manure	Dairy Animal Units	524	16,453 (17%)
		Beef Animal Units	15,474	
		Horse Animal Units	455	
Human	ITPHS septic systems and unsewered communities	Systems	50	50 (<1%)
	Municipal wastewater treatment facilities	People	0	
Wildlife	Deer	Deer	106	183 (<1%)
	Waterfowl	Geese and ducks	77	
Urban Stormwater Runoff	Improperly managed waste from dogs and cats	Dogs and cats	48	48 (<1%)
Total				**99,002**

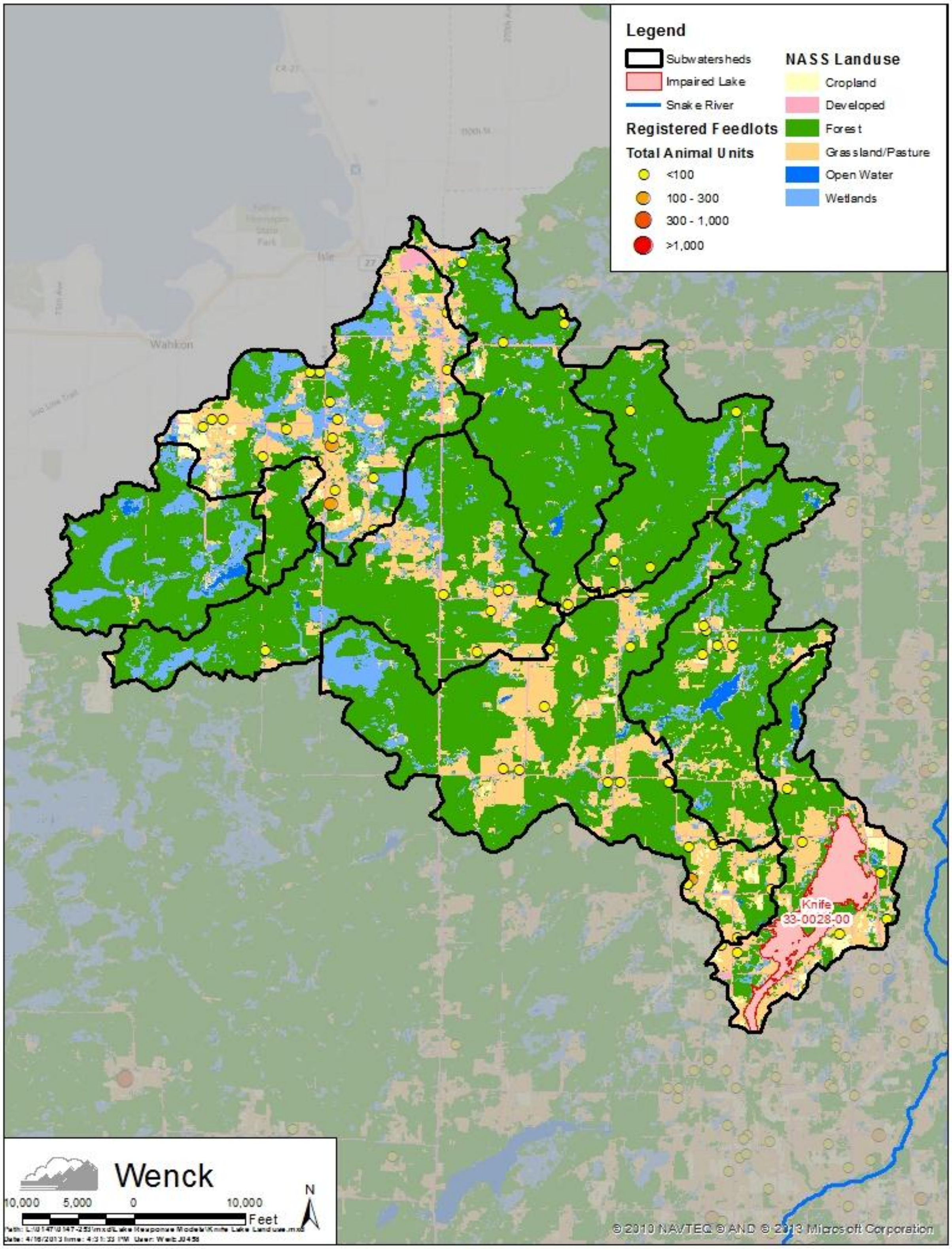
Appendix D

Knife Lake Supporting Documents

Knife Lake Monitoring Sites



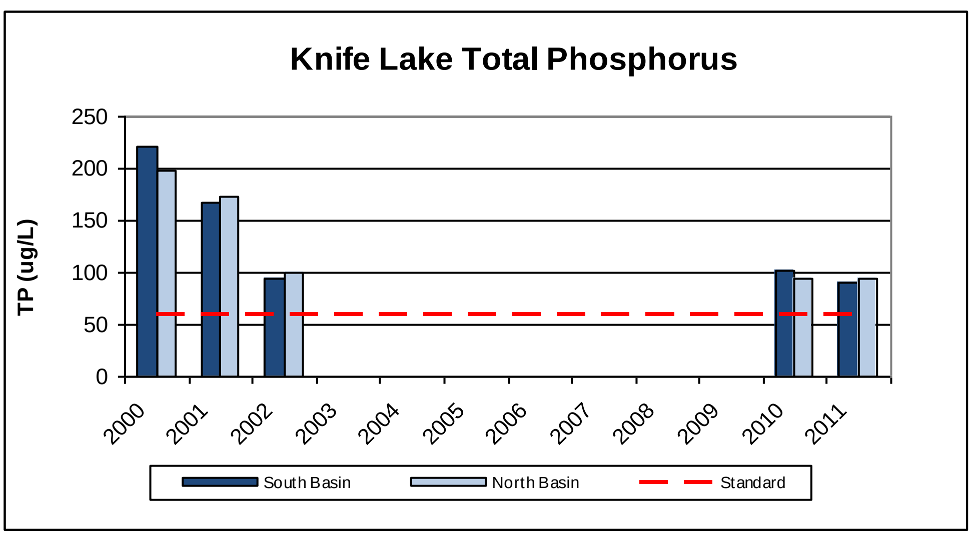
Knife Lake Watershed Landuse and Feedlots

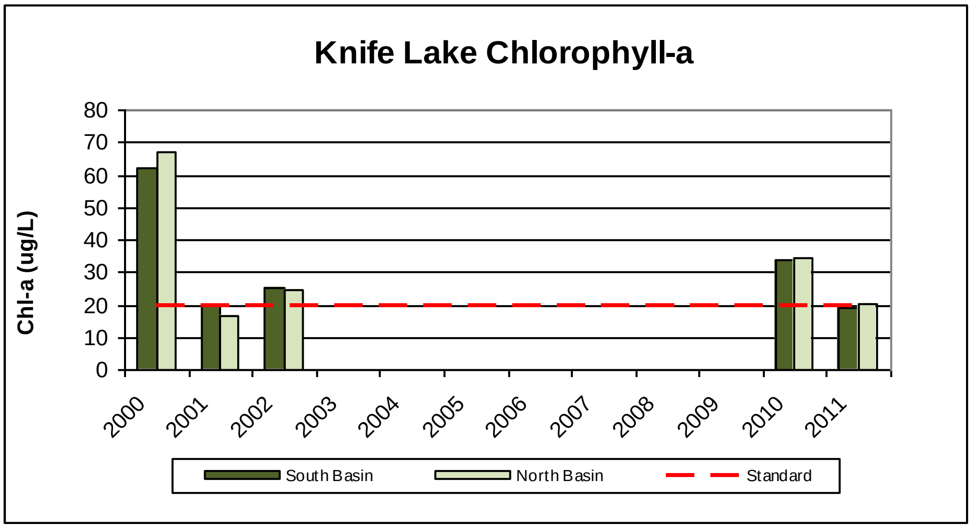


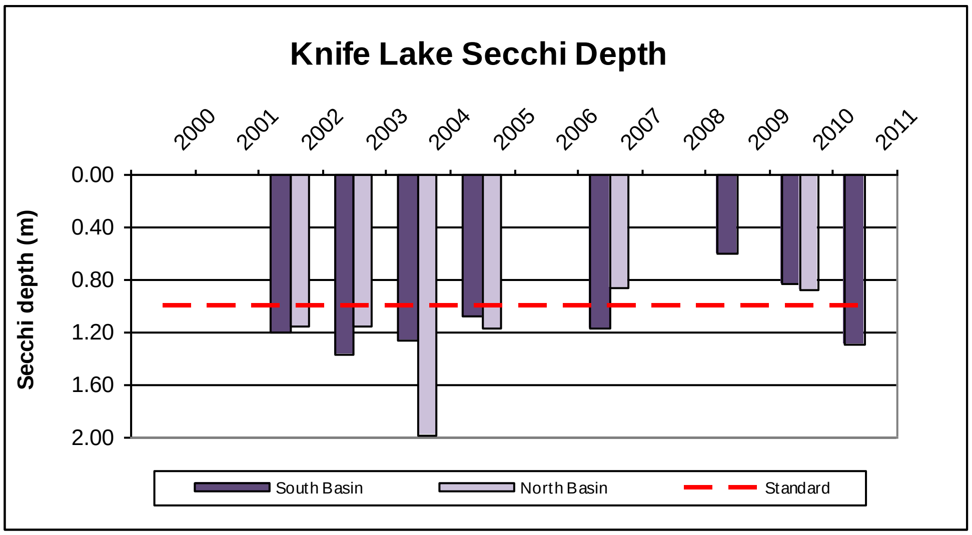
Knife Lake Historic Water Quality Sampling

Year	Total Phosphorus (ug/L)				Chlorophyll-a (ug/L)				Secchi (m)			
	South Basin		North Basin		South Basin		North Basin		South Basin		North Basin	
	N	Ave	N	Ave	N	Ave	N	Ave	N	Ave	N	Ave
2000	7	222	7	199	7	62	7	67	--	--	--	--
2001	9	168	9	173	9	20	9	17	--	--	--	--
2002	9	94	9	101	9	25	9	25	9	1.19	9	1.15
2003	--	--	--	--	--	--	--	--	9	1.37	8	1.16
2004	--	--	--	--	--	--	--	--	9	1.26	1	1.98
2005	--	--	--	--	--	--	--	--	9	1.08	9	1.17
2006	--	--	--	--	--	--	--	--	--	--	--	--
2007	--	--	--	--	--	--	--	--	7	1.17	7	0.87
2008	--	--	--	--	--	--	--	--	--	--	--	--
2009	--	--	--	--	--	--	--	--	12	0.60	--	--
2010	5	102	4	95	5	34	4	35	12	0.83	4	0.88
2011	8	91	8	94	8	19	8	21	14	1.29	1	1.40

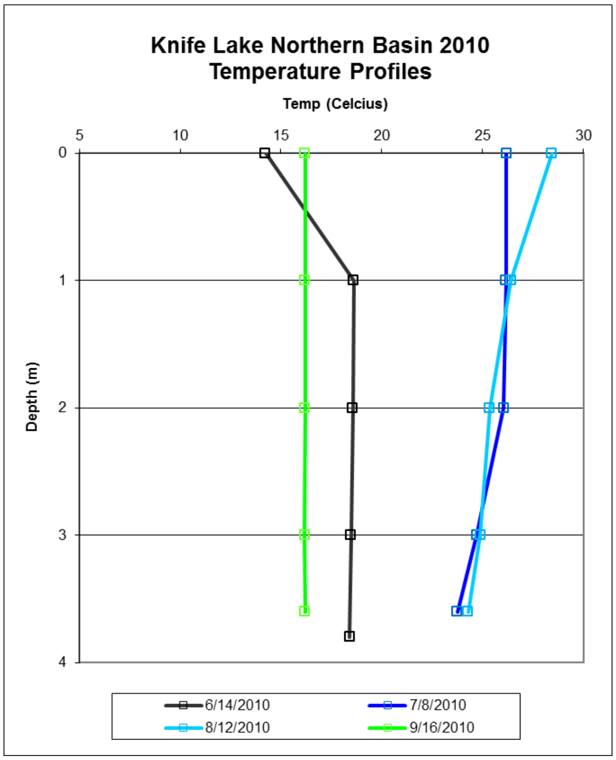
Note: Only June 1 through September 30 sample events presented

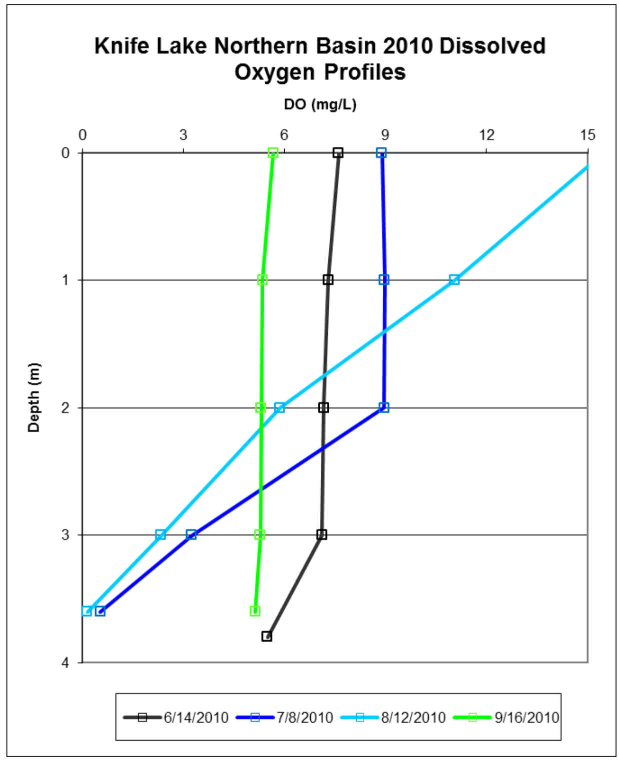


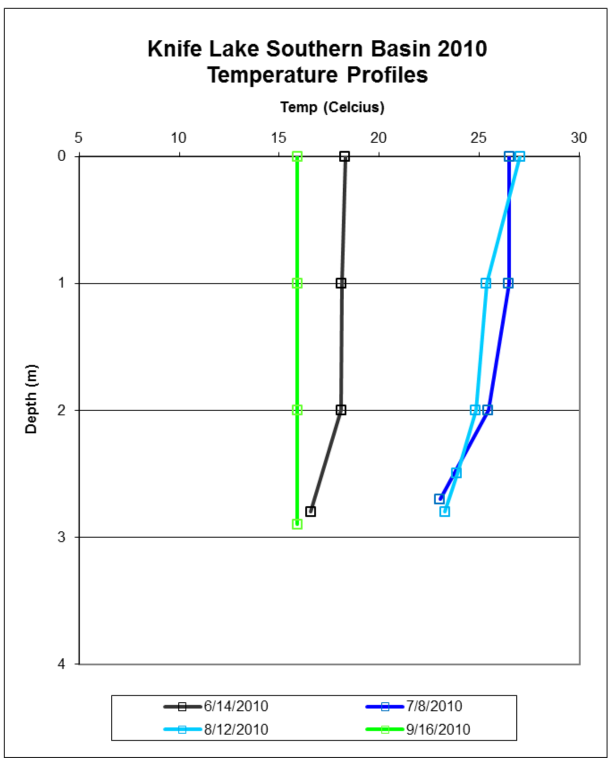

Knife Lake Chlorophyll-a
Chl-a (ug/L)
80
70
60
50
40
30
20
10
0
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
South Basin
North Basin
Standard

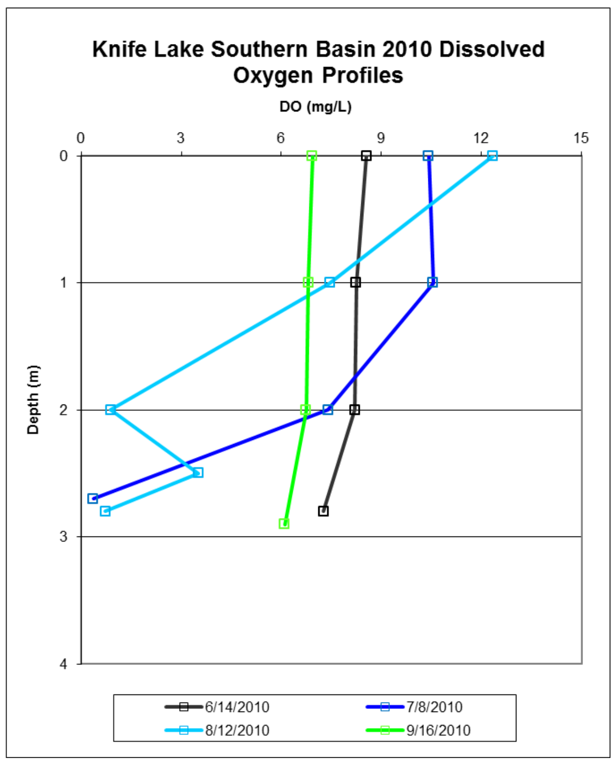

Knife Lake Secchi Depth
Secchi depth (m)
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
0.00
0.40
0.80
1.20
1.60
2.00
South Basin
North Basin
Standard

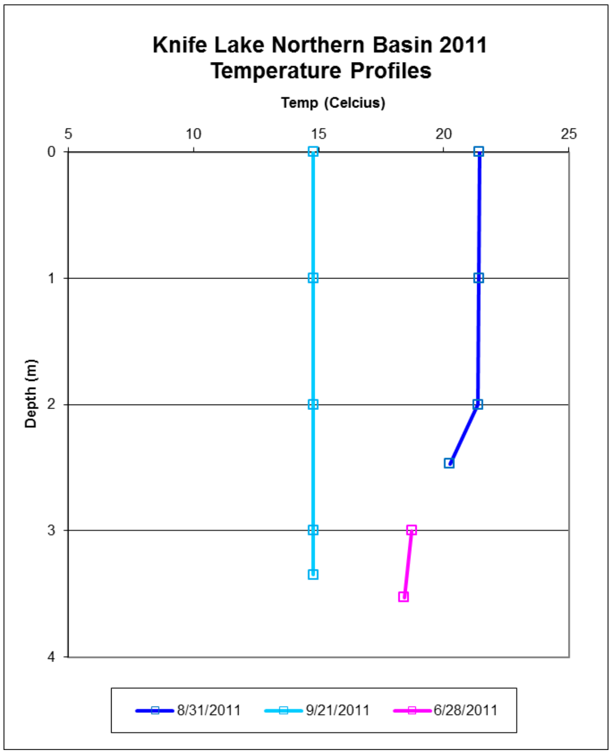
Knife Lake Temperature and Dissolved Oxygen Profiles

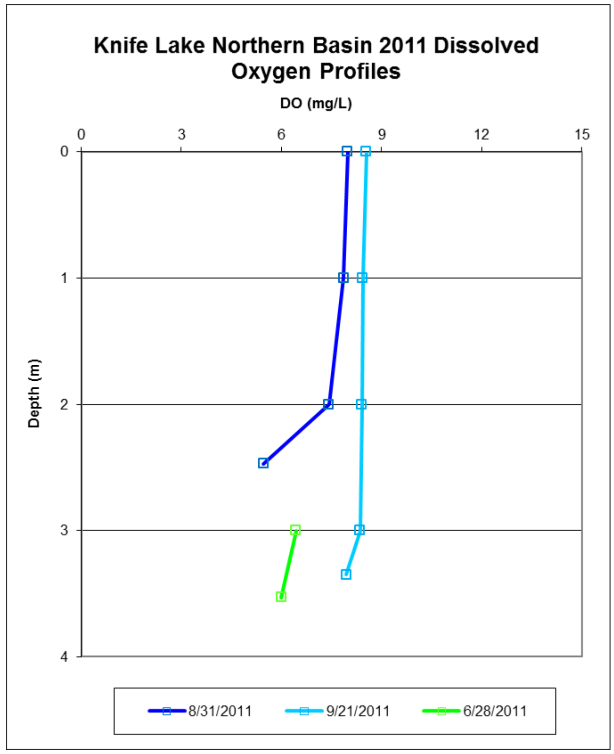


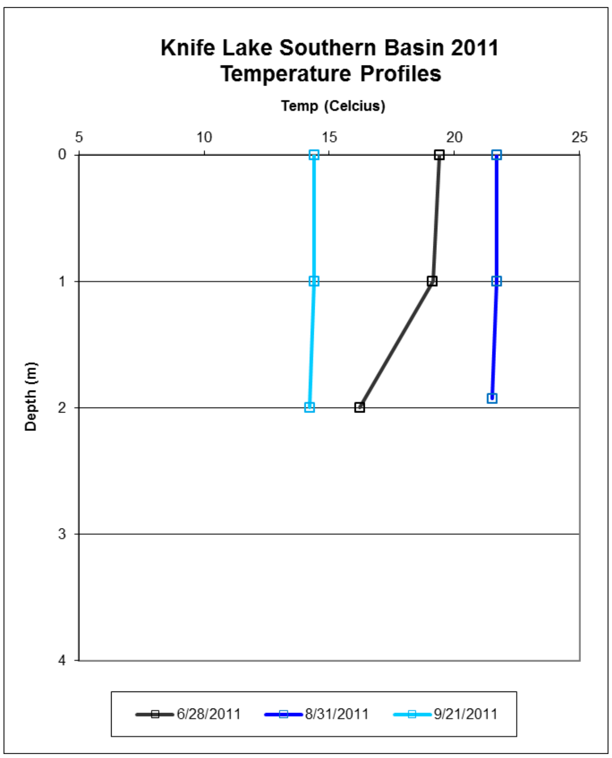


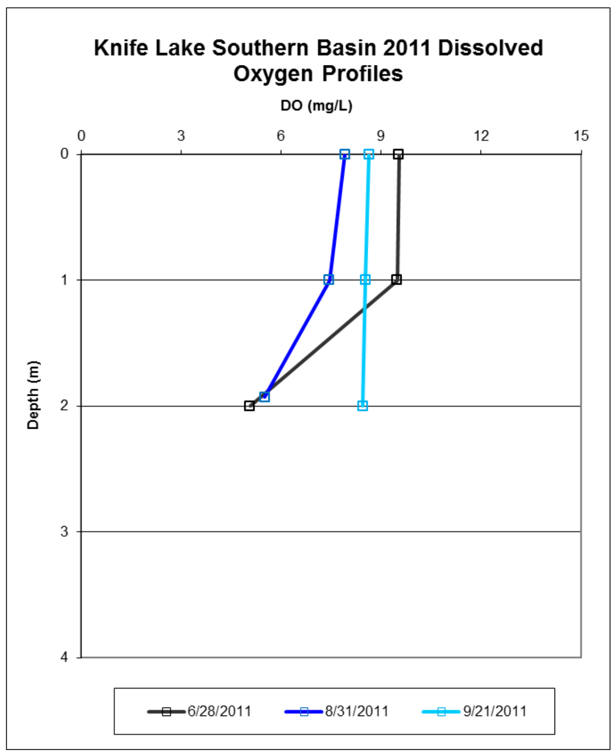




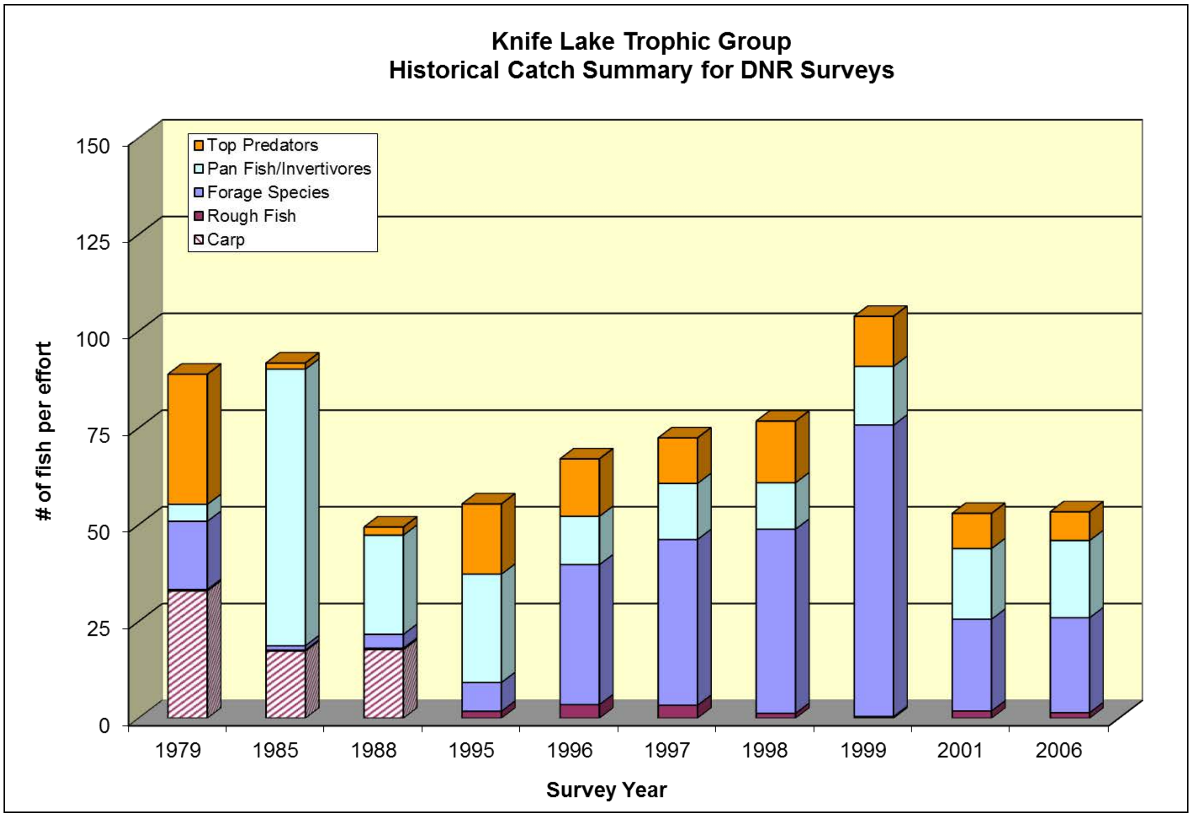

Knife Lake Northern Basin 2011 Temperature Profiles
Temp (Celcius)
5
10
15
20
25
0
1
2
3
4
Depth (m)
8/31/2011
9/21/2011
6/28/2011

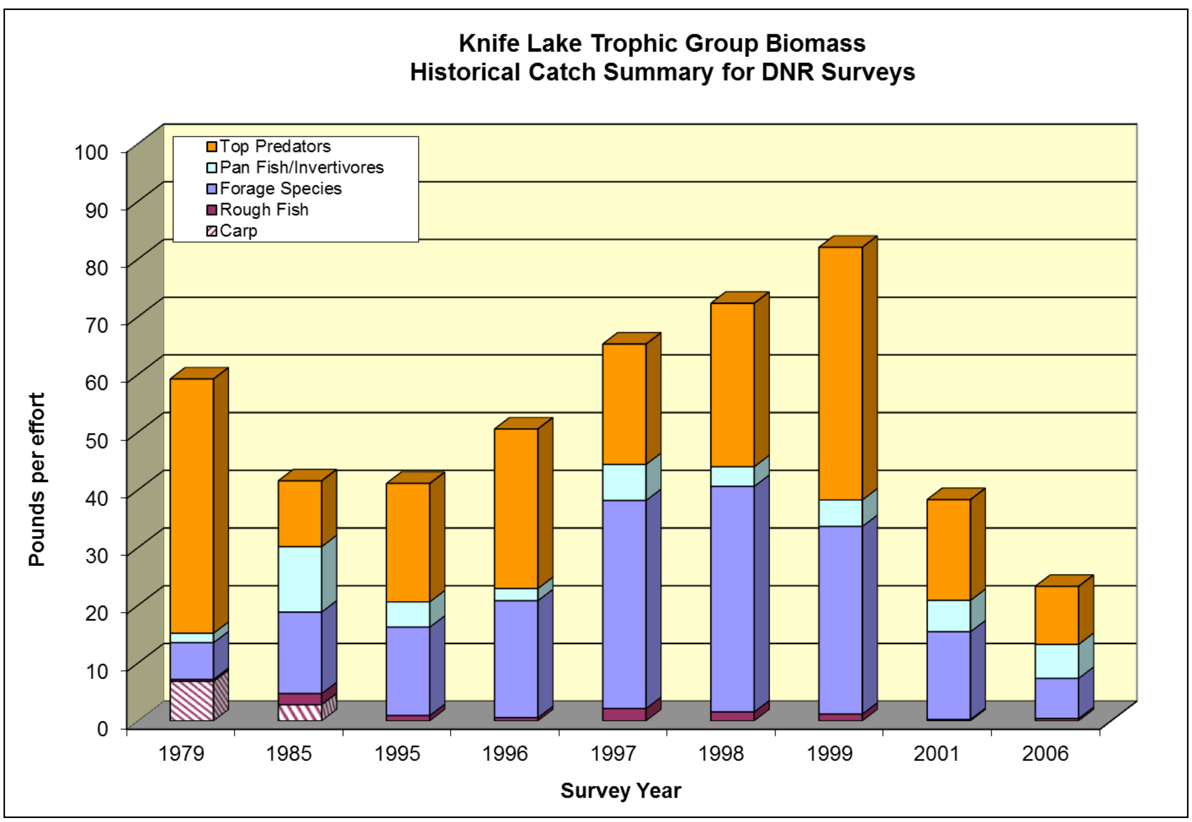

Knife Lake Northern Basin 2011 Dissolved Oxygen Profiles
DO (mg/L)
0
3
6
9
12
15
0
1
2
3
4
Depth (m)
8/31/2011
9/21/2011
6/28/2011


Knife Lake Southern Basin 2011 Temperature Profiles
Temp (Celcius)
5
10
15
20
25
0
1
2
3
4
Depth (m)
6/28/2011
8/31/2011
9/21/2011

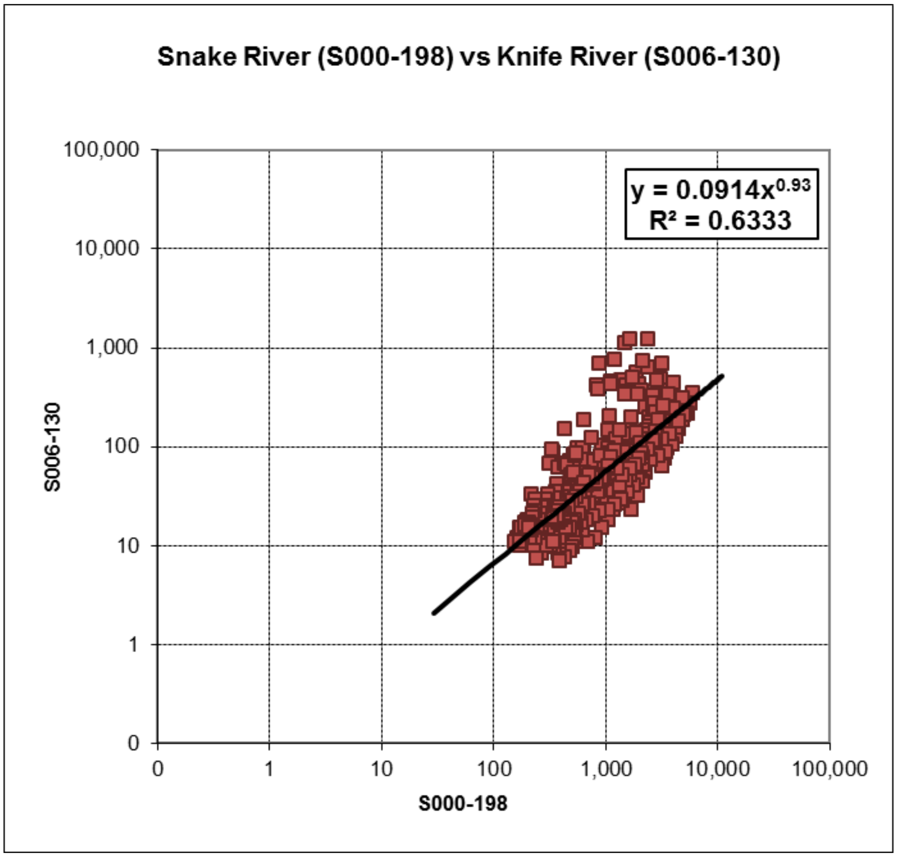

Knife Lake Southern Basin 2011 Dissolved Oxygen Profiles
DO (mg/L)
0
3
6
9
12
15
0
1
2
3
4
Depth (m)
6/28/2011
8/31/2011
9/21/2011

Knife Lake DNR Fish Surveys by Trophic Group





Knife River Flow Regression



Knife Lake Watershed FLUX Modeling

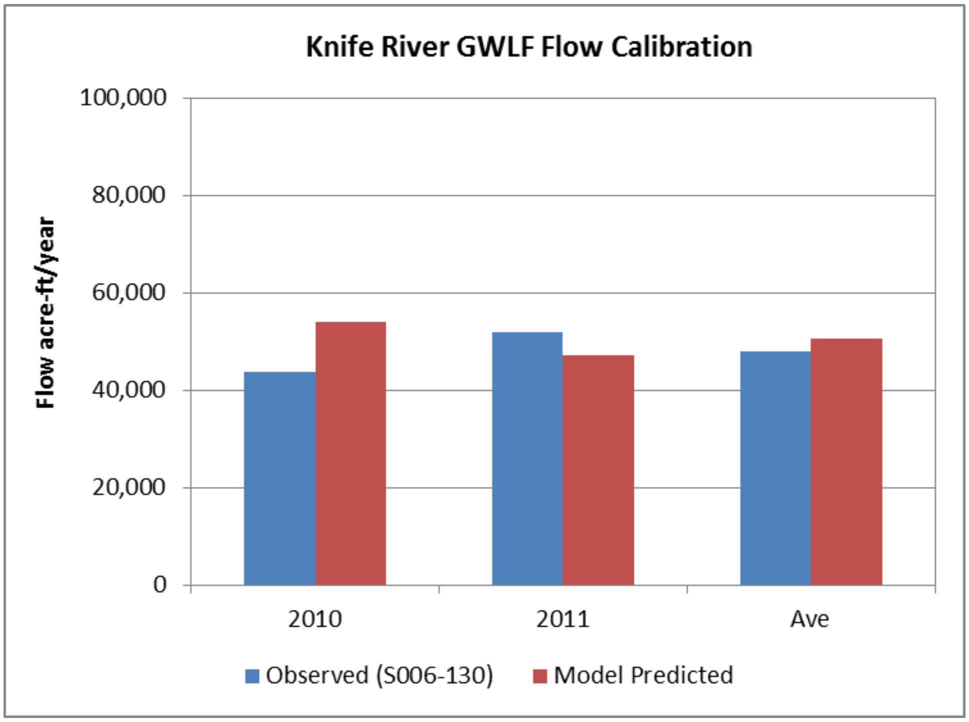
Site/ Watershed	Year	Monitored Flow (acre-ft)	FLUX Annual Load (lbs)	Concentration (ug/L)	FLUX Stratification	FLUX Method	C.V
S006-130 Knife River	2004	23,146	4,072	65	None	3	0.04
S006-130 Knife River	2006	15,727	2,700	63	None	2	0.24
S006-130 Knife River	2007	19,368	3,131	59	None	2	0.19
S006-130 Knife River	2008	30,634	14,149	170	None	2	0.70

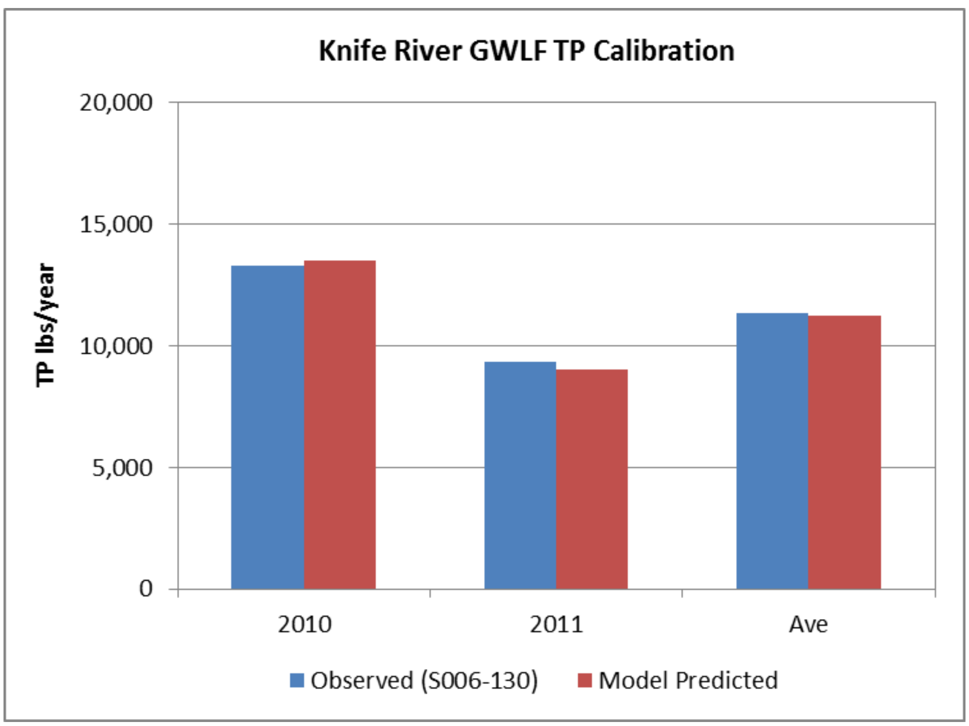
S006-130 Knife River	2010	43,814	13,305	112	0-75; 75+ cfs	2	0.17
S006-130 Knife River	2011	51,950	9,345	66	0-65; 65+ cfs	3	0.05
S006-130 Knife River	Ave	30,773	7,784	93			

Knife Lake Watershed Loads

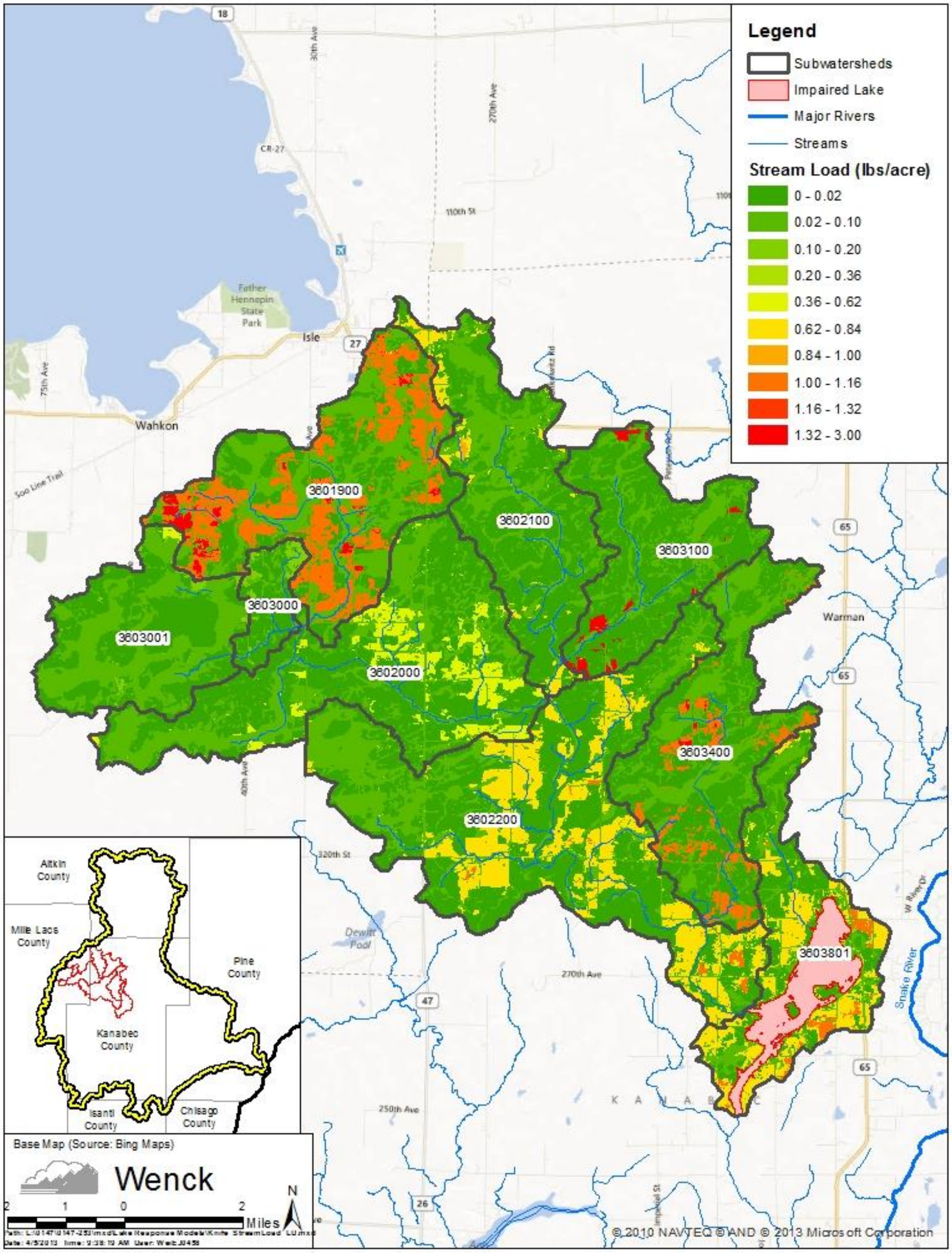
Watershed	Model Year	Precip (in)	Runoff (in)	Discharge (acre-ft)	TP Load (lbs)	TP conc. (ug/L)	Notes
Knife River	2010	40.7	9.6	43,631	13,036	110	Used runoff and FLUX TP conc. from S006-130, subtracted WWTF flow/loads and septic loads
Knife River	2011	27.5	11.4	51,688	8,915	63	Used runoff and FLUX TP conc. from S006-130, subtracted WWTF flow/loads and septic loads
Direct	2010	40.7	9.6	3,425	996	107	Used runoff and FLUX TP conc. from Knife River S006-130, subtracted septic loads
Direct	2011	27.5	11.4	4,057	673	61	Used runoff and FLUX TP conc. from Knife River S006-130, subtracted septic loads

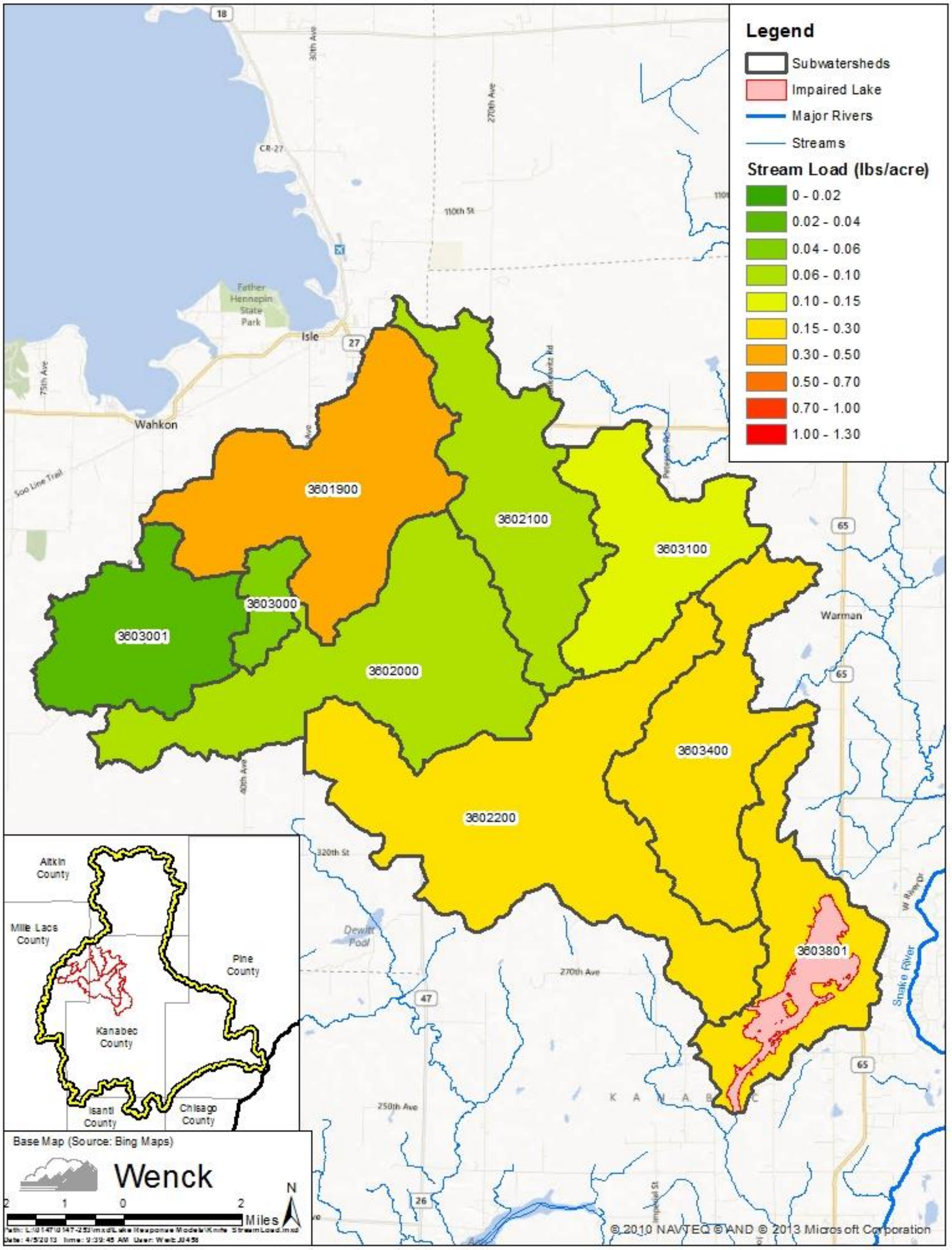
Knife Lake Watershed GWLF Model Performance





Knife Lake Watershed GWLF Model Results





Legend
Subwatersheds
Impaired Lake
Major Rivers
Streams
Stream Load (lbs/acre)
0 - 0.02
0.02 - 0.04
0.04 - 0.06
0.06 - 0.10
0.10 - 0.15
0.15 - 0.30
0.30 - 0.50
0.50 - 0.70
0.70 - 1.00
1.00 - 1.30
3601900
3602100
3603100
3603000
3603001
3602000
3603400
3602200
3603801
Isle
Wahkon
Warman
Aitkin County
Mille Lacs County
Pine County
Kanabec County
Isanti County
Chisago County
Base Map (Source: Bing Maps)
Wenck
Miles
© 2010 NAVTEQ © AND © 2013 Microsoft Corporation

Knife Lake Watershed Septic Loads

HUID	Watershed	Major Watershed	County	Total Pop.	Pop. On Septics	Total Systems	Imm. Threat Systems	Gen Failing Systems	TP Load (lbs/yr)
3603801	Knife Direct	Knife Direct	Kanabec	439	439	146	0	22	0
3602200	Knife River	Knife River	Kanabec	207	207	69	1	11	1
3603400	Knife River	Knife River	Kanabec	183	183	61	0	9	0
3603100	Knife River	Knife River	Kanabec	55	55	18	0	3	0
3602100	Knife River	Knife River	Kanabec	75	67	22	1	4	1
3602000	Knife River	Knife River	Mille Lacs	93	93	31	1	7	7
3603000	Knife River	Knife River	Mille Lacs	11	11	4	1	1	2
3603001	Knife River	Knife River	Mille Lacs	20	20	7	1	2	3
3601900	Knife River	Knife River	Mille Lacs	280	271	90	6	27	45

Knife Lake Current Conditions BATHTUB Lake Response Model

Current Conditions Loading Summary for Knife Lake

Water Budgets | **Phosphorus Loading**

Inflow from Drainage Areas

	Name	Drainage Area [acre]	Runoff Depth [in/yr]	Discharge [ac-ft/yr]	Phosphorus Concentration [ug/L]	Loading Calibration Factor (CF)[1] [--]	Load [lb/yr]
1	Knife River	54,259	10.5	47,660	85	1.0	10,975
2	Knife Lake Direct	4,259	10.5	3,741	82	1.0	835
3						1.0	
4						1.0	
5						1.0	
	Summation	*58,518*	*21*	*51,401*			*11,810*

Point Source Dischargers

	Name			Discharge [ac-ft/yr]	Phosphorus Concentration [ug/L]	Loading Calibration Factor (CF)[1] [--]	Load [lb/yr]
1	Wahkon WWTF			85	434	1.0	100
2	Isle WWTF			138	545.9	1.0	204
3				0	0.0	1.0	0
4				0	0.0	1.0	0
5				0	0.0	1.0	0
	Summation			*222*			*304*

Failing Septic Systems

	Name	Total Systems	Failing Systems	Discharge [ac-ft/yr]	Failure [%]		Load [lb/yr]
1	All Failing Systems						60
2							
3							
4							
5							
	Summation	*0*	*0*	*0.0*			*60*

Inflow from Upstream Lakes

	Name			Discharge [ac-ft/yr]	Estimated P Concentration [ug/L]	Calibration Factor [--]	Load [lb/yr]
1					-	1.0	
2					-	1.0	
3					-	1.0	
	Summation			*0*	-		*0*

Atmosphere

Lake Area [acre]	Precipitation [in/yr]	Evaporation [in/yr]	Net Inflow [ac-ft/yr]	Aerial Loading Rate [lb/ac-yr]	Calibration Factor [--]	Load [lb/yr]
1259	34.1	34.1	0.00	0.24	1.0	301
			Dry-year total P deposition =	0.222		
			Average-year total P deposition =	0.239		
			Wet-year total P deposition =	0.259		
			(Barr Engineering 2004)			

Groundwater

Lake Area [acre]	Groundwater Flux [m/yr]		Net Inflow [ac-ft/yr]	Phosphorus Concentration [ug/L]	Calibration Factor [--]	Load [lb/yr]

Internal

Lake Area [km²]	Anoxic Factor [days]			Release Rate [mg/m²-day]	Calibration Factor [--]	Load [lb/yr]
5.10	122		Oxic	0.7	1.0	959
5.10	54.4		Anoxic	9.5	1.0	5,805
Summation						6,764
	Net Discharge [ac-ft/yr] =		**51,623**	**Net Load [lb/yr] =**		**19,240**

Modeled Parameter	**Equation**	**Parameters**	**Value**	**[Units]**
TOTAL IN-LAKE PHOSPHORUS CONCENTRATION				
$P = \dfrac{P_i}{\left(1 + C_P \times C_{CB} \times \left(\dfrac{W_P}{V}\right)^b \times T\right)}$		as f(W,Q,V) from Canfield & Bachmann (1981)		
		C_P =	0.58	[--]
		C_{CB} =	0.162	[--]
		b =	0.458	[--]
		W (total P load = inflow + atm.) =	8,727	[kg/yr]
		Q (lake outflow) =	63.7	[10^6 m^3/yr]
		V (modeled lake volume) =	13.3	[10^6 m^3]
		T = V/Q =	0.21	[yr]
		P_i = W/Q =	137	[µg/l]
Model Predicted In-Lake [TP]			**99**	**[ug/l]**
Observed In-Lake [TP]			**99**	**[ug/l]**

Knife Lake Current Conditions BATHTUB Lake Response Model (WWTFs at St Croix TMDL Allocations)

	Current Conditions (St Croix WWTF allocations) Loading Summary for Knife Lake						
	Water Budgets				Phosphorus Loading		
Inflow from Drainage Areas							
		Drainage Area	Runoff Depth	Discharge	Phosphorus Concentration	Loading Calibration Factor (CF)[1]	Load
	Name	[acre]	[in/yr]	[ac-ft/yr]	[ug/L]	[--]	[lb/yr]
1	Knife River	54,259	10.5	47,660	85	1.0	10,975
2	Knife Lake Direct	4,259	10.5	3,741	82.0	1.0	835
3						1.0	
4						1.0	
5						1.0	
	Summation	*58,518*	*21*	*51,401*			*11,810*
Point Source Dischargers							
				Discharge	Phosphorus Concentration	Loading Calibration Factor (CF)[1]	Load
	Name			[ac-ft/yr]	[ug/L]	[--]	[lb/yr]
1	Wahkon WWTF			136	1000	1.0	369
2	Isle WWTF			224	999	1.0	609
3				0	0.0	1.0	0
4				0	0.0	1.0	0
5				0	0.0	1.0	0
	Summation			*360*			*978*
Failing Septic Systems							
	Name	Total Systems	Failing Systems	Discharge [ac-ft/yr]	Failure [%]		Load [lb/yr]
1	All Failing System:						60
2							
3							
4							
5							
	Summation	*0*	*0*	*0.0*			*60*
Inflow from Upstream Lakes							
				Discharge	Estimated P Concentration	Calibration Factor	Load
	Name			[ac-ft/yr]	[ug/L]	[--]	[lb/yr]
1					-	1.0	
2					-	1.0	
3					-	1.0	
	Summation			*0*	-		*0*
Atmosphere							
	Lake Area	Precipitation	Evaporation	Net Inflow	Aerial Loading Rate	Calibration Factor	Load
	[acre]	[in/yr]	[in/yr]	[ac-ft/yr]	[lb/ac-yr]	[--]	[lb/yr]
	1259	34.1	34.1	0.00	0.24	1.0	301
		Dry-year total P deposition =			0.222		
		Average-year total P deposition =			0.239		
		Wet-year total P deposition =			0.259		
		(Barr Engineering 2004)					
Groundwater							
	Lake Area	Groundwater Flux		Net Inflow	Phosphorus Concentration	Calibration Factor	Load
	[acre]	[m/yr]		[ac-ft/yr]	[ug/L]	[--]	[lb/yr]
Internal							
	Lake Area	Anoxic Factor			Release Rate	Calibration Factor	Load
	[km^2]	[days]			[mg/m^2-day]	[--]	[lb/yr]
	5.10	122		Oxic	0.7	1.0	959
	5.10	54.4		Anoxic	9.5	1.0	5,805
	Summation						6,764
		Net Discharge [ac-ft/yr] =		**51,760**	**Net Load [lb/yr] =**		**19,914**

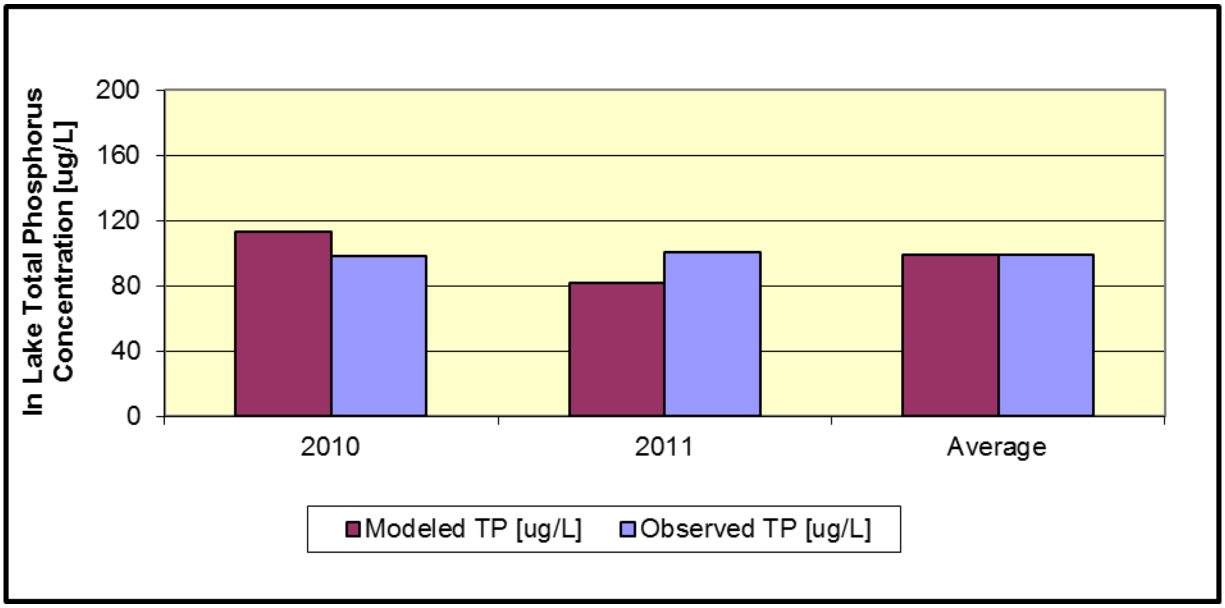
Modeled Parameter	Equation	Parameters	Value	[Units]
TOTAL IN-LAKE PHOSPHORUS CONCENTRATION				
$P = \dfrac{P_i}{\left(1 + C_P \times C_{CB} \times \left(\dfrac{W_P}{V}\right)^b \times T\right)}$		as f(W,Q,V) from Canfield & Bachmann (1981)		
		C_P =	0.58	[--]
		C_{CB} =	0.162	[--]
		b =	0.458	[--]
		W (total P load = inflow + atm.) =	9,033	[kg/yr]
		Q (lake outflow) =	63.9	[10^6 m^3/yr]
		V (modeled lake volume) =	13.3	[10^6 m^3]
		T = V/Q =	0.21	[yr]
		P_i = W/Q =	141	[µg/l]
Model Predicted In-Lake [TP]			**102**	**[ug/l]**
Observed In-Lake [TP]			**99**	**[ug/l]**

Knife Lake TMDL Conditions BATHTUB Lake Response Model

	TMDL Loading Summary for Knife Lake						
	Water Budgets			Phosphorus Loading			
Inflow from Drainage Areas							
		Drainage Area	Runoff Depth	Discharge	Phosphorus Concentration	Loading Calibration Factor (CF)[1]	Load
	Name	[acre]	[in/yr]	[ac-ft/yr]	[ug/L]	[--]	[lb/yr]
1	Knife River	54,259	10.5	47,660	58	0.7	7,493
2	Knife Lake Direct	4,259	10.5	3,741	58	0.7	589
3						1.0	
4						1.0	
5						1.0	
	Summation	*58,518*	*21*	*51,401*			*8,081*
Point Source Dischargers							
				Discharge	Phosphorus Concentration	Loading Calibration Factor (CF)[1]	Load
	Name			[ac-ft/yr]	[ug/L]	[--]	[lb/yr]
1	Wahkon WWTF			136	1000	1.0	369
2	Isle WWTF			224	999	1.0	609
3				0	0.0	1.0	0
4				0	0.0	1.0	0
5				0	0.0	1.0	0
	Summation			*360*			*978*
Failing Septic Systems							
	Name	Total Systems	Failing Systems	Discharge [ac-ft/yr]	Failure [%]		Load [lb/yr]
1							
2							
3							
4							
5							
	Summation	*0*	*0*	*0.0*			*0.0*
Inflow from Upstream Lakes							
				Discharge	Estimated P Concentration	Calibration Factor	Load
	Name			[ac-ft/yr]	[ug/L]	[--]	[lb/yr]
1					-	1.0	
2					-	1.0	
3					-	1.0	
	Summation			*0*	-		*0*
Atmosphere							
	Lake Area	Precipitation	Evaporation	Net Inflow	Aerial Loading Rate	Calibration Factor	Load
	[acre]	[in/yr]	[in/yr]	[ac-ft/yr]	[lb/ac-yr]	[--]	[lb/yr]
	1259	34.1	34.1	0.00	0.24	1.0	301
		Dry-year total P deposition =			0.222		
		Average-year total P deposition =			0.239		
		Wet-year total P deposition =			0.259		
		(Barr Engineering 2004)					
Groundwater							
	Lake Area	Groundwater Flux		Net Inflow	Phosphorus Concentration	Calibration Factor	Load
	[acre]	[m/yr]		[ac-ft/yr]	[ug/L]	[--]	[lb/yr]
Internal							
	Lake Area	Anoxic Factor			Release Rate	Calibration Factor	Load
	[km^2]	[days]			[mg/m^2-day]	[--]	[lb/yr]
	5.10	122		Oxic	0.7	1.0	959
	5.10	54.4		Anoxic	1.0	1.0	611
	Summation						1,570
		Net Discharge [ac-ft/yr] =		**51,760**	**Net Load [lb/yr] =**		**10,931**

Modeled Parameter	**Equation**	**Parameters**	**Value**	**[Units]**
TOTAL IN-LAKE PHOSPHORUS CONCENTRATION				
	$$P = \frac{P_i}{\left(1 + C_P \times C_{CB} \times \left(\frac{W_P}{V}\right)^b \times T\right)}$$	as f(W,Q,V) from Canfield & Bachmann (1981)		
		C_P =	0.58	[--]
		C_{CB} =	0.162	[--]
		b =	0.458	[--]
		W (total P load = inflow + atm.) =	4,958	[kg/yr]
		Q (lake outflow) =	63.9	[10^6 m^3/yr]
		V (modeled lake volume) =	13.3	[10^6 m^3]
		T = V/Q =	0.21	[yr]
		P_i = W/Q =	78	[µg/l]
Model Predicted In-Lake [TP]			**60**	**[ug/l]**
Observed In-Lake [TP]			**99**	**[ug/l]**

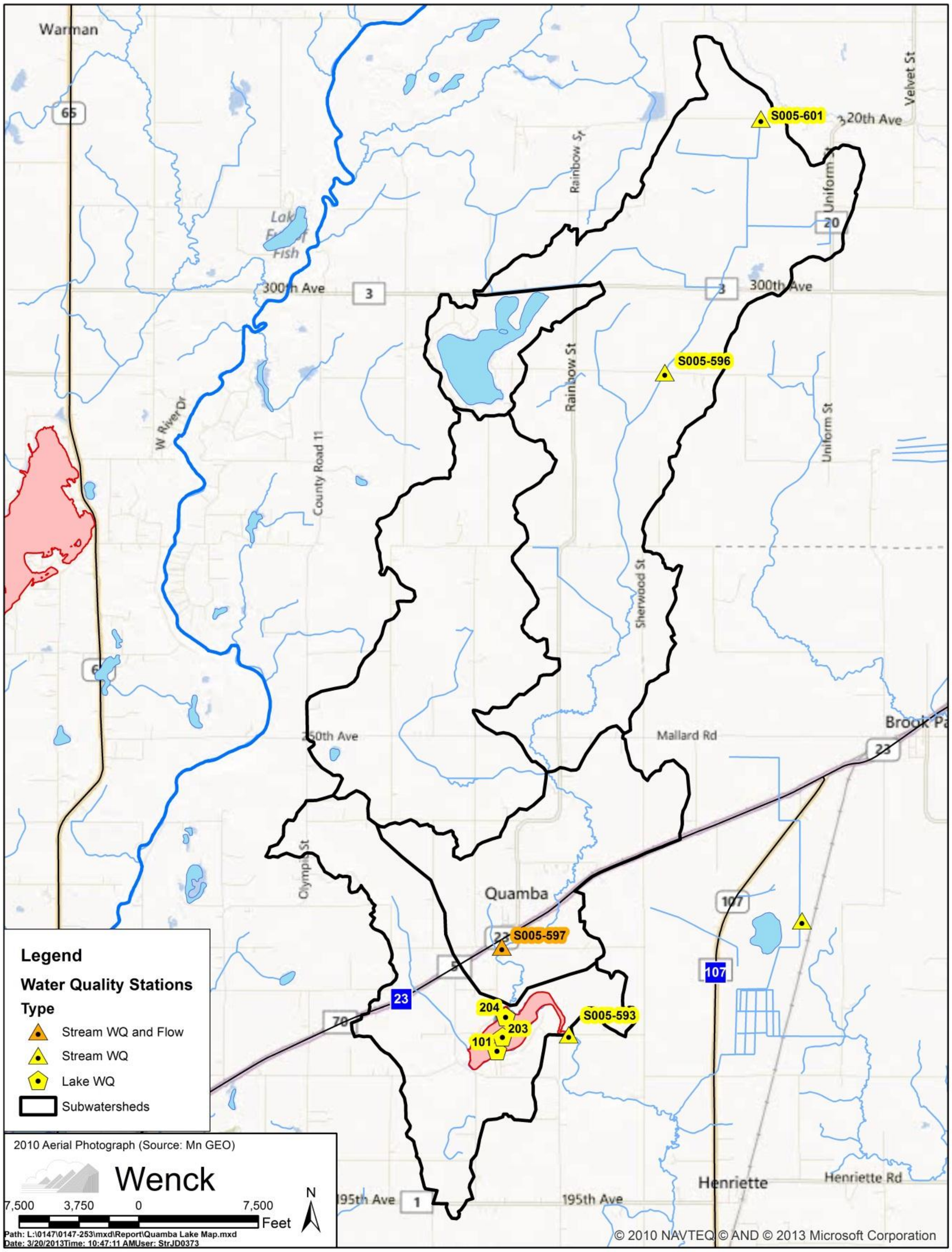
Knife Lake BATHTUB Lake Response Model Performance



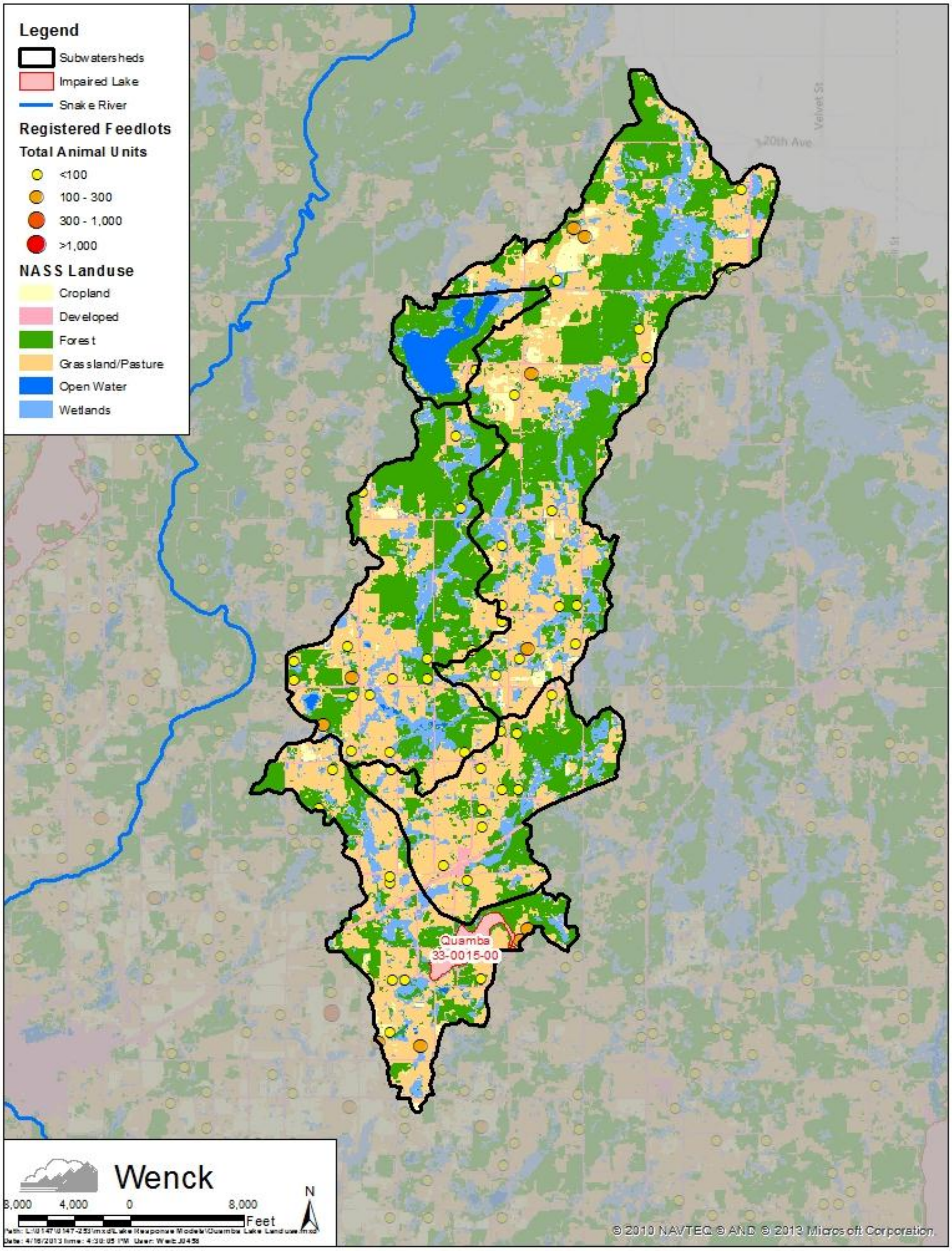
Appendix E

Quamba Lake Supporting Documents

Quamba Lake Monitoring Sites



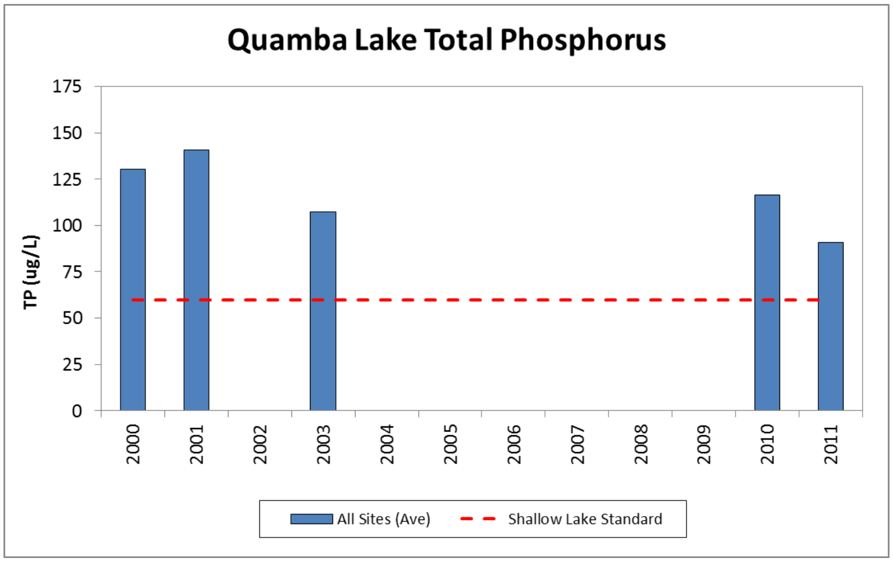
Quamba Lake Watershed Landuse and Feedlots

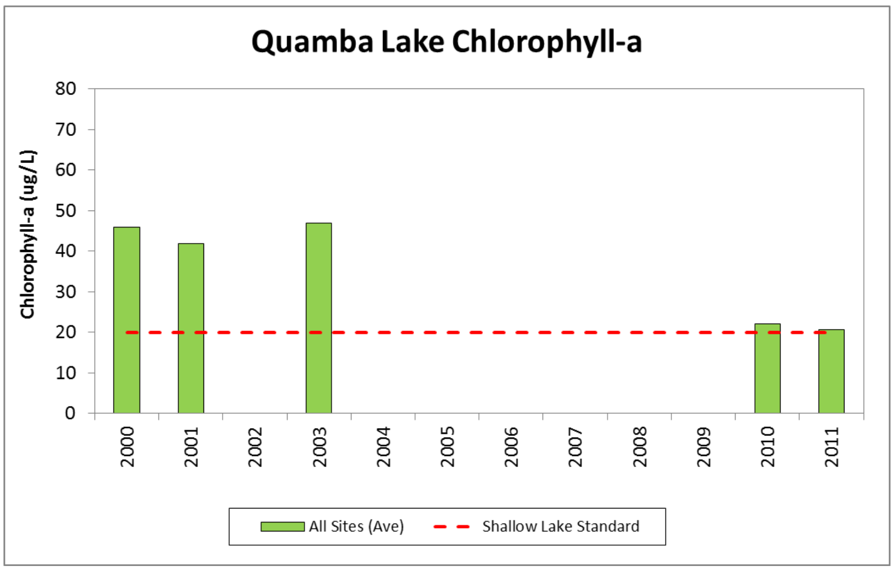


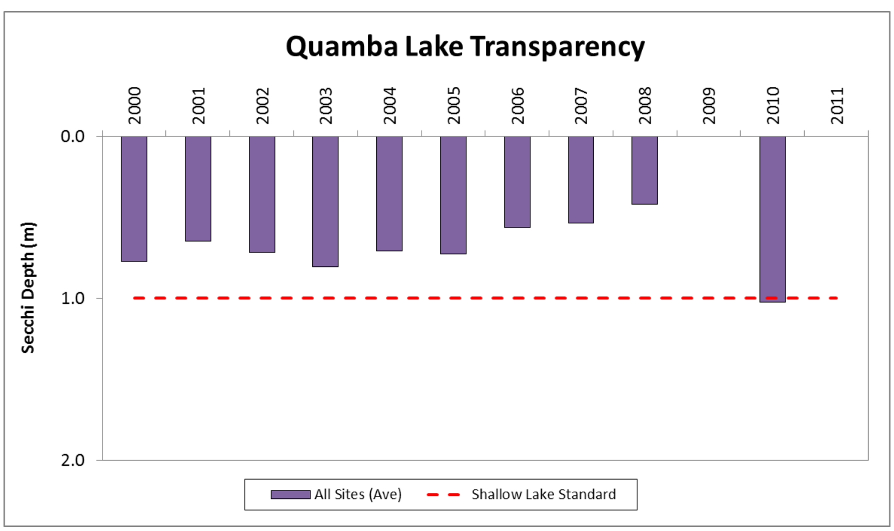
Quamba Lake Historic Water Quality Sampling

Year	Total Phosphorus (ug/L)		Chlorophyll-a (ug/L)		Secchi (m)	
	N	Ave	N	Ave	N	Ave
2000	4	130	4	46	12	0.77
2001	5	141	5	42	14	0.65
2002	3	124	3	34	11	0.72
2003	4	107	4	47	10	0.81
2004	--	--	--	--	13	0.71
2005	--	--	--	--	19	0.73
2006	--	--	--	--	16	0.56
2007	--	--	--	--	4	0.54
2008	--	--	--	--	4	0.42
2009	--	--	--	--	--	--
2010	8	116	8	22	4	1.03
2011	7	91	7	21	1	1.00

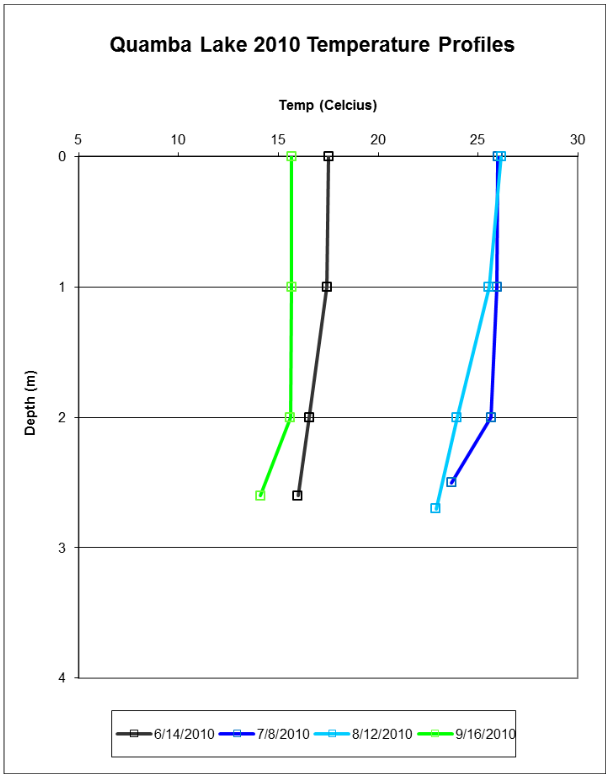
Note: Only June 1 through September 30 sample events presented

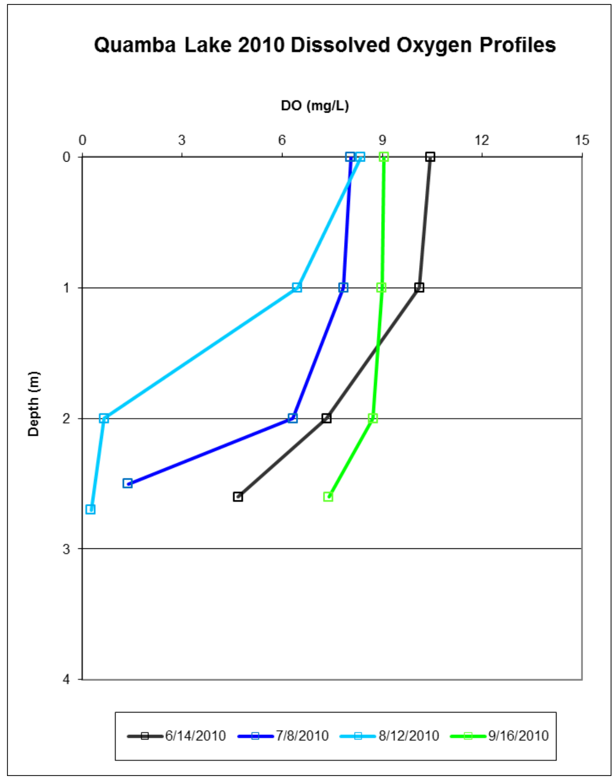

Quamba Lake Total Phosphorus
TP (ug/L)
175
150
125
100
75
50
25
0
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
All Sites (Ave)
Shallow Lake Standard

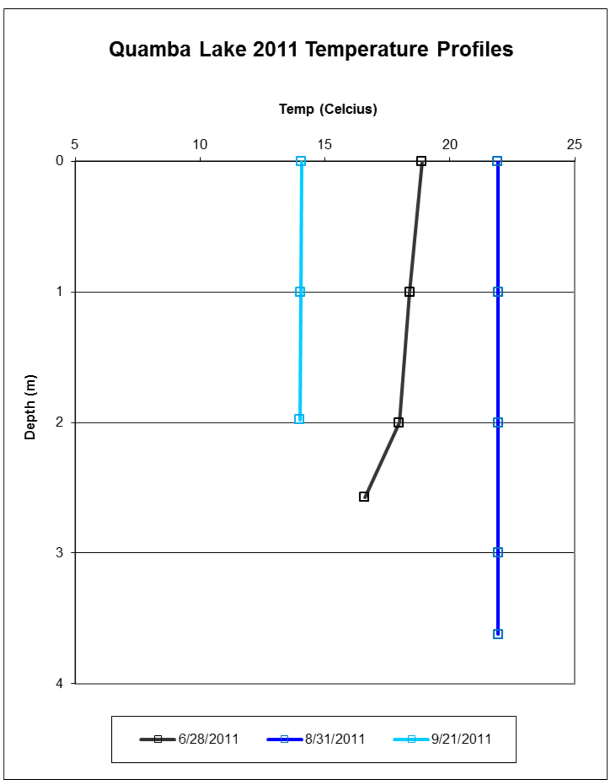

Quamba Lake Chlorophyll-a
Chlorophyll-a (ug/L)
80
70
60
50
40
30
20
10
0
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
All Sites (Ave)
Shallow Lake Standard

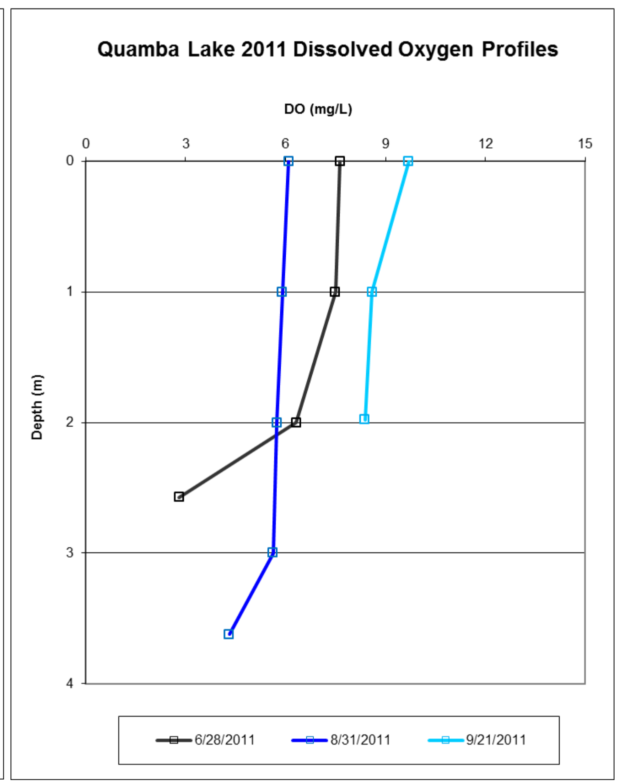

Quamba Lake Transparency
Secchi Depth (m)
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
0.0
1.0
2.0
All Sites (Ave)
Shallow Lake Standard

Quamba Lake Temperature and Dissolved Oxygen Profiles

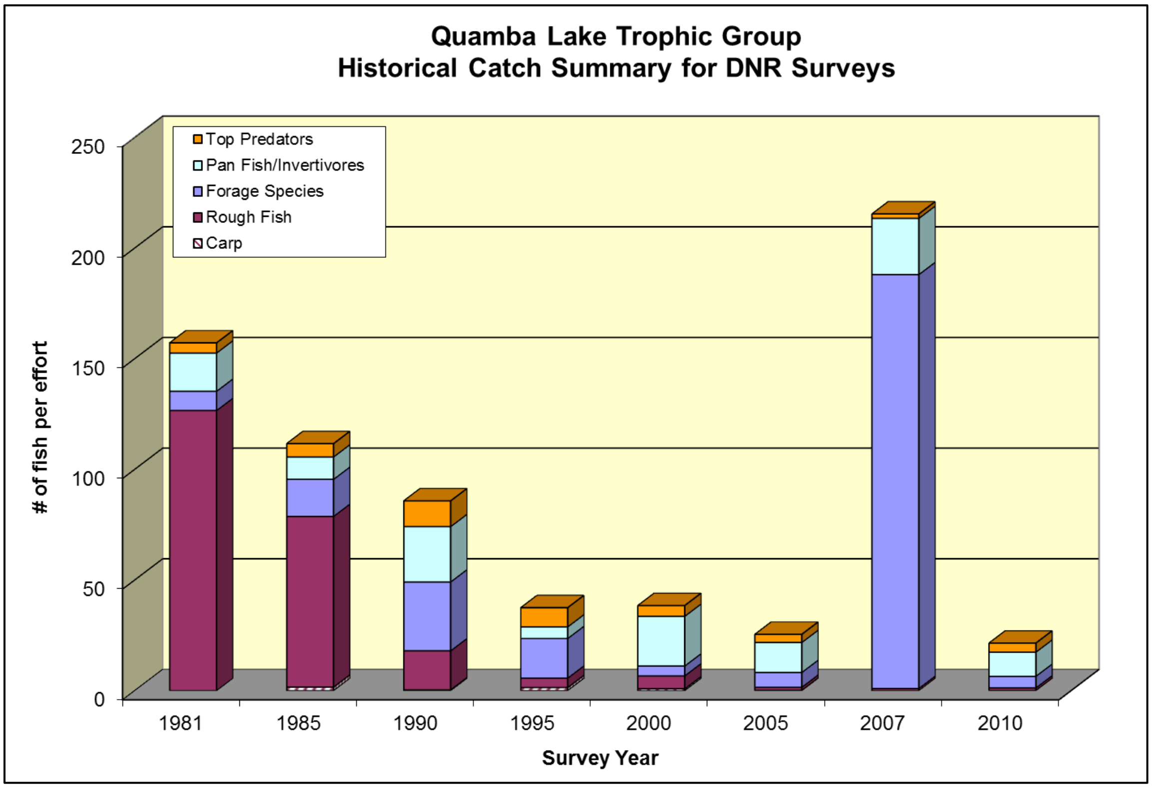


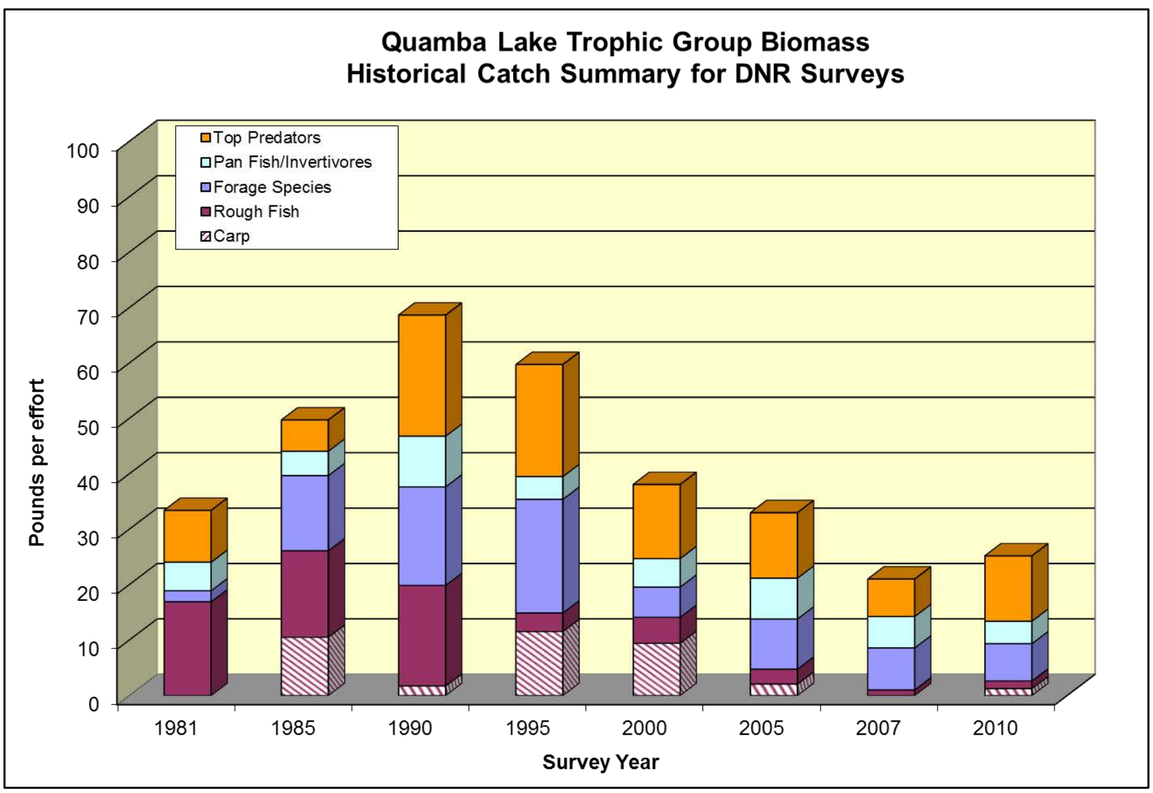




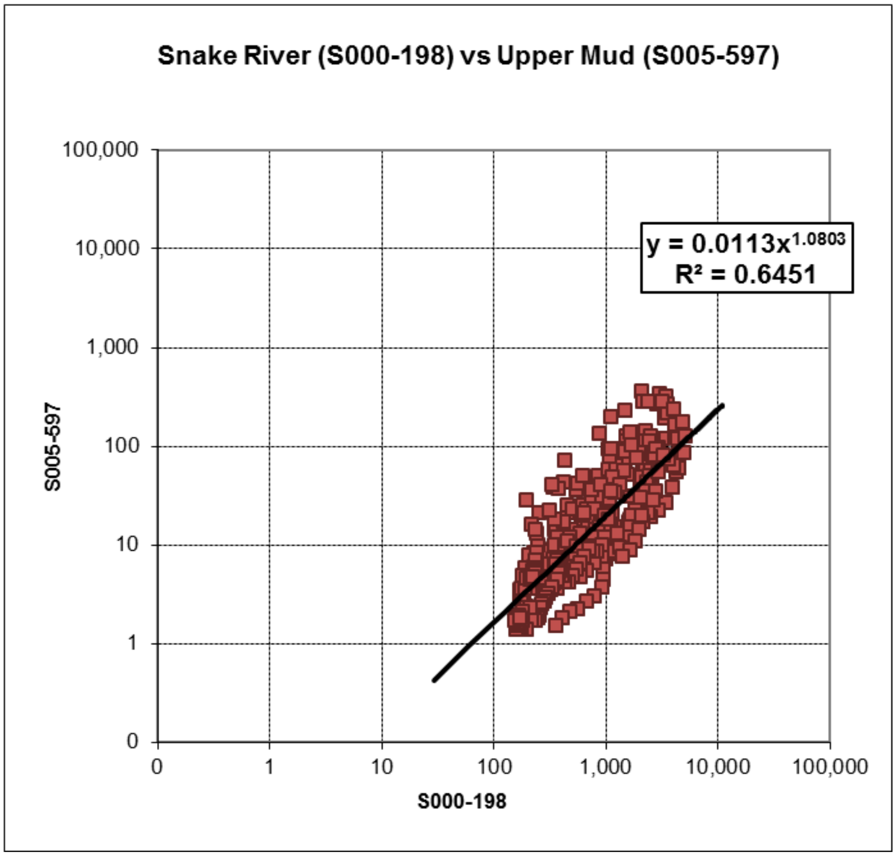


Quamba Lake DNR Fish Surveys by Trophic Group





Upper Mud Creek Flow Regression



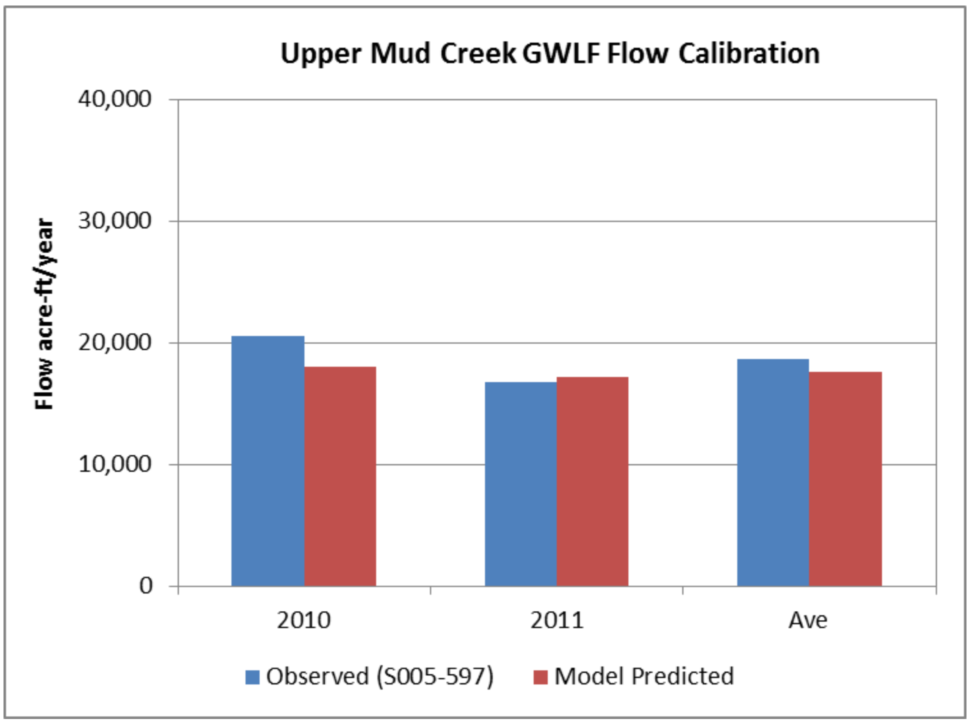
Quamba Lake Watershed FLUX Modeling

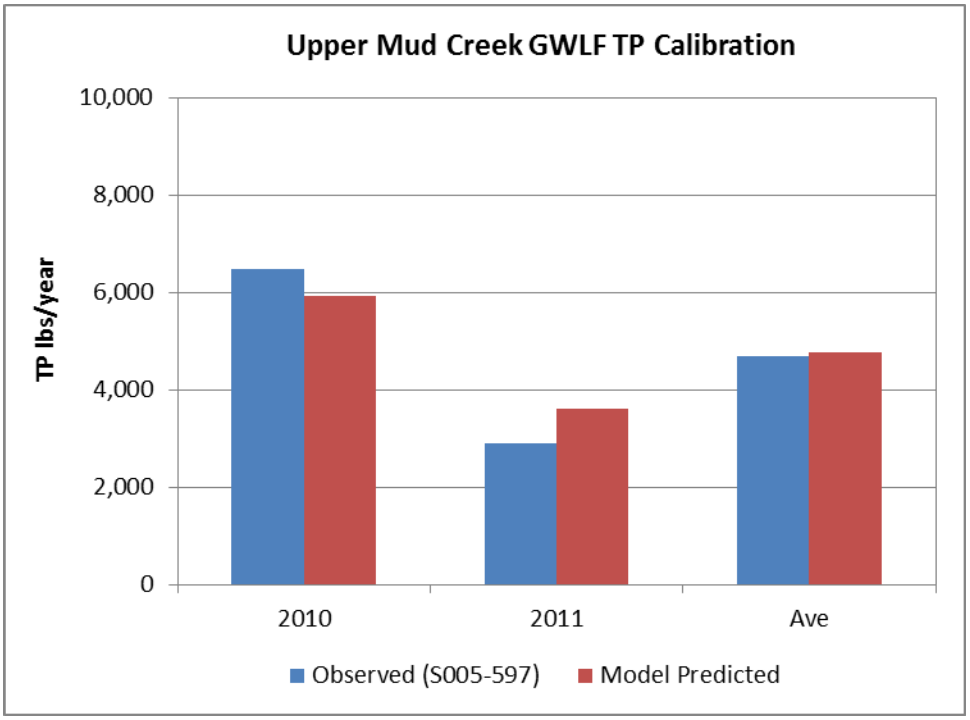
Site/ Watershed	Year	Monitored Flow (acre-ft)	FLUX Annual Load (lbs)	Concentration (ug/L)	FLUX Stratification	FLUX Method	C.V
S005-597 Mud Creek	2010	19,619	6,188	116	1/1-5/15; 5/15-9/5; 9/5-12/31	2	0.06
S005-597 Mud Creek	2011	16,056	2,774	64	0-10; 10+ cfs	2	0.05
S005-597 Mud Creek	Ave	17,837	4,481	92			

Quamba Lake Watershed Loads

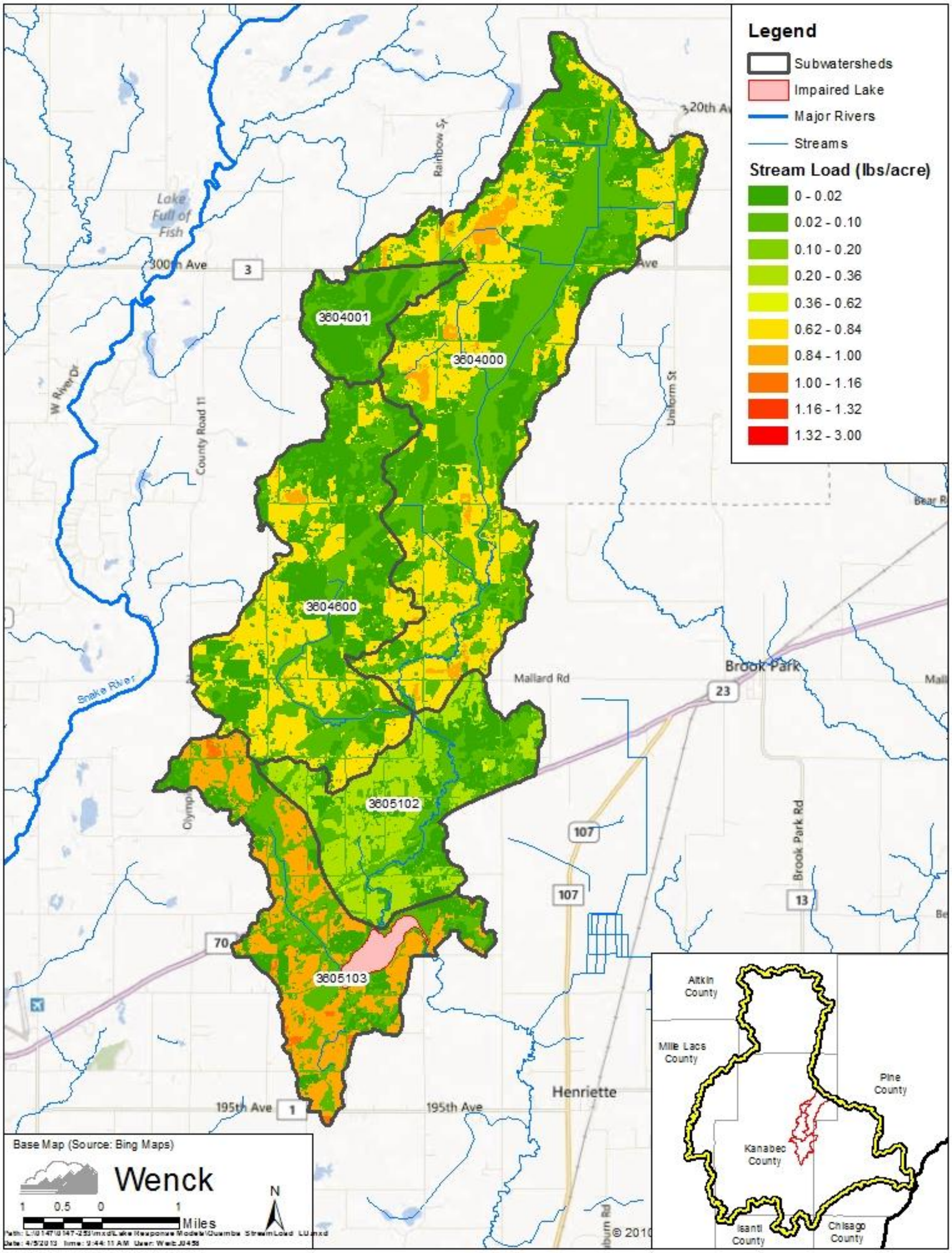
Watershed	Model Year	Precip (in)	Runoff (in)	Discharge (acre-ft)	TP Load (lbs)	TP conc. (ug/L)	Notes
Mud Creek and Direct	2010	40.7	12.1	24,349	7,665	116	Used runoff depth and FLUX TP conc. from S005-597, subtracted septic loads
Mud Creek and Direct	2011	27.5	9.9	19,927	3,426	63	Used runoff depth and FLUX TP conc. from S005-597, subtracted septic loads

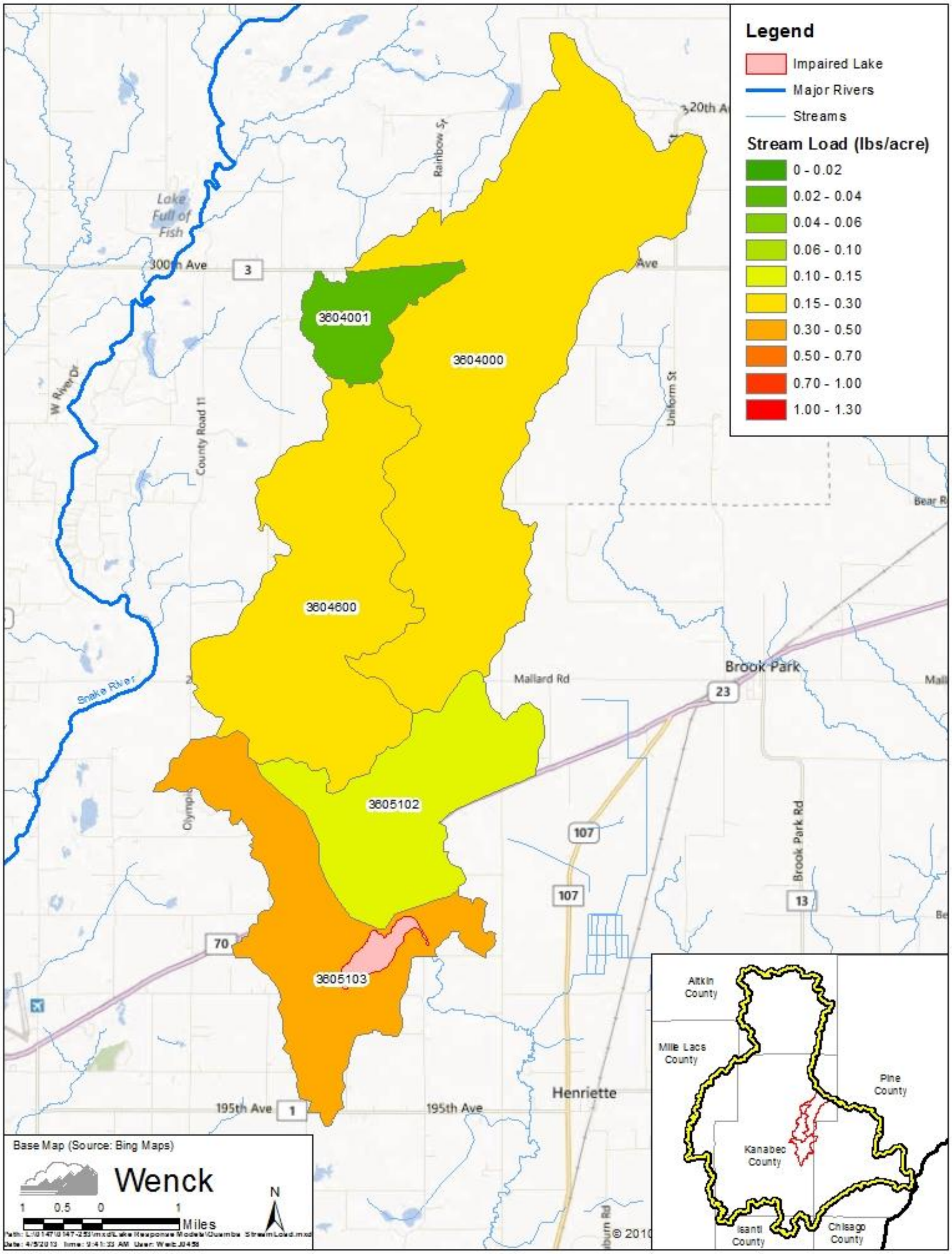
Quamba Lake Watershed GWLF Model Performance




Upper Mud Creek GWLF TP Calibration
TP lbs/year
10,000
8,000
6,000
4,000
2,000
0
2010
2011
Ave
Observed (S005-597)
Model Predicted

Quamba Lake Watershed GWLF Model Results




Legend
Impaired Lake
Major Rivers
Streams
Stream Load (lbs/acre)
0 - 0.02
0.02 - 0.04
0.04 - 0.06
0.06 - 0.10
0.10 - 0.15
0.15 - 0.30
0.30 - 0.50
0.50 - 0.70
0.70 - 1.00
1.00 - 1.30
3604001
3604000
3604600
3605102
3605103
Lake Full of Fish
Snake River
Brook Park
Henriette
Mallard Rd
195th Ave
Aitkin County
Mille Lacs County
Pine County
Kanabec County
Isanti County
Chisago County
Base Map (Source: Bing Maps)
Wenck
Miles

Quamba Lake Watershed Septic Loads

HUID	Watershed	Major Watershed	County	Total Pop.	Pop. On Septics	Total Systems	Imm Threat Systems	Gen Failing Systems	TP Load (lbs/yr)
360510103	Quamba Lake Direct	Quamba Direct	Kanabec	298	298	99	0	15	0
3604600	Mud Creek (Lake)	Quamba Mud	Kanabec	172	172	57	0	9	0
3604000	Mud Creek (Lake)	Quamba Mud	Kanabec	198	198	66	1	10	3
3604001	Mud Creek (Lake)	Quamba Mud	Kanabec	57	57	19	0	3	0
360510102	Mud Creek (Lake)	Quamba Mud	Kanabec	281	158	53	2	9	12

Quamba Lake Current Conditions BATHTUB Lake Response Model

	Average Loading Summary for	***Quamba***					
	Water Budgets				**Phosphorus Loading**		
Inflow from Drainage Areas							
		Drainage Area	Runoff Depth	Discharge	Phosphorus Concentration	Loading Calibration Factor (CF)[1]	Load
	Name	[acre]	[in/yr]	[ac-ft/yr]	[ug/L]	[--]	[lb/yr]
1	Mud Creek and Direct	24,124	11.0	22,138	92	1.0	5,545
2							
3							
4							
5							
	Summation	*24,124*	*11*	*22,138*			*5,545*
Point Source Dischargers							
				Discharge	Phosphorus Concentration	Loading Calibration Factor (CF)[1]	Load
	Name			[ac-ft/yr]	[ug/L]	[--]	[lb/yr]
1						1.0	
2						1.0	
3						1.0	
4						1.0	
5						1.0	
	Summation			*0*			*0*
Failing Septic Systems							
	Name						Load [lb/yr]
1	All Failing Septics						15
2							
3							
4							
5							
	Summation						*15*
Inflow from Upstream Lakes							
				Discharge	Estimated P Concentration	Calibration Factor	Load
	Name			[ac-ft/yr]	[ug/L]	[--]	[lb/yr]
1					-	1.0	
2					-	1.0	
3					-	1.0	
	Summation			*0*	-		*0*
Atmosphere							
	Lake Area	Precipitation	Evaporation	Net Inflow	Aerial Loading Rate	Calibration Factor	Load
	[acre]	[in/yr]	[in/yr]	[ac-ft/yr]	[lb/ac-yr]	[--]	[lb/yr]
	226	33.0	33.0	0.00	0.24	1.0	54
		Dry-year total P deposition =			0.222		
		Average-year total P deposition =			0.239		
		Wet-year total P deposition =			0.259		
		(Barr Engineering 2004)					
Internal							
	Lake Area	Anoxic Factor			Release Rate	Calibration Factor	Load
	[km²]	[days]			[mg/m²-day]	[--]	[lb/yr]
	0.92	122		Oxic	0.4	1.0	99
	0.92	55.7		Anoxic	11.1	1.0	1,248
	Summation						1,347
		Net Discharge [ac-ft/yr] =		**22,138**	**Net Load [lb/yr] =**		**6,961**

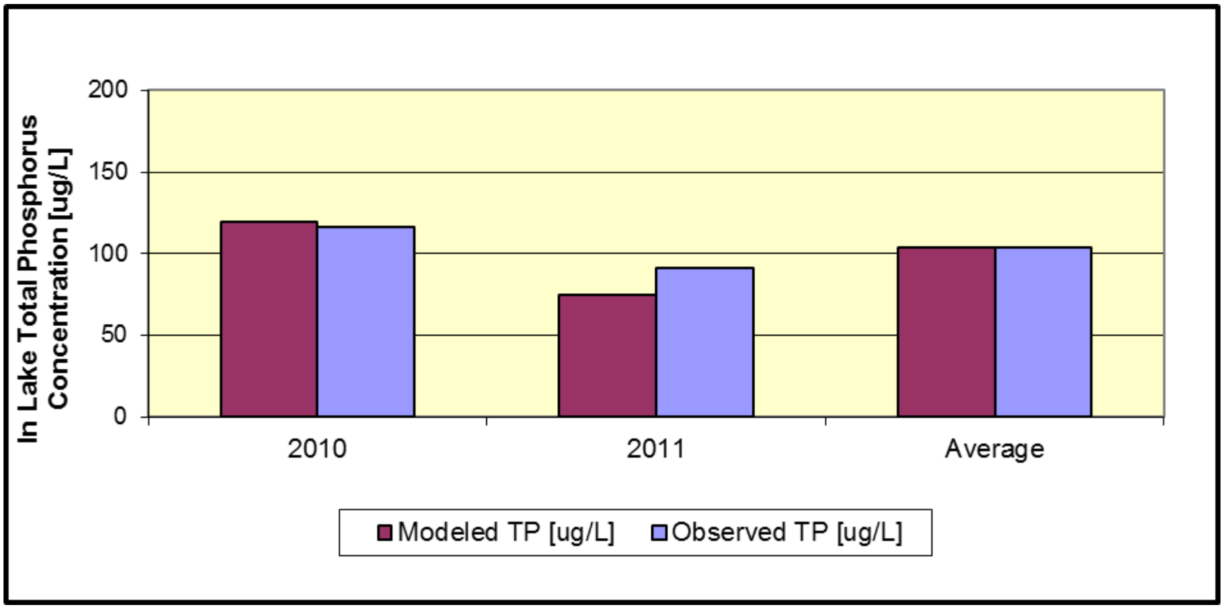
Modeled Parameter	**Equation**	**Parameters**	**Value**	**[Units]**
TOTAL IN-LAKE PHOSPHORUS CONCENTRATION				
$$P = \frac{P_i}{\left(1 + C_P \times C_{CB} \times \left(\frac{W_P}{V}\right)^b \times T\right)}$$		as f(W,Q,V) from Canfield & Bachmann (1981)		
		C_P =	0.38	[--]
		C_{CB} =	0.162	[--]
		b =	0.458	[--]
		W (total P load = inflow + atm.) =	3,157	[kg/yr]
		Q (lake outflow) =	27.3	[10^6 m³/yr]
		V (modeled lake volume) =	1.6	[10^6 m³]
		T = V/Q =	0.06	[yr]
		P_i = W/Q =	116	[µg/l]
Model Predicted In-Lake [TP]			**104**	**[ug/l]**
Observed In-Lake [TP]			**104**	**[ug/l]**

Quamba Lake TMDL Conditions BATHTUB Lake Response Model

TMDL Loading Summary for Quamba							
Water Budgets				Phosphorus Loading			
Inflow from Drainage Areas							
	Name	Drainage Area [acre]	Runoff Depth [in/yr]	Discharge [ac-ft/yr]	Phosphorus Concentration [ug/L]	Loading Calibration Factor (CF)[1] [--]	Load [lb/yr]
1	Mud Creek and Direct	24,124	11.0	22,138	61	0.7	3,670
2						1.0	
3						1.0	
4						1.0	
5						1.0	
	Summation	*24,124*	*11*	*22,138*			*3,670*
Point Source Dischargers							
	Name			Discharge [ac-ft/yr]	Phosphorus Concentration [ug/L]	Loading Calibration Factor (CF)[1] [--]	Load [lb/yr]
1						1.0	
2						1.0	
3						1.0	
4						1.0	
5						1.0	
	Summation			*0*			*0*
Failing Septic Systems							
	Name	Total Systems	Failing Systems	Discharge [ac-ft/yr]	Failure [%]		Load [lb/yr]
1	All Failing Septics						0
2							
3							
4							
5							
	Summation	*0*	*0*	*0*			*0*
Inflow from Upstream Lakes							
	Name			Discharge [ac-ft/yr]	Estimated P Concentration [ug/L]	Calibration Factor [--]	Load [lb/yr]
1					-	1.0	
2					-	1.0	
3					-	1.0	
	Summation			*0*	-		*0*
Atmosphere							
	Lake Area [acre]	Precipitation [in/yr]	Evaporation [in/yr]	Net Inflow [ac-ft/yr]	Aerial Loading Rate [lb/ac-yr]	Calibration Factor [--]	Load [lb/yr]
	226	33.0	33.0	0.00	0.24	1.0	54
		Dry-year total P deposition =			0.222		
		Average-year total P deposition =			0.239		
		Wet-year total P deposition =			0.259		
		(Barr Engineering 2004)					
Internal							
	Lake Area [km^2]	Anoxic Factor [days]			Release Rate [mg/m^2-day]	Calibration Factor [--]	Load [lb/yr]
	0.92	122		Oxic	0.4	1.0	99
	0.92	55.7		Anoxic	1.0	1.0	112
	Summation						211
		Net Discharge [ac-ft/yr] =		**22,138**	Net Load [lb/yr] =		**3,935**

Modeled Parameter	Equation	Parameters	Value	[Units]
TOTAL IN-LAKE PHOSPHORUS CONCENTRATION				
$P = \dfrac{P_i}{\left(1 + C_P \times C_{CB} \times \left(\dfrac{W_P}{V}\right)^b \times T\right)}$	as f(W,Q,V) from Canfield & Bachmann (1981)			
		C_P =	0.38	[--]
		C_{CB} =	0.162	[--]
		b =	0.458	[--]
		W (total P load = inflow + atm.) =	1,785	[kg/yr]
		Q (lake outflow) =	27.3	[10^6 m^3/yr]
		V (modeled lake volume) =	1.6	[10^6 m^3]
		T = V/Q =	0.06	[yr]
		P_i = W/Q =	65	[µg/l]
Model Predicted In-Lake [TP]			**60**	**[ug/l]**
Observed In-Lake [TP]			**104**	**[ug/l]**

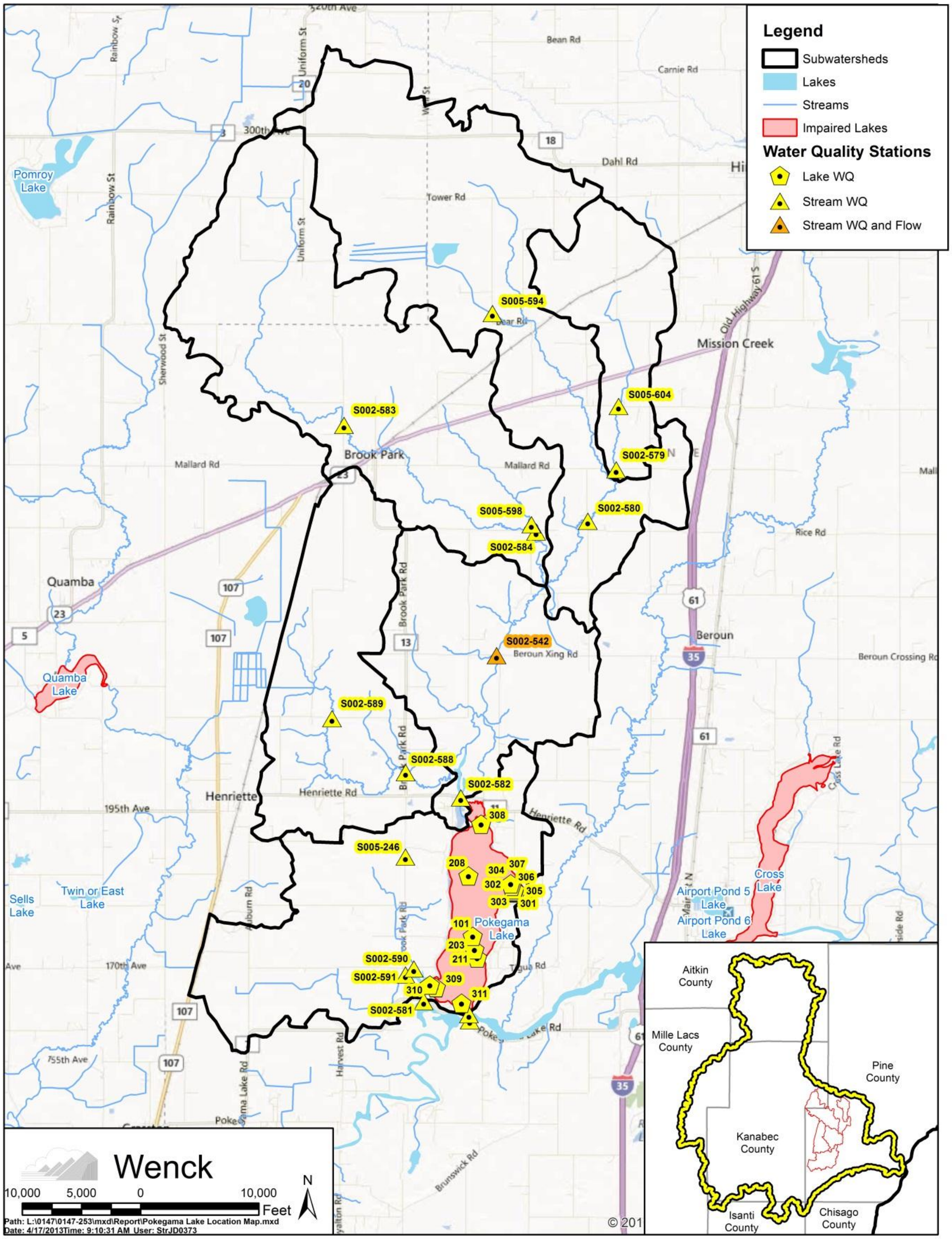
Quamba Lake BATHTUB Lake Response Model Performance



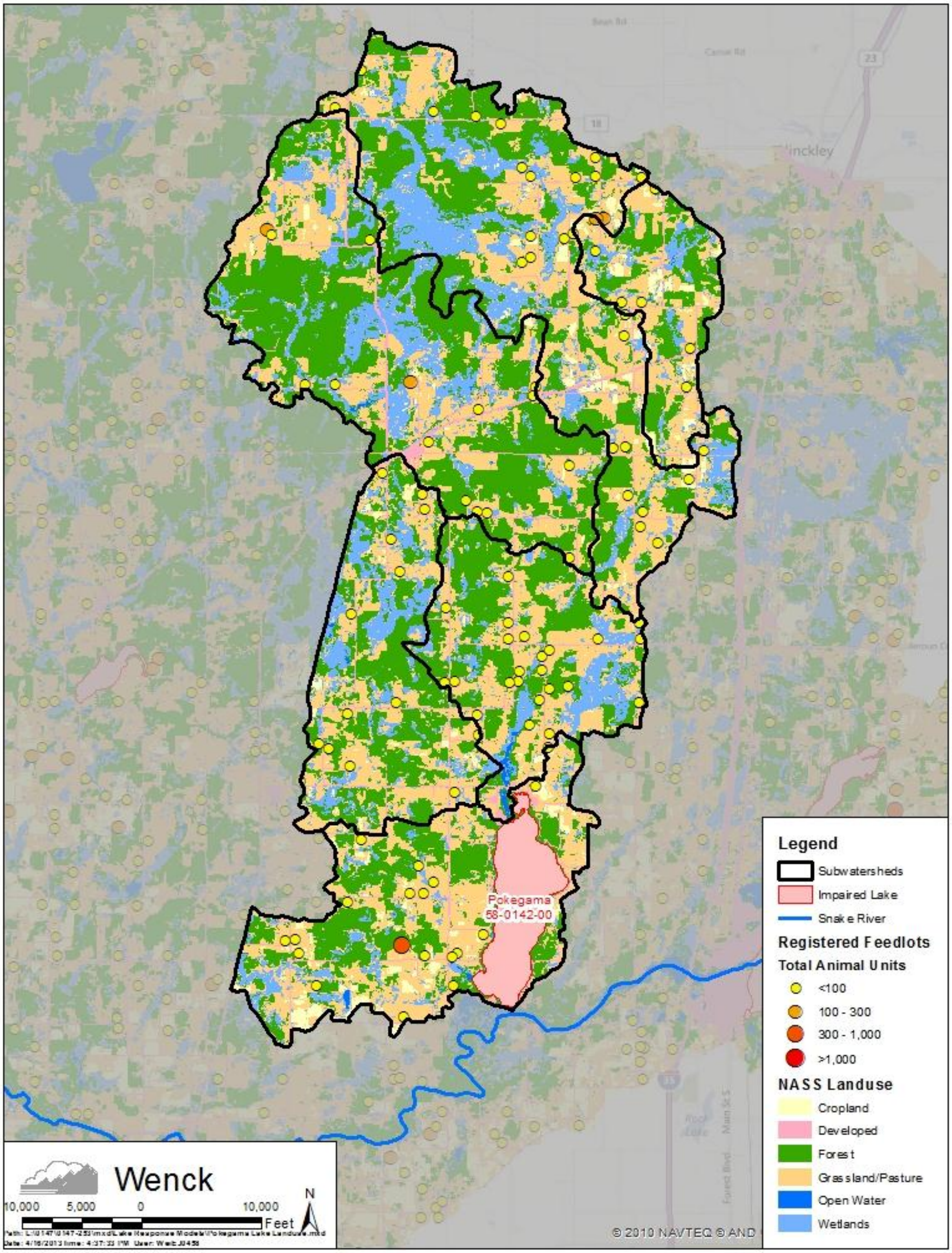
Appendix F

Pokegama Lake Supporting Documents

Pokegama Lake Monitoring Sites



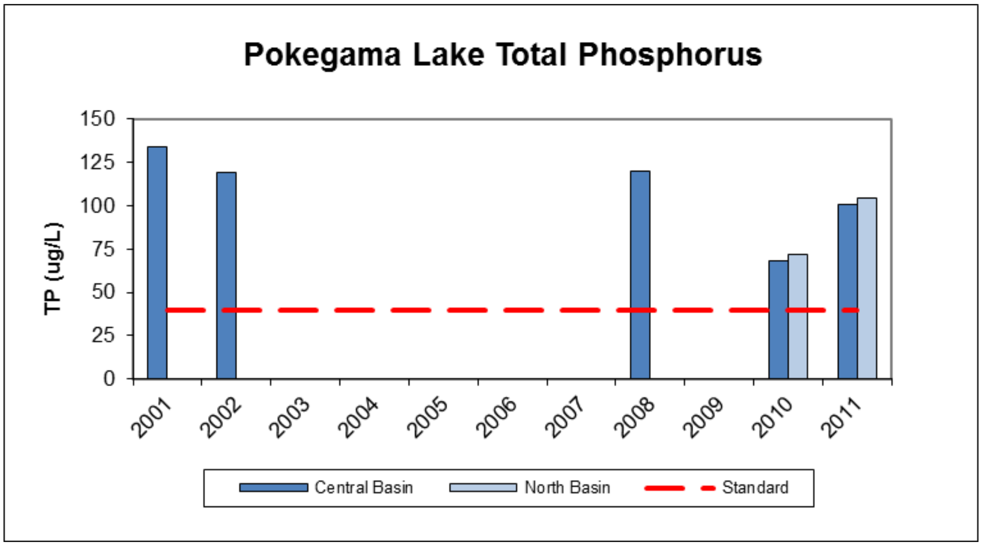
Pokegama Lake Watershed Landuse and Feedlots

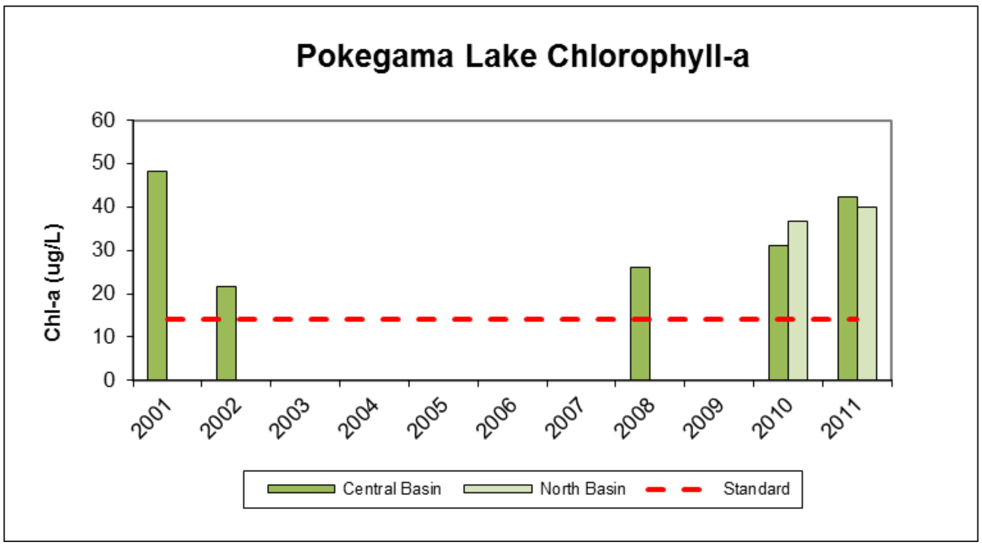


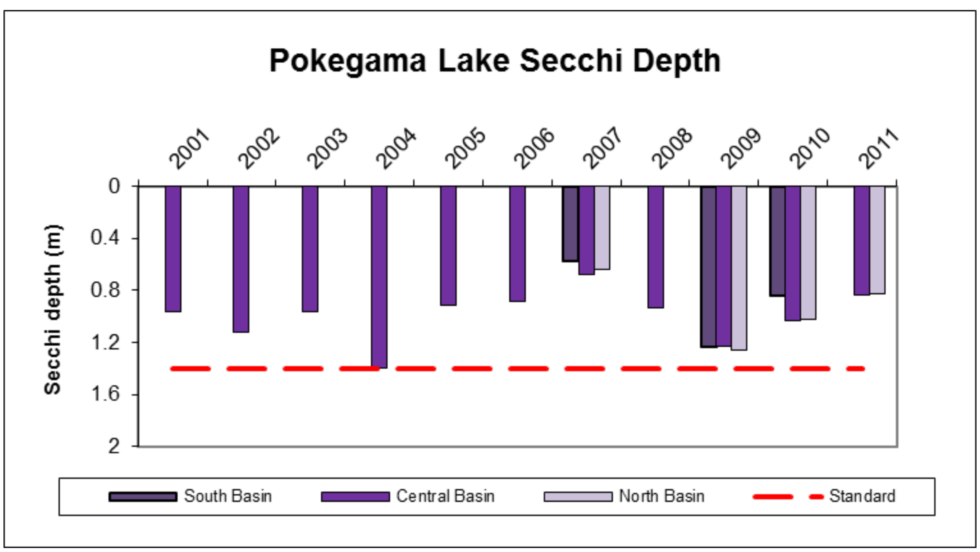
Pokegama Lake Historic Water Quality Sampling

Year	Total Phosphorus (ug/L)						Chlorophyll-a (ug/L)						Secchi (m)					
	South Basin		Central Basin		North Basin		South Basin		Central Basin		North Basin		South Basin		Central Basin		North Basin	
	N	Ave	N	Ave	N	Ave	N	Ave	N	Ave	N	Ave	N	Ave	N	Ave	N	Ave
2000	--	--	4	130	--	--	--	--	4	59	--	--	--	--	16	0.81	--	--
2001	--	--	4	134	--	--	--	--	4	48	--	--	1	1.37	11	0.97	--	--
2002	--	--	4	119	--	--	--	--	4	22	--	--	--	--	11	1.12	--	--
2003	--	--	1	100	--	--	--	--	1	24	--	--	--	--	12	0.96	--	--
2004	1	79	1	124	1	121	1	1	1	1	1	1	--	--	12	1.40	--	--
2005	1	135	2	154	1	153	1	85	2	80	1	79	--	--	12	0.91	--	--
2006	--	--	--	--	--	--	--	--	--	--	--	--	--	--	13	0.89	--	--
2007	--	--	1	197	--	--	--	--	1	100	--	--	4	0.58	15	0.68	4	0.64
2008	--	--	4	120	--	--	--	--	4	26	--	--	3	0.75	12	0.93	3	0.82
2009	--	--	--	--	--	--	--	--	--	--	--	--	4	1.24	17	1.23	4	1.26
2010	--	--	7	68	7	72	--	--	8	31	8	37	7	0.84	8	1.04	8	1.02
2011	--	--	7	101	7	104	--	--	7	42	7	40	3	0.50	11	0.84	15	0.83

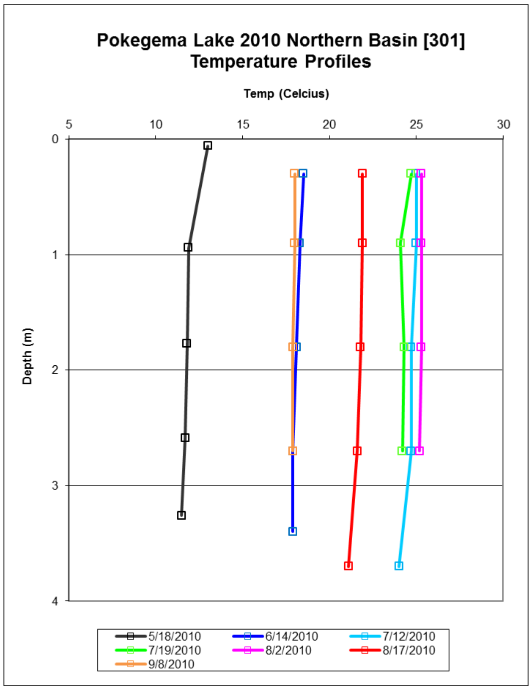
Note: Only June 1 through September 30 sample events presented

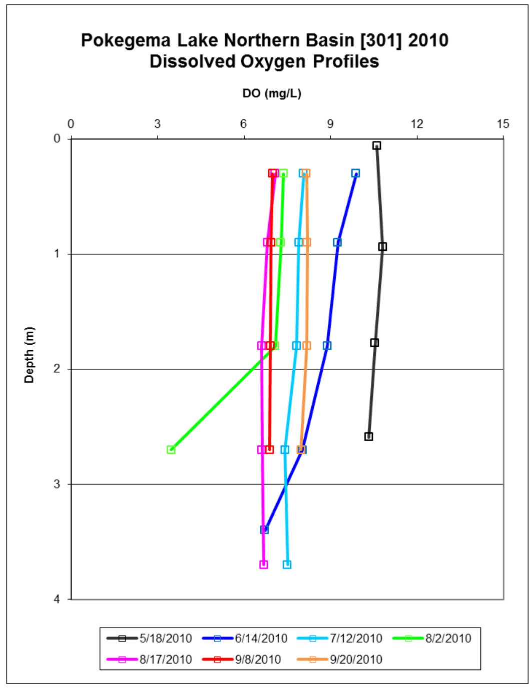

Pokegama Lake Total Phosphorus
TP (ug/L)
0
25
50
75
100
125
150
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
Central Basin
North Basin
Standard

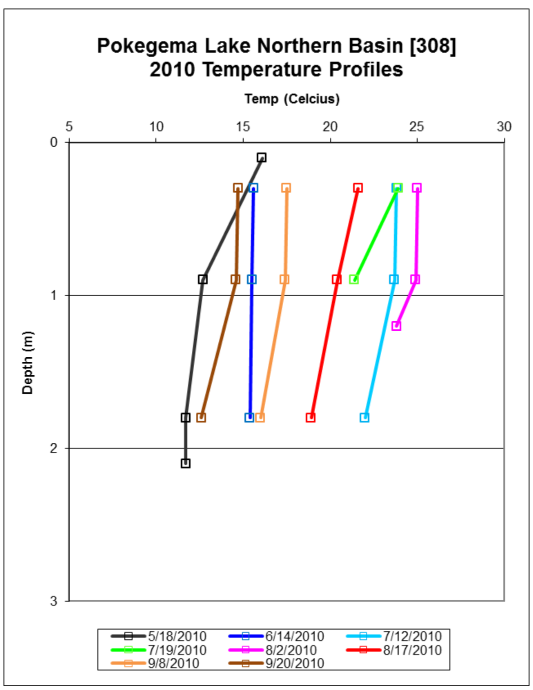

Pokegama Lake Chlorophyll-a
Chl-a (ug/L)
0
10
20
30
40
50
60
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
Central Basin
North Basin
Standard

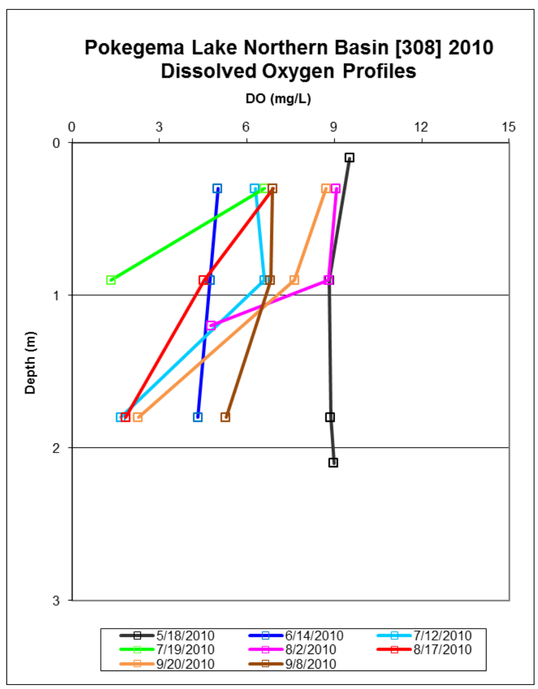

Pokegama Lake Secchi Depth
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
Secchi depth (m)
0
0.4
0.8
1.2
1.6
2
South Basin
Central Basin
North Basin
Standard

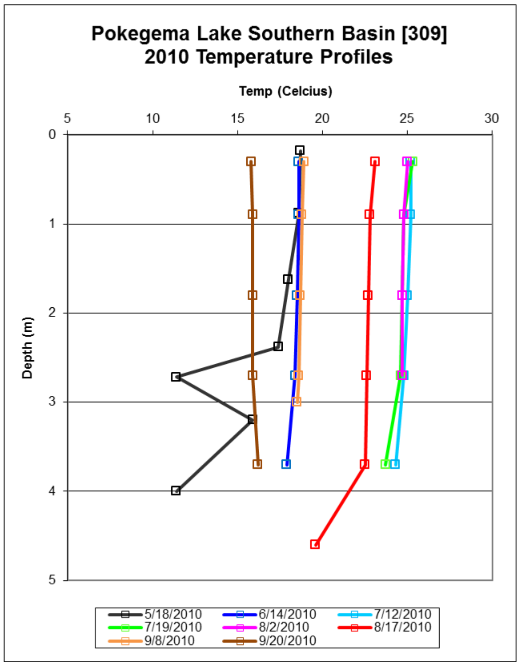
Pokegama Lake Temperature and Dissolved Oxygen Profiles

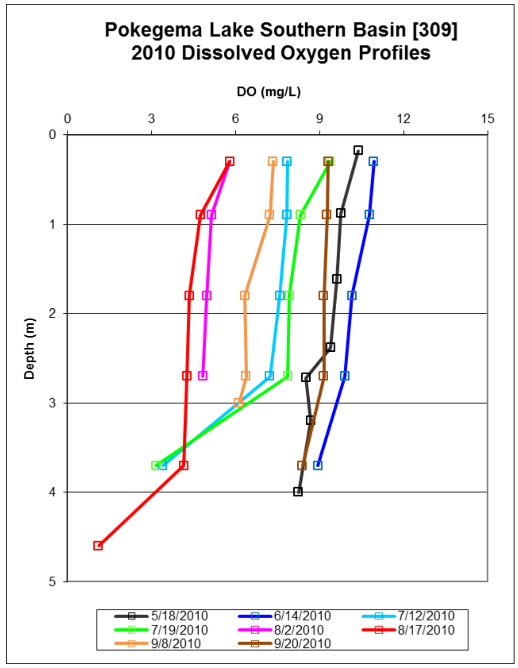


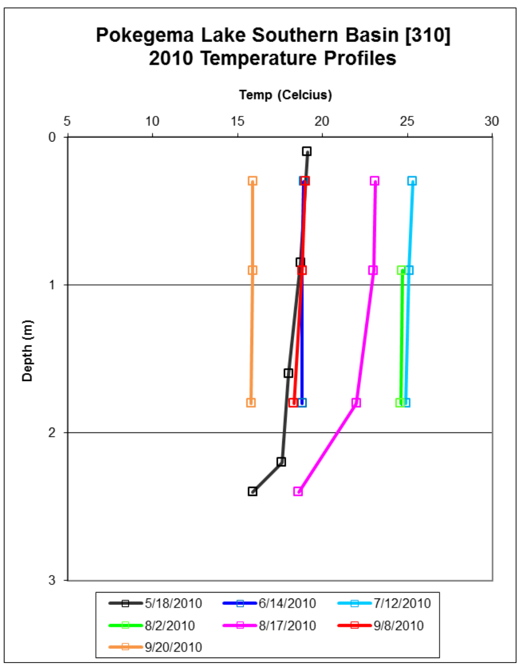


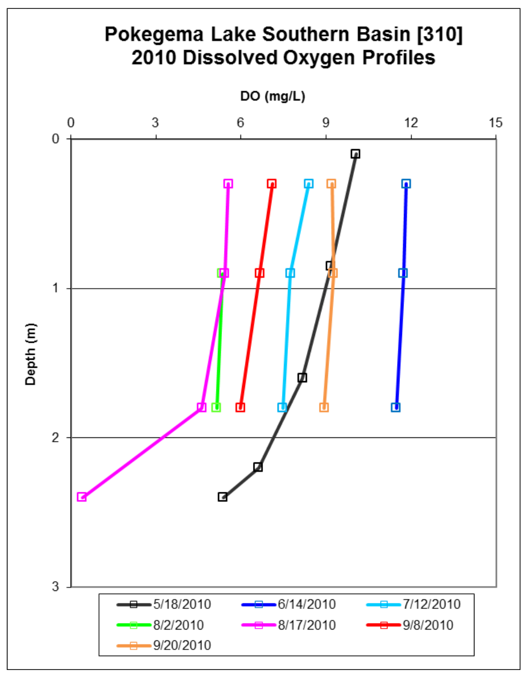


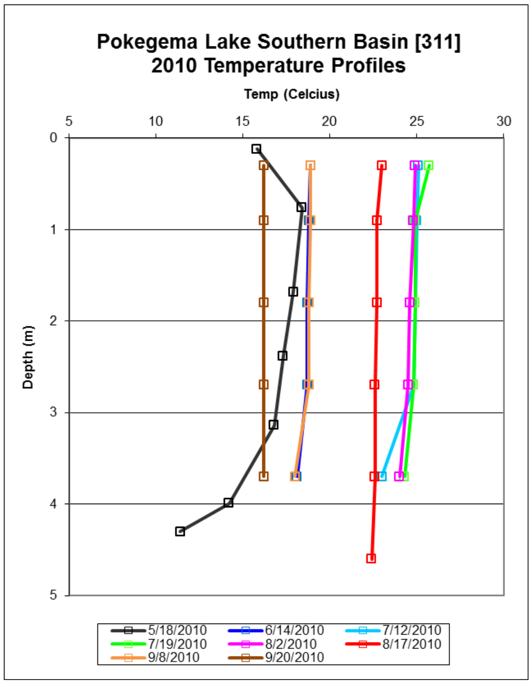


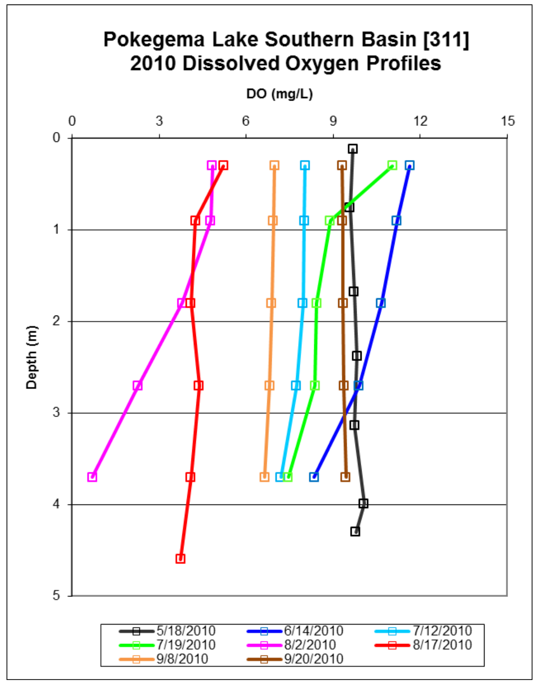

Pokegema Lake Southern Basin [309]
2010 Temperature Profiles
Temp (Celcius)
5
10
15
20
25
30
0
1
2
3
4
5
Depth (m)
5/18/2010
6/14/2010
7/12/2010
7/19/2010
8/2/2010
8/17/2010
9/8/2010
9/20/2010

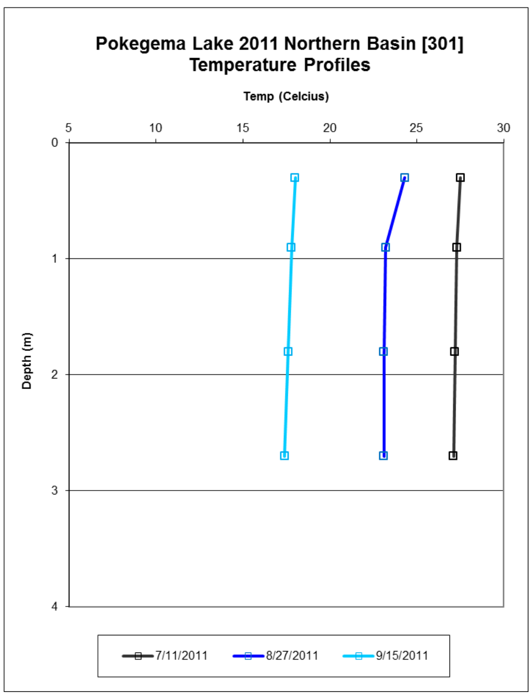

Pokegema Lake Southern Basin [309]
2010 Dissolved Oxygen Profiles
DO (mg/L)
0
3
6
9
12
15
0
1
2
3
4
5
Depth (m)
5/18/2010
6/14/2010
7/12/2010
7/19/2010
8/2/2010
8/17/2010
9/8/2010
9/20/2010

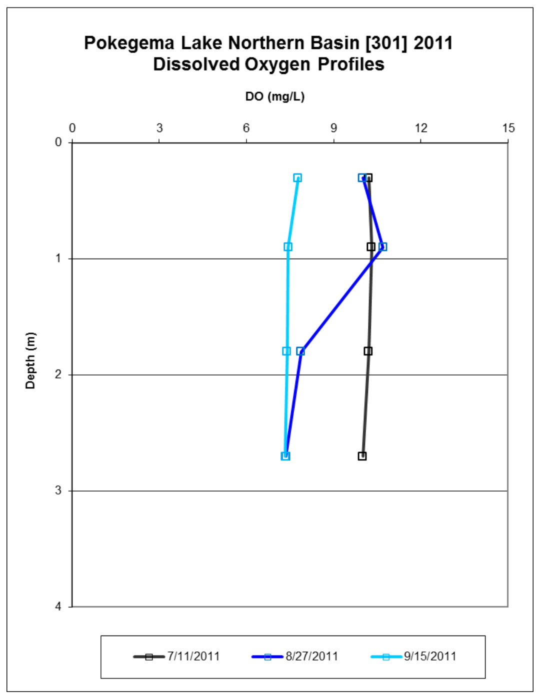

Pokegema Lake Southern Basin [310]
2010 Temperature Profiles
Temp (Celcius)
5
10
15
20
25
30
0
1
2
3
Depth (m)
5/18/2010
6/14/2010
7/12/2010
8/2/2010
8/17/2010
9/8/2010
9/20/2010

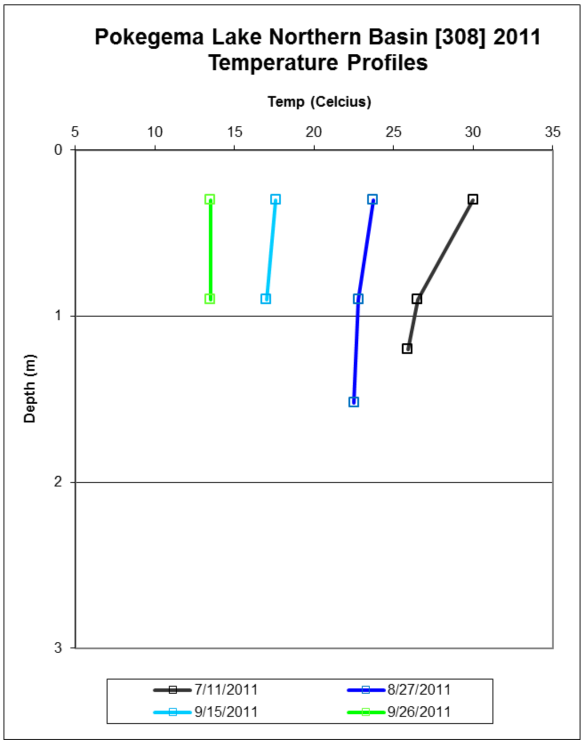

Pokegema Lake Southern Basin [310]
2010 Dissolved Oxygen Profiles
DO (mg/L)
0
3
6
9
12
15
0
1
2
3
Depth (m)
5/18/2010
6/14/2010
7/12/2010
8/2/2010
8/17/2010
9/8/2010
9/20/2010

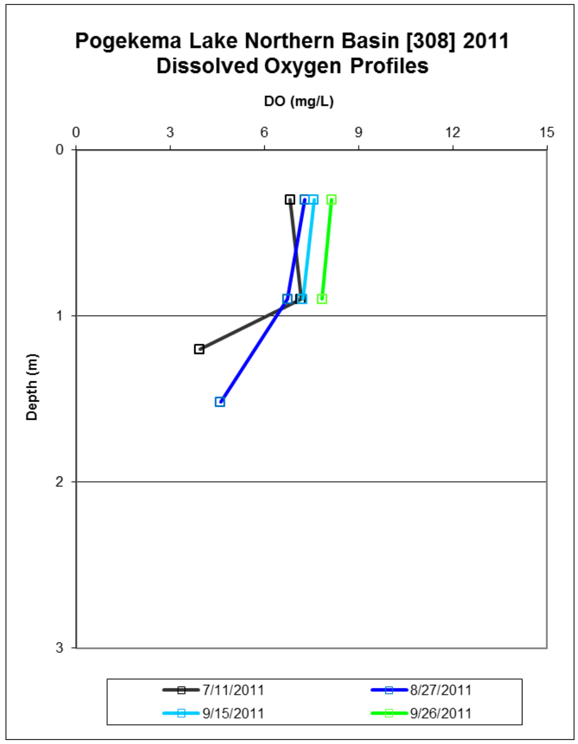

Pokegema Lake Southern Basin [311]
2010 Temperature Profiles
Temp (Celcius)
5 10 15 20 25 30
Depth (m)
0 1 2 3 4 5
5/18/2010
6/14/2010
7/12/2010
7/19/2010
8/2/2010
8/17/2010
9/8/2010
9/20/2010

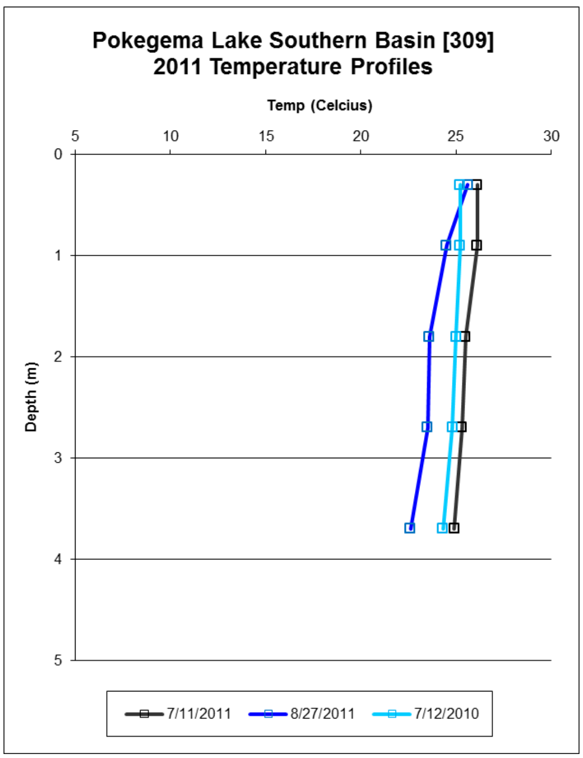

Pokegema Lake Southern Basin [311]
2010 Dissolved Oxygen Profiles
DO (mg/L)
0 3 6 9 12 15
Depth (m)
0 1 2 3 4 5
5/18/2010
6/14/2010
7/12/2010
7/19/2010
8/2/2010
8/17/2010
9/8/2010
9/20/2010

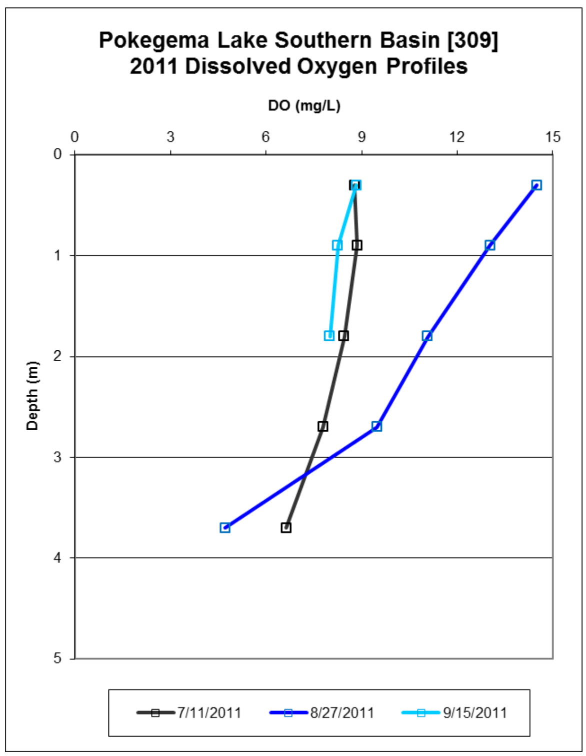

Pokegema Lake 2011 Northern Basin [301]
Temperature Profiles
Temp (Celcius)
5 10 15 20 25 30
Depth (m)
0 1 2 3 4
7/11/2011
8/27/2011
9/15/2011

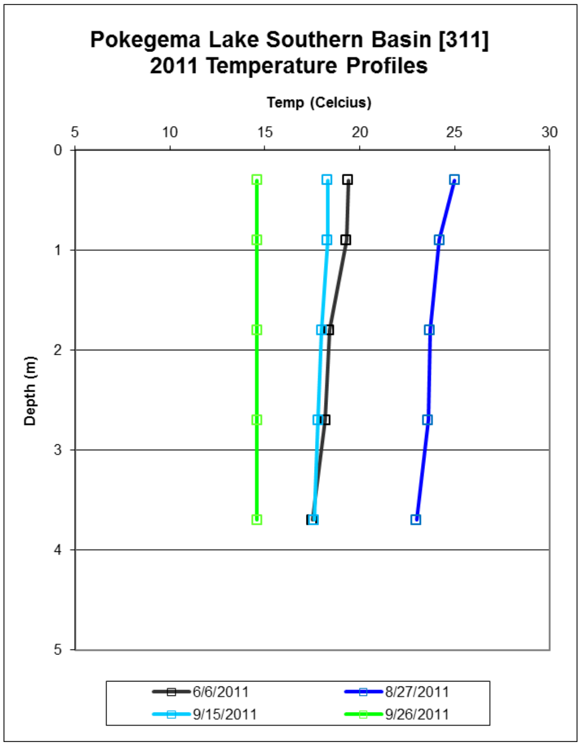

Pokegema Lake Northern Basin [301] 2011
Dissolved Oxygen Profiles
DO (mg/L)
0 3 6 9 12 15
Depth (m)
0 1 2 3 4
7/11/2011
8/27/2011
9/15/2011

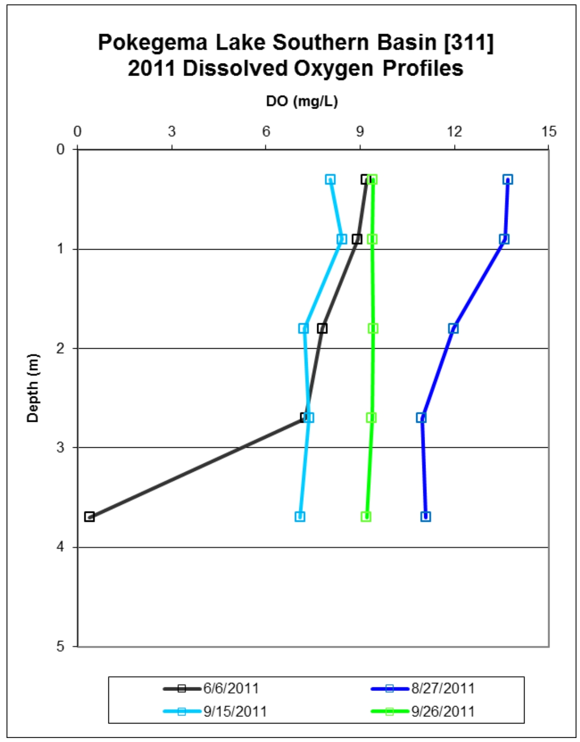

Pokegema Lake Northern Basin [308] 2011
Temperature Profiles
Temp (Celcius)
5
10
15
20
25
30
35
0
1
2
3
Depth (m)
7/11/2011
8/27/2011
9/15/2011
9/26/2011


Pogekema Lake Northern Basin [308] 2011
Dissolved Oxygen Profiles
DO (mg/L)
0
3
6
9
12
15
0
1
2
3
Depth (m)
7/11/2011
8/27/2011
9/15/2011
9/26/2011

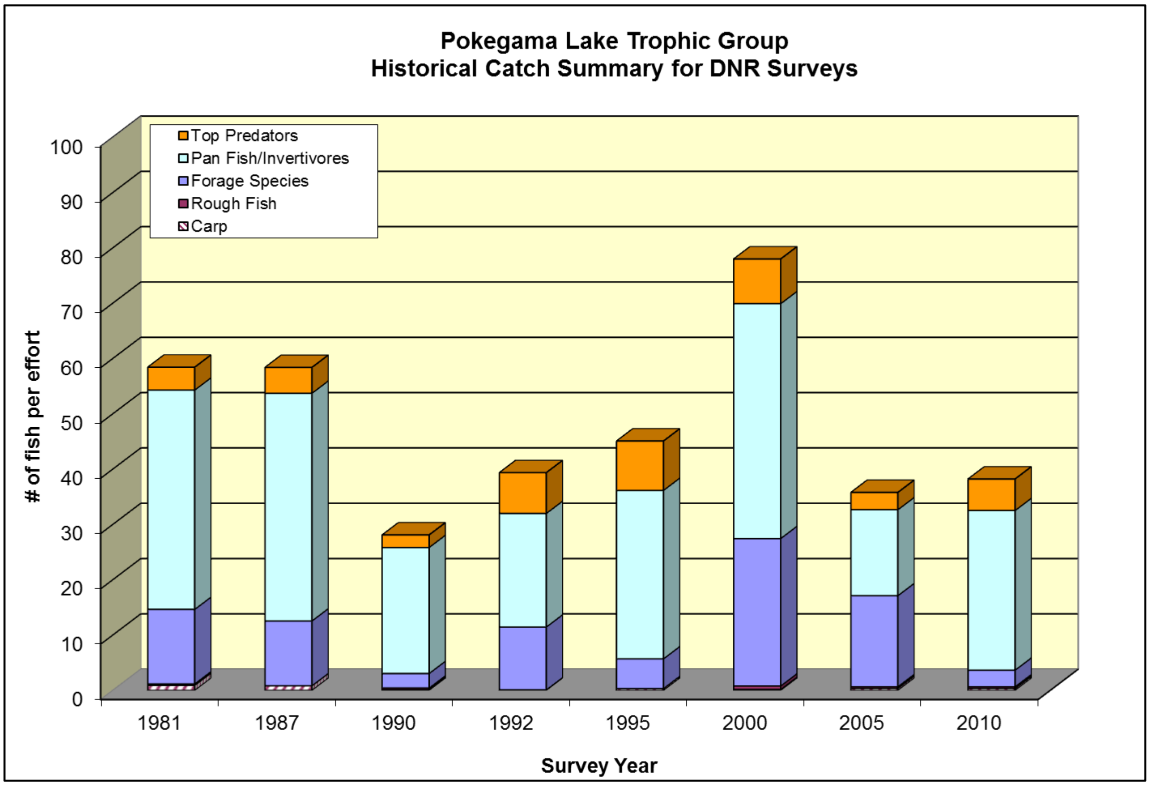

Pokegema Lake Southern Basin [309]
2011 Temperature Profiles
Temp (Celcius)
5
10
15
20
25
30
0
1
2
3
4
5
Depth (m)
7/11/2011
8/27/2011
7/12/2010

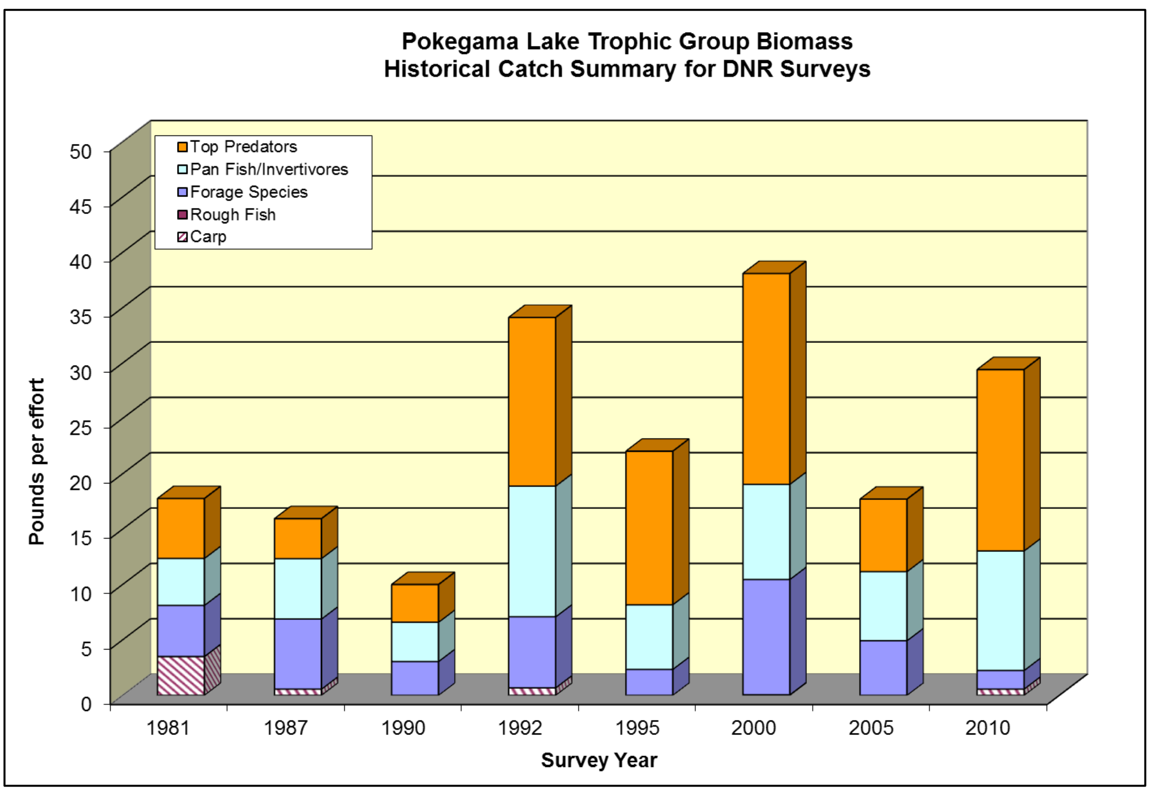

Pokegema Lake Southern Basin [309]
2011 Dissolved Oxygen Profiles
DO (mg/L)
0
3
6
9
12
15
0
1
2
3
4
5
Depth (m)
7/11/2011
8/27/2011
9/15/2011


Pokegema Lake Southern Basin [311]
2011 Temperature Profiles
Temp (Celcius)
Depth (m)
6/6/2011
8/27/2011
9/15/2011
9/26/2011

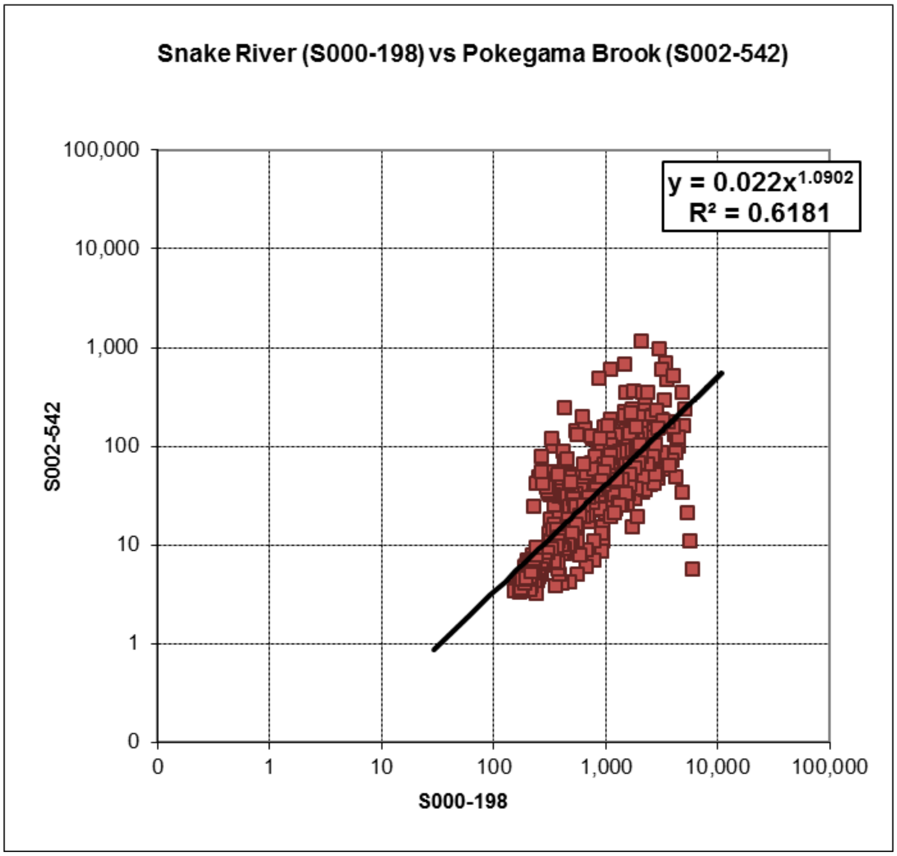

Pokegema Lake Southern Basin [311]
2011 Dissolved Oxygen Profiles
DO (mg/L)
Depth (m)
6/6/2011
8/27/2011
9/15/2011
9/26/2011

Pokegama Lake DNR Fish Surveys by Trophic Group





Pokegama Brook Flow Regression



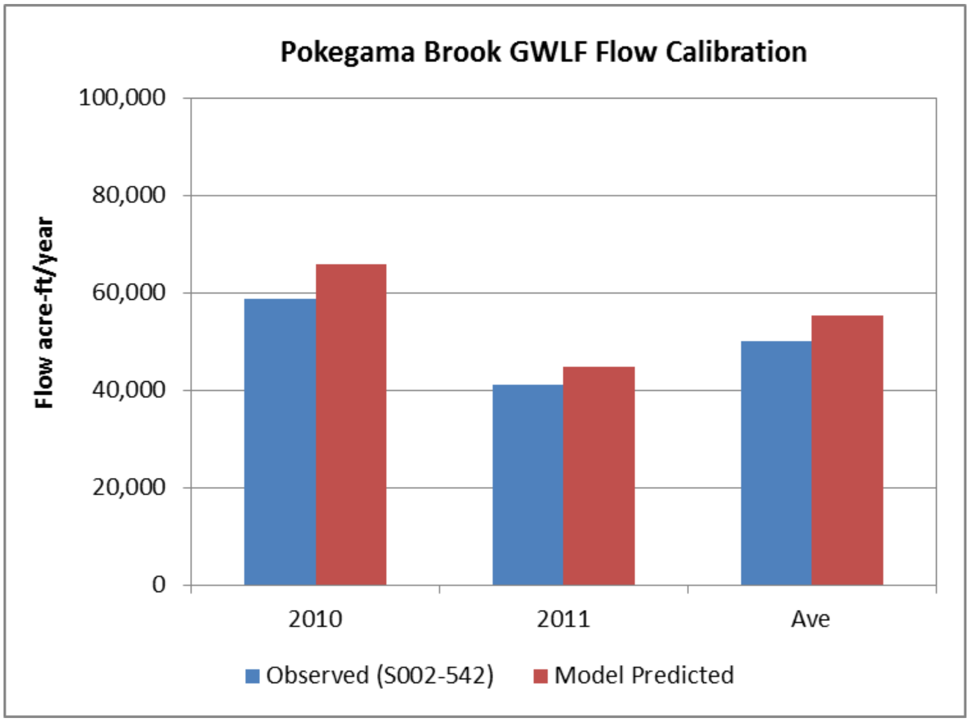
Pokegama Lake Watershed FLUX Modeling

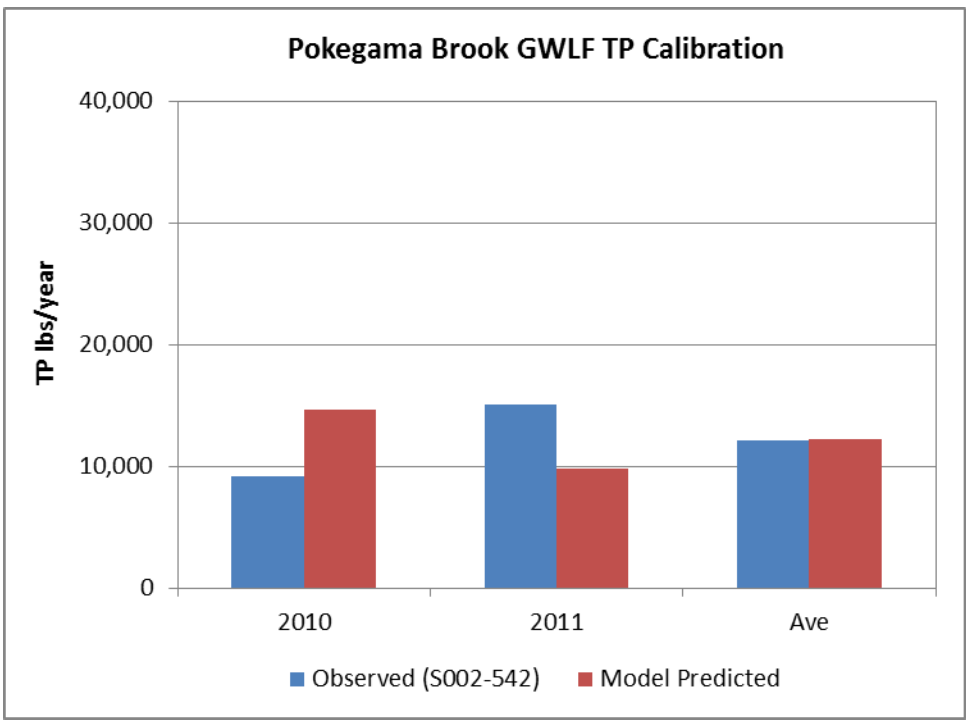
Site/ Watershed	Year	Monitored Flow (acre-ft)	FLUX Annual Load (lbs)	Concentration (ug/L)	FLUX Stratification	FLUX Method	C.V
S002-542 Pokegama Brook	2001	32,206	6,660	76	Hydrograph separation	3	0.07
S002-542 Pokegama Brook	2002	29,033	6,622	84	1/1-6/1; 6/1-12/31	2	0.11
S002-542 Pokegama Brook	2004	16,833	2,516	55	None	3	0.07
S002-542 Pokegama Brook	2005	24,981	6,150	90	Hydrograph separation	2	0.10
S002-542 Pokegama Brook	2008	24,100	6,752	103	1/1-9/15; 9/15-12/31	2	0.07
S002-542 Pokegama Brook	2009	17,948	4,191	86	None	2	0.16
S002-542 Pokegama Brook	2010	43,270	11,148	95	0-100; 100+ cfs	3	0.07
S002-542 Pokegama Brook	Ave	26,910	6,291	86			

Pokegama Lake Watershed Loads

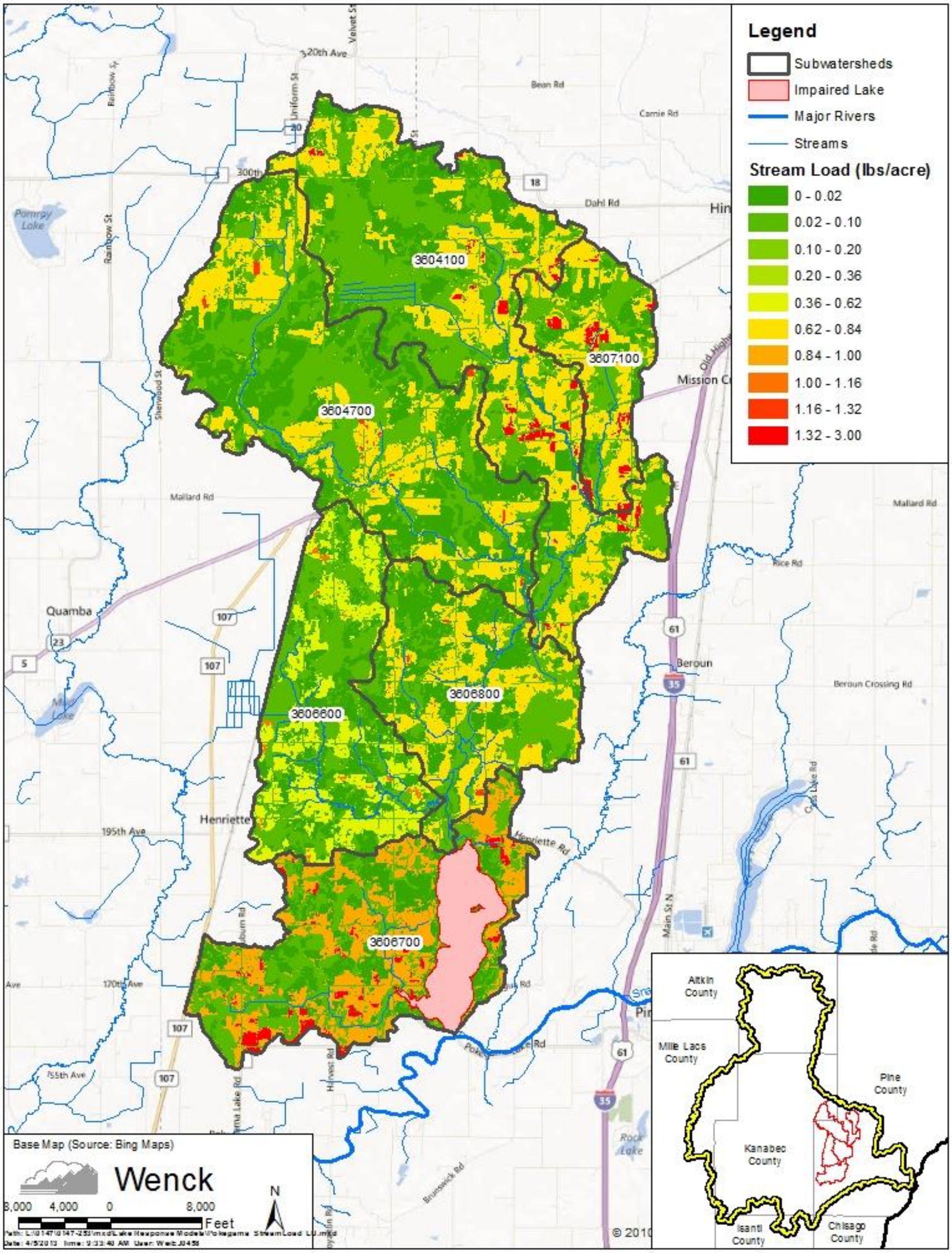
Watershed	Model Year	Precip (in)	Runoff (in)	Discharge (acre-ft)	TP Load (lbs)	TP conc. (ug/L)	Notes
Pokegama Brook	2001	33.8	12.3	36,559	7,090	71	Used runoff and FLUX TP conc. from S002-52, subtracted septic loads
Pokegama Brook	2002	39.1	11.1	32,958	7,063	79	Used runoff and FLUX TP conc. from S002-52, subtracted septic loads
Pokegama Brook	2008	35.2	9.2	27,357	7,197	97	Used runoff and FLUX TP conc. from S002-52, subtracted septic loads
Pokegama Brook	2010	40.7	16.5	49,119	12,183	91	Used runoff and FLUX TP conc. from S002-542, subtracted septic loads
West Trib	2001	33.8	12.3	7,216	1,328	68	Used runoff depth from S002-542, flow weighted TP concentration from S002-588, subtracted septic loads
West Trib	2002	39.1	11.1	6,505	1,178	67	Used runoff depth from S002-542, flow weighted TP concentration from S002-588, subtracted septic loads
West Trib	2008	35.2	9.2	5,400	945	64	Used runoff depth from S002-542, flow weighted TP concentration from S002-588, subtracted septic loads
West Trib	2010	40.7	16.5	9,695	1,903	72	Used runoff depth from S002-542, flow weighted TP concentration from S002-588, subtracted septic loads
Direct	2001	33.8	12.3	7,995	9,195	423	Used runoff depth from S002-542, flow weighted TP concentration from S002-590 and S002-591, subtracted septic loads
Direct	2002	39.1	11.1	7,208	8,274	422	Used runoff depth from S002-542, flow weighted TP concentration from S002-590 and S002-591, subtracted septic loads
Direct	2008	35.2	9.2	5,983	6,843	420	Used runoff depth from S002-542, flow weighted TP concentration from S002-590 and S002-591, subtracted septic loads
Direct	2010	40.7	16.5	10,742	12,045	424	Used runoff depth from S002-542, flow weighted TP concentration from S002-590 and S002-591, subtracted septic loads

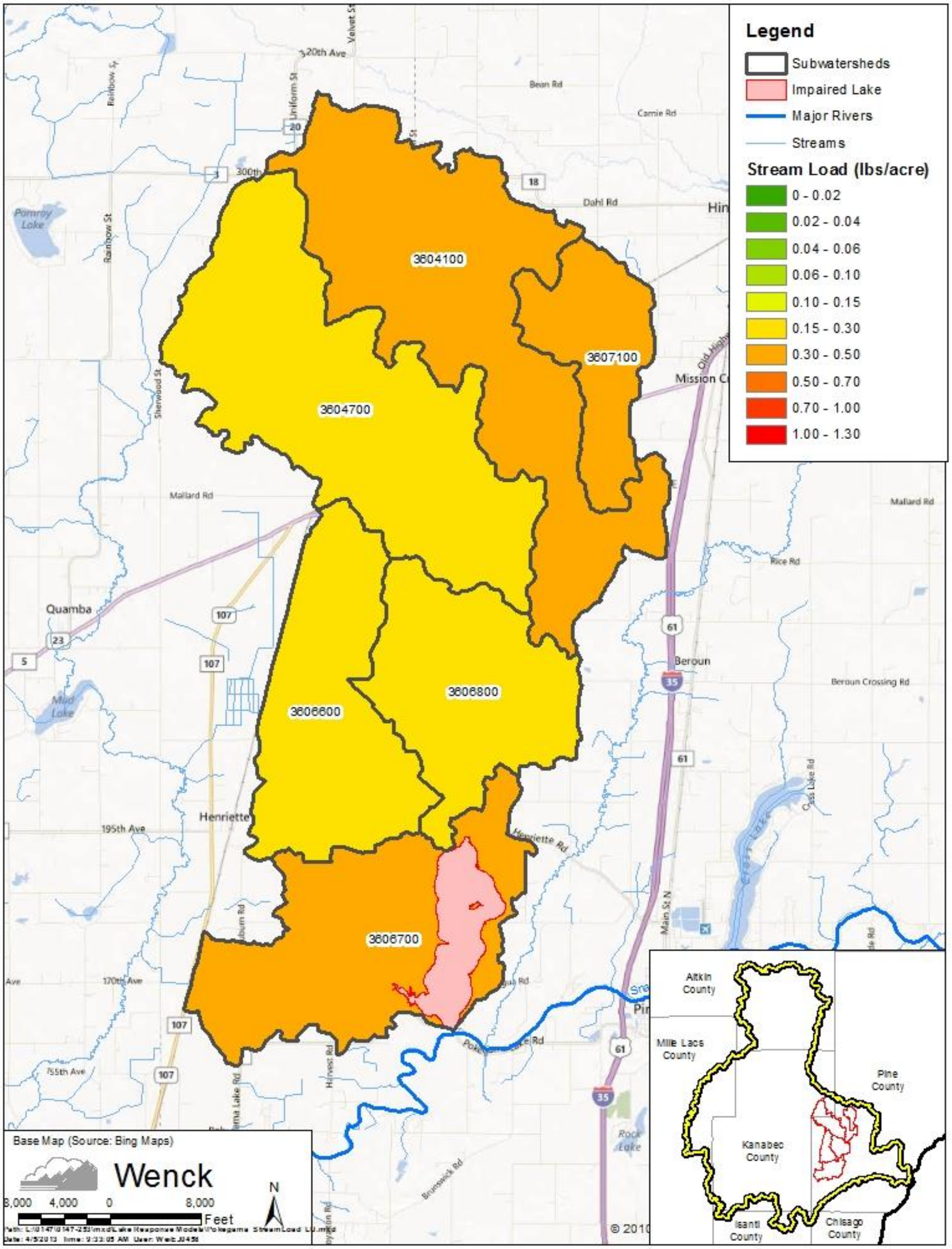
Pokegama Brook Watershed GWLF Model Performance





Pokegama Lake Watershed GWLF Model Results




Legend
Subwatersheds
Impaired Lake
Major Rivers
Streams
Stream Load (lbs/acre)
0 - 0.02
0.02 - 0.04
0.04 - 0.06
0.06 - 0.10
0.10 - 0.15
0.15 - 0.30
0.30 - 0.50
0.50 - 0.70
0.70 - 1.00
1.00 - 1.30
3604100
3607100
3604700
3606600
3606800
3606700
Quamba
Henriette
Beroun
Mission C
Aitkin County
Mille Lacs County
Pine County
Kanabec County
Isanti County
Chisago County
Base Map (Source: Bing Maps)
Wenck
8,000 4,000 0 8,000
Feet
N
© 2010

Pokegama Lake Watershed Septic Loads

HUID	Watershed	County	Total Pop.	Pop. on Septics	Total Systems	Imm. Threat System	Gen Failing System	Failing System TP (lbs/yr)
3606800	Pokegama Creek	Pine	321	321	107	28	41	204
3604700	Pokegama Creek	Pine	332	332	111	17	28	125
3604100	Pokegama Creek	Pine	335	335	112	15	30	110
3607100	Pokegama Creek	Pine	105	105	35	3	8	25
3606700	Direct	Pine	235	235	78	20	30	149
3606600	West Trib	Pine	346	346	115	27	40	195

Pokegama Lake Current Conditions BATHTUB Lake Response Model

	Average Loading Summary for Pokegama						
	Water Budgets				**Phosphorus Loading**		
Inflow from Drainage Areas							
		Drainage Area	Runoff Depth	Discharge	Phosphorus Concentration	Loading Calibration Factor (CF)[1]	Load
	Name	[acre]	[in/yr]	[ac-ft/yr]	[ug/L]	[--]	[lb/yr]
1	Pokegama Brook	35,754	12.3	36,498	84	1.0	8,384
2	NW Trib	7,057	12.3	7,204	68.3	1.0	1,338
3	Direct Watershed	7,819	12.3	7,982	422.7	1.0	9,179
4							
5							
	Summation	*50,630*	*37*	*51,684*			*18,901*
Point Source Dischargers							
				Discharge	Phosphorus Concentration	Loading Calibration Factor (CF)[1]	Load
	Name			[ac-ft/yr]	[ug/L]	[--]	[lb/yr]
1							
2							
3							
4							
5							
	Summation			*0*			*0.0*
Failing Septic Systems							
	Name						Load [lb/yr]
1	All Failing Systems						808
2							
3							
4							
5							
	Summation	*0*	*0*	*0.0*			*808*
Inflow from Upstream Lakes							
				Discharge	Estimated P Concentration	Calibration Factor	Load
	Name			[ac-ft/yr]	[ug/L]	[--]	[lb/yr]
1					-	1.0	
2					-	1.0	
3					-	1.0	
	Summation			*0*	-		*0*
Atmosphere							
	Lake Area	Precipitation	Evaporation	Net Inflow	Aerial Loading Rate	Calibration Factor	Load
	[acre]	[in/yr]	[in/yr]	[ac-ft/yr]	[lb/ac-yr]	[--]	[lb/yr]
	1515	37.2	37.2	0.00	0.24	1.0	362
		Dry-year total P deposition =			0.222		
		Average-year total P deposition =			0.239		
		Wet-year total P deposition =			0.259		
		(Barr Engineering 2004)					
Groundwater							
	Lake Area	Groundwater Flux		Net Inflow	Phosphorus Concentration	Calibration Factor	Load
	[acre]	[m/yr]		[ac-ft/yr]	[ug/L]	[--]	[lb/yr]
	1515	0.0		0.00	0	1.0	0
Internal							
	Lake Area	Anoxic Factor			Release Rate	Calibration Factor	Load
	[km^2]	[days]			[mg/m^2-day]	[--]	[lb/yr]
	6.13	122		Oxic	0.5	1.0	825
	6.13	56.2		Anoxic	16.3	1.0	12,378
	Summation						13,203
		Net Discharge [ac-ft/yr] =		**51,684**	**Net Load [lb/yr] =**		**33,275**

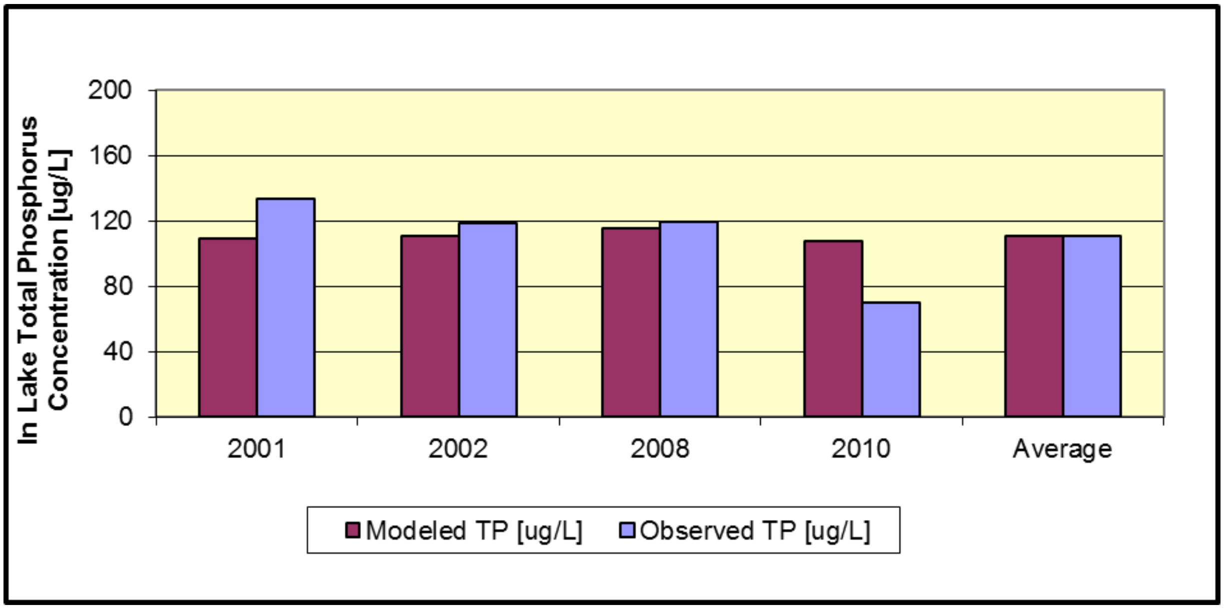
Modeled Parameter	**Equation**	**Parameters**	**Value**	**[Units]**
TOTAL IN-LAKE PHOSPHORUS CONCENTRATION				
$$P = \frac{P_i}{\left(1 + C_P \times C_{CB} \times \left(\frac{W_P}{V}\right)^b \times T\right)}$$		as f(W,Q,V) from Canfield & Bachmann (1981)		
		C_P =	1.03	[--]
		C_{CB} =	0.162	[--]
		b =	0.458	[--]
		W (total P load = inflow + atm.) =	15,093	[kg/yr]
		Q (lake outflow) =	63.8	[10^6 m^3/yr]
		V (modeled lake volume) =	22.0	[10^6 m^3]
		T = V/Q =	0.35	[yr]
		P_i = W/Q =	237	[µg/l]
Model Predicted In-Lake [TP]			**110.5**	**[ug/l]**
Observed In-Lake [TP]			**110.5**	**[ug/l]**

Pokegama Lake TMDL Conditions BATHTUB Lake Response Model

	TMDL Loading Summary for Pokegama						
	Water Budgets				**Phosphorus Loading**		
Inflow from Drainage Areas							
		Drainage Area	Runoff Depth	Discharge	Phosphorus Concentration	Loading Calibration Factor (CF)[1]	Load
	Name	[acre]	[in/yr]	[ac-ft/yr]	[ug/L]	[--]	[lb/yr]
1	Pokegama Brook	35,754	12.3	36,498	51	0.6	5,061
2	NW Trib	7,057	12.3	7,204	51.0	0.7	1,000
3	Direct Watershed	7,819	12.3	7,982	51.0	0.1	1,107
4						1.0	
5						1.0	
	Summation	*50,630*	*37*	*51,684*			*7,168*
Point Source Dischargers							
				Discharge	Phosphorus Concentration	Loading Calibration Factor (CF)[1]	Load
	Name			[ac-ft/yr]	[ug/L]	[--]	[lb/yr]
1						1.0	
2						1.0	
3						1.0	
4						1.0	
5						1.0	
	Summation			*0*			*0*
Failing Septic Systems							
	Name	Total Systems	Failing Systems	Discharge [ac-ft/yr]	Failure [%]		Load [lb/yr]
1	All Failing systems						0
2							
3							
4							
5							
	Summation	*0*	*0*	*0.0*			*0*
Inflow from Upstream Lakes							
				Discharge	Estimated P Concentration	Calibration Factor	Load
	Name			[ac-ft/yr]	[ug/L]	[--]	[lb/yr]
1					-	1.0	
2					-	1.0	
3					-	1.0	
	Summation			*0*	-		*0*
Atmosphere							
	Lake Area	Precipitation	Evaporation	Net Inflow	Aerial Loading Rate	Calibration Factor	Load
	[acre]	[in/yr]	[in/yr]	[ac-ft/yr]	[lb/ac-yr]	[--]	[lb/yr]
	1515	37.2	37.2	0.00	0.24	1.0	362
				Dry-year total P deposition =	0.222		
				Average-year total P deposition =	0.239		
				Wet-year total P deposition =	0.259		
				(Barr Engineering 2004)			
Groundwater							
	Lake Area	Groundwater Flux		Net Inflow	Phosphorus Concentration	Calibration Factor	Load
	[acre]	[m/yr]		[ac-ft/yr]	[ug/L]	[--]	[lb/yr]
	1515	0.0		0.00	0	1.0	0
Internal							
	Lake Area	Anoxic Factor			Release Rate	Calibration Factor	Load
	[km^2]	[days]			[mg/m^2-day]	[--]	[lb/yr]
	6.13	122		Oxic	0.5	1.0	825
	6.13	56.2		Anoxic	1.0	1.0	759
	Summation						1,584
		Net Discharge [ac-ft/yr] =		**51,684**	**Net Load [lb/yr] =**		**9,114**

Modeled Parameter	**Equation**	**Parameters**	**Value**	**[Units]**
TOTAL IN-LAKE PHOSPHORUS CONCENTRATION				
$$P = \frac{P_i}{\left(1 + C_P \times C_{CB} \times \left(\frac{W_P}{V}\right)^b \times T\right)}$$	as f(W,Q,V) from Canfield & Bachmann (1981)			
		C_P =	1.03	[--]
		C_{CB} =	0.162	[--]
		b =	0.458	[--]
		W (total P load = inflow + atm.) =	4,134	[kg/yr]
		Q (lake outflow) =	63.8	[10^6 m^3/yr]
		V (modeled lake volume) =	22.0	[10^6 m^3]
		T = V/Q =	0.35	[yr]
		P_i = W/Q =	65	[µg/l]
Model Predicted In-Lake [TP]			**40**	**[ug/l]**
Observed In-Lake [TP]			**111**	**[ug/l]**

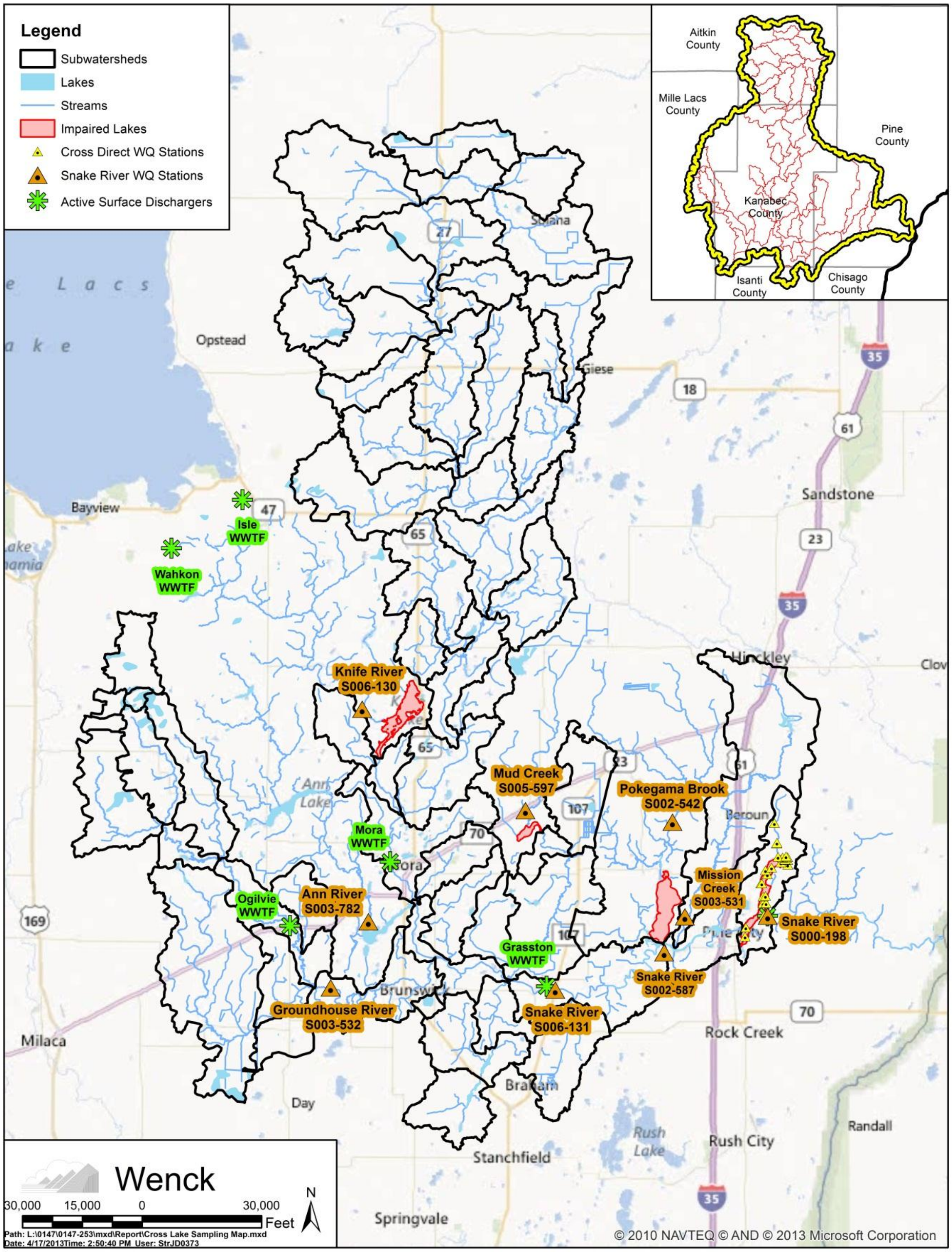
Pokegama Lake BATHTUB Lake Response Model Performance

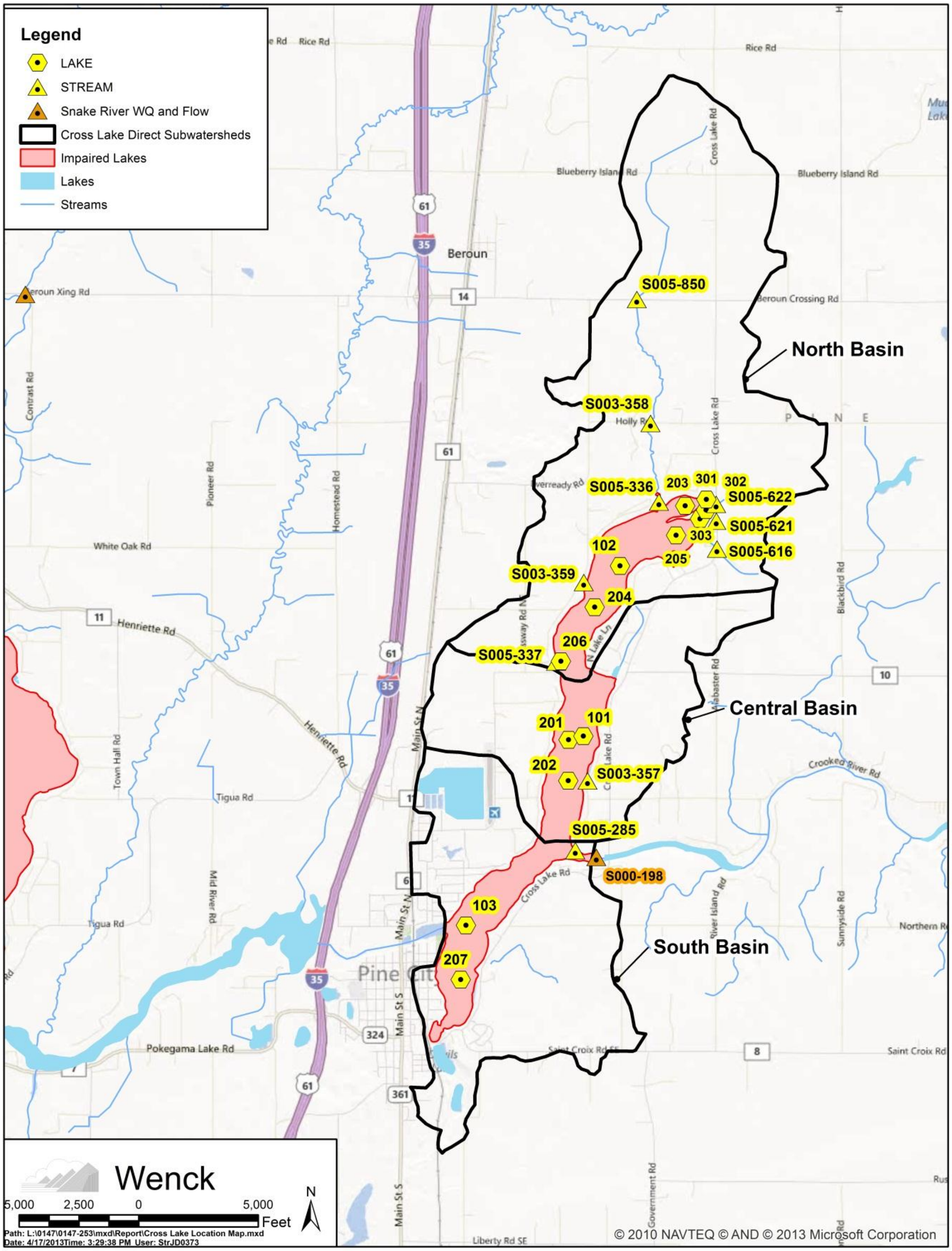


Appendix G

Cross Lake Supporting Documents

Cross Lake Monitoring Sites




Legend
LAKE
STREAM
Snake River WQ and Flow
Cross Lake Direct Subwatersheds
Impaired Lakes
Lakes
Streams
North Basin
Central Basin
South Basin
S005-850
S003-358
S005-336
203
301
302
S005-622
S005-621
303
S005-616
205
102
S003-359
204
206
S005-337
201
101
202
S003-357
S005-285
S000-198
103
207
Beroun
Pine City
Wenck
5,000 2,500 0 5,000
Feet
N
Path: L:\0147\0147-253\mxd\Report\Cross Lake Location Map.mxd
Date: 4/17/2013Time: 3:29:38 PM User: StrJD0373
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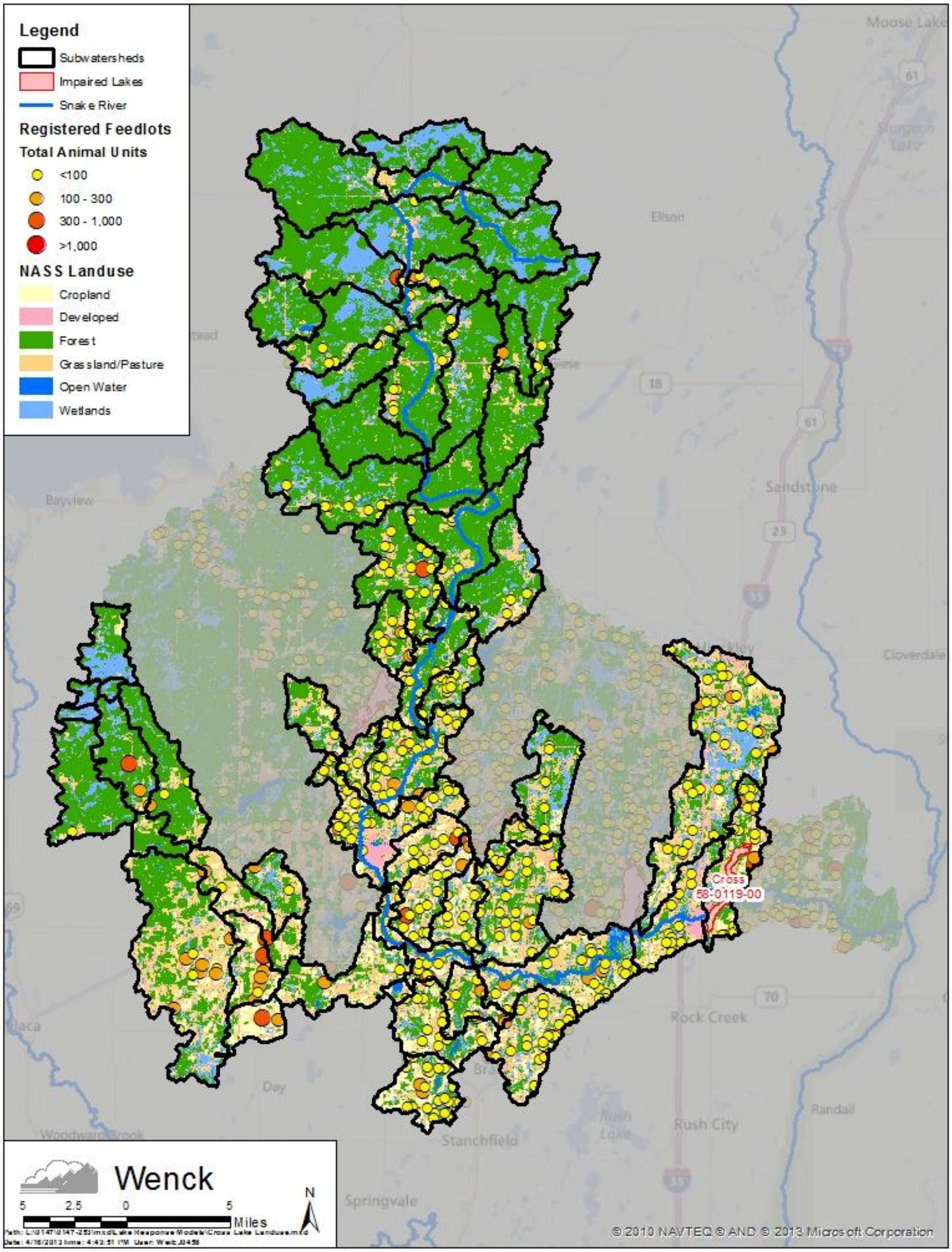
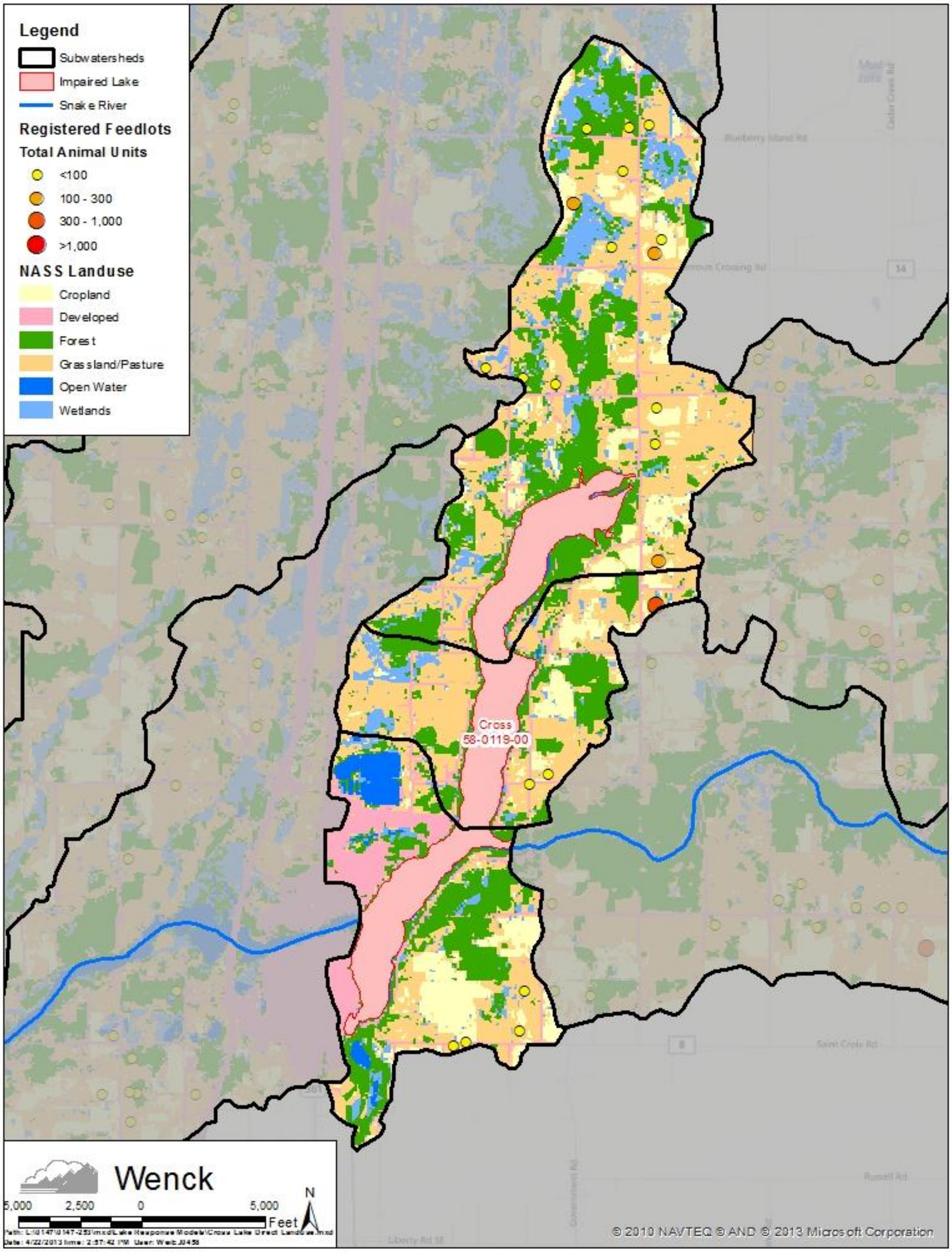
Cross Lake Watershed Landuse and Feedlots




Legend
Subwatersheds
Impaired Lake
Snake River
Registered Feedlots
Total Animal Units
<100
100 - 300
300 - 1,000
>1,000
NASS Landuse
Cropland
Developed
Forest
Grassland/Pasture
Open Water
Wetlands
Cross
58-0119-00
Wenck
5,000 2,500 0 5,000
Feet
N
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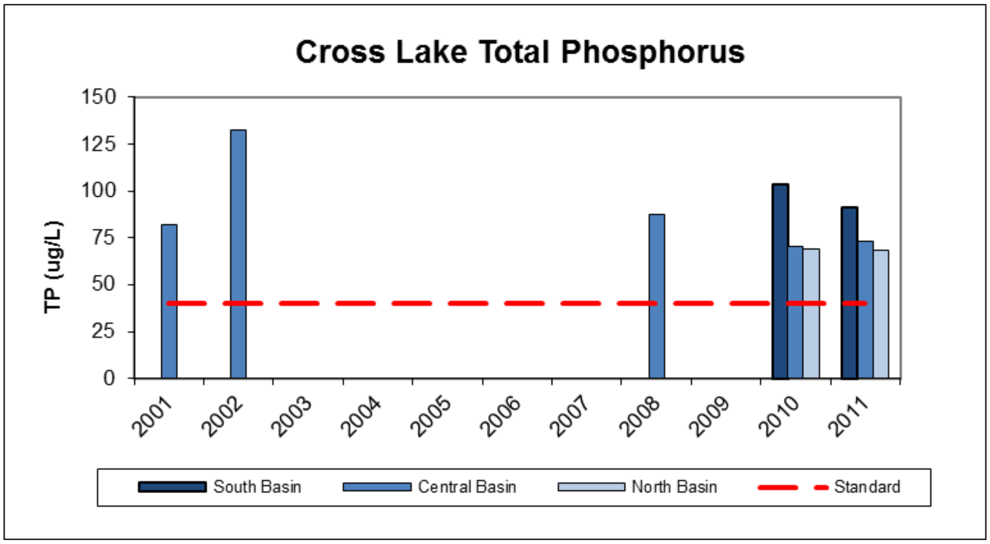
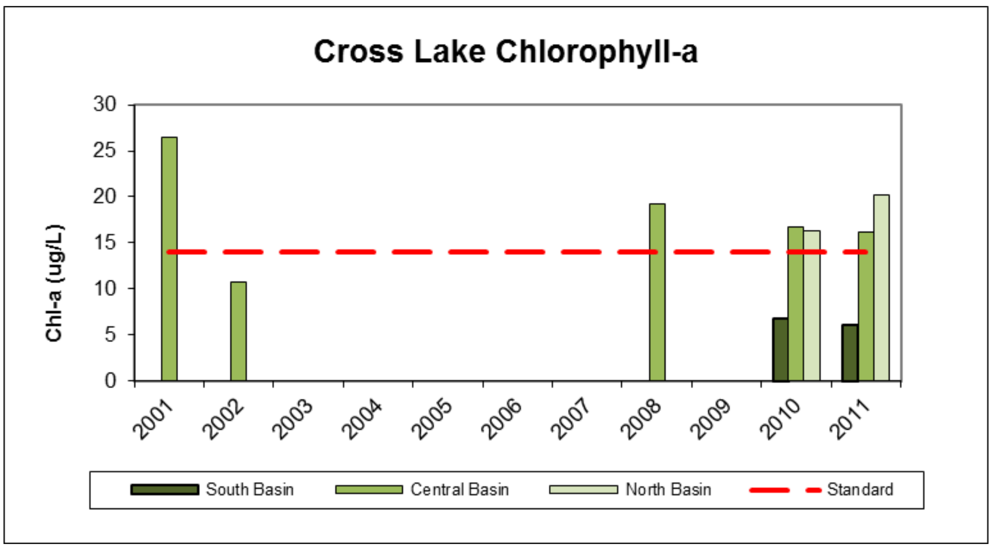
Cross Lake Historic Water Quality Sampling

Year	Total Phosphorus (ug/L)						Chlorophyll-a (ug/L)						Secchi (m)					
	South Basin		Central Basin		North Basin		South Basin		Central Basin		North Basin		South Basin		Central Basin		North Basin	
	N	Ave	N	Ave	N	Ave	N	Ave	N	Ave	N	Ave	N	Ave	N	Ave	N	Ave
2000	--	--	4	92	--	--	--	--	4	41	--	--	--	--	--	--	4	1.05
2001	--	--	4	82	--	--	--	--	4	27	--	--	--	--	--	--	4	1.07
2002	--	--	4	133	--	--	--	--	4	11	--	--	--	--	--	--	4	1.30
2003	--	--	1	135	--	--	--	--	1	4	--	--	--	--	--	--	--	--
2004	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
2005	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
2006	--	--	--	--	--	--	--	--	--	--	--	--	--	--	4	0.95	--	--
2007	--	--	--	--	--	--	--	--	--	--	--	--	--	--	4	0.84	--	--
2008	--	--	4	87	--	--	--	--	4	19	--	--	4	1.07	4	0.91	4	0.94
2009	--	--	--	--	--	--	--	--	--	--	--	--	4	1.19	5	1.09	4	1.19
2010	9	103	9	70	9	69	9	7	9	17	9	16	4	1.17	7	1.05	7	1.10
2011	7	92	7	73	7	68	7	6	7	16	7	20	--	--	7	1.03	--	--

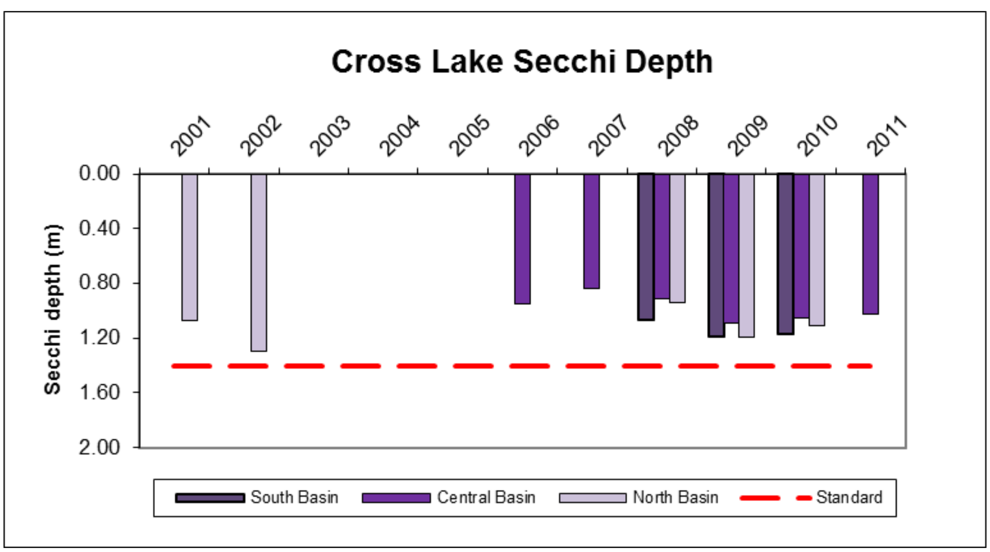
Note: Only June 1 through September 30 sample events presented



Cross Lake Total Phosphorus
TP (ug/L)
150
125
100
75
50
25
0
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
South Basin
Central Basin
North Basin
Standard

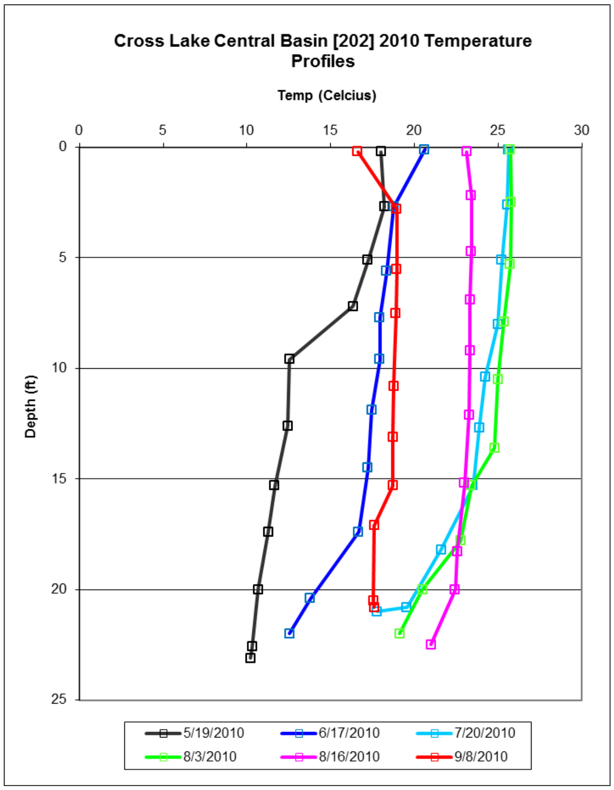


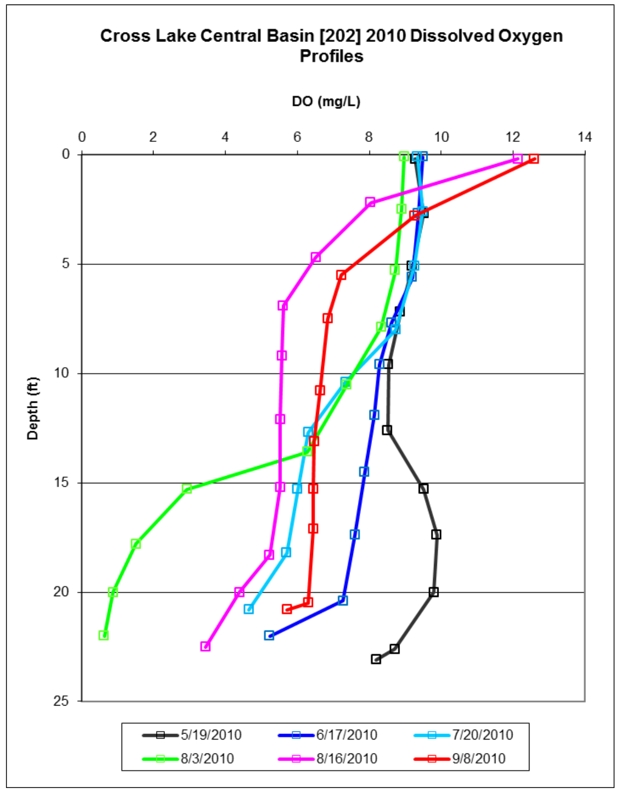
Cross Lake Chlorophyll-a
Chl-a (ug/L)
30
25
20
15
10
5
0
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
South Basin
Central Basin
North Basin
Standard

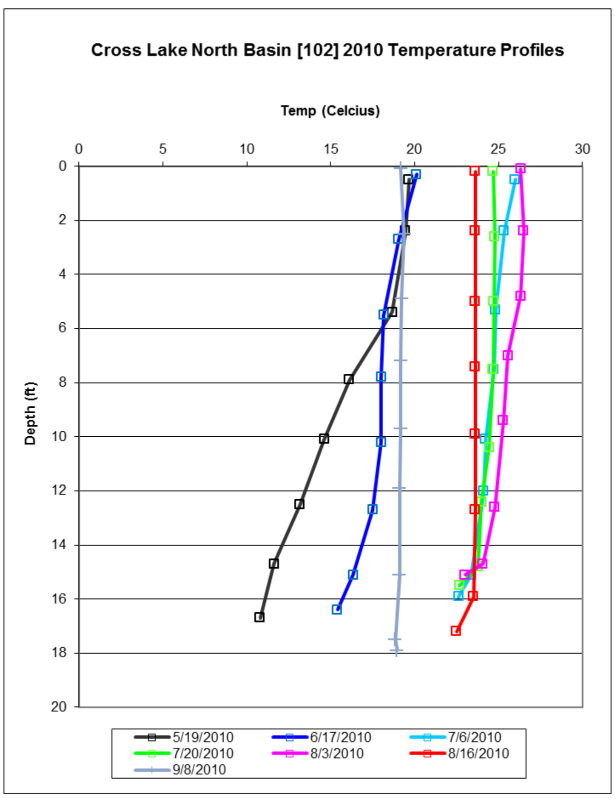


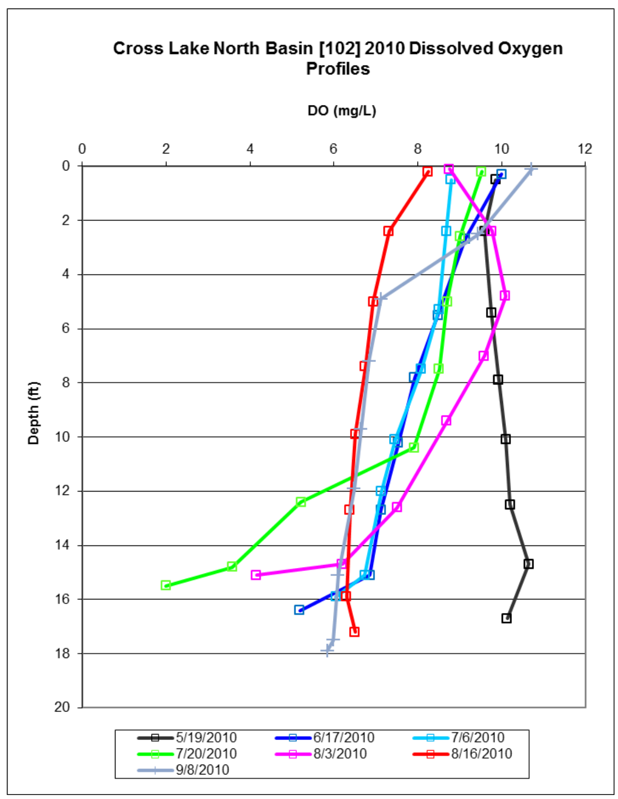
Cross Lake Secchi Depth
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
Secchi depth (m)
0.00
0.40
0.80
1.20
1.60
2.00
South Basin
Central Basin
North Basin
Standard

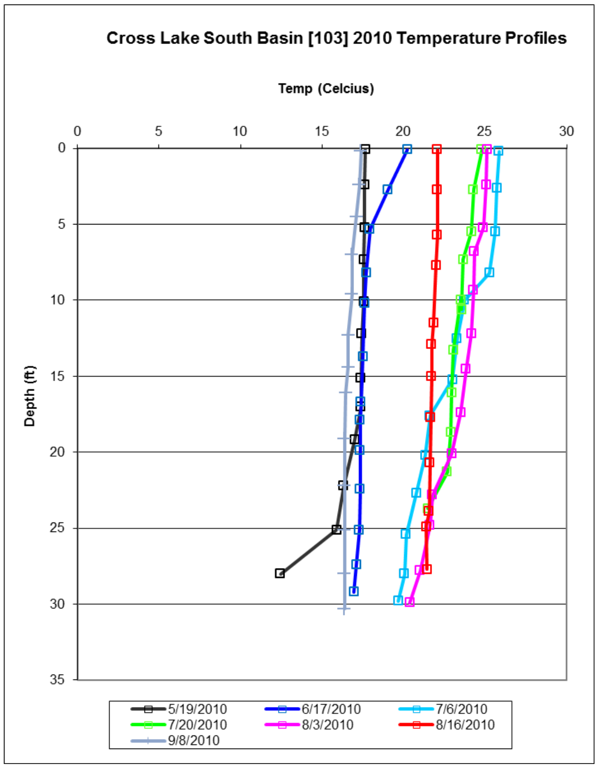
Cross Lake Temperature and Dissolved Oxygen Profiles

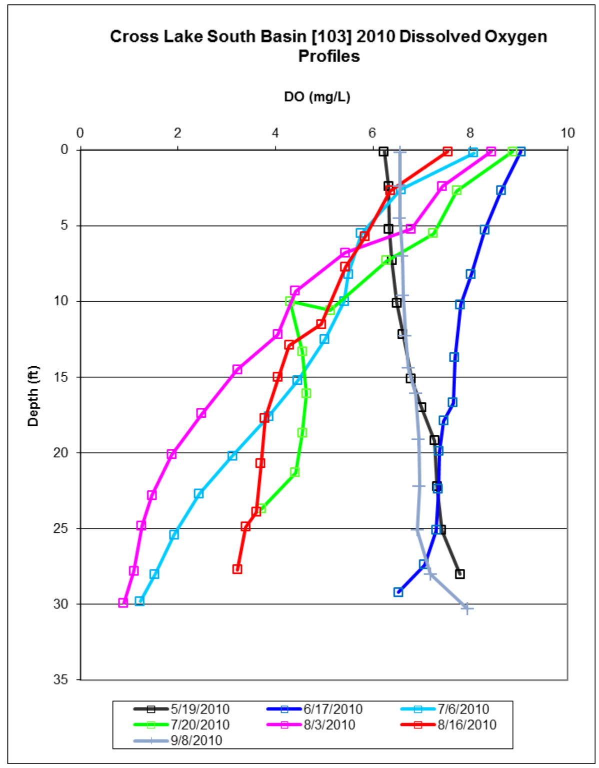




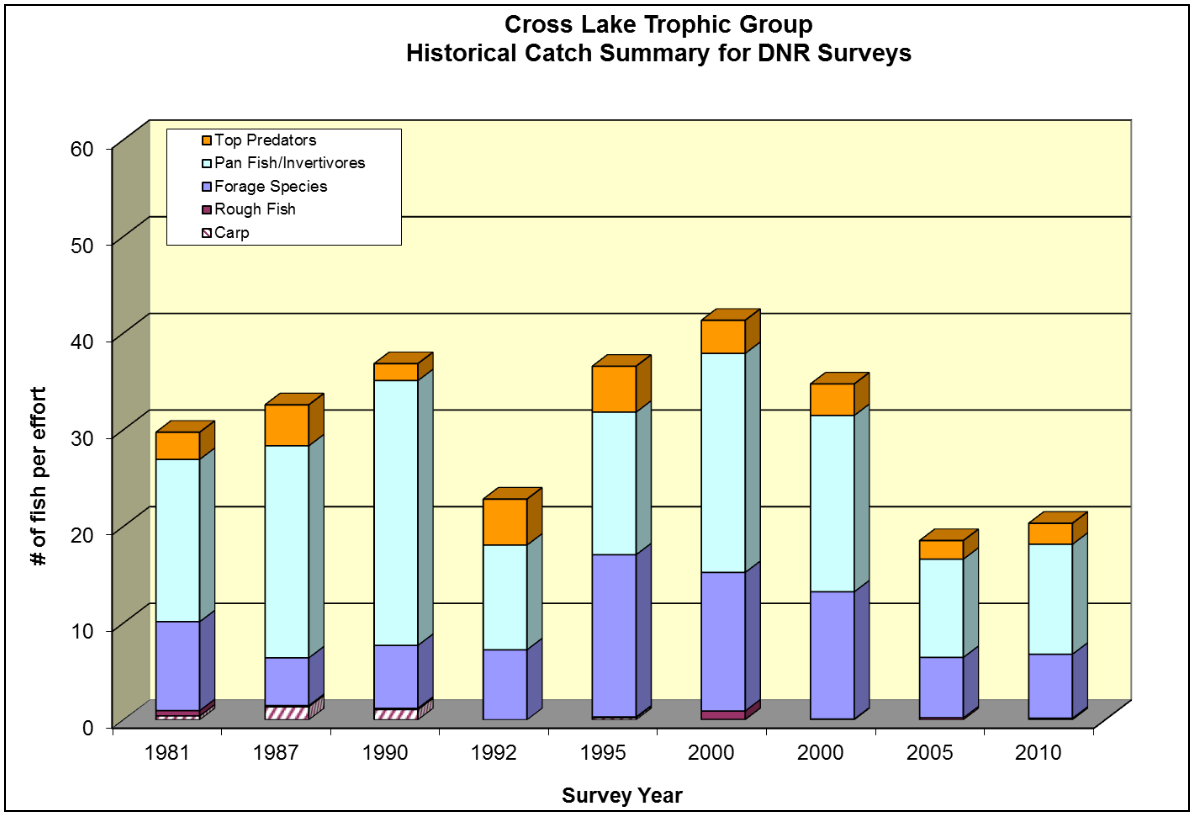


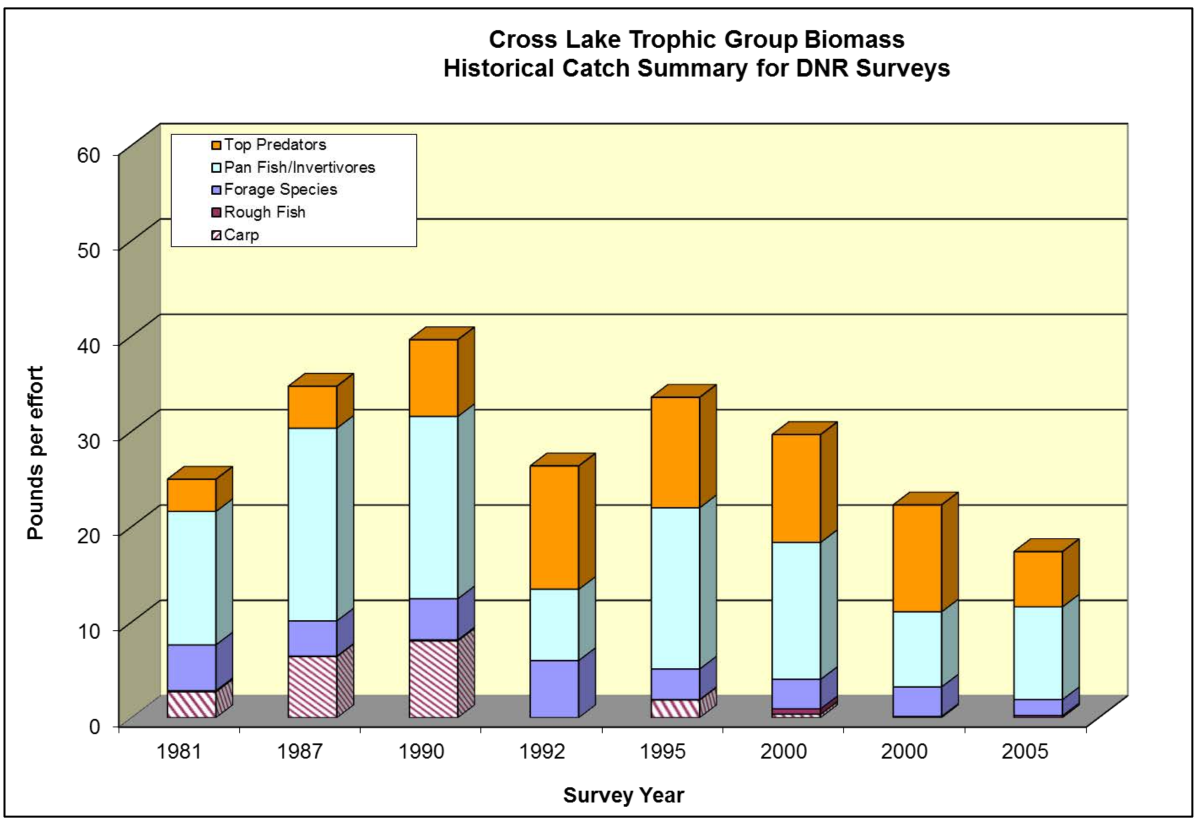



Cross Lake South Basin [103] 2010 Temperature Profiles
Temp (Celcius)
Depth (ft)
5/19/2010
6/17/2010
7/6/2010
7/20/2010
8/3/2010
8/16/2010
9/8/2010

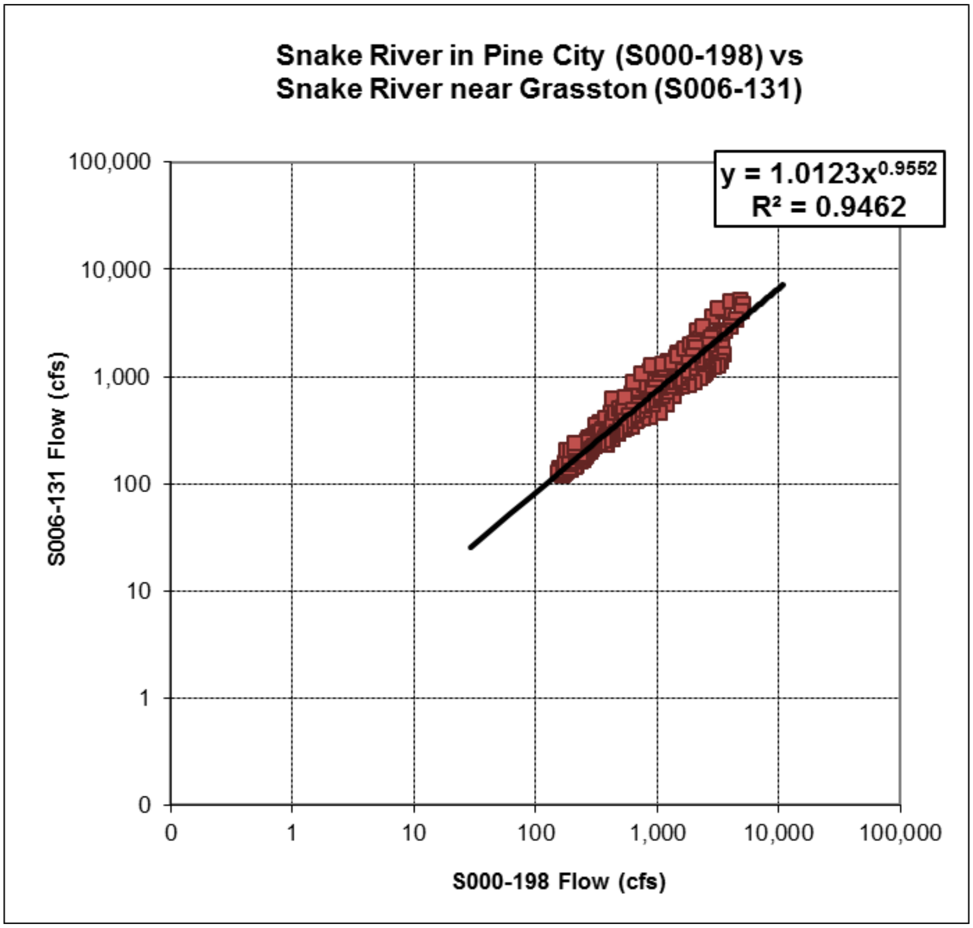

Cross Lake South Basin [103] 2010 Dissolved Oxygen Profiles
DO (mg/L)
Depth (ft)
5/19/2010
6/17/2010
7/6/2010
7/20/2010
8/3/2010
8/16/2010
9/8/2010

Cross Lake DNR Fish Surveys by Trophic Group





Snake River Flow Regression



Snake River Watershed FLUX Modeling

Site/ Watershed	Year	Monitored Flow (acre-ft)	FLUX Annual Load (lbs)	Concentration (ug/L)	FLUX Stratification	FLUX Method	C.V
S006-131 Snake River	2001	518,201	125,018	89	0-639; 639+ cfs	2	0.14
S006-131 Snake River	2002	509,340	120,836	87	None	3	0.11
S006-131 Snake River	2004	315,527	59,339	69	0-605; 605+ cfs	3	0.05
S006-131 Snake River	2005	439,216	99,778	84	0-542; 542-1,500; 1,500 cfs	2	0.08
S006-131 Snake River	2010	473,800	136,597	106	0-585; 585+ cfs	3	0.12
S006-131 Snake River	Ave	451,217	108,313	88			

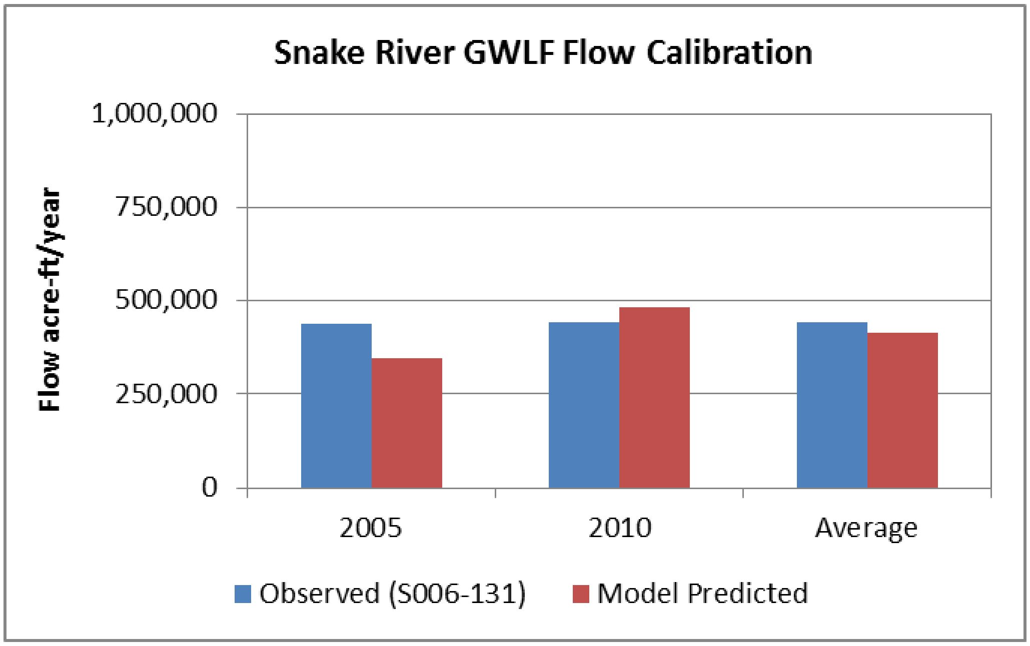
Cross Lake Watershed Loads

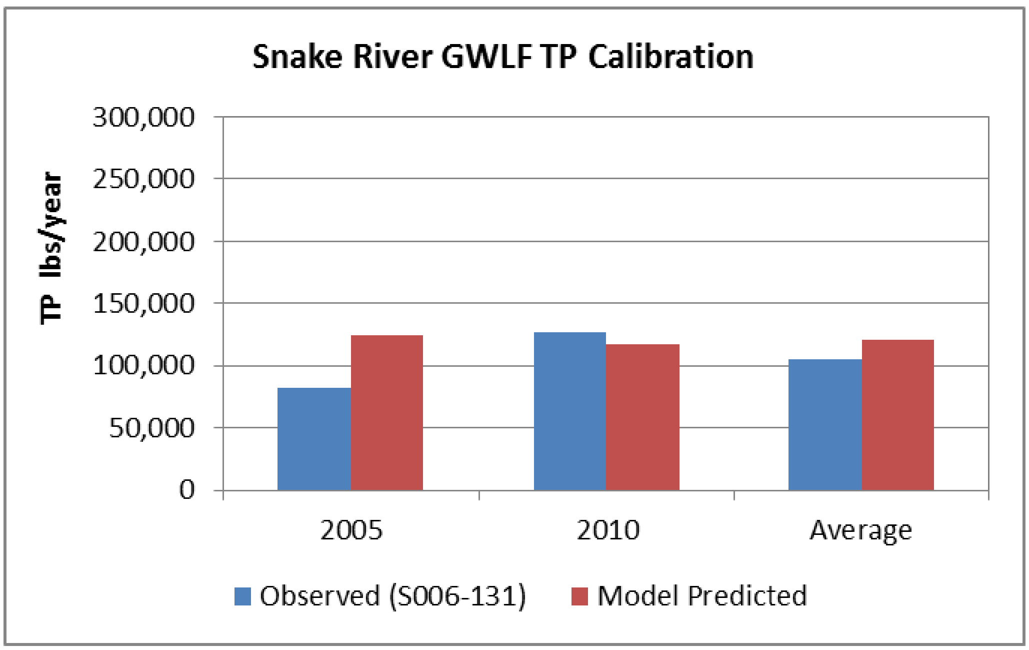
Watershed	Model Year	Precip (in)	Runoff (in)	Discharge (acre-ft)	TP Load (lbs)	TP conc. (ug/L)	Notes
Snake River	2010	40.7	10.8	408,530	82,094	74	Used runoff depth and 2010 FLUX calculated TP conc. from S006-131; subtracted loading and flow contribution from upstream impaired lakes, WWTFs, and failing septics
Snake River	2011	27.5	12.9	505,606	83,518	61	Used runoff depth and 2001-2010 FLUX average TP conc. from S006-131; subtracted loading and flow contribution from upstream impaired lakes, WWTFs, and failing septics
Mission Creek	2010	40.7	10.8	21,751	6,902	117	Used 2010 runoff depth from S006-131 and 2010 monitored flow-weighted mean TP conc. from Mission Creek (S003-531) and subtracted loading contribution from failing septics
Mission Creek	2011	27.5	12.9	26,106	7,325	103	Used 2011 runoff depth from S006-131 and 2001-2010 average monitored flow-weighted mean TP conc. from Mission Creek (S003-531) and subtracted loading contribution from failing septics
Cross Lake South Basin Direct	2010	40.7	10.8	1,670	656	144	Used 2010 runoff depth from S006-131 and 2008-2011 average monitored flow-weighted mean TP concentration from Central and North Basin Direct watershed monitoring stations and subtracted loading contribution from failing septics. No stream water quality data has been collected in the South Basin direct watershed
Cross Lake South Basin Direct	2011	27.5	12.9	2,005	800	147	Used 2011 runoff depth from S006-131 and 2008-2011 average monitored flow-weighted mean TP concentration from Central and North Basin Direct watershed monitoring stations and subtracted loading contribution from failing septics. No stream water quality data has been collected in the South Basin direct watershed
Cross Lake Central Basin Direct	2010	40.7	10.8	1,321	1,044	291	Used 2010 runoff depth from S006-131 and 2010 monitored flow-weighted mean TP concentration from the Central Basin Direct watershed monitoring station (S003-357) and subtracted loading contribution from failing septics

Watershed	Model Year	Precip (in)	Runoff (in)	Discharge (acre-ft)	TP Load (lbs)	TP conc. (ug/L)	Notes
Cross Lake Central Basin Direct	2011	27.5	12.9	1,586	1,433	332	Used 2011 runoff depth from S006-131 and 2008-2010 average monitored flow-weighted mean TP concentration from the Central Basin Direct watershed monitoring station (S003-357) and subtracted loading contribution from failing septics
Cross Lake North Basin Direct	2010	40.7	10.8	3,392	1,471	159	Used 2010 runoff depth from S006-131 and 2010 monitored flow-weighted mean TP concentration from all North Basin Direct watershed monitoring stations and subtracted loading contribution from failing septics
Cross Lake North Basin Direct	2011	27.5	12.9	4,071	808	73	Used 2011 runoff depth from S006-131 and 2011 monitored flow-weighted mean TP concentration from all North Basin Direct watershed monitoring stations and subtracted loading contribution from failing septics
Knife Lake	2010	40.7	9.7	48,269	13,340	102	Used 2010 runoff depth from Knife River station S006-130 and 2010 in-lake monitored flow-weighted mean TP concentration
Knife Lake	2011	27.5	11.5	57,233	14,108	91	Used 2011 runoff depth from Knife River station S006-130 and 2011 in-lake monitored flow-weighted mean TP concentration
Fish Lake	2010	40.7	10.0	46,019	7,224	58	Used 2010 runoff depth from Ann River station S003-782 and 2010 in-lake monitored flow-weighted mean TP concentration
Fish Lake	2011	27.5	10.8	50,007	11,897	88	Used 2011 runoff depth from Ann River station S003-782 and 2011 in-lake monitored flow-weighted mean TP concentration
Quamba Lake	2010	40.7	12.1	24,577	7,809	117	Used 2010 runoff depth from Mud Creek station S005-597 and 2010 in-lake monitored flow-weighted mean TP concentration
Quamba Lake	2011	27.5	9.9	20,114	4,310	79	Used 2011 runoff depth from Mud Creek station S005-597 and 2011 in-lake monitored flow-weighted mean TP concentration

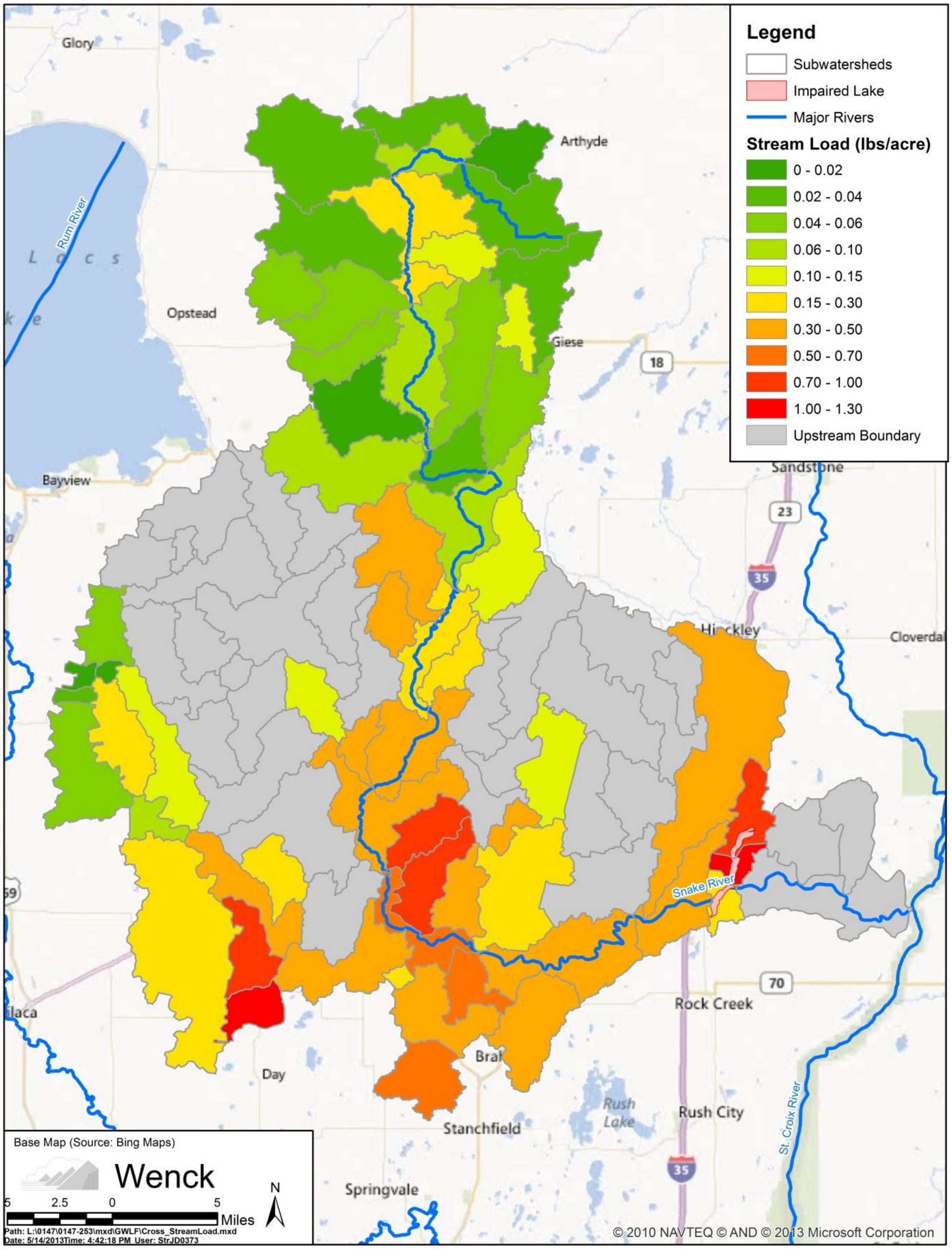
Watershed	Model Year	Precip (in)	Runoff (in)	Discharge (acre-ft)	TP Load (lbs)	TP conc. (ug/L)	Notes
Pokegama Lake	2010	40.7	16.5	71,638	14,561	75	Used 2010 runoff depth from Pokegama Brook station S002-542 and 2010 in-lake monitored flow-weighted mean TP concentration
Pokegama Lake	2011	27.5	11.5	50,103	7,804	57	Used 2011 runoff depth from Pokegama Brook station S002-542 and 2011 in-lake monitored flow-weighted mean TP concentration
Ogilvie WWTF	2010	NA	NA	140	675	1,770	Used 2010 measured effluent flow volume and TP concentration according to facility's discharge monitoring report
Ogilvie WWTF	2011	NA	NA	170	726	1,569	Used 2011 measured effluent flow volume and TP concentration according to facility's discharge monitoring report
Mora WWTF	2010	NA	NA	511	4,985	3,584	Used 2010 measured effluent flow volume and TP concentration according to facility's discharge monitoring report
Mora WWTF	2011	NA	NA	634	4,803	2,785	Used 2011 measured effluent flow volume and TP concentration according to facility's discharge monitoring report
Grasston WWTF	2010	NA	NA	0	0	0	Grasston facility does not currently discharge effluent to surface water
Grasston WWTF	2011	NA	NA	0	0	0	Grasston facility does not currently discharge effluent to surface water

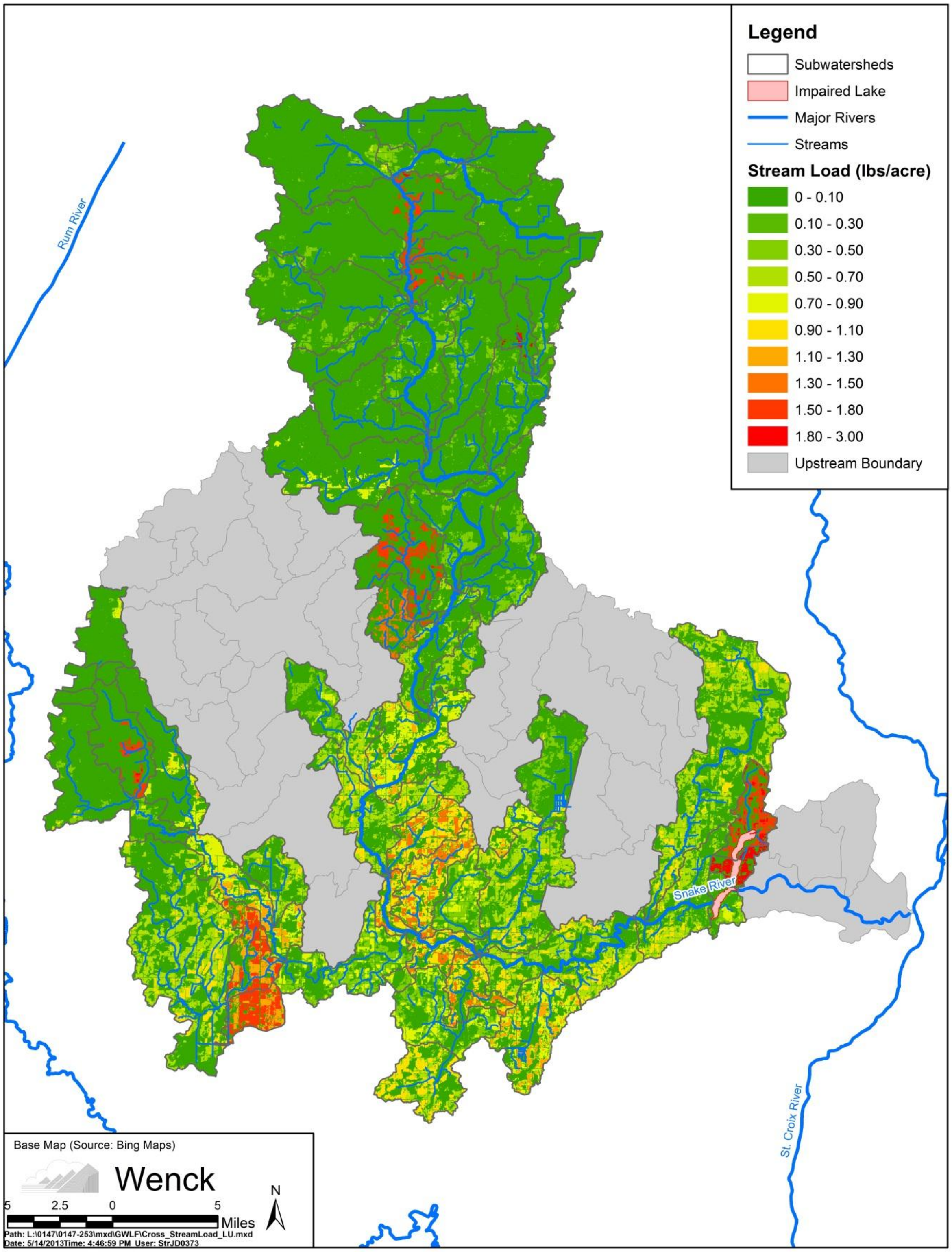
Snake River Watershed GWLF Model Performance

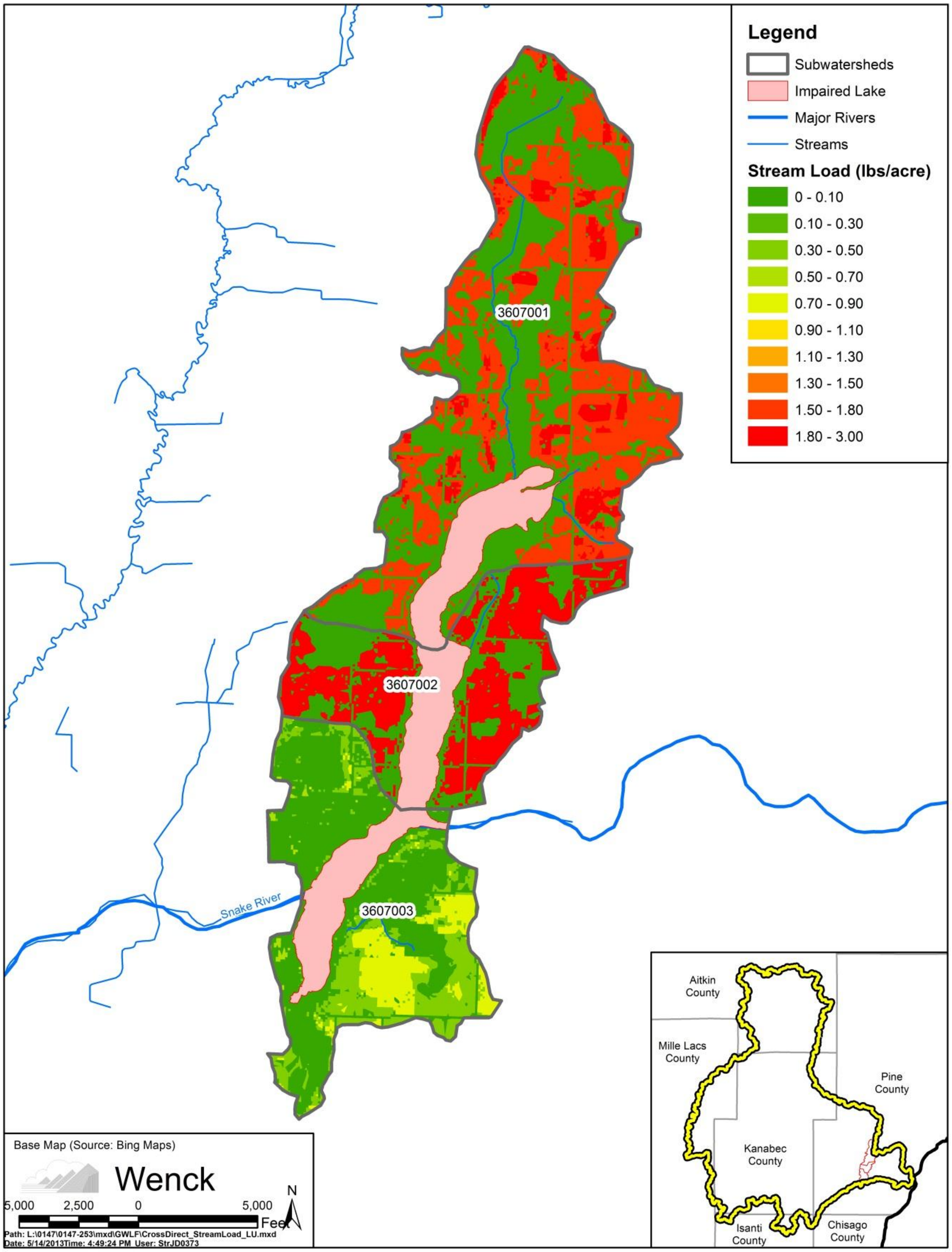




Cross Lake Watershed GWLF Model Results




Legend
Subwatersheds
Impaired Lake
Major Rivers
Streams
Stream Load (lbs/acre)
0 - 0.10
0.10 - 0.30
0.30 - 0.50
0.50 - 0.70
0.70 - 0.90
0.90 - 1.10
1.10 - 1.30
1.30 - 1.50
1.50 - 1.80
1.80 - 3.00
Upstream Boundary
Rum River
Snake River
St. Croix River
Base Map (Source: Bing Maps)
Wenck
5 2.5 0 5
Miles
N
Path: L:\0147\0147-253\mxd\GWLF\Cross_StreamLoad_LU.mxd
Date: 5/14/2013Time: 4:46:59 PM User: StrJD0373



Legend
Subwatersheds
Impaired Lake
Major Rivers
Streams
Stream Load (lbs/acre)
0 - 0.10
0.10 - 0.30
0.30 - 0.50
0.50 - 0.70
0.70 - 0.90
0.90 - 1.10
1.10 - 1.30
1.30 - 1.50
1.50 - 1.80
1.80 - 3.00
3607001
3607002
3607003
Snake River
Aitkin County
Mille Lacs County
Pine County
Kanabec County
Isanti County
Chisago County
Base Map (Source: Bing Maps)
Wenck
5,000 2,500 0 5,000
Feet
N
Path: L:\0147\0147-253\mxd\GWLF\CrossDirect_StreamLoad_LU.mxd
Date: 5/14/2013Time: 4:49:24 PM User: StrJD0373

Cross Lake Watershed Septic Loads

Watershed	County	Total Pop.	Pop. On Septics	Total Systems	Imm. Threat System	Gen Failing System	Failing System TP (lbs/yr)
Cross Lake Direct South Basin	Pine	950	97	32	8	12	61
Cross Lake Direct Central Basin	Pine	72	46	15	4	6	29
Cross Lake Direct North Basin	Pine	129	129	43	11	16	82

Cross Lake Current Conditions BATHTUB Lake Response Model

Segment Mass Balance Based Upon Predicted Concentrations

Component: TOTAL P — **Segment: 1 SouthBasin**

Trib	Type	Location	Flow hm^3/yr	Flow %Total	Load kg/yr	Load %Total	Conc mg/m^3
1	1	SnakeRiver	564.0	67.9%	38297.0	58.8%	68
2	1	DirectSouth	2.3	0.3%	358.2	0.5%	158
3	1	MissionCreek	29.5	3.6%	3445.9	5.3%	117
4	1	KnifeLake	65.1	7.8%	6229.6	9.6%	96
5	1	FishLake	59.2	7.1%	4337.0	6.7%	73
6	1	QuambaLake	27.6	3.3%	2749.1	4.2%	100
7	1	PokegamaLake	75.1	9.0%	5077.7	7.8%	68
8	3	OgilvieWWTF	0.2	0.0%	318.7	0.5%	1660
9	3	MoraWWTF	0.7	0.1%	2218.3	3.4%	3142
PRECIPITATION			1.1	0.1%	33.8	0.1%	31
INTERNAL LOAD			0.0	0.0%	1638.4	2.5%	
TRIBUTARY INFLOW			822.8	99.0%	60494.4	92.8%	74
POINT-SOURCE INFLOW			0.9	0.1%	2537.0	3.9%	2825
ADVECTIVE INFLOW			6.4	0.8%	458.6	0.7%	72
***TOTAL INFLOW			831.2	100.0%	65162.1	100.0%	78
ADVECTIVE OUTFLOW			830.1	99.9%	80580.9	123.7%	97
NET DIFFUSIVE OUTFLOW			0.0	0.0%	518.8	0.8%	
***TOTAL OUTFLOW			830.1	99.9%	81099.7	124.5%	98
***EVAPORATION			1.1	0.1%	0.0	0.0%	
***RETENTION			0.0	0.0%	-15937.6	-24.5%	

Hyd. Residence Time = 0.0048 yrs
Overflow Rate = 658.8 m/yr
Mean Depth = 3.2 m

Component: TOTAL P — **Segment: 2 CentralBasin**

Trib	Type	Location	Flow hm^3/yr	Flow %Total	Load kg/yr	Load %Total	Conc mg/m^3
11	1	DirectCentral	1.8	24.4%	575.9	15.3%	321
PRECIPITATION			0.9	12.9%	29.2	0.8%	31
INTERNAL LOAD			0.0	0.0%	2356.9	62.5%	
TRIBUTARY INFLOW			1.8	24.4%	575.9	15.3%	321
ADVECTIVE INFLOW			4.6	62.7%	315.3	8.4%	68
NET DIFFUSIVE INFLOW			0.0	0.0%	494.6	13.1%	
***TOTAL INFLOW			7.3	100.0%	3771.8	100.0%	514
ADVECTIVE OUTFLOW			6.4	87.1%	458.6	12.2%	72
***TOTAL OUTFLOW			6.4	87.1%	458.6	12.2%	72
***EVAPORATION			0.9	12.9%	0.0	0.0%	
***RETENTION			0.0	0.0%	3313.2	87.8%	

Hyd. Residence Time = 0.8040 yrs
Overflow Rate = 5.9 m/yr
Mean Depth = 4.7 m

Component: TOTAL P — **Segment: 3 North**

Trib	Type	Location	Flow hm^3/yr	Flow %Total	Load kg/yr	Load %Total	Conc mg/m^3
12	1	DirectNorth	4.6	79.3%	552.6	26.7%	120
PRECIPITATION			1.2	20.7%	37.3	1.8%	31
INTERNAL LOAD			0.0	0.0%	1457.1	70.4%	
TRIBUTARY INFLOW			4.6	79.3%	552.6	26.7%	120
NET DIFFUSIVE INFLOW			0.0	0.0%	24.3	1.2%	
***TOTAL INFLOW			5.8	100.0%	2071.2	100.0%	357
ADVECTIVE OUTFLOW			4.6	79.3%	315.3	15.2%	68
***TOTAL OUTFLOW			4.6	79.3%	315.3	15.2%	68
***EVAPORATION			1.2	20.7%	0.0	0.0%	
***RETENTION			0.0	0.0%	1755.9	84.8%	

Hyd. Residence Time = 1.4458 yrs
Overflow Rate = 3.3 m/yr
Mean Depth = 4.8 m

Cross Lake TMDL Conditions BATHTUB Lake Response Model

Segment Mass Balance Based Upon Predicted Concentrations

Component: TOTAL P — Segment: 1 SouthBasin

Trib	Type	Location	Flow hm³/yr	Flow %Total	Load kg/yr	Load %Total	Conc mg/m³
1	1	SnakeRiver	564.0	67.8%	38297.0	67.1%	68
2	1	DirectSouth	2.3	0.3%	226.7	0.4%	100
3	1	MissionCreek	29.5	3.5%	2952.8	5.2%	100
4	1	KnifeLake	65.1	7.8%	3905.7	6.8%	60
5	1	FishLake	59.2	7.1%	3554.9	6.2%	60
6	1	QuambaLake	27.6	3.3%	1654.4	2.9%	60
7	1	PokegamaLake	75.1	9.0%	3004.6	5.3%	40
8	3	OgilvieWWTF	0.3	0.0%	318.0	0.6%	1000
9	3	MoraWWTF	1.1	0.1%	1106.0	1.9%	1000
10	3	GrasstonWWTF	0.1	0.0%	106.0	0.2%	2000
PRECIPITATION			1.1	0.1%	33.8	0.1%	31
INTERNAL LOAD			0.0	0.0%	1638.4	2.9%	
TRIBUTARY INFLOW			822.8	98.9%	53596.0	93.9%	65
POINT-SOURCE INFLOW			1.5	0.2%	1530.0	2.7%	1036
ADVECTIVE INFLOW			6.4	0.8%	255.9	0.4%	40
***TOTAL INFLOW			831.8	100.0%	57054.1	100.0%	69
ADVECTIVE OUTFLOW			830.7	99.9%	70207.4	123.1%	85
NET DIFFUSIVE OUTFLOW			0.0	0.0%	909.0	1.6%	
***TOTAL OUTFLOW			830.7	99.9%	71116.5	124.6%	86
***EVAPORATION			1.1	0.1%	0.0	0.0%	
***RETENTION			0.0	0.0%	-14062.4	-24.6%	

Hyd. Residence Time = 0.0048 yrs
Overflow Rate = 659.3 m/yr
Mean Depth = 3.2 m

Component: TOTAL P — Segment: 2 CentralBasin

Trib	Type	Location	Flow hm³/yr	Flow %Total	Load kg/yr	Load %Total	Conc mg/m³
11	1	DirectCentral	1.8	24.4%	179.4	8.4%	100
PRECIPITATION			0.9	12.9%	29.2	1.4%	31
INTERNAL LOAD			0.0	0.0%	840.0	39.2%	
TRIBUTARY INFLOW			1.8	24.4%	179.4	8.4%	100
ADVECTIVE INFLOW			4.6	62.7%	184.1	8.6%	40
NET DIFFUSIVE INFLOW			0.0	0.0%	908.9	42.4%	
***TOTAL INFLOW			7.3	100.0%	2141.7	100.0%	292
ADVECTIVE OUTFLOW			6.4	87.1%	255.9	11.9%	40
***TOTAL OUTFLOW			6.4	87.1%	255.9	11.9%	40
***EVAPORATION			0.9	12.9%	0.0	0.0%	
***RETENTION			0.0	0.0%	1885.8	88.1%	

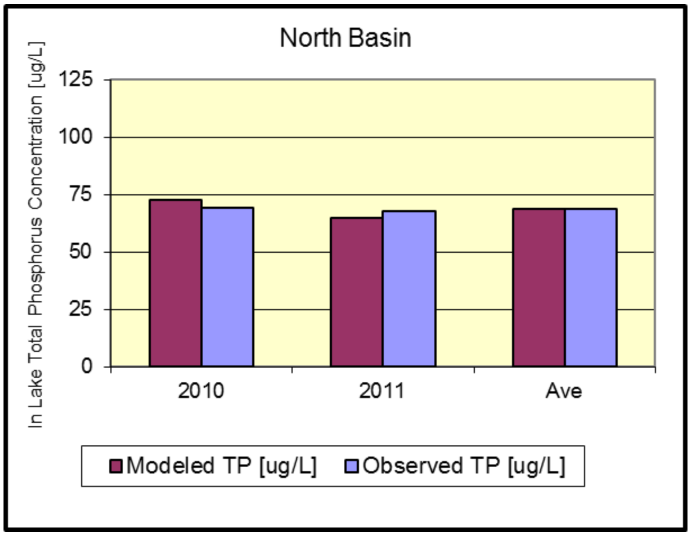
Hyd. Residence Time = 0.8040 yrs
Overflow Rate = 5.9 m/yr
Mean Depth = 4.7 m

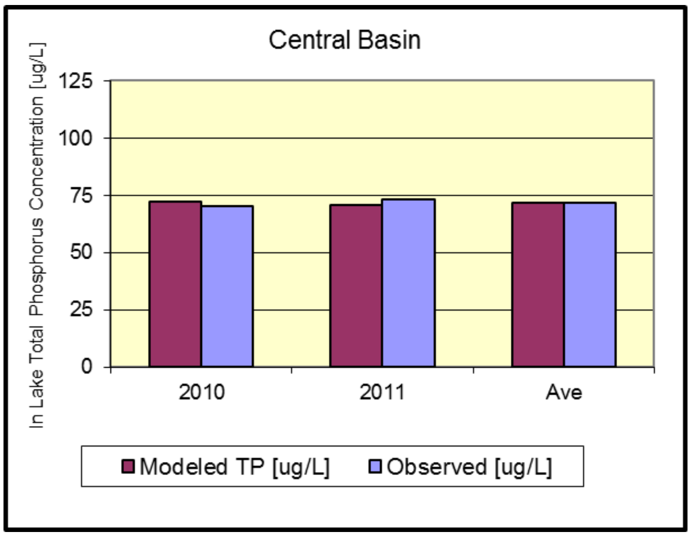
Component: TOTAL P — Segment: 3 North

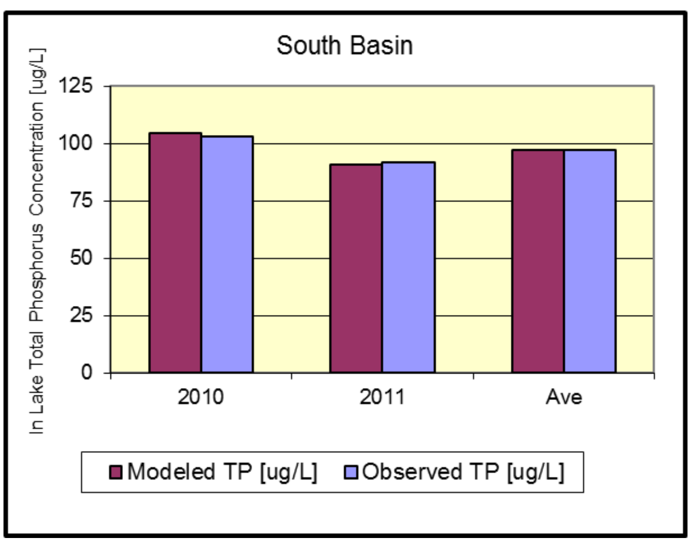
Trib	Type	Location	Flow hm³/yr	Flow %Total	Load kg/yr	Load %Total	Conc mg/m³
12	1	DirectNorth	4.6	79.3%	460.5	41.1%	100
PRECIPITATION			1.2	20.7%	37.3	3.3%	31
INTERNAL LOAD			0.0	0.0%	621.9	55.5%	
TRIBUTARY INFLOW			4.6	79.3%	460.5	41.1%	100
NET DIFFUSIVE INFLOW			0.0	0.0%	0.1	0.0%	
***TOTAL INFLOW			5.8	100.0%	1119.8	100.0%	193
ADVECTIVE OUTFLOW			4.6	79.3%	184.1	16.4%	40
***TOTAL OUTFLOW			4.6	79.3%	184.1	16.4%	40
***EVAPORATION			1.2	20.7%	0.0	0.0%	
***RETENTION			0.0	0.0%	935.7	83.6%	

Hyd. Residence Time = 1.4458 yrs
Overflow Rate = 3.3 m/yr
Mean Depth = 4.8 m

Cross Lake BATHTUB Lake Response Model Performance







Appendix H

Internal Phosphorous Loading and Sediment Phosphorous Fractionation Study

Internal Phosphorus Loading and Sediment Phosphorus Fractionation Analysis for Cross, Knife, Mud, and Pokegama Lakes, Minnesota

01 August, 2012

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OBJECTIVES

The objectives of this investigation were to determine rates of phosphorus (P) release from sediments under laboratory-controlled oxic (i.e., aerobic) and anoxic (i.e., anaerobic) conditions and to quantify biologically-labile (i.e., subject to recycling) and refractory (i.e., biologically inert and subject to burial) P fractions for sediments collected in Cross, Knife, Mud, and Pokegama Lakes, Minnesota.

APPROACH

Laboratory-derived rates of P release from sediment under oxic and anoxic conditions: Replicate sediment cores were collected by Wenck Associates from stations located in the north, central, and south basins of Cross Lake; the north and south basins of Knife and Pogekama Lakes, and the central basin of Mud Lake in May, 2012, for determination of rates of P release from sediment under oxic and anoxic conditions (Table 1). All cores were drained of overlying water and the upper 10 cm of sediment was transferred intact to a smaller acrylic core liner (6.5-cm dia and 20-cm ht) using a core remover tool. Surface water collected from the lake was filtered through a glass fiber filter (Gelman A-E), with 300 mL then siphoned onto the sediment contained in the small acrylic core liner without causing sediment resuspension. Sediment incubation systems consisted of the upper 10-cm of sediment and filtered overlying water contained in acrylic core liners that were sealed with rubber stoppers. They were placed in a darkened environmental chamber and incubated at a constant temperature (20 to 25 ^{o}C). The oxidation-reduction environment in the overlying water was controlled by gently bubbling air (oxic) or nitrogen (anoxic) through an air stone placed just above the sediment surface in each system. Bubbling action insured complete mixing of the water column but did not disrupt the sediment. Anoxic conditions were verified using a dissolved oxygen electrode.

Water samples for soluble reactive P were collected from the center of each system using an acid-washed syringe and filtered through a 0.45 µm membrane syringe filter (Nalge). The water volume removed from each system during sampling was replaced by addition of filtered lake water preadjusted to the proper oxidation-reduction condition. These volumes were accurately measured for determination of dilution effects. Soluble reactive P was measured colorimetrically using the ascorbic acid method (APHA 2005). Rates of P release from the sediment (mg m^{-2} d^{-1}) were calculated as the linear change in mass in the overlying water divided by time (days) and the area (m^2) of the incubation core liner. Regression analysis was used to estimate rates over the linear portion of the data.

Sediment chemistry: The upper 10 cm of an additional core collected from the lake was sectioned for analysis of moisture content (%), sediment density (g/mL), loss on ignition (i.e., organic matter content, %), loosely-bound P, iron-bound P, aluminum-bound P, calcium-bound P, labile and refractory organic P, total P, total nitrogen (N), total iron (Fe), total manganese (Mn), and total calcium (Ca; all expressed at mg/g). A known volume of sediment was dried at 105 ^oC for determination of moisture content and sediment density and burned at 500 ^oC for determination of loss-on-ignition organic matter content (Håkanson and Jansson 2002). Additional sediment was dried to a constant weight, ground, and digested for analysis of total N, P, Fe, Mn and Ca using standard methods (Plumb 1980; APHA 2005).

Phosphorus fractionation was conducted according to Hieltjes and Lijklema (1980), Psenner and Puckso (1988), and Nürnberg (1988) for the determination of ammonium-chloride-extractable P (loosely-bound P), bicarbonate-dithionite-extractable P (i.e., iron-bound P), sodium hydroxide-extractable P (i.e., aluminum-bound P), and hydrochloric acid-extractable P (i.e., calcium-bound P). A subsample of the sodium hydroxide extract was digested with potassium persulfate to determine nonreactive sodium hydroxide-extractable P (Psenner and Puckso 1988). Labile organic P was calculated as the difference between reactive and nonreactive sodium hydroxide-extractable P. Refractory organic P was estimated as the difference between total P and the sum of the other fractions.

The loosely-bound and iron-bound P fractions are readily mobilized at the sediment-water interface as a result of anaerobic conditions that result in desorption of P from sediment and diffusion into the overlying water column (Mortimer 1971, Boström 1984, Nürnberg 1988). The sum of the loosely-bound and iron-bound P fractions are referred to as redox-sensitive P (i.e., the P fraction that is active in P release under anaerobic and reducing conditions). In addition, labile organic P can be converted to soluble P via bacterial mineralization (Jensen and Andersen 1992) or hydrolysis of bacterial polyphosphates to soluble phosphate under anaerobic conditions (Gächter et al. 1988; Gächter and Meyer 1993; Hupfer et al. 1995). The sum of redox-sensitive P and labile organic P are collectively referred to a biologically-labile P. This fraction is generally active in recycling pathways that result in exchanges of phosphate from the sediment to the overlying water column and potential assimilation by algae. In contrast, aluminum-bound, calcium-bound, and refractory organic P fractions are more chemically inert and subject to burial rather than recycling.

RESULTS AND INTERPRETATION

Rates of Phosphorus Release from Sediment

For all lakes, P mass and concentration increased linearly and rapidly in the overlying water column of sediment systems maintained under anoxic conditions (Figures 1-4). For Cross Lake stations, rates of P mass and concentration increase were generally greatest over the first four to six days, reaching an asymptote by the end of the incubation period (Figure 1). Maximum mean P concentration in the overlying water column of sediment incubation systems was relatively high at the end of the incubation period for sediments collected in Cross Lake. Maximum mean P concentrations were 1.513 (±0.199 SE), 2.885 (± 0.035 SE) and 1.817 (± 0.369 SE) mg/L for the north, central, and south basin station of Cross Lake, respectively. P mass and concentration increases in the overlying water column of Pokegama Lake sediments exhibited a similar nonlinear pattern as that observed for Cross Lake sediments. P Mass and concentration increased linearly over the first four to six days then nonlinearly thereafter (Figure 3). Mean maximum P concentration in the overlying water column at the end of the incubation period was relatively high at 1.425 (± 0.342 SE) mg/L for Pokegama Lake sediments. Sediments collected from Knife and Mud Lakes exhibited linear increases in P mass and concentration in the overlying water column throughout the incubation period (Figures 2 and 4). The mean maximum P concentrations were 0.907 (± 0.114 SE) and 1.124 (± 0.015 SE) mg/L for the south and north basin sediments of Knife Lake, respectively, and 1.318 (± 0.141 SE) mg/L for sediments collected in the central basin of Mud Lake.

Overall, mean rates of P release from sediment under anoxic conditions were relatively high for all lakes and stations, indicating that sediments are a potentially important source of internal P loading under conditions of hypolimnetic anoxia. In addition, mean anoxic P release rates fell well above median rates measured of lakes in Minnesota (Figure 5). Sediments collected in the central basin of Cross Lake exhibited the highest mean anoxic P release rate at 31.1 (± 0.7 SE) mg m^{-2} d^{-1}, and represented a maximal rate compared to other lakes in Minnesota (Figure 5). Mean rates were also very high for the north (17.8 mg m^{-2} d^{-1} ± 2.3 SE) and south (18.8 mg m^{-2} d^{-1} ± 3.8 SE) basin sediments of Cross Lake, falling well above the upper 25% quartile (Figure 5). Knife, Mud, and Pokegama Lake sediments exhibited similar high anoxic P release rates compared to other Minnesota Lakes (Table 2, Figure 5).

Increases in P mass and concentration were much lower in the overlying water column of sediment incubation systems under oxic conditions (Figures 6-9), a pattern that may be related to binding of P onto iron oxyhydroxides under oxic conditions which would limit P diffusion. Nevertheless, mean oxic P release rates ranged between 0.4 and 1.8 mg m^{-2} d^{-1} (Table 2), implying potential internal P loading from profundal sediments during periods of intermittent mixing and bottom water reaeration. In particular, mean oxic P release rates determined for all lake stations fell within or above the 25% upper quartile compared to other Minnesota Lakes (Figure 10).

Sediment Textural and Chemical Characteristics

Profundal sediments generally exhibited a moisture content that exceeded 75%, indicating fined-grained flocculent sediment (Table 3). An exception was for sediment collected in the south basin of Cross Lake (Table 3). Moisture content was ~ 75% and bulk density was much higher than 1.0 g/cm^3 (i.e., the approximate density of water near 4 ^{o}C) at this station, suggesting that sands and coarser silts comprised a more significant portion of the particle size distribution (Table 3). Overall, moisture content was greatest (i.e., > 85%), and bulk density lowest (i.e., < 1.150 g/cm^3) for profundal sediments collected in Knife, Mud, and Pokegama Lakes (Table 3). Organic matter content ranged between 11.6 and 15.9% for Cross Lake sediments (Table 3) and fell below the lower 25% quartile for Minnesota Lakes (Figure 11). In contrast, sediment organic matter content was high at ~ 46% for the north basin of Knife Lake compared to other Minnesota Lakes (Figure 11). Other lake sediments exhibited moderate concentrations that ranged between ~17 and ~ 25% (Table 3 and Figure 11).

Overall, biologically-labile (i.e., subject to recycling back to the overlying water column; loosely-bound P, iron-bound P, and labile organic P) P accounted for at least 50% of the sediment total P concentration (Range = 49.2% to 63.1%; Table 2; Figure 12 and 13), suggesting the potential for internal P loading from sediments. Iron-bound P concentrations, which have been positively correlated with rates of P release from sediment under anoxic conditions (Nürnberg 1988), accounted for over 70% of the biologically-available P for profundal sediments collected in Cross Lake and the south basin of Pokegama Lake (Figure 12 and 13). This fraction represented ~38% to 53% of the biologically-labile P in the north basin of Knife and Pokegama Lake and the central basin of Mud Lake. In contrast, labile organic P accounted for a greater percentage of the biologically-labile P fraction for sediments in these latter lake basins (Figure 13). Concentrations of iron-bound P were also high in Cross Lake and the south basin of Pokegama Lake relative to other lakes in Minnesota (Figure 14).

With the exception of the south basin of Cross Lake, there was a linear relationship between iron-bound P (expressed on a mg P/g fresh sediment mass basis; Nürnberg 1988) and the mean anoxic P release rate (Figure 15; mean anoxic P release rate = 0.1371· iron-bound P + 5.8034; r^2 = 0.87), suggesting that the iron-bound P concentration was an important factor in anoxic P release and that higher concentrations translated into greater anoxic P release. Sediments from the south basin of Cross Lake exhibited a lower moisture content and higher bulk density than the other stations. Since diffusive P flux from sediment is related to porosity (i.e, the interstitial porewater fraction of the total sediment volume), higher sediment density and lower porosity would tend to constrain and regulate diffusion of P across the sediment interface under anoxic conditions.

Biologically-refractory P (i.e., aluminum-bound, calcium-bound, and refractory organic P), more inert and subject to burial rather than recycling, accounted for ~ 37% to 51% of the sediment total P for all lake stations (Table 2; Figure 12 and 13). All three extractable fractions tended to be co-dominant for most lakes. Exceptions were the north basin of Cross and Pokegama Lakes, where the refractory organic P fraction was minor relative to aluminum-bound and calcium-bound P (Figure 13). Calcium-bound P concentrations were high for Cross Lake sediments relative to other lake in Minnesota, falling in the upper 25% quartile (Figure 16). Similarly, Pogekama, Mud, and the south basin of Knife Lake exhibited high calcium-bound P concentrations that fell within or above the upper 25% quartile (Figure 16).

Sediment total P concentrations were greatest for the central and south basins of Cross Lake and the south basin of Pokegama Lake (Table 2 and Figure 13). In addition, concentrations at these sediment stations fell above the upper 25% quartile in relation to other Minnesota Lakes (Figure 14). In contrast, sediment total P concentrations were moderate at other stations (Knife Lake, Mud Lake, Cross Lake north basin, and Pokegma Lake north basin) and generally fell below the lower 25% quartile (Figure 14). Sediment total Fe concentrations were relatively high for all lake stations, ranging between 17 and 56 mg/g (Table 2 and Figure 16). Total Fe was also very high relative to total P, resulting in sediment total Fe:P ratios that ranged between 17 and 42 (Table 2), which fell well above the upper 25% quartile (Figure 17). This pattern may be related to the mineral geology of north-central Minnesota, which is rich in iron deposits. Ratios > 10 have been associated with regulation of P release from sediments under oxic conditions (Jensen et al. 1992).

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Table 1. Redox (i.e., oxic and/or anoxic) conditions used for determination of rates of phosphorus release from sediment for various stations.

Lake	Basin	Redox Condition	
		Oxic	Anoxic
Cross Lake	North	X	X
	Central	X	X
	South		X
Knife Lake	North	X	X
	South	X	X
Pokegama Lake	North	X	
	South		X
Mud Lake	Central	X	X

Table 2. Mean (1 standard error in parentheses; n=3) rates of phosphorus (P) release, concentrations of biologically labile and refractory P, and metals concentrations for sediments collected in Cross, Knife, Pokegama, and Mud Lakes. DW = dry mass, FW = fresh mass, N = nitrogen, Fe = iron, Mn = manganese, Ca = calcium.

Station	Diffusive P flux		Redox-sensitive and biologically labile P				Refractory P		
	Oxic ($mg\ m^{-2}\ d^{-1}$)	Anoxic ($mg\ m^{-2}\ d^{-1}$)	Loosely-bound P (mg/g DW)	Iron-bound P (mg/g DW)	Iron-bound P (ug/g FW)	Labile organic P (mg/g DW)	Aluminum-bound P (mg/g DW)	Calcium-bound P (mg/g DW)	Refractory organic P (mg/g DW)
Cross North	0.5 (0.1)	17.8 (2.3)	0.029	0.395	80	0.116	0.201	0.204	0.049
Cross Central	1.8 (0.1)	31.1 (0.7)	0.077	0.952	163	0.147	0.286	0.210	0.269
Cross South		18.8 (3.8)	0.105	1.069	265	0.068	0.268	0.196	0.463
Knife North	0.7 (0.1)	9.5 (0.1)	0.024	0.169	13	0.256	0.108	0.076	0.196
Knife South	0.4 (0.1)	7.7 (1.0)	0.019	0.292	33	0.208	0.106	0.185	0.191
Pokegama North	0.5 (0.1)		0.011	0.304	35	0.260	0.113	0.223	0.033
Pokegama South		16.3 (4.5)	0.068	1.017	112	0.218	0.192	0.238	0.333
Mud	0.4 (0.1)	11.1 (1.2)	0.029	0.233	27	0.206	0.124	0.228	0.131

Station	Total P	Redox P		Bio-labile P		Refractory P	
	(mg/g DW)	(mg/g DW)	(% total P)	(mg/g DW)	(% total P)	(mg/g DW)	(% total P)
Cross North	0.993	0.424	42.7	0.540	54.4	0.454	45.7
Cross Central	1.941	1.029	53.0	1.176	60.6	0.765	39.4
Cross South	2.169	1.174	54.1	1.242	57.3	0.927	42.7
Knife North	0.829	0.193	23.3	0.449	54.2	0.380	45.8
Knife South	1.001	0.311	31.1	0.519	51.8	0.482	48.2
Pokegama North	0.944	0.315	33.4	0.575	60.9	0.369	39.1
Pokegama South	2.066	1.085	52.5	1.303	63.1	0.763	36.9
Mud	0.951	0.262	27.5	0.468	49.2	0.483	50.8

Station	Total Fe (mg/g DW)	Total Mn (mg/g DW)	Total Ca (mg/g DW)	Fe:P
Cross North	33.65	0.678	7.04	33.9
Cross Central	56.21	1.027	7.51	29.0
Cross South	42.39	1.297	7.75	19.5
Knife North	17.32	0.461	8.89	20.9
Knife South	29.5	0.638	8.02	29.5
Pokegama North	39.99	0.520	7.54	42.4
Pokegama South	34.59	0.695	6.42	16.7
Mud	35.24	0.447	8.15	37.1

Table 3. Textural characteristics for sediments collected in Cross, Knife, Pokegama, and Mud Lakes.

Station	Moisture Content (%)	Bulk Density (g/cm^3)	Sediment Density (g/cm^3)	Loss-on-ignition (%)
Cross North	79.8	1.120	0.267	14.2
Cross Central	82.9	1.097	0.192	15.9
Cross South	75.3	1.156	0.315	11.6
Knife North	92.6	1.026	0.084	44.5
Knife South	88.7	1.055	0.125	25.1
Pokegama North	88.6	1.059	0.122	20.7
Pokegama South	89.0	1.060	0.128	16.7
Mud	88.4	1.058	0.127	22.4

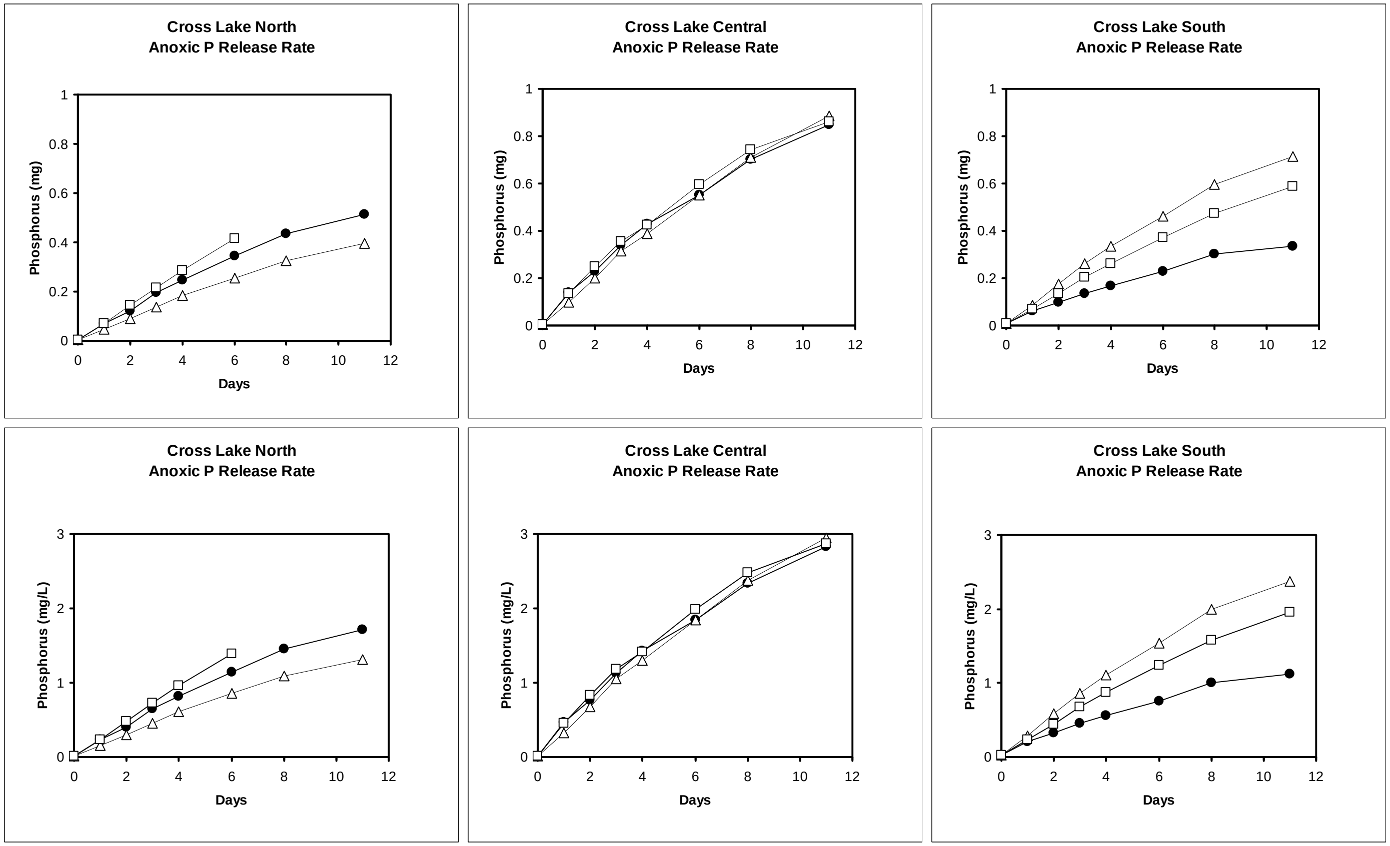

Figure 1. Changes in soluble reactive phosphorus mass (upper panel) and concentration (lower panel) in the overlying water column under anoxic conditions versus time for sediment cores collected in Cross Lake.

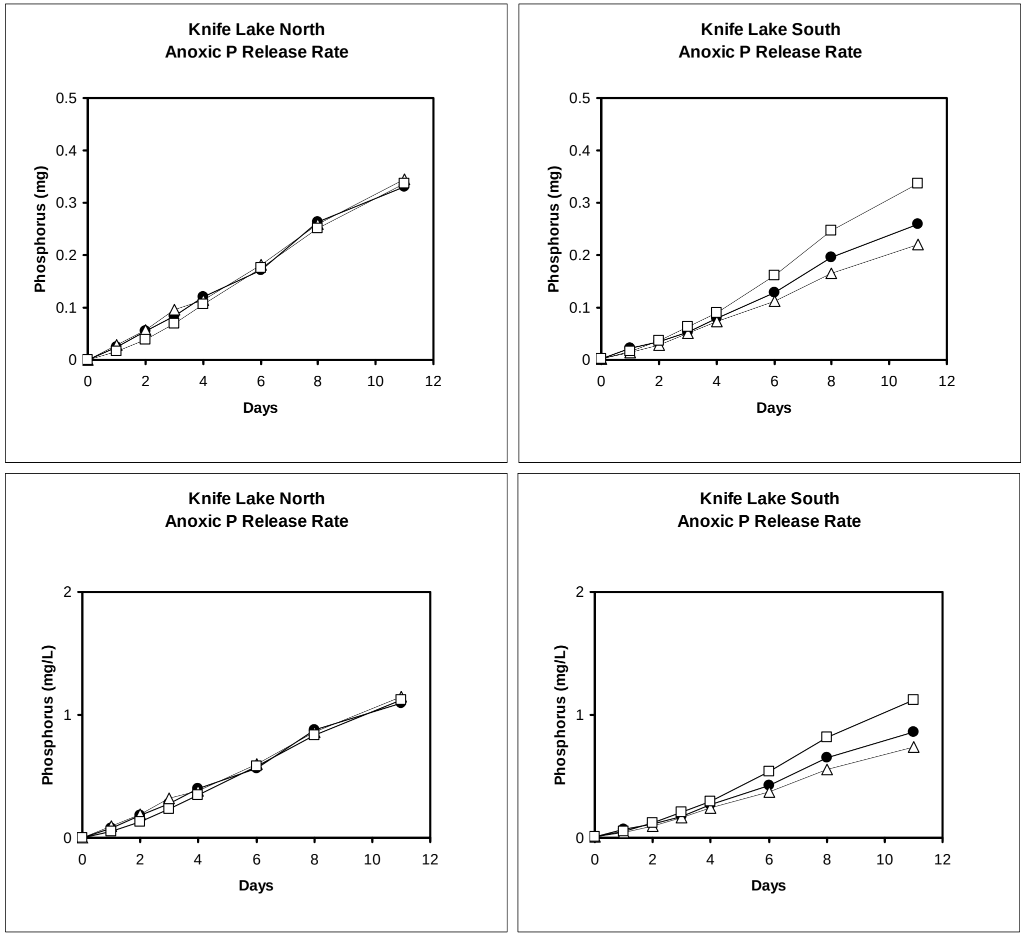

Figure 2. Changes in soluble reactive phosphorus mass (upper panel) and concentration (lower panel) in the overlying water column under anoxic conditions versus time for sediment cores collected in Knife Lake.

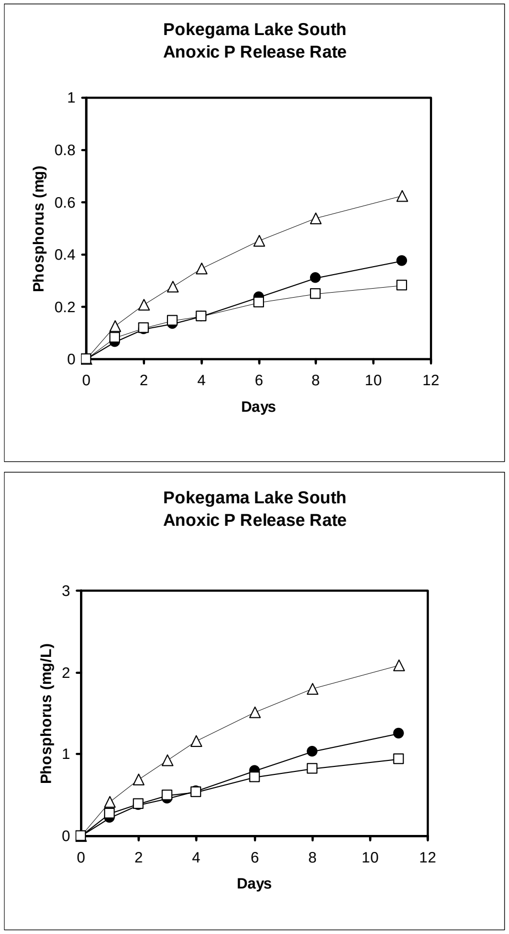

Figure 3. Changes in soluble reactive phosphorus mass (upper panel) and concentration (lower panel) in the overlying water column under anoxic conditions versus time for sediment cores collected in the south basin of Pokegama Lake.

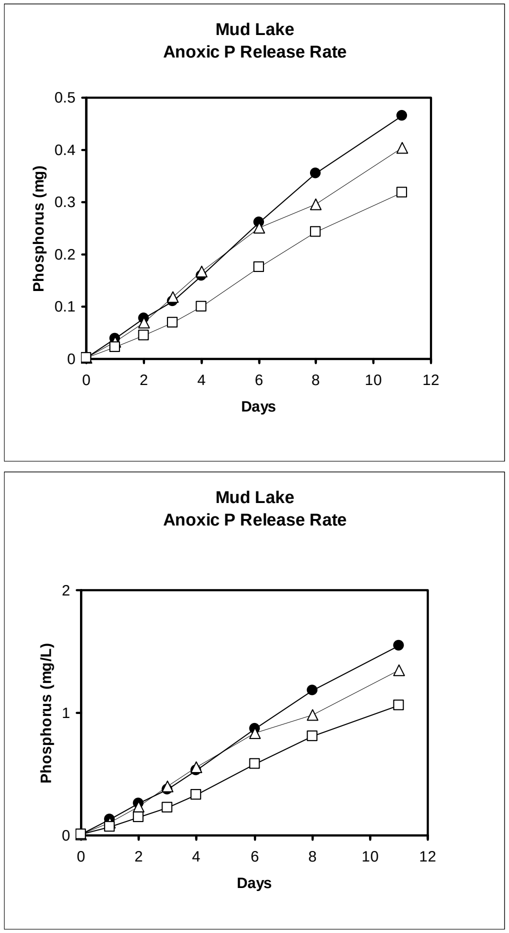

Figure 4. Changes in soluble reactive phosphorus mass (upper panel) and concentration (lower panel) in the overlying water column under anoxic conditions versus time for sediment cores collected in the central basin of Mud Lake.

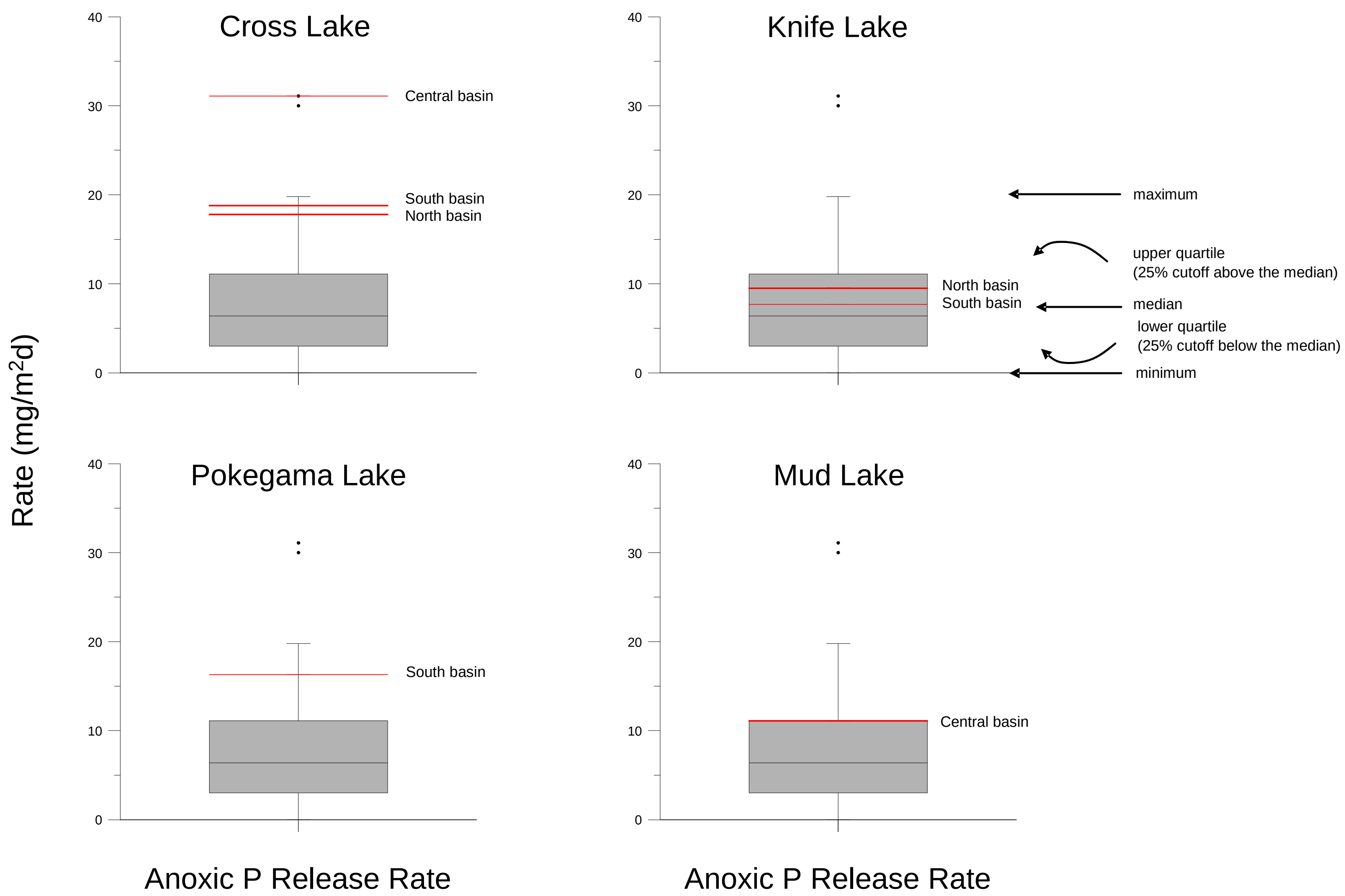

Figure 5. Box and whisker plot comparing the anoxic phosphorus (P) release rate measured for Cross, Knife, Pokegama, and Mud Lake sediments (red lines) with statistical ranges (n=50) for lakes in the State of Minnesota.

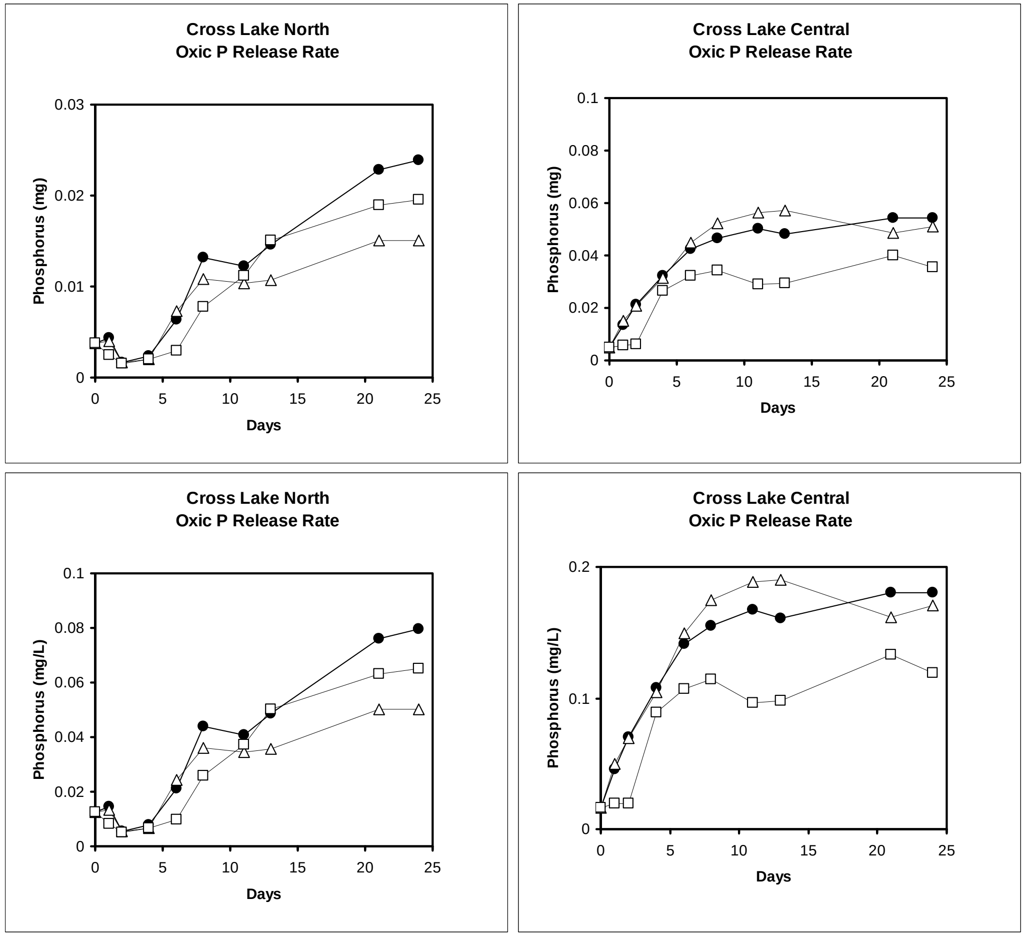

Figure 6. Changes in soluble reactive phosphorus mass (upper panel) and concentration (lower panel) in the overlying water column under oxic conditions versus time for sediment cores collected in Cross Lake.

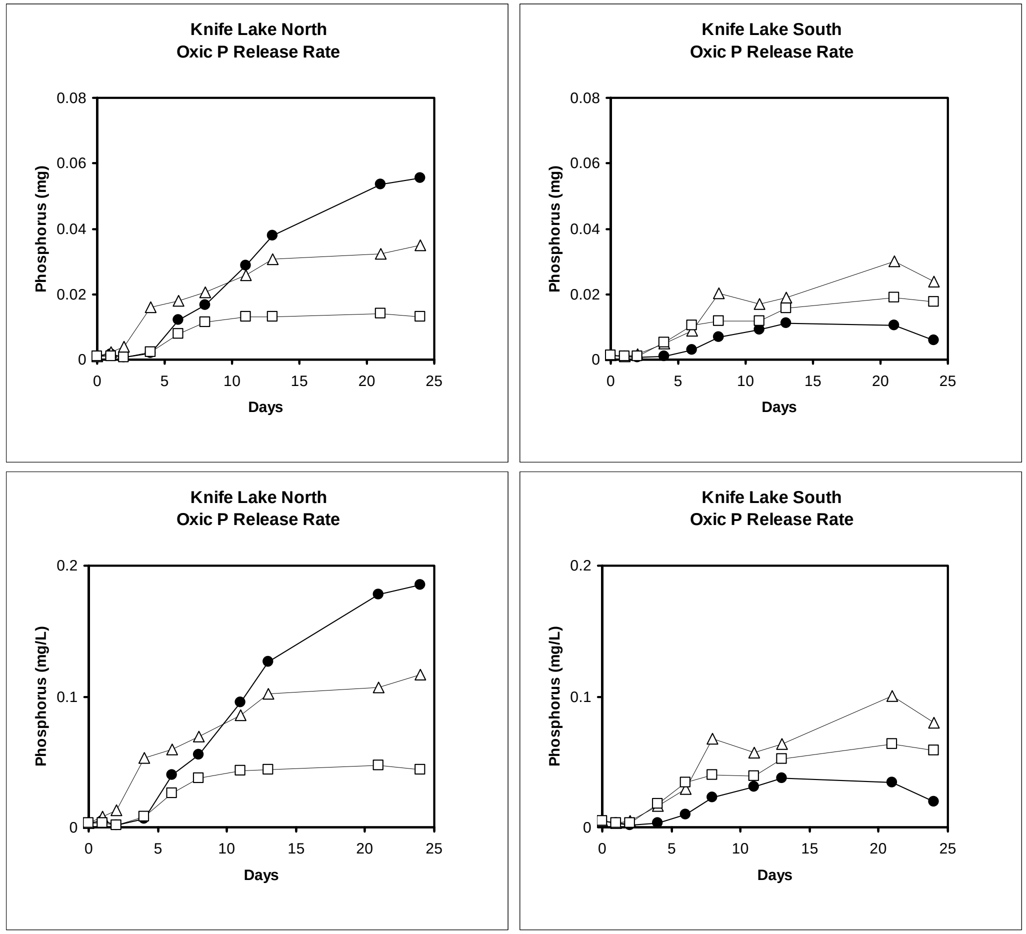

Figure 7. Changes in soluble reactive phosphorus mass (upper panel) and concentration (lower panel) in the overlying water column under oxic conditions versus time for sediment cores collected in Knife Lake.

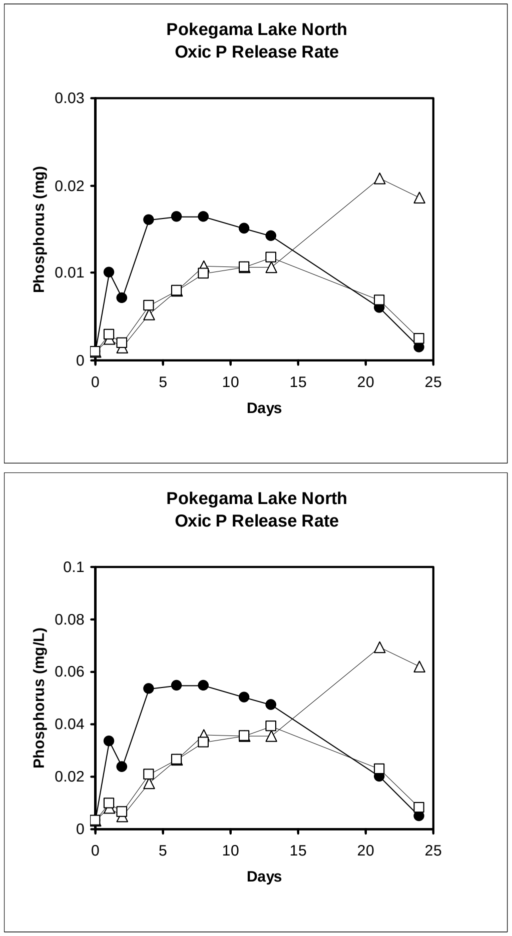

Figure 8. Changes in soluble reactive phosphorus mass (upper panel) and concentration (lower panel) in the overlying water column under oxic conditions versus time for sediment cores collected in the north basin of Pokegama Lake.

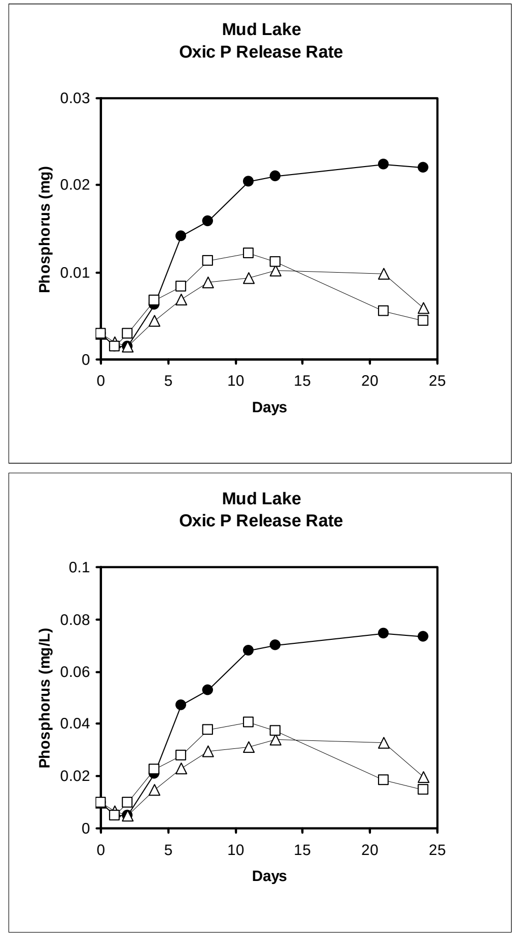

Figure 9. Changes in soluble reactive phosphorus mass (upper panel) and concentration (lower panel) in the overlying water column under oxic conditions versus time for sediment cores collected in the central basin of Mud Lake.

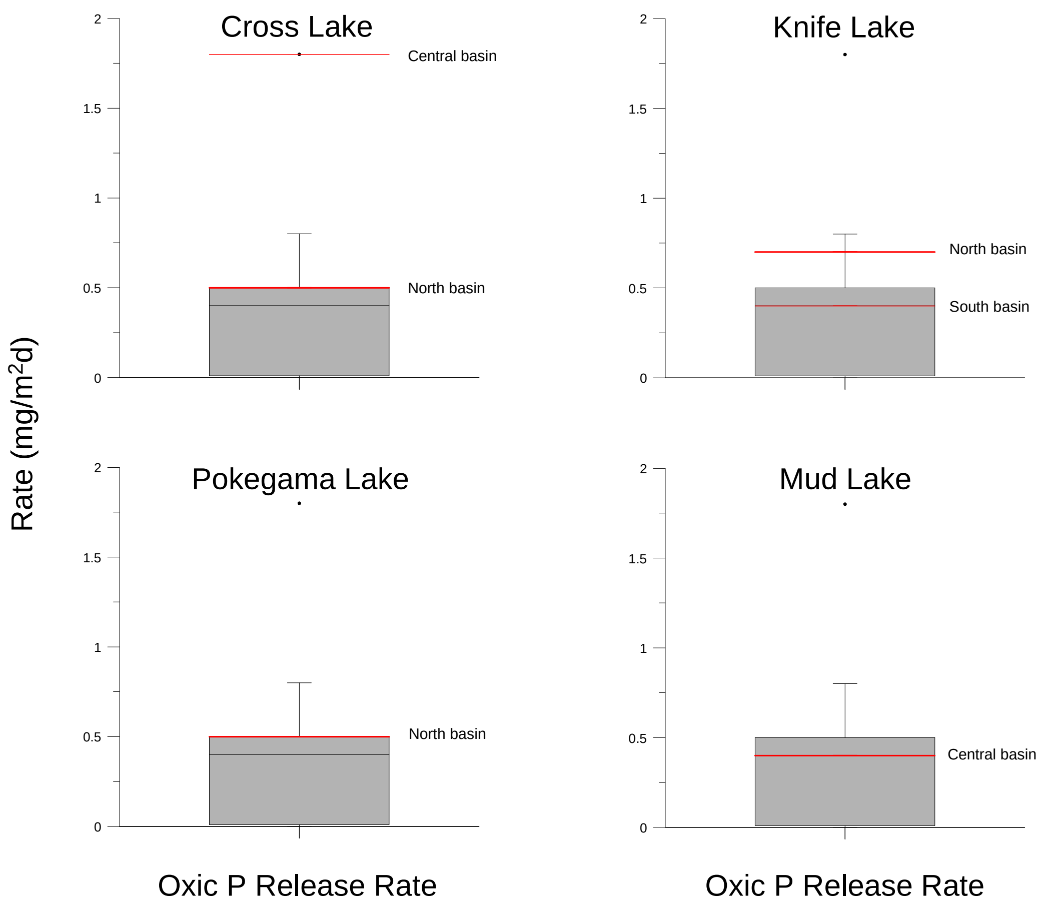

Figure 10. Box and whisker plot comparing the oxic phosphorus (P) release rate measured for Cross, Knife, Pokegama, and Mud Lake sediments (red lines) with statistical ranges (n=50) for lakes in the State of Minnesota.

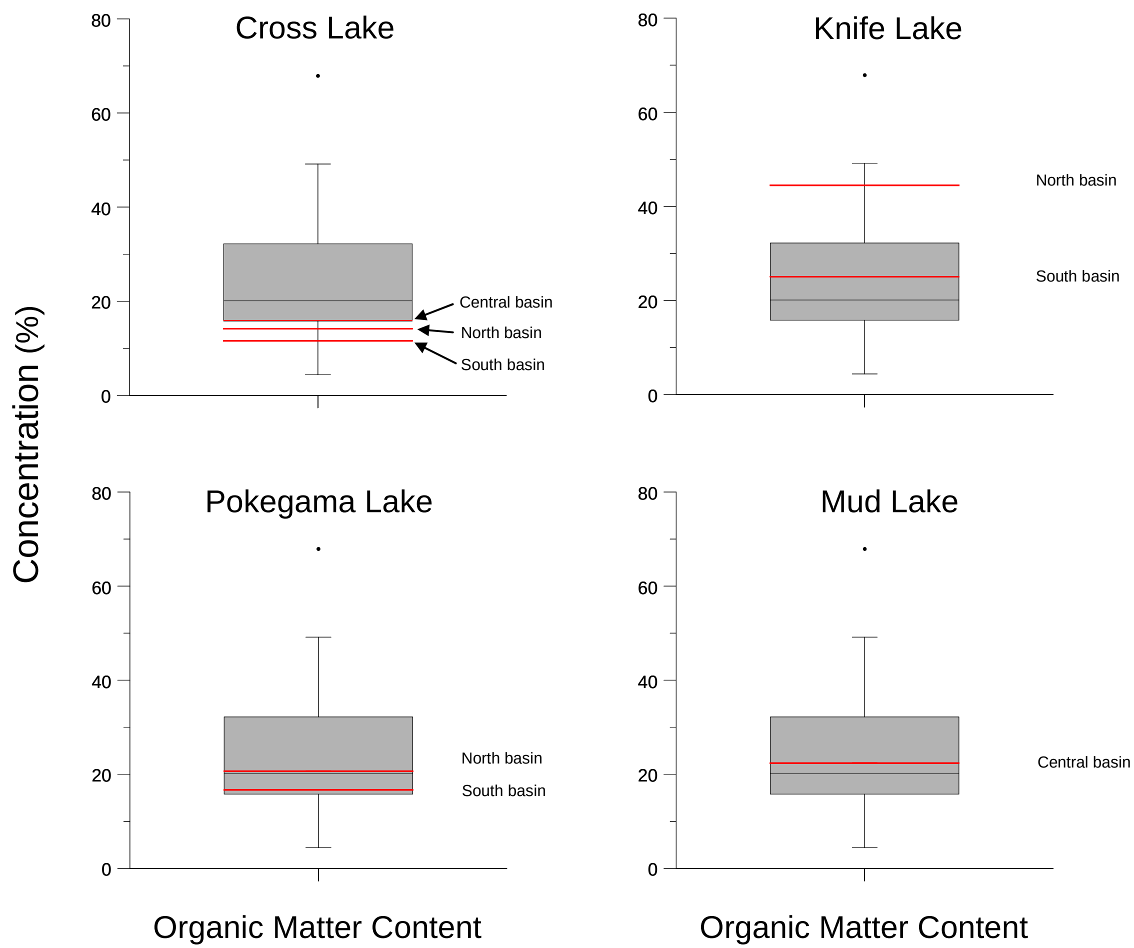

Figure 11. Box and whisker plot comparing loss-on-ignition organic matter content of sediments for Cross, Knife, Pokegama, and Mud Lake sediments (red lines) with statistical ranges (n=50) for lakes in the State of Minnesota.

Figure 12. Total phosphorus (P) composition for sediment collected at various lake stations. Loosely-bound, iron-bound, and labile organic P are biologically reactive (i.e., subject to recycling) while aluminum-bound, calcium-bound, and refractory organic P are more inert to transformation (i.e., subject to burial). Values next to each label represent concentration ($mg \cdot g^{-1}$) and percent total P, respectively.

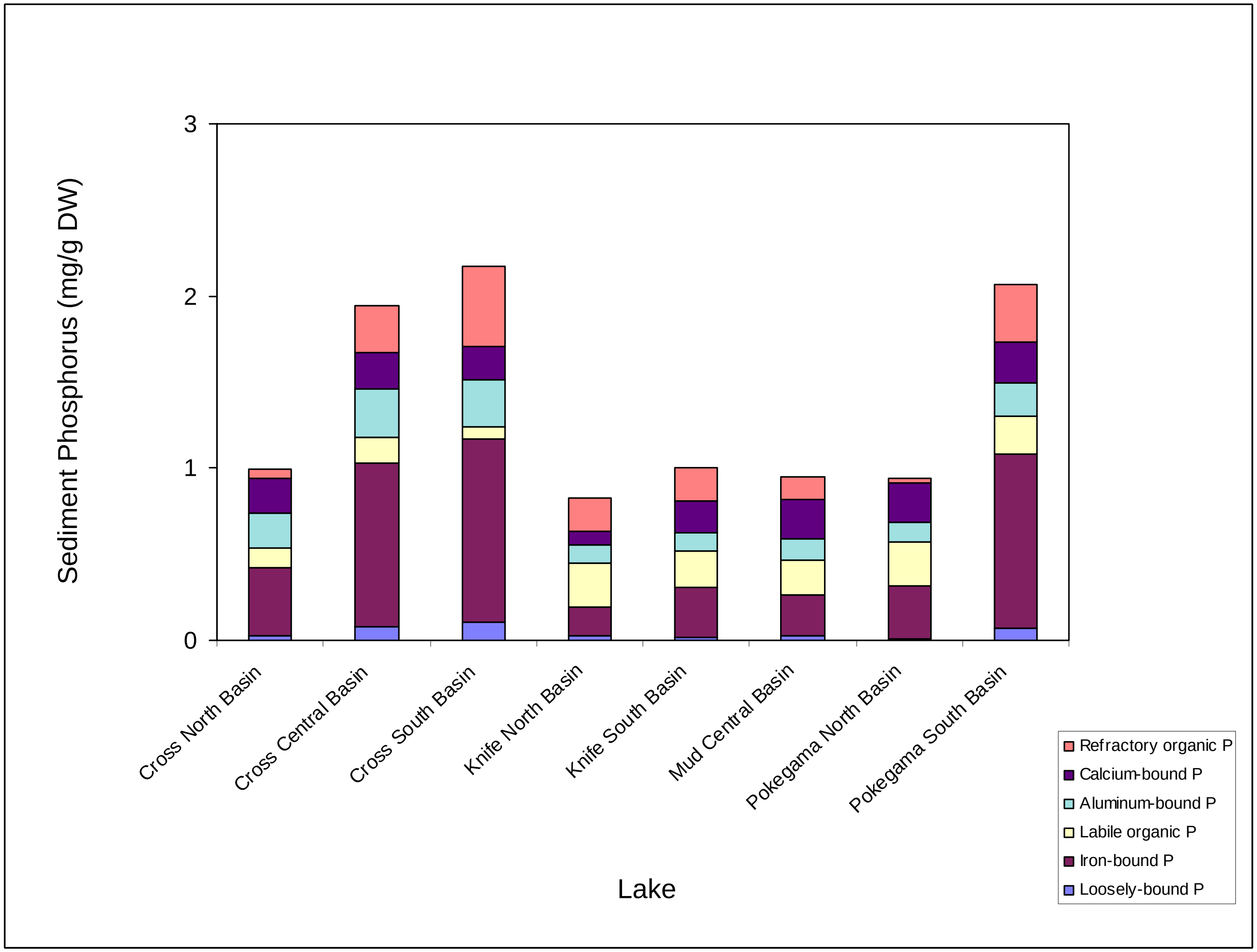

Figure 13. Comparison of total phosphorus (P) and biologically-labile (loosely-bound, iron-bound, and labile organic P and biologically refractory (aluminum-bound, calcium-bound, and refractory organic P) concentrations.

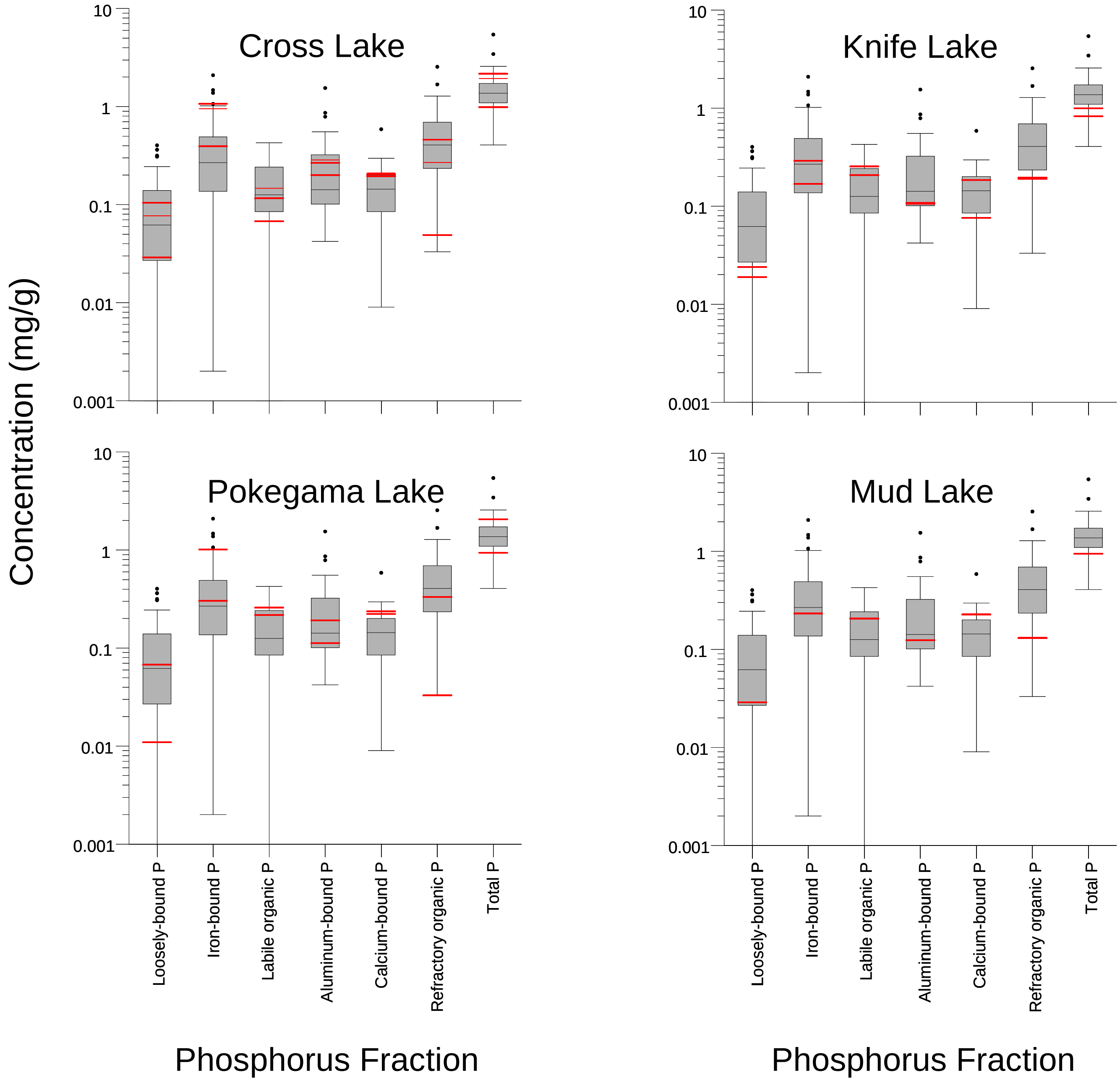

Figure 14. Box and whisker plots comparing various sediment phosphorus (P) fractions measured for Cross, Knife, Mud and Pokegama Lake sediments (red lines) with statistical ranges (n=50) for lakes in the State of Minnesota. Loosely-bound, iron-bound, and labile organic P are biologically-labile (i.e., subject to recycling) and aluminum-bound, calcium-bound, and refractory organic P are more are more inert to transformation (i.e., subject to burial). Please note the logarithmic scale.

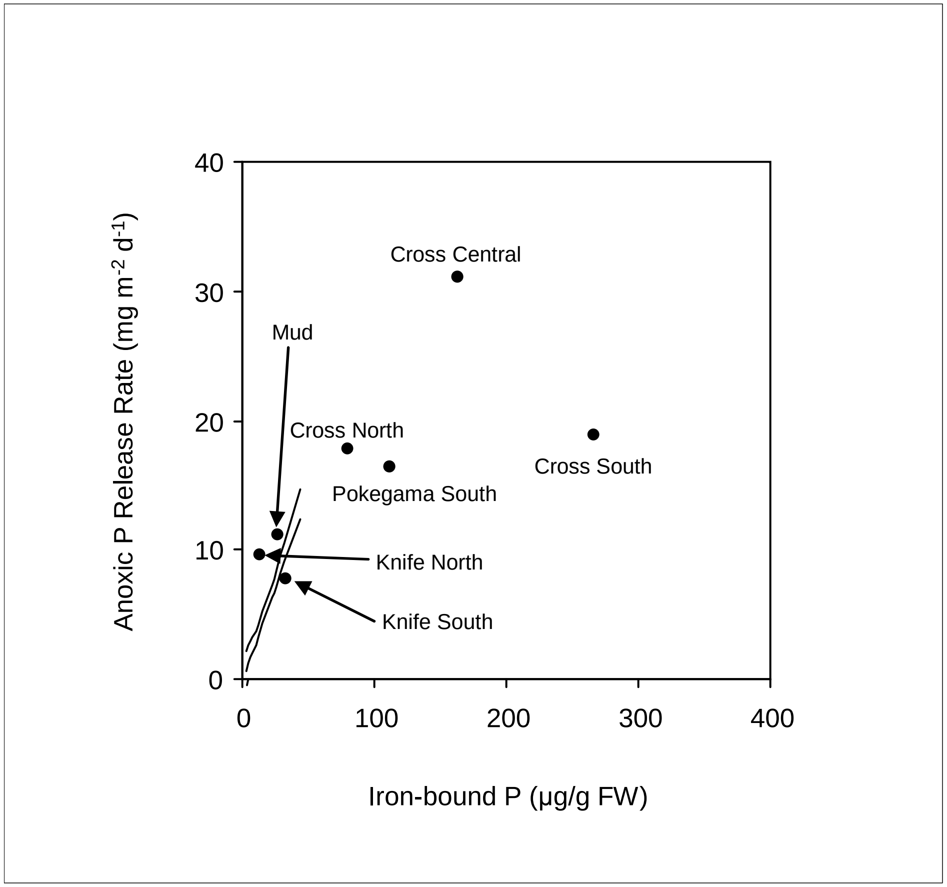

Figure 15. Relationships between iron-bound phosphorus (P; mg g^{-1} fresh sediment mass) and rates of P release from sediments under anoxic conditions. Regression line and 95% confidence intervals from Nürnberg (1988) are shown for comparison.

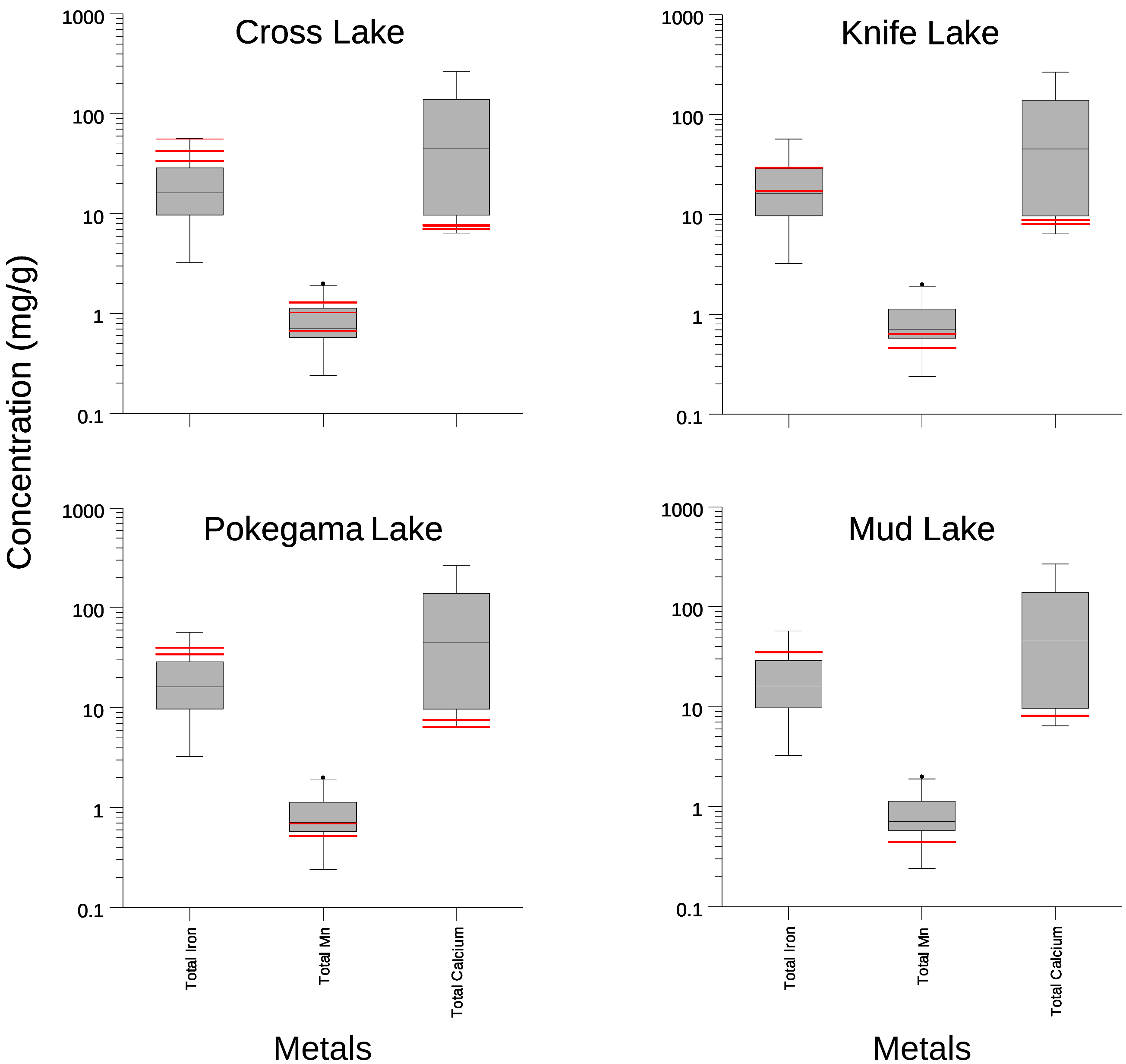

Figure 16. Box and whisker plots comparing various metal concentrations measured for Cross, Knife, Mud and Pokegama Lake sediments (red lines) with statistical ranges (n=50) for lakes in the State of Minnesota. Please note the logarithmic scale.

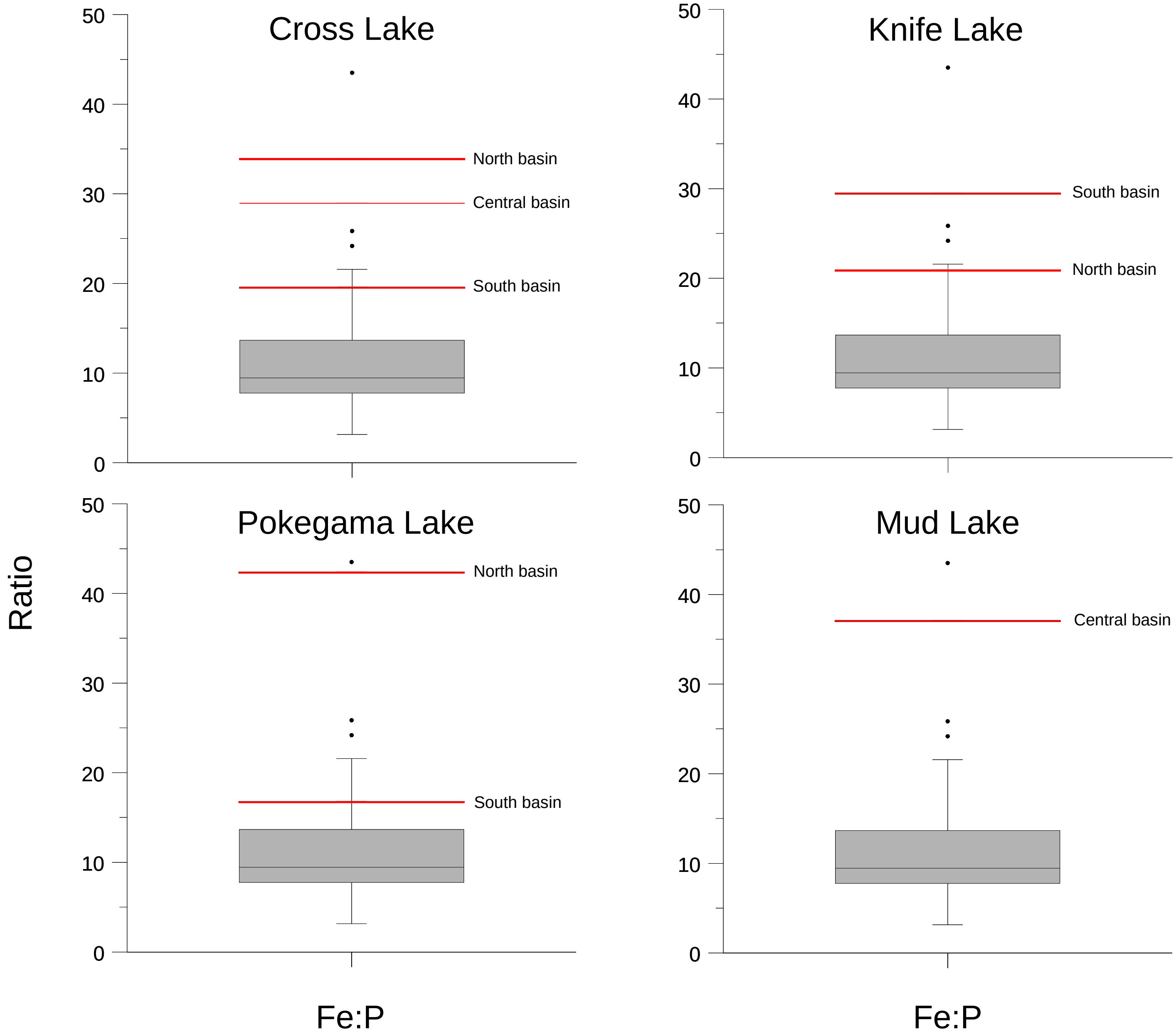

Figure 17. Box and whisker plots comparing the sediment iron:phosphors (Fe:P) ratio measured for Cross, Knife, Mud and Pokegama Lake sediments (red lines) with statistical ranges (n=50) for lakes in the State of Minnesota.

Appendix I

Biotic Impairment Supporting Documents

Source: Ohio DNR STREAM Sediment Equations Module

Site 3: 06SC110 data from J Jasperson, MPCA, Wenck

Threshold of Motion		metric units		conversion	English units with grain size in mm	
depth	d	**0.5**	m	3.28	1.6	ft
slope	S	**0.0007**	m/m	1	0.0007	ft/ft
diameter sediment	d_s	**0.00006**	m	1000	0.060	mm
gravitational acceleration	g	9.81	m/sec^2	3.28	32.2	ft/sec^2
density fluid	f	1000	kg/m^3	0.00194	1.94	slugs/ft^3
density sediment	s	2650	kg/m^3	0.00194	5.15	slugs/ft^3
specific weight of water	γ	9810	N/m^3		62.5	lb/ft^3
		1000	kg$_f$/m^3			
shear stress		3.4	N/m^2		0.072	lb/ft^2
		0.4	kg$_f$/m^2			
Shields parameter	τ_{*c}	3.535	dimensionless		3.534	dimensionless
Particle at threshold of motion	D_{cr}	0.00354	m	1000	3.54	mm

Bedload per unit channel width		metric units		conversion	English units with grain size in mm		check back to SI	
depth	d	**0.5**	m	3.28	1.6	ft		
slope	S	**0.0007**	m/m		0.0007	ft/ft		
diameter sediment	d_s	**0.00006**	m		0	mm		
gravitational acceleration	g	9.81	m/sec^2	3.28	32.2	ft/sec^2		
density fluid	f	1000	kg/m^3	0.00194	1.94	slugs/ft^3		
density sediment	s	2650	kg/m^3	0.00194	5.15	slugs/ft^3		
relative density	s	2.65	dimensionless		2.65	dimensionless		
shear stress		3.4	N/m^2		0.072	lb$_f$/ft^2		
dimensionless parameter	Ψ	0.28			0.28			
bed-load transport (Meyer-Peter)	Φ	52.122			52.102			
	q_s	**0.0001**	m^2/s		**0.0010**	ft^2/s	9.74E-05	m^2/s
bed-load transport (Einstein$_{42}$)	Φ	1.925			1.925			
	q_s	**0.00000**	m^2/s		**0.00004**	ft^2/s	3.6E-06	m^2/s
bed-load transport (Einstein$_{50}$)	Φ	FALSE			FALSE			
	q_s	**0.00000**	m^2/s		**0.00000**	ft^2/s	0	m^2/s
Ackers and White	n	0.012			0.012			
	U	1.41	m/s		4.63	ft/s		
	q_b	**0.00005**	m^2/s		**0.00057**	ft^2/s	5.29E-05	m^2/s

Source: Ohio DNR STREAM Sediment Equations Module

Site 6:near 235th Street and CR 5 — data from J Jasperson, MPCA

Threshold of Motion		metric units		conversion	English units with grain size in mm	
depth	d	**0.7**	m	3.28	2.3	ft
slope	S	**0.0003125**	m/m	1	0.0003125	ft/ft
diameter sediment	d_s	**0.00013**	m	1000	0.13	mm
gravitational acceleration	g	9.81	m/sec^2	3.28	32.2	ft/sec^2
density fluid	$_f$	1000	kg/m^3	0.00194	1.94	$slugs/ft^3$
density sediment	$_s$	2650	kg/m^3	0.00194	5.15	$slugs/ft^3$
specific weight of water	γ	9810	N/m^3		62.5	lb/ft^3
		1000	kg_f/m^3			
shear stress		2.1	N/m^2		0.045	lb/ft^2
		0.2	kg_f/m^2			
Shields parameter	τ_{*c}	1.020	dimensionless		1.020	dimensionless
Particle at threshold of motion	D_{cr}	0.00221	m	1000	2.21	mm

Bedload per unit channel width		metric units		conversion	English units with grain size in mm		check back to SI	
depth	d	**0.7**	m	3.28	2.3	ft		
slope	S	**0.0003125**	m/m		0.0003125	ft/ft		
diameter sediment	d_s	**0.00013**	m		0.13	mm		
gravitational acceleration	g	9.81	m/sec^2	3.28	32.2	ft/sec^2		
density fluid	$_f$	1000	kg/m^3	0.00194	1.94	$slugs/ft^3$		
density sediment	$_s$	2650	kg/m^3	0.00194	5.15	$slugs/ft^3$		
relative density	s	2.65	dimensionless		2.65	dimensionless		
shear stress		2.1	N/m^2		0.045	lb_f/ft^2		
dimensionless parameter	Ψ	0.98			0.98			
bed-load transport (Meyer-Peter)	Φ	7.676			7.673			
	q_s	**0.0000**	m^2/s		**0.0005**	ft^2/s	4.6E-05	m^2/s
bed-load transport ($Einstein_{42}$)	Φ	1.465			1.465			
	q_s	**0.0000087**	m^2/s		**0.00009**	ft^2/s	8.7E-06	m^2/s
bed-load transport ($Einstein_{50}$)	Φ	7.569			7.567			
	q_s	**0.00005**	m^2/s		**0.00049**	ft^2/s	4.5E-05	m^2/s
Ackers and White	n	0.013			0.013			
	U	1.07	m/s		3.50	ft/s		
	q_b	**0.00003**	m^2/s		**0.00031**	ft^2/s	2.9E-05	m^2/s

Source: Ohio DNR STREAM Sediment Equations Module

Site 7: 98SC018 data from J Jasperson, MPCA

Threshold of Motion		metric units		conversion	English units with grain size in mm	
depth	d	**0.82**	m	3.28	2.7	ft
slope	S	**0.0005**	m/m	1	0.0005	ft/ft
diameter sediment	d_s	**0.0005**	m	1000	0.50	mm
gravitational acceleration	g	9.81	m/sec^2	3.28	32.2	ft/sec^2
density fluid	$_f$	1000	kg/m^3	0.00194	1.94	slugs/ft^3
density sediment	$_s$	2650	kg/m^3	0.00194	5.15	slugs/ft^3
specific weight of water	γ	9810	N/m^3		62.5	lb/ft^3
		1000	kg$_f$/m^3			
shear stress		4.0	N/m^2		0.084	lb/ft^2
		0.4	kg$_f$/m^2			
Shields parameter	τ_{*c}	0.497	dimensionless		0.497	dimensionless
Particle at threshold of motion	D_{cr}	0.00414	m	1000	4.14	mm

Bedload per unit channel width		metric units		conversion	English units with grain size in mm		check back to SI	
depth	d	**0.82**	m	3.28	2.7	ft		
slope	S	**0.0005**	m/m		0.0005	ft/ft		
diameter sediment	d_s	**0.0005**	m		0.50	mm		
gravitational acceleration	g	9.81	m/sec^2	3.28	32.2	ft/sec^2		
density fluid	$_f$	1000	kg/m^3	0.00194	1.94	slugs/ft^3		
density sediment	$_s$	2650	kg/m^3	0.00194	5.15	slugs/ft^3		
relative density	s	2.65	dimensionless		2.65	dimensionless		
shear stress		4.0	N/m^2		0.084	lb$_f$/ft^2		
dimensionless parameter	Ψ	2.01			2.01			
bed-load transport (Meyer-Peter)	Φ	2.415			2.414			
	q_s	**0.0001**	m^2/s		**0.0012**	ft^2/s	0.00011	m^2/s
bed-load transport (Einstein$_{42}$)	Φ	0.979			0.979			
	q_s	**0.000044**	m^2/s		**0.00047**	ft^2/s	4.4E-05	m^2/s
bed-load transport (Einstein$_{50}$)	Φ	3.149			3.148			
	q_s	**0.00014**	m^2/s		**0.00152**	ft^2/s	0.00014	m^2/s
Ackers and White	n	0.015			0.015			
	U	1.28	m/s		4.19	ft/s		
	q_b	**0.00006**	m^2/s		**0.00068**	ft^2/s	6.3E-05	m^2/s

Source: Ohio DNR STREAM Sediment Equations Module

Site 10: 06SC109 data from J Jasperson, MPCA

Threshold of Motion		metric units		conversion	English units with grain size in mm	
depth	d	**0.727**	m	3.28	2.4	ft
slope	S	**0.001588903**	m/m	1	0.0015889	ft/ft
diameter sediment	d_s	**0.023**	m	1000	23.0	mm
gravitational acceleration	g	9.81	m/sec^2	3.28	32.2	ft/sec^2
density fluid	$_f$	1000	kg/m^3	0.00194	1.94	slugs/ft^3
density sediment	$_s$	2650	kg/m^3	0.00194	5.15	slugs/ft^3
specific weight of water	γ	9810	N/m^3		62.5	lb/ft^3
		1000	kg$_f$/m^3			
shear stress		11.3	N/m^2		0.237	lb/ft^2
		1.2	kg$_f$/m^2			
Shields parameter	τ_{*c}	0.030	dimensionless		0.030	dimensionless
Particle at threshold of motion	D_{cr}	0.01167	m	1000	11.7	mm

Bedload per unit channel width		metric units		conversion	English units with grain size in mm		check back to SI	
depth	d	**0.727**	m	3.28	2.4	ft		
slope	S	**0.001588903**	m/m		0.0015889	ft/ft		
diameter sediment	d_s	**0.023**	m		23	mm		
gravitational acceleration	g	9.81	m/sec^2	3.28	32.2	ft/sec^2		
density fluid	$_f$	1000	kg/m^3	0.00194	1.94	slugs/ft^3		
density sediment	$_s$	2650	kg/m^3	0.00194	5.15	slugs/ft^3		
relative density	s	2.65	dimensionless		2.65	dimensionless		
shear stress		11.3	N/m^2		0.237	lb$_f$/ft^2		
dimensionless parameter	Ψ	32.85			32.86			
bed-load transport (Meyer-Peter)	Φ	#NUM!			#NUM!			
	q_s	**#NUM!**	m^2/s		**#NUM!**	ft^2/s	#NUM!	m^2/s
bed-load transport (Einstein$_{42}$)	Φ	0.000			0.000			
	q_s	**0.0000001**	m^2/s		**0.00000**	ft^2/s	7.93E-08	m^2/s
bed-load transport (Einstein$_{50}$)	Φ	FALSE			FALSE			
	q_s	**0.00000**	m^2/s		**0.00000**	ft^2/s	0	m^2/s
Ackers and White	n	0.029			0.029			
	U	1.12	m/s		3.68	ft/s		
	q_b	**#NUM!**	m^2/s		**#NUM!**	ft^2/s	#NUM!	m^2/s