Little Rock Lake Nutrient TMDL

Prepared by

Benton Soil and Water Conservation District

In cooperation with:
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Prepared for
Minnesota Pollution Control Agency

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wq-iw8-31e

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Units

Units	Definition	Conversions
hm^3	cubic hectometer	10^6 m^3 or 810 acre-feet
km^2	square kilometer	0.39 mi^2 or 247 acres
ppb	parts per billion	1 microgram per liter
m	meter	3.28 feet
kg	kilogram	2.2 pounds
mt	metric ton	1000 kg or 2200 lbs
AU	animal unit	1000 lbs live animal weight ~ 1 dairy cow

TMDL Summary Table

(to be included in report preceding executive summary)

EPA/MPCA Required Elements	Summary	TMDL Report Section
Location	Lower portion of the Little Rock Watershed, in Benton County, approximately ten miles North of St. Cloud, Minnesota in the Upper Mississippi River Basin.	Section 1
303(d) Listing Information	Little Rock Lake, 05-0013-00, was added to the 303(d) list in 2008 due to excess nutrients causing impaired aquatic recreation, class 2B waters, as set forth in Minnesota Rules 7050.0150. Little Rock Lake was prioritized to start in 2008 and be completed in 2012, with the original listing year of 2008.	Section 1
Applicable Water Quality Standards/ Numeric Targets	Minnesota Chapter 7050 sets forth criteria for applicable water quality standards. The Eutrophication standards are total phosphorus less than or equal to 60 µg/L, chlorophyll-a less than or equal to 20 µg/L, and secchi depth not less than 1.0 meter. Little Rock Lake's numeric target is a total phosphorus concentration of 60 µg/L, also known as 60 ppb.	Section 2.3
Loading Capacity (expressed as daily load)	The loading capacity is the total maximum daily load for phosphorus in the Little Rock Lake during critical conditions, summer growing season, and is displayed in Table 6. Total Maximum Daily Total Phosphorus Load (kg/day): 13.2	Section 2.4, 2.5, 2.6

<table>
<tr>
<td>Waste Load Allocation</td>
<td>The following are Concentrated Animal Feeding Operations (CAFO, over 1,000 animal units) permitted sources in the Little Rock Watershed:

<table>
<tr><td>CAFO Permit Number</td><td>Permitted Load Amount</td></tr>
<tr><td>MNG440950</td><td>0</td></tr>
<tr><td>MNG441098</td><td>0</td></tr>
</table>

The following Municipal Separate Storm Sewer Systems are covered under Minnesota General Permit MNR040000.
Watab Township: ID = MS400161
Benton County: ID = MS400067
MnDOT Outstate: ID = MS400180
These MS4s are given a categorical WLA of 0.5 kg/day.

Construction Stormwater is given a WLA of 2 kg per year (0.008kg per day).</td>
<td>Section 2.6.2, Table 6</td>
</tr>
<tr>
<td>Load Allocation</td>
<td>The portion of the loading capacity allocated to existing nonpoint sources.

<table>
<tr><td>Source</td><td>Load Allocation (kg/day)</td></tr>
<tr><td>Lake Inflows
LR Creek – CH 12
Zuleger
Sucker
Total Gauged (includes WLA)</td><td>7.0
2.0
1.0
10.5</td></tr>
<tr><td>Lakeshed
Total Watershed</td><td>2.3
12.8</td></tr>
<tr><td>Shoreland Septic Tanks
Total External
Rainfall
Total Inflow</td><td>0
12.8
0.4
13.2</td></tr>
</table></td>
<td>Section 2.6.1, Table 6</td>
</tr>
<tr>
<td>Margin of Safety</td>
<td>An implicit Margin of Safety was used to provide assurance that the lake water quality standards will be achieved.</td>
<td>Section 2.8</td>
</tr>
</table>

Seasonal Variation	Seasonal variation is provided given the strong correlation between chlorophyll-a and TP levels across individual sampling events. The lake TP concentrations achieved under TMDL conditions would provide significant reductions in the magnitude and frequency of extreme algal blooms. Considerations of seasonal variations in water quality and critical conditions associated with severe mid-summer algal blooms and resulting use impairment are embedded in the derivation of the 60 µg/L Total Phosphorus standard.	Section 2.7
Reasonable Assurance	Reasonable assurance is provided by a combined effort of Benton and Morrison Soil and Water Conservation Districts, local government units that manage and direct natural resources management programs at the local level.	Section 3.0
Monitoring	The monitoring plan for Little Rock Lake suggests integrating the monitoring plan for Little Rock Creek (LRC), the MPCA's Citizens Monitoring Program and the Minnesota DNR survey of fish and vegetation with a similar design to the monitoring of Little Rock Lake in 2008.	Section 2.9
Implementation	This TMDL proposed an adaptive implementation plan with a wide range of implementation strategies. The final implementation plan will be a part of a master plan to address all TMDLs in the Little Rock Watershed. The estimated cost of implementation is 5.21 million dollars.	Section 2.9
Public Participation	Public Meetings Technical Advisory Committee Little Rock Watershed Stakeholder Committee Public Comment period Comments received	Section 4

Executive Summary

Little Rock Lake was listed as an impaired water by the Minnesota Pollution Control Agency (MPCA) on the 2008 303 (d) list. This Total Maximum Daily Load (TMDL) study addresses an excessive nutrient impairment in Little Rock Lake. The goal of this TMDL is to quantify the phosphorus reduction needed to meet Minnesota's water quality standards in accordance with section 303(d) of the Clean Water Act.

Little Rock Lake is located in western Benton County. It lies within the North Central Hardwood Forest Ecoregion. The 67,650 acre watershed is nearly evenly split between Benton (36,030 acres) and Morrison (31,620 acres) Counties. The watershed land use is predominately row crops, with some woodland, grass/pasture and wetlands. Historically, Little Rock Lake resembled more of a wetland, but with the installation of the Sartell Dam in 1911, water levels were raised approximately seven feet. Today, Little Rock Lake's surface area is approximately 1,270 acres and is classified as a shallow lake. Little Rock Lake has a high value both as a recreational and shoreline development for it is one of two recreational lakes in Benton County.

Little Rock Lake is impaired primarily by non point pollutant sources. There are two individual permitted Concentrated Animal Feeding Operations (CAFO), over 1,000 animal units, within the watershed (permit numbers MNG440950 & MNG441098), however both permits are written to zero for phosphorus allowance. Regulated portions of Watab Township, the Minnesota Department of Transportation (MnDOT Outstate) and Benton County cover a small part of the watershed. These Municipal Separate Storm Sewer Systems (MS4s) received a wasteload allocation (WLA) of 0.5 kg/day. Construction stormwater has a WLA of 2 kg/year (0.008 kg/day).

The daily average nutrient load reduction of 13.2 kg/day (29.10 lb/day) would be required to meet Minnesota's water quality standard for shallow lakes in the North Central Hardwood Forest Ecoregion. Load reductions relative to the baseline range from 54 to 69% for the individual tributaries discharging directly into the lake. A combination of external and internal implementation strategies are recommended for the restoration of Little Rock Lake, beginning with emphasis on external sources. Continued monitoring is essential to track Little Rock Lake's responses to implementation of phosphorus loading controls and to ensure improving water quality in Little Rock Lake.

The Little Rock Lake TMDL study was conducted by Benton Soil and Water Conservation District with cooperation from William W. Walker, Jr, Ph.D. William Walker constructed a report titled Development of Phosphorus TMDL for Little Rock Lake, Minnesota. Walker's entire report is included in this TMDL report as sections 2 and 5.

1.0 Introduction

1.1 Purpose

This Total Maximum Daily Load (TMDL) study addresses an excessive nutrient impairment in Little Rock Lake (LRL). The goal of this TMDL is to quantify the phosphorus reduction needed to meet Minnesota's water quality standards in accordance with section 303(d) of the Clean Water Act. Phosphorus reduction strategies will be developed and presented in the associated implementation Plan.

LA (s) + WLA (s) + Margin of Safety + Reserve Capacity = Total Maximum Daily Load

Where:
LA= Load allocation from nonpoint sources
WLA= Waste load allocations from point sources
Margin of Safety= to account for potential scientific error
Reserve Capacity= set aside for future development

This TMDL provides allocations for Little Rock Lake. This TMDL is based on Minnesota's current eutrophication water quality standard for shallow lakes, in the North Central Hardwood Forest Ecoregion (NCHF), total phosphorus less than or equal to 60 µg/L, chlorophyll-a less than or equal to 20 µg/L, and secchi depth not less than 1.0 meter (MN Rules 7050.0222).

Note that 60 µg/L is the same as 60 ppb and is used interchangeably throughout this document.

1.2 Problem Statement

In 2008, Little Rock Lake was placed on the 303(d) list of impaired waters for aquatic recreation due to elevated nutrient levels. Little Rock Lake is a Class 2B water of the state. Designated beneficial uses for this class of water include supporting aesthetic enjoyment and navigation. Phosphorus levels exceeded the 60 µg/L North Central Hardwood Forest Ecoregion phosphorus standards for shallow lakes. The following is an excerpt from Minnesota State Chapter 7050 providing a formal definition of a shallow lake.

> "Shallow lake" means an enclosed basin filled or partially filled with standing fresh water with a maximum depth of 15 feet or less or with 80 percent or more of the lake area shallow enough to support emergent and submerged rooted aquatic plants (the littoral zone). It is uncommon for shallow lakes to thermally stratify during the summer. The quality of shallow lakes will permit the propagation and maintenance of a healthy indigenous aquatic community and they will be suitable for boating and other forms of aquatic recreation for which they may be usable.

Little Rock Lake has been the subject of numerous water quality investigations since 1971. The determination of this impairment was derivative of the following:

- 1971 investigational report
- 1990 Lake Assessment (LAP) study
- Little Rock Lake Data Gathering Project completed by Benton Soil and Water Conservation District in 2001
- Hydrologic and Hydraulic Analysis of Lake Levels and Outflow Rates study conducted by Minnesota Department of Natural Resources Waters (DNR) in 2003
- MN Outdoor Corps collection and analysis of water samples tested for total orthophosphate, total phosphorus, and chlorophyll-A
- AQUAtech completed Little Rock Lake Inlet Study on five sites gathering baseline data on the nutrient levels of the north inlets to Little Rock Lake
- 2006 and 2007 Benton SWCD collected water samples and data on the lake and tested for total orthophosphate, total phosphorus and chlorophyll-A.
- Data from Citizen Lake Monitoring Program (CLMP)

Due to the large blue-green algae bloom in 2007, the public demanded that Little Rock Lake be listed as an impaired waterbody and that a TMDL study be completed. The Little Rock Lake nutrient TMDL was then scheduled to begin in 2008 with completion by 2012.

1.3 General Background

Little Rock Lake (Hydrologic Unit Code 07010201) is located in western Benton County, approximately 10 miles north of St. Cloud Minnesota (Map 1). The Minnesota Department of Natural Resources (MN DNR) lake identification number for Little Rock Lake is 05-0013-00. It is in the North Central Hardwood Forests Ecoregion, within the [Mississippi River (Sartell)] Platte-Spunk sub-basin (Figure 1). The terrain varies from rolling hills to smaller plains, upland areas are forested by hardwoods and conifers; plains include livestock, hay fields and row crops.

Figure 1 Little Rock Watershed Location

In 2007, Little Rock Lake experienced a large blue-green algae bloom, raising the concerns of landowners in the area. In response to the large blue-green algae bloom in 2007 and the rising concerns of landowners, algae samples were collected by MPCA and it was determined that the algae toxin levels were 120 parts per billion (ppb), which falls into the high risk category, according to the World Health Organization standards (State of MN Office Memorandum, 2007), displayed in Table 1. The full State of Minnesota Office Memorandum of 2007 can be found in Appendix A.

Table 1 World Health Organization Algae Standards

Level (ppb)	Risk
0.075 – 1.0	Very Low
1.0 – 10.0	Low
10.0 – 20.0	Moderate
20.0 – 2000.0	High
> 2000.0	Very High

Certain forms of blue-green algae have the ability to produce toxins. The most common toxin found is microcystin. Microcystin is a hepatotoxin, a toxic chemical substance that damages the liver. People and animals can get ill from microcystin toxins if they come in direct contact with a blue green algae bloom. People are advised to avoid swimming, wading, or playing in lake water that appears covered with scum or blue-green algae if a bloom has recently occurred. People are advised to avoid drinking or swallowing recreational water from lakes, streams and other surface waters that are contaminated. It is also advised not to irrigate lawns or gardens with lake water that appears covered with scum or blue-green algae or recently after a blue green algae bloom (Iowa Department of Public Health).

Historically, algae blooms occurred regularly in the lake, including toxic blue-green algae. Little Rock Lake was determined to be impaired for aquatic recreation due to nutrient/eutrophication biological indicators and included on the MPCA 303(d) Impaired Waters List in 2008. The Little Rock Lake TMDL project began in 2008 and is scheduled to be completed in 2012

The Little Rock Lake Nutrient TMDL Project combines the data collected from the ongoing Little Rock Creek (LRC) Biological TMDL Phase II Study, which was completed September 2009 (started in June 2006). Little Rock Creek, one of five tributaries to Little Rock Lake, is a designated trout stream, and is currently the subject of a biological TMDL study to determine the cause of an impaired fish community.

1.4 Lake Description

Little Rock Lake's unique history begins around 12,000 years ago. At that time, Minnesota was covered by glaciers that deposited glacial till consisting of clays and rocks. The Superior and Des Moines glacial lobes were the last glacial event to affect the area around Little Rock Lake. As these glaciers melted, they released vast quantities of water. With such a high discharge of water, sediment was carried downstream through the ancient Mississippi River, which at one time was up to eight miles wide. The present-day Mississippi River ranges from one quarter to one mile wide. Little Rock Lake rests on an abandoned river terrace, which is an area of land that once was a riverbed. The bottom of these old rivers consisted of sands and gravels. This is why Little Rock Lake and the western half of its watershed consist of primarily sandy soils. Sands and gravels have a high porosity so water can percolate through these materials easily with little runoff. The headwaters of Little Rock Lake's tributaries are located in the east portion of the watershed and are not part of the old river terrace. This area is a 'drumlin field' consisting of glacial till deposited as rolling hills created by glaciers moving across the landscape. Glacial till is made up of mostly silts and clays, which do not allow water to easily percolate through the soil. Knowing this, greater amounts of surface runoff are expected to occur in the eastern part of the watershed when compared to the sandier western portion.

The glaciers melted away, and the rivers of water formed by the melting glaciers all but disappeared. The water in Little Rock Lake began eroding the shorelines as wave action began to work on the shoreline. After a period of time, the water and the soil around the lake reached equilibrium, e.g. the erosivity of the wave action was matched by the resistance to erosion of the lakeshore now that the slope of the shoreline was reduced and vegetation began to grow. The original lake was shallow, most likely resembling a marsh wetland more than a lake, and possibly had large amounts of emergent and submergent aquatic vegetation present (Garrison & LaLiberte, 2009). This shallow lake, or wetland, existed until 1911when the Watab Pulp and Paper Company completed construction of a 21 foot high dam on the Mississippi River. This dam, known as the "Sartell Dam" existed until the 1960's when it was rebuilt. This dam, although three miles downstream and on the Mississippi River, backed up the water into the already existing Little Rock Lake. The lake freely exchanges water with the Mississippi River, through what is called the 'Little Rock Channel,' 'No Name Lake,' or 'Harris Channel.' The water level in Little Rock Lake was raised approximately seven feet by the installation of the dam. This introduced new in-lake dynamics, created a new shoreline and destabilized a system that was once at equilibrium. The lake has not yet reached a new state of equilibrium after only 94 years of existence. It is uncertain when this system will again reach a state of equilibrium (Heiskary, 1991).

Today, Little Rock Lake has an approximate surface area of 1,270 acres and is in the upper 25 percent of the lakes in the state, in terms of surface area (lake map w/ contours). It is a very shallow lake, with a mean depth of about eight feet and a maximum depth of 17 feet. The littoral zone, (less than 15 feet in depth) covers approximately 1219 acres or 96% of the surface area. The total length of the shoreline around the lake is 15.7 miles. The 67,648 acre watershed is nearly evenly split between Benton (36,030 acres) and Morrison (31,620 acres) counties. The resulting watershed to lake surface area is relatively large at 53:1. The fetch is approximately 2 miles long. The estimated water residence time is 0.3 to 0.5 years (Heiskary, 1991) (Table 2).

Table 2 Morphometric and Watershed Characteristics

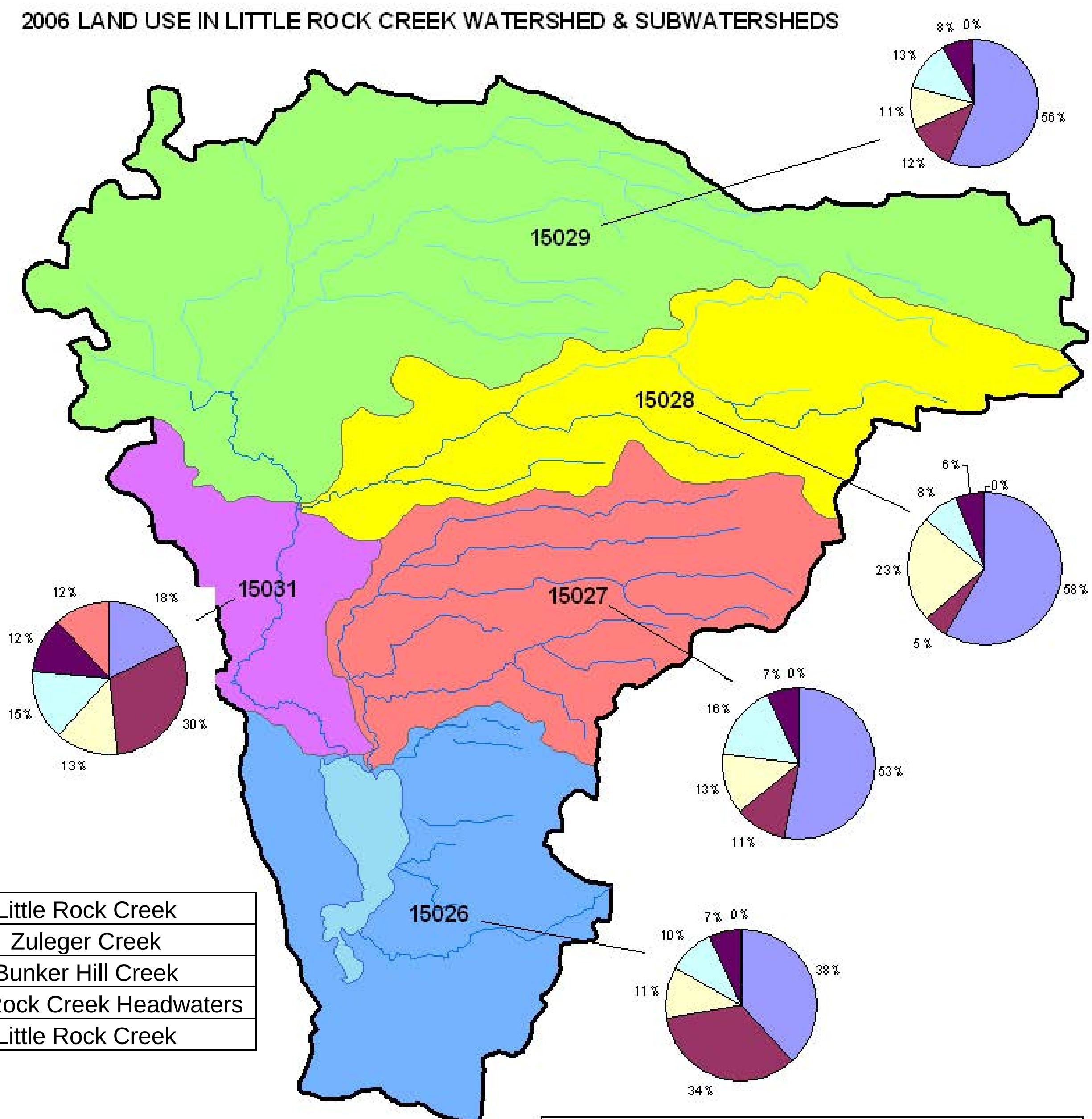
Morphometric and Watershed Characteristics	Data	Shallow Lake Standards
Area (lake)	1270 acres	N/A
Mean Depth	7.9 feet	
Maximum Depth	17.0 feet	15 feet or less
Littoral Zone	96%	80% or more
Volume	10,084 acre-feet	N/A
Fetch	2 miles	Fetch is variable depending on size and shape
Watershed area	67,648 acres	N/A
Watershed: Lake surface ratio	53:1	N/A
Estimated average water residence time	0.3 to 0.5 years	N/A
Total Phosphorus (ppb)**	<u>1979 – 2003</u> 116 - 179 <u>2006 - 2008</u> 202 – 315	60 or less
Chlorophyll Mean (ppb)**	<u>1979 - 2003</u> 69 - 90 <u>2006 - 2008</u> 114 – 227	20 or less
Secchi Disk (meters)	<u>1979 – 2003</u> 0.5 – 1.1 <u>2006 - 2008</u> 0.3 - 0.6	1.0 or more

*Shallow Lake Standards taken from MPCA Lake Nutrient TMDL Protocols and Submittal Requirements, March 2007 and MN Rules 7050.0222
**Note: ppb= µg/L

1.5 Land Cover/Use

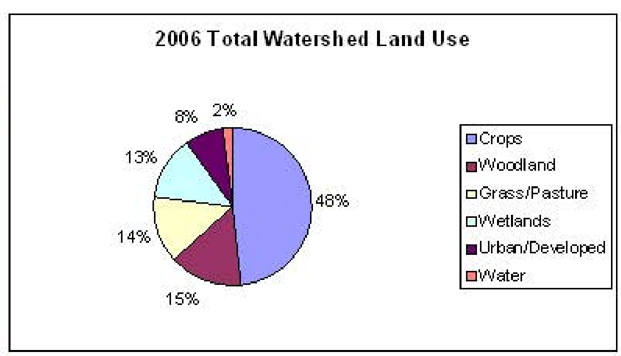
According to the National Agricultural Statistical Service, in 2006 the land use in the watershed consisted of 48% crops, 15% woodland, 14% grass/pasture, 13% wetlands, 8% urban development, and 2% water (Figure 2). Figure 2 subwatershed boundaries only apply to land use they are not representative of boundaries described in Table 6. Animal agriculture operations within this watershed include poultry, hog, and dairy operations. Due to the predominance of sandy soils in the western half of the watershed, many croplands are irrigated. Irrigated cash crops consist of corn, soybeans, rye, wheat, potatoes, and kidney beans.

Figure 2 2006 Watershed Land Use



15026	Little Rock Creek
15027	Zuleger Creek
15028	Bunker Hill Creek
15029	Little Rock Creek Headwaters
15031	Little Rock Creek

	Land Cover Type	% Total Watershed	% Subwatershed 15026	15027	15028	15029	15031
CROPS	Corn	33	31	33	43	39	13
	Alfalfa	6	0	7	8	7	2
	Winter Wheat	0	0	0	0	0	0
	Spring Wheat	0	1	1	0	0	0
	Soybeans	9	4	12	7	10	3
	Rye	0	0	0	0	0	0
	Potatoes	0	2	0	0	0	0
	Oats	0	0	0	0	0	0
OTHER	Woodland	15	34	11	5	12	30
	Wetlands	13	10	16	8	13	15
	Water	2	0	0	0	0	12
	Urban/Developed	8	7	7	6	8	12
	Grass/Pasture	14	11	13	23	11	13
	Shrubland	0	0	0	0	0	0



Little Rock Lake is one of two recreational lakes in Benton County. Thus it is has a high value both as a recreational water and shoreline development. Many of the "summer cabins" around the lake are being replaced by year-round residences. Table 3 illustrates 2008 resident and seasonal Parcel numbers provided by Benton County Department of Development.

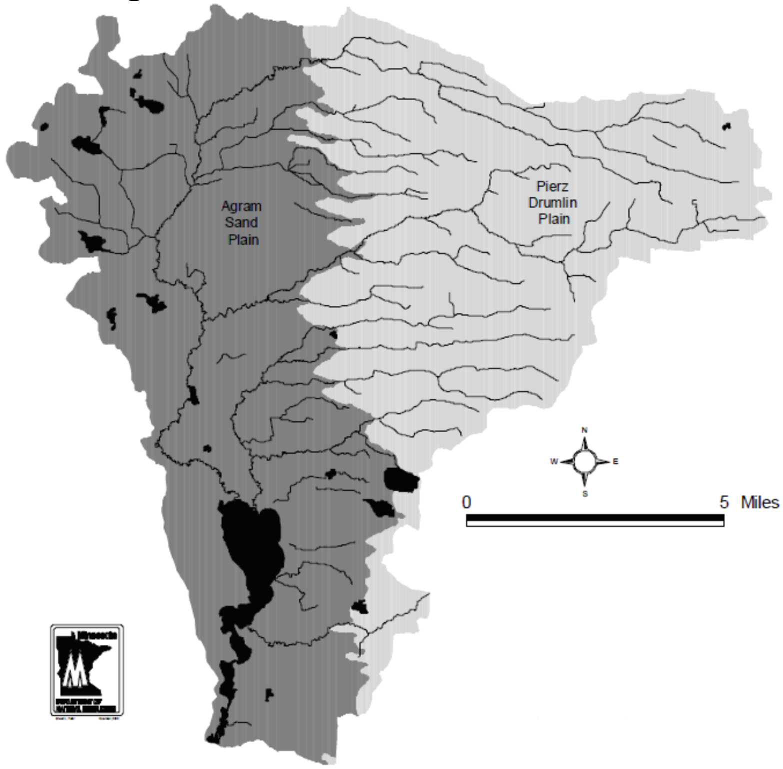
Table 3 Lakeshore Parcels

Residential Parcels	**Seasonal Parcels**
200 with buildings	95 with buildings
60 bare land	28 bare land
Residential Parcel Total: 260	Seasonal Parcel Total: 123
Grand Total Parcels: 383	

1.5.1 Soils

The watershed has alluvial soils made up predominantly of fine sands. The topography is flat to gently rolling. Most of the watershed is in the Agram Sand Plain (37,799 acres) and the Pierz Drumlin Plain (31,322 acres) (Figure 3). A very small part of the watershed near the Little Rock Lake outlet is in the Mississippi Sand Plain (less than 4 acres) (Figure 3).

Figure 3 Little Rock Lake Watershed Soils



1.6 Source Assessment

The reality is that there are many sources of any single pollutant within a watershed. Little Rock Lake Watershed is no exception to that reality. Sources of phosphorus are spread throughout the watershed. Phosphorus occurs naturally in rocks, soil, animal waste, plant material and even the atmosphere. However, human activity has dramatically increased the amount of phosphorus released into the environment (CCME, 2009). Currently, there is not sufficient data to provide a quantifiable source assessment. However, a source assessment based on general knowledge can be provided as follows: Sources of phosphorus include: internal loading, septic loads, greywater, direct lakeshed runoff, streambank/shoreline erosion, runoff from the agricultural land uses (livestock, row-crop) as well as practices that might worsen pollutant delivery such as row-crop, tiling, winter manure application, and impervious surfaces.

Agricultural land use is dominant in the Little Rock Lake watershed. Animal unit densities are high in proportion to acres giving a high manure production/acre ratio. Spring runoff is a high concern in the Little Rock Lake Watershed, high levels of fecal coliforms, BOD, ammonia-N, Kjeldahl-N, Total P, and soluble reactive P were located A more detailed assessment of agricultural animal components can be located in section 2.9

Little Rock Lake lakeshed agricultural land use is low, but the percentage of development is moderate. Urban development sources of concern are greywater, septic system loads, impervious surfaces, and urban runoff. The relative importance of sources depends upon location in the watershed and the source itself. Septic systems, greywater, and impervious surfaces are a larger concern in the lakeshed compared to in tributary subwatersheds. Winter manure application, row-crop, and livestock directly on tributaries and waterways are of a higher concern than not along a waterway.

1.7 Monitoring Data

In lake monitoring data are available sporadically from 1976 through 2009. Based on water quality data collected between 1999 and 2008, Little Rock Lake is hypereutrophic and highly degraded, with an average Carlson's Trophic Status (TSI) of 74 (total phosphorus 80 ppb, chlorophyll 77 ppb, Secchi disk 0.7 meters). The concept of trophic status is based on the fact that changes in nutrient levels (measured by total phosphorus) causes changes in algal biomass (measured by chlorophyll a) which in turn causes changes in lake clarity (measured by Secchi disk transparency) (EPA, Carlson's Trophic State Index).

1.8 Fish Community Data

According to Minnesota Department of Natural Resources website (http://www.dnr.state.mn.us/lakefind/showreport.html?downum=05001300), Little Rock Lake's history of severe algae blooms has an effect on the fish community along with the wide connection to the Mississippi River. Table 4 is an excerpt from the MN DNR's website cited above, demonstrating the diversity of Little Rock Lake's fish community.

Table 4 Fish Sampled in Little Rock Lake for the 2008 Survey Year

Species	Number of fish per net	
	Caught	Normal Range
Bigmouth Buffalo	5.10	0.2 - 1.5
Black Bullhead	0.70	1.3 - 78.1
Black Crappie	11.40	1.0 - 12.3
Bluegill	2.60	1.0 - 14.9
Bowfin (dogfish)	0.50	0.1 - 0.7
Channel Catfish	0.50	N/A
Common Carp	3.50	0.7 - 5.1
Largemouth Bass	0.30	0.1 - 0.8
Northern Pike	0.50	N/A
Shorthead Redhorse	0.10	0.7 - 2.1
Silver Redhorse	2.60	N/A
Smallmouth Bass	0.10	N/A
Walleye	1.00	0.3 - 1.7
White Crappie	0.10	0.5 - 15.9
White Sucker	6.10	0.3 - 1.3
Yellow Bullhead	0.80	0.5 - 4.1
Yellow Perch	0.30	0.3 - 2.6

1.9 Plant Community

A lake management plan was created by MN DNR and Little Rock Lake Association members in 2007. The plan is in effect until January 1, 2011. Significant elements of the plan were related to water quality, land and water use and fisheries and aquatic vegetation. The MN DNR conducted a lakewide assessment of the vegetation in Little Rock Lake in May-June of 2005. The following is the summary excerpt from the Aquatic Vegetation of Little Rock Lake report; the full report can be located at http://www.dnr.state.mn.us/lakefind/results.html.

> Little Rock Lake is a shallow, nutrient rich lake in central Minnesota. Historically, this lake contained a relatively diverse, native aquatic plant community. Water clarity has declined over the decades and the lake experiences frequent summer algal blooms. An aquatic vegetation survey was conducted in May and June 2005 to assess the spring plant community. This survey focused on assessing curly-leaf pondweed, a non-native submerged plant that is most common in late Spring and early Summer.
>
> This survey included a lakewide assessment of vegetation and water depths at 311 sample stations. Plants were found to a depth of 13 feet but were most frequent in the 4 to 6 feet depth zone, where 87% of the sites contained plants. Lakewide, about 50% of the sites contained plants.
>
> The non-native submerged species, curly-leaf pondweed (*Potamogeton crispus*), was the most commonly occurring plant and was found in 44% of the sites. At most of the sites (34%) where curly-leaf was found, it was the only plant observed. Only 8% of the sites contained a mix of curly-leaf and native plants and only 6% of the sites contained only natives.
>
> Six native submerged plant species were found in the lake but only 14% of the sites contained native plants. The most common native plants were Canada waterweed (*Elodea canadensis*), narrow-leaf pondweed (*Potamogeton* sp.), sago pondweed (*Stuckenia pectinata*), and coontail (*Ceratophyllum demersum*). These are native species that are adapted to low water clarity. Native plants that require clear water are no longer found in the lake, or occur infrequently.

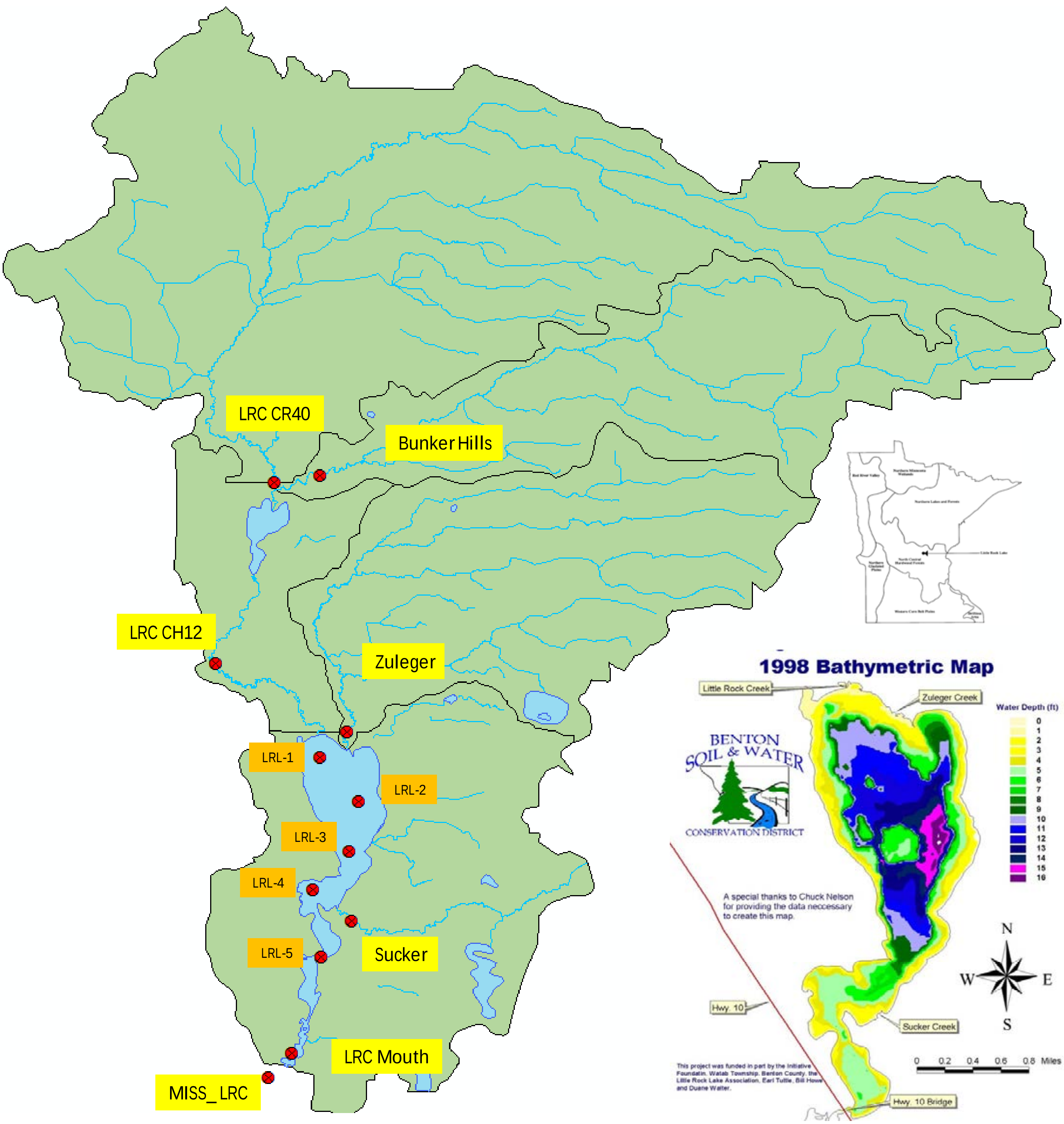
2.0 William Walker, Jr., Ph.D. Development of Phosphorus TMDL for Little Rock Lake, Minnesota

William W. Walker, Jr., Ph.D. prepared *Development of Phosphorus TMDL for Little Rock Lake, Minnesota* for Benton Soil and Water Conservation District. The following information is from William Walkers report with added information from Benton SWCD.

2.1 Introduction

Little Rock Lake (LRL, Figure 4) is a shallow hyper-eutrophic impoundment located in the Minnesota's North Central Hardwood Forest (NCHF) Ecoregion. It has a surface area of 1270 acres, mean depth of 17 feet, and total watershed area of 67,648 acres. Major watersheds include Little Rock Creek (LRC, 67%), Zuleger Creek (18%), Sucker Creek (4%), local drainage (lakeshed, 9%), and lake (2%). Outlines of subwatersheds are shown in Figure 2; however Figure 2 does not demonstrate the outline of the lakeshed. The lakeshed includes a small portion of the Little Rock Creek Watershed between the gauge and the lake (1.58 km^2) and the area draining directly into the lake (23.4 km^2) for a total of 25.2 km^2 which is also demonstrated in Table 6. Land uses include cropland (48%), grass/pasture (14%), urban (8%), woodland (15%), wetland (13%), and water (2%). The watershed contains 106 feedlots and 25 to 37 thousand Animal Units (1 AU = 1000 lbs live animal weight ~ 1 dairy cow) consisting of 26% dairy cattle, 12% beef cattle, 11% swine, and 51% poultry. There are approximately 260 residential parcels around the shoreline (Table 3). Considerable erosion in the watershed is indicated by sand deposits in stream channels and at points of discharge into the lake. BSWCD (2009) provides detailed information on the watershed characteristics that impact flow, ecological habitat, and nutrient loads.

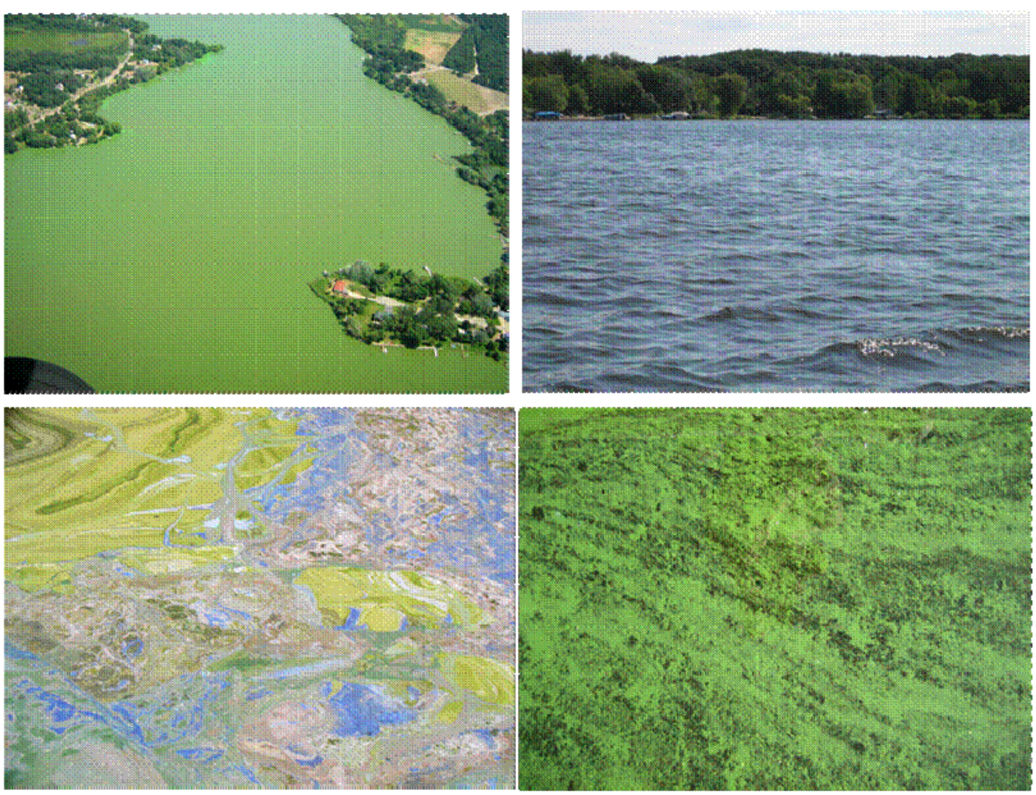
Figure 4 Little Rock Lake & Watershed Monitoring Sites in 2008



Originally a wetland, the lake basin was formed in 1911 when a dam was constructed on the Mississippi River downstream of the Little Rock Creek (LRC) outlet. Water levels were further raised in 1934 and Little Rock Lake (LRL) evolved from a vegetated marsh to turbid impoundment (Ford et al, 2003; Garrison & LaLiberte, 2009). Major flooding events on the Mississippi River and dam operation have increased both the mean and the variability of lake water levels, although typical seasonal and year-to-year variations in water level are driven primarily by runoff from the LRL watershed (Ford et al., 2003). Shoreline areas are subject to erosion as a consequence of variability in water levels, wind-driven currents, and local runoff.

While it supports an abundant fishery, LRL has extremely high nutrient (phosphorus, P) concentrations that support severe algal blooms (Figure 5). As a result, the lake does not meet nutrient water quality standards established by the Minnesota Pollution Control Agency to support its designated beneficial uses, particularly with respect to aesthetics and recreation (Heiskary & Wilson, 2005; 2008), as listed in the MPCA water quality standards MN Rule CH 7050: "Class 2B, aquatic life use". Toxic bluegreen algal blooms (Figure 5, lower left), anaerobic conditions, and noxious odors resulting from atmospheric releases of hydrogen sulfide were observed in 2007 (Lindon et al, 2007). These conditions were associated with extremely high phosphorus concentrations in spring runoff (>500 ppb) and a relatively dry and warm summer.

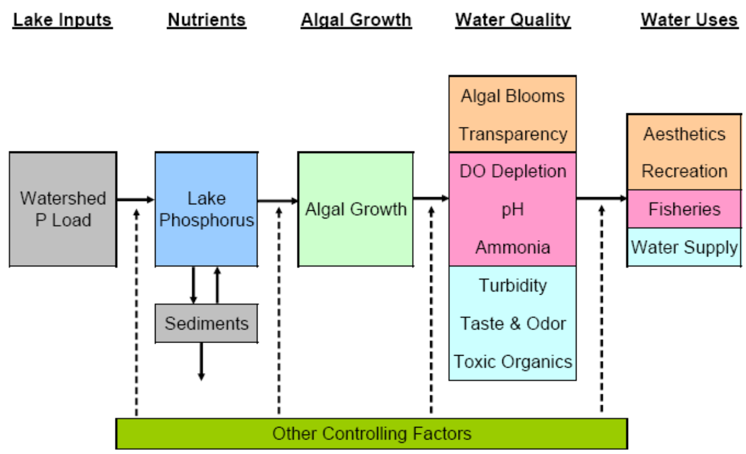
Figure 5 LRL Photos



LRL Photos taken from various perspectives in 2007 (left) and 2008 (right)

Figure 6 shows cause-effect pathways linking algal blooms to impairment in water quality and water uses. While highly variable depending on such factors as season, hydrology, and climate, algal blooms in eutrophic lakes are ultimately triggered by external phosphorus loads that are stored and recycled between the water column and bottom sediments (Sondergaard et al., 1999, 2005; Hakanson, 2004; Scheffer, 2004). Hyper-eutrophic conditions are not unusual in shallow lakes with large agricultural watersheds; depending on the extent to which phosphorus sources (animal waste, fertilizer, and crop residues) are effectively managed (Schippers et al, 2006; Sharpley et al., 2003, 2006; NRDC, 2010).

Figure 6 Causal Pathways Linking TP Load to Lake Water Quality & Uses



The Clean Water Act requires development and implementation of a plan to reduce watershed nutrient loads sufficiently to achieve water quality standards. The “Total Maximum Daily Load” (TMDL) regulations provide a framework for this process (USEPA, 2009; MPCA, 2009). The TMDL is essentially the assimilative capacity of the lake, or the amount of load that it can accept without exceeding water quality standards. Despite the reference to “daily load” in the regulations, lake phosphorus TMDLs are typically formulated on long-term-average time scales that govern lake water quality responses to nutrient loads and are consistent with derivation of the standards as long-term summer means (Heiskary & Wilson, 2008; Walker, 2003).

Table 5 compares historical LRL water quality conditions with the designated lake standards for shallow lakes in the NCHF ecoregion of Minnesota. Comparisons of 1979-2003 with 2006-2008 data indicate significant long-term increases in total phosphorus (TP) and chlorophyll-a (Chl-a, measure of algal density) concentrations, as well as decreases in transparency (Secchi depth). While causal factors responsible for the historical trends are difficult to evaluate because of data limitations and climatologic variations described below, it is clear that significant reductions in phosphorus loads and lake concentrations are needed to meet the standards.

Table 5 Observed Water Quality vs. Shallow Lake Standards

	Standard	1979-2003	2006-2008
Total P (ppb)	< 60	116 - 179	202 - 315
Chl-a (ppb)	< 20	69 - 90	114 - 227
Secchi Depth (m)	> 1	0.5 - 1.1	0.3 - 0.6

This report describes development of a TMDL estimate using a mathematical model that links external phosphorus load to the 60 ppb (µg/L) lake target (Figure 6). The term "estimate" reflects the uncertainty commonly associated with predicting lake responses to P load reduction, particularly in shallow hyper-eutrophic impoundments (Heiskary & Lindon, 2005). Data limitations preclude development of relatively complex dynamic mass-balance models used in other TMDL assessments for other shallow lakes supported by ten or more years of data (Walker, 2000ab; 2001; 2009; Walker & Havens, 2003). Sufficient site-specific and regional data exist to support estimation of the TMDL using relatively simple, empirical models calibrated to data from other lakes (Canfield & Bachman, 1981; Wilson & Walker, 1988; Heiskary & Wilson, 2008). Despite uncertainties, the TMDL estimate provides an explicit goal that can be refined in the future as additional data are collected, load reductions are achieved, and lake responses are measured.

The TMDL development and supporting data analyses are described in the following sections:

- Data Sources
- Water Quality Standards
- Lake Water Quality Conditions
- Water and Mass Balances
- TMDL Derivation
- Spatial and Temporal Variations
- Margin of Safety
- TMDL Implementation
- Conclusions
- References

Appendix B contains supporting computations, data summaries, data displays, and related information on shallow lake P dynamics derived from the literature reviewed in the course of developing the TMDL model.

2.2 Data Sources

The following data and reports provide information for developing the TMDL and for tracking changes in the lake and tributaries as P loading controls are implemented:

- Watershed and lake water quality monitoring data collected by Benton County Soil and Water District in 2006-2008 to support development of TMDLs for the lake and tributaries (BSWCD, 2008; 2009).

- Streamflow and lake water level monitoring conducted by MPCA in 2006-2009.

- Water quality data from diagnostic studies performed by MPCA (1974) and Heiskary (1991).

- Transparency and user perception data collected in various years between 1990 and 2008 under the statewide Citizens Monitoring Program (MPCA, 2009b).

- Regional precipitation, runoff, and air temperature data compiled from internet sources.

- Measurements of sediment characteristics and phosphorus release rates at several lake stations in 2008 (James, 2008).

- A sediment core study conducted in 2008 to document historical conditions and estimate sediment accumulation rates at the deepest point in the lake (Garrison & LaLiberte, 2009).

- GIS data layers (land use, hydrography, land elevation, soil types, feedlots) derived from statewide databases.

- Analysis of historical fluctuations in water levels, as controlled by water levels in the Mississippi River and runoff from the LRL watershed (Ford et al, 2003).

The lake and tributary water quality data are listed and displayed across various spatial and temporal dimensions in Appendix B.

Six lake sites located along the north-south axis were monitored between July and October of 2008 (Figure 4). The sampling design included field data (transparency and vertical profiles of dissolved oxygen, temperature, conductivity, pH, and turbidity) and 0-2 meter integrated samples analyzed for nutrients, chlorophyll-a, and inorganic chemistry at each site. Bottom samples were collected at the deepest point (Site 204, LRL-4). Limited water quality data from previous years (1979-1981, 1990, 2003, 2006, and 2007) were obtained from the MPCA (2009b) STORET database. Codes used to identify lake monitoring sites varied over the years and have been consolidated to reflect the basic downstream order (LRL-1 to LRL-6, Figure 4).

Tributary water quality data were collected at five tributary sites (two on Little Rock Creek, Bunker Hills, Zuleger, and Sucker) between May 2006 and October 2008 (Figure 4). The watershed sites were generally monitored biweekly with supplemental samples collected during high runoff periods. Two additional stream sites were located downstream of the lake at the confluence of Little Rock Creek and the Mississippi River. These sites were included in the 2008 survey design to provide a basis for evaluating the potential effects of phosphorus transport into LRL from the River as a result of backflow and/or dispersion. Under the 2006-2008 monitored conditions, the River functioned primarily as a "dam" for the lake, as opposed to a source of inflow. Hydraulic modeling results indicate that backflow has occurred during infrequent episodes of extremely high water levels in the River (Ford et al, 2003). While these events are likely to trigger shoreline erosion, backflow itself is not likely to represent a significant long-term source, based upon the fact that phosphorus concentrations in local runoff in 2006-2008 exceeded those measured in the River (see Appendix B).

The MPCA made daily streamflow measurements during the summer season starting in July 2006 and commencing in October 2009 at each site except Zuleger, where monitoring was infeasible due to backwater conditions from the lake. The streamflow measurements started in July 2006 and thus did not reflect the entire runoff season. Regression models were used to estimate missing flow data and provide a complete daily flow record for March-October of 2006-2009. Direct inflows to LRL from Little Rock and Sucker Creeks reflected ~71% of total watershed runoff. The remaining inflows were estimated based upon drainage area ratios relative to Little Rock Creek. Lake outflows were computed from the water budget (inflow + precipitation – evaporation – volume increase).

There is considerable uncertainty in characterizing the long-term-average phosphorus budgets and lake water quality conditions based on the 2006-2008 data collected to support development of the TMDL (Appendix B). The uncertainty results from data gaps, short period of record, and drought conditions. Tributary sampling did not capture early spring runoff periods in 2006 and 2008. LRC spring runoff peaked at 148 cfs in 2007 as compared with 583 cfs in 2009, when water quality sampling was not conducted. No data were available on tributary flows, P concentrations, or P loads prior to 2006. Because of relatively dry and warm summers, lake water quality conditions observed in 2006-2008 may not have been representative of long-term-average conditions under current watershed conditions and nutrient loading regimes. Because of P storage and recycling between the lake water column and sediments (Figure 6), it is likely that water quality conditions in 2006-2008 were impacted by phosphorus loads that occurred in previous years.

Despite the data limitations, sufficient site-specific and regional data exist to support TMDL estimation using relatively simple, empirical models calibrated to data from other lakes. Continued lake and watershed monitoring over the course of TMDL implementation will provide a basis for refining the water and phosphorus balances and tracking responses to implementation of phosphorus controls using an adaptive management strategy (Walker, 2003).

2.3 Water Quality Standards

Absent an approved site-specific standard, regulations require that the TMDL be formulated to meet the eutrophication standards with respect to TP, chlorophyll-a, and Secchi depth (MN Rule 7050.222). Heiskary and Lindon (2005) describe the derivation of the standard based upon regional lake datasets and considerations of the following factors:

- Correlations between TP concentration in Minnesota lakes with the following
    - Mean chlorophyll-a and frequency of nuisance algal blooms
    - Secchi depth (transparency)
    - User perceptions of aesthetic qualities and recreational potential
    - Fish populations and vegetation characteristics
- Comparisons with data from reference (minimally impacted) shallow lakes in the ecoregion
- Comparisons with estimates of TP concentrations under pre-settlement (1750-1900) conditions estimated from sediment core studies.
- Review of literature pertaining to effects of TP levels on algal blooms, vegetation, and fisheries.

The TMDL is derived to meet the eutrophication standards with respect to TP, chlorophyll-a, and Secchi depth by reducing the TP load sufficiently to meet each standard (MN Rule 7050.222). The following text (Heiskary & Lindon, 2005, p. iv) summarizes the objectives, rationale, assumptions, and caveats associated with derivation of the standards:

> *"This study did not develop a predictive model; rather we characterized linkages among nutrient concentration, algal abundance and composition, macrophyte (submergent and floating-leaf) composition and coverage, fishery composition and management and related factors based on a set of representative shallow lakes from across west central Minnesota. These linkages combined with region-wide patterns in lake trophic status (both pre-European and modern-day), user perception and literature review, provide a basis for establishing nutrient criteria to protect uses such as secondary contact (boating and aesthetics) and fish and waterfowl habitat.*
>
> *In summary, based on the various interrelationships among trophic status variables, rooted plant metrics and other considerations it appears that appropriate ranges for selecting eutrophication criteria values for shallow lakes in the NCHF ecoregion are:*
>
> - *Secchi transparency - greater than 0.7 to 1.0 meters;*
> - *Chlorophyll-a - less than 20 – 30 μg/L;*
> - *Total phosphorus – less than 60 – 80 μg/L;*
>
> *Given this range of values, and acknowledging that other biotic and abiotic factors can be very significant in determining whether a lake can support a healthy and diverse population of rooted macrophytes, we are inclined to*

recommend criteria be set at the lower end of each range of the aforementioned values, i.e. maintain summer average Secchi of 1.0 m or greater, summer average chlorophyll-a of 20 μg/L or lower, and summer average total phosphorus of 60 μg/L or lower. While we are not offering nitrogen criteria at this time, it would appear to be beneficial to keep TKN below 2.0 mg/L when possible. Based on the relationship between TP and TKN, maintaining TP below 60-80 μg/L should yield TKN <2.0 mg/L.

Maintaining values at or below these ranges will not absolutely ensure that a shallow lake will remain in a macrophyte-dominated state and support the various uses described for 2b & 2c waters (Minn. Rule Ch. 7050), but should reduce the likelihood that the lake will switch to an algal-dominated state, which is repeatedly noted in the literature can be rather hard to reverse once the change has occurred. Also, maintaining trophic status values at or below these ranges should decrease the likelihood that curly-leaf, a non-native species, will become dominant and further contribute to a shift towards algal dominance.

Lakes currently below the TP and chlorophyll-a thresholds should be protected against further increases in TP whenever possible because as these shallow lakes become increasingly nutrient-rich these nutrients will yield distinct increases in chlorophyll-a, which in turn will contribute to reduced transparency and increase the likelihood of a shift from plant-dominance to algal dominance. For lakes currently above these levels reducing TP to 60 μg/L or lower should result in reductions in chlorophyll-a and improved transparency. While this should increase the likelihood of a shift to plant dominance it cannot be guaranteed because of numerous biotic and abiotic factors noted in this study and in the literature on this topic.

The 60 ppb standard was set at the lower end of the 60-80 ppb range consistent with sustaining a plant-dominated ("clear-water") state as opposed to an algal-dominated (turbid) state. For enriched lakes similar to LRL that are already in the turbid category, achieving reductions in lake TP would be expected to provide reductions in algal density (chlorophyll-a) and increases in transparency. Sas (1989) noted significant reductions in bluegreen bloom frequencies at TP concentrations below 100 ppb. While a shift towards a plant-dominated state may occur at lower TP levels, there is no expectation that it would be complete. A partial shift to native vegetation species, as manifested by increased growth in the shoreline areas, for example, could be considered beneficial because it would improve fish habitat and help to stabilize bottom sediments. As noted by Heiskary and Lindon (2005), achieving reductions in TP levels could also reduce the risk of excessive growth of the exotic curly-leafed pondweed, which has been observed in portions of the lake (LRLA & MDNR, 2007). The derivation of the standard acknowledges that there is considerable uncertainty in forecasting the trajectory of hyper-eutrophic shallow lakes such as LRL to reductions in P load. The uncertainty can be addressed through adaptive implementation of the TMDL.

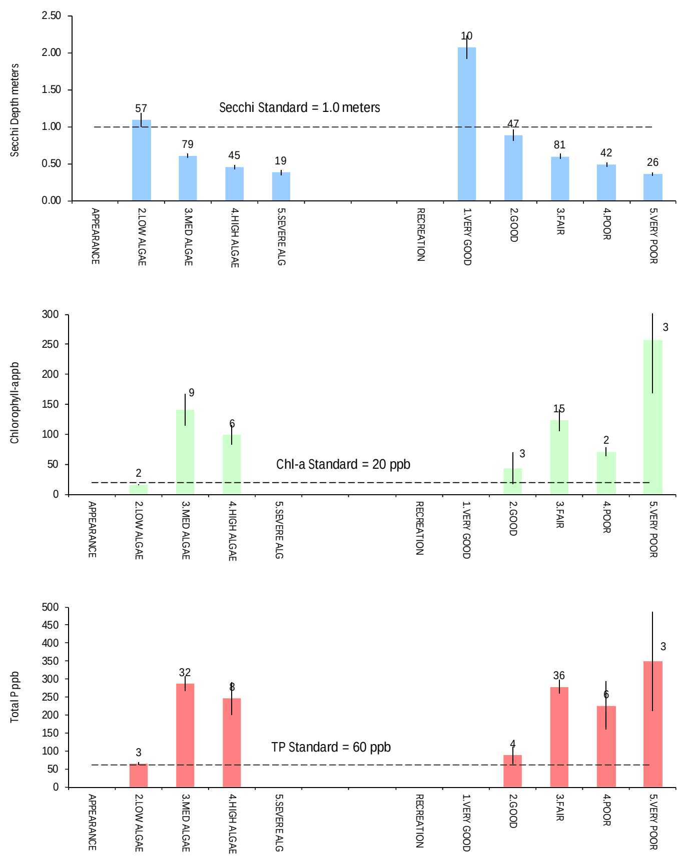
2.4 Lake Water Quality Conditions

LRL water quality and user survey data collected under MPCA's Citizen Lake Monitoring Program over the 1990-2008 period are summarized in Figure 7. Water quality data from each sampling event are paired with user perceptions of aesthetic quality and suitability for recreational uses (Heiskary & Walker, 1985). Survey results are expressed on a scale of 1 to 5 (generally, excellent to poor). On four sampling dates when recreational potential was ranked in the second category ("good"), the average TP concentration was 88 ± 24 ppb. On three days when the aesthetic quality was ranked in the second category ("low algae"), the average TP concentration was 64 ± 4 ppb. The user survey results are also reasonably consistent with the distributions of the chlorophyll-a and transparency data.

Figure 8 shows that phosphorus levels are highly correlated with chlorophyll-a levels and Secchi depths across individual sampling events. These correlations indicate that achieving incremental reductions in lake TP levels over the course of TMDL implementation would provide significant reductions in algal blooms that would be perceptible by lake users.

Figure 7 User Perceptions vs. Water Quality Measurements

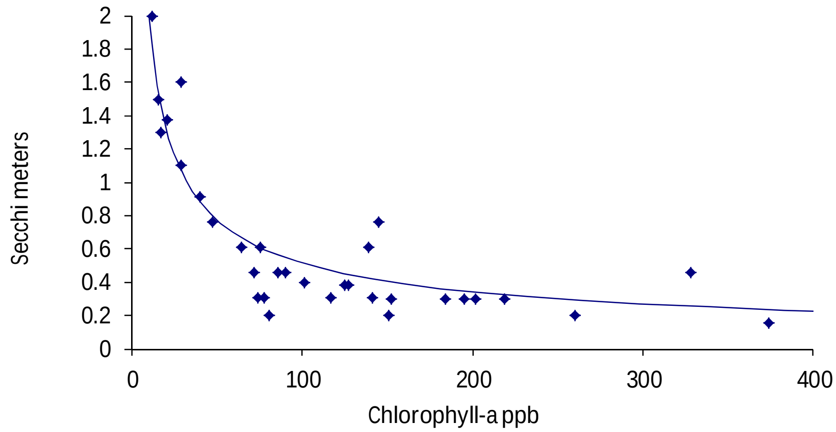
(Units: ppb = micrograms per liter (µg/L))

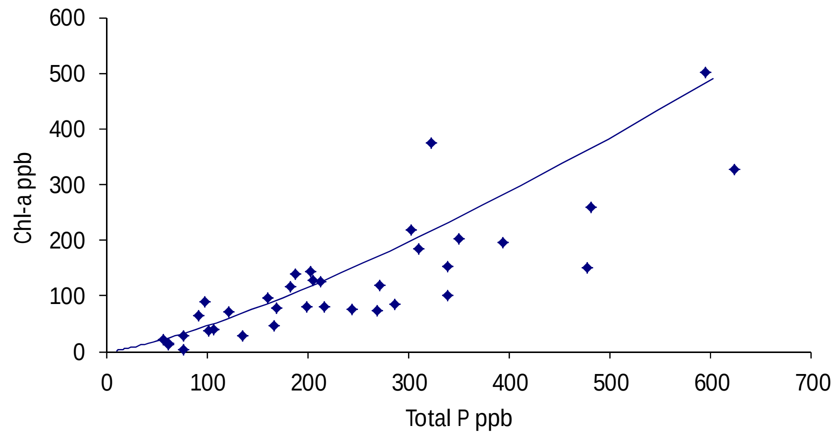


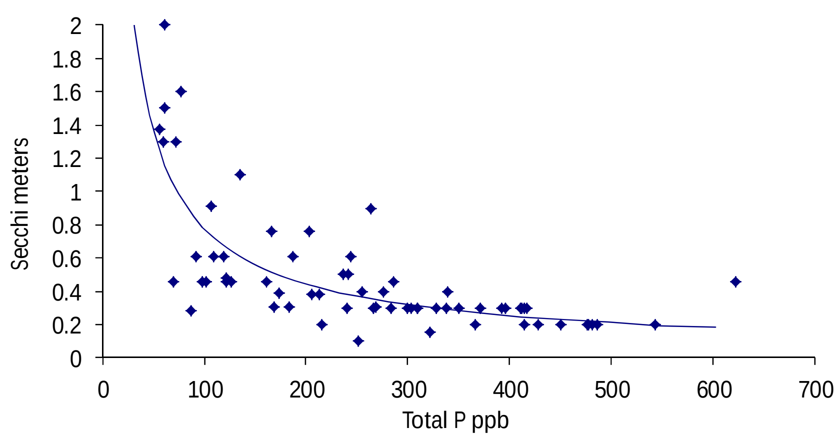
Means and standard errors of trophic state indicators in user perception categories
for physical appearance and recreational potential. Labeled with number of observations.
All Little Rock Lake sites, 1990-2008, Citizens Monitoring Program
Dashed lines indicate MPCA watedr quality for shallow lakes in the CHF Ecoregion.
Units: ppb = micrograms per liter (µg/L)

Figure 8 Correlations vs. MPCA Statewide Regressions

(Units: ppb = micrograms per liter (µg/L))



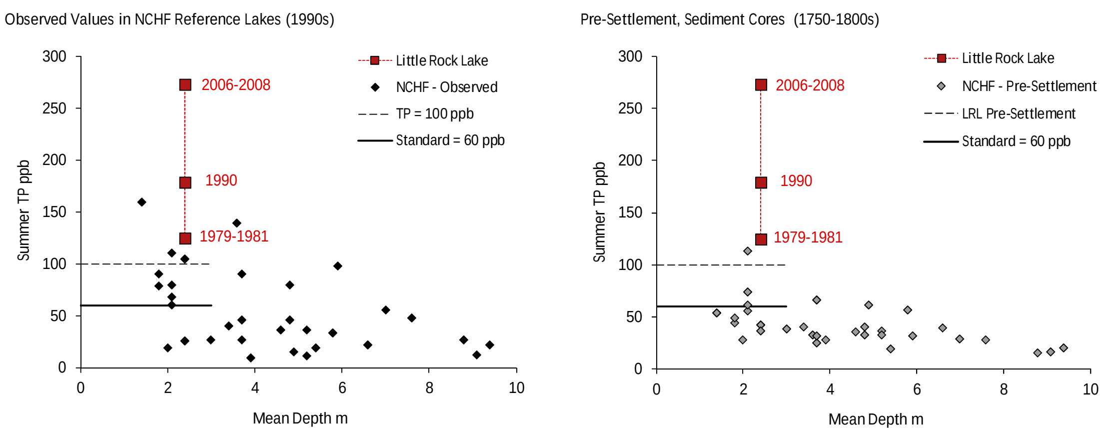




LRL data are from May-September, 1990-2008; each point represents a paired sample. Lines based upon state-wide regressions of summer-mean data from other Minnesota Lakes (Heiskary & Wilson, 2008). Units ppb = micrograms per liter (µg/L).

Figure 9 compares historical summer-mean TP levels with data from other regional lakes classified as "reference" or "minimally-impacted" (Heiskary & Wilson, 2005). The susceptibility of shallow lakes to eutrophication problems is reflected by the negative correlation between TP concentrations and water depth. The left panel shows TP levels measured in the 1990s. The right panel shows estimates for pre-settlement conditions (1750-1900) derived from sediment cores. TP concentrations in LRL more than doubled over the years to levels that far exceed the standard and values observed in the other shallow lakes. TP concentrations averaged 125 ± 5 ppb in 1979-1981, 179 ± 23 in 1990, and 273 ± 35 ppb in 2006-2008. As discussed below, high values measured in 2006-2008 may be partially attributed to extreme climatologic conditions (warm and dry), as opposed to a long-term trend in the lake water quality. The mean value for the reference lakes under pre-settlement conditions (on right) is similar to the 60 ppb phosphorus component of the eutrophication standard.

Figure 9 LRL Summer TP Concentrations vs. Data from Other NCHF Lakes

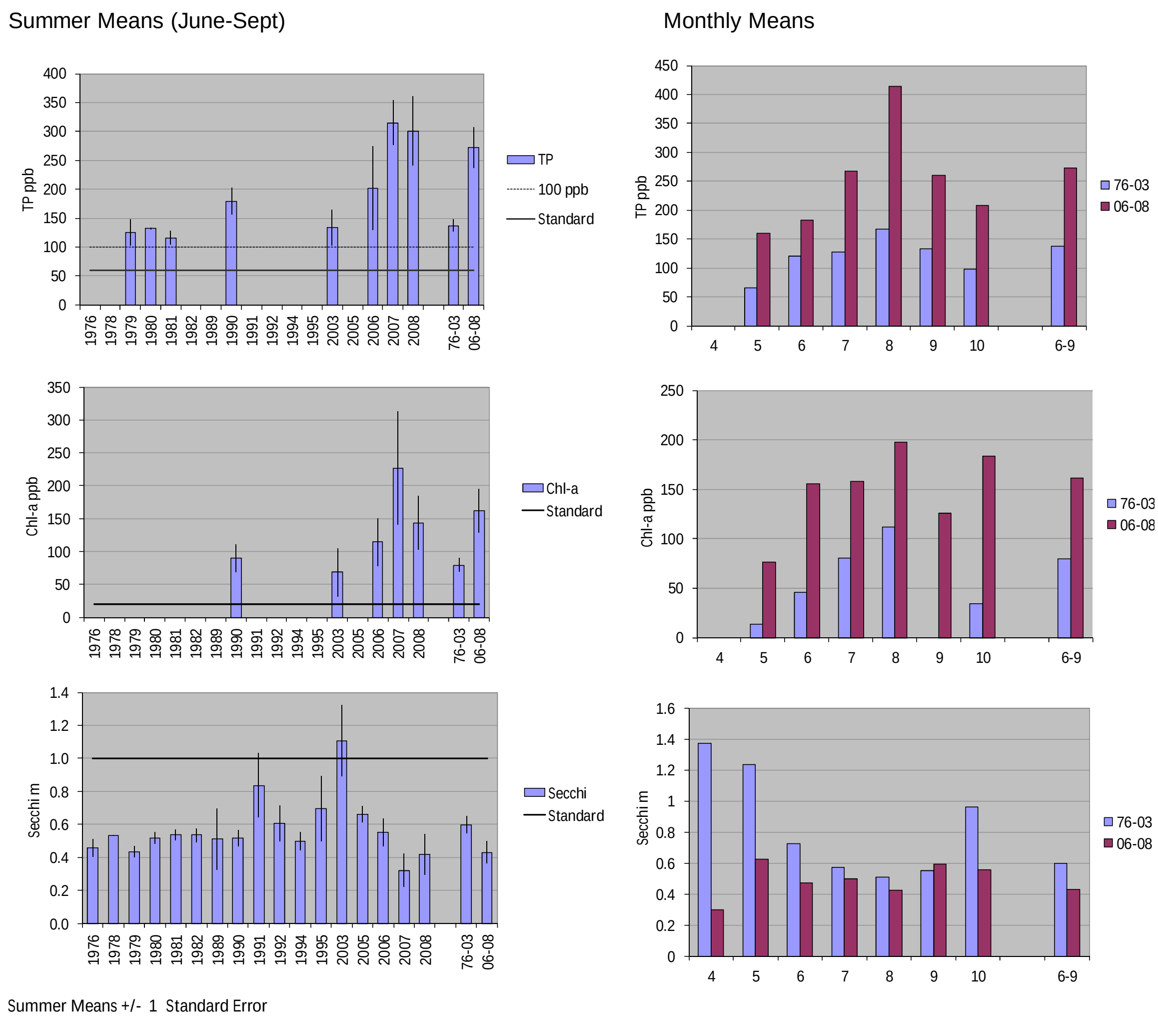


Sediment core studies indicate that LRL historical summer-average TP concentrations ranged from 109 ppb in 1911 to 176 ppb in 2008 (Garrison et al, 2009). These estimates were based upon diatom species distribution at sediment depths of 50-52 cm and 0-2 cm, respectively. While the relevance of the 1911 estimate (109 ppb) is questionable because LRL was a wetland at that time, it is similar to the 100 ppb TP criterion for extreme bluegreen blooms in turbid lakes (Sas, 1989; MPCA, 1974). While within the range of historical data, the 2008 estimate is relatively uncertain because it required extrapolation of the dating methodology beyond its calibration range. Other sediment profile data, including lower iron-bound P levels in the surface sediments (James, 2008) and increased dominance of microcystis (Garrison et al, 2009), are consistent with increases in nutrient enrichment and transition from a wetland to a turbid hyper-eutrophic lake over the years since LRL was formed.

Trends in summer-mean TP, chlorophyll-a, and transparency data over the 1976-2008 period are shown in Figure 10. The means are based upon samples collected in at least three out of the four summer months (June-September) in each year. The data for each parameter indicate that LRL was considerably more eutrophic during the 2006-2008 TMDL study, as compared with previous years. That conclusion is supported by apparent trends in the yearly time series and by comparisons of the 1976-2003 with the 2006-2008 averages by month shown at the right in

Figure 10. While insufficient to support computation of summer means, TP concentrations of 200 ppb in September 1970 and 70 ppb in June 1971 were reported in the first LRL diagnostic study, which also noted a “heavy bloom” of bluegreen algae (Aphanizomenon) in September 1970 (MPCA, 1974).

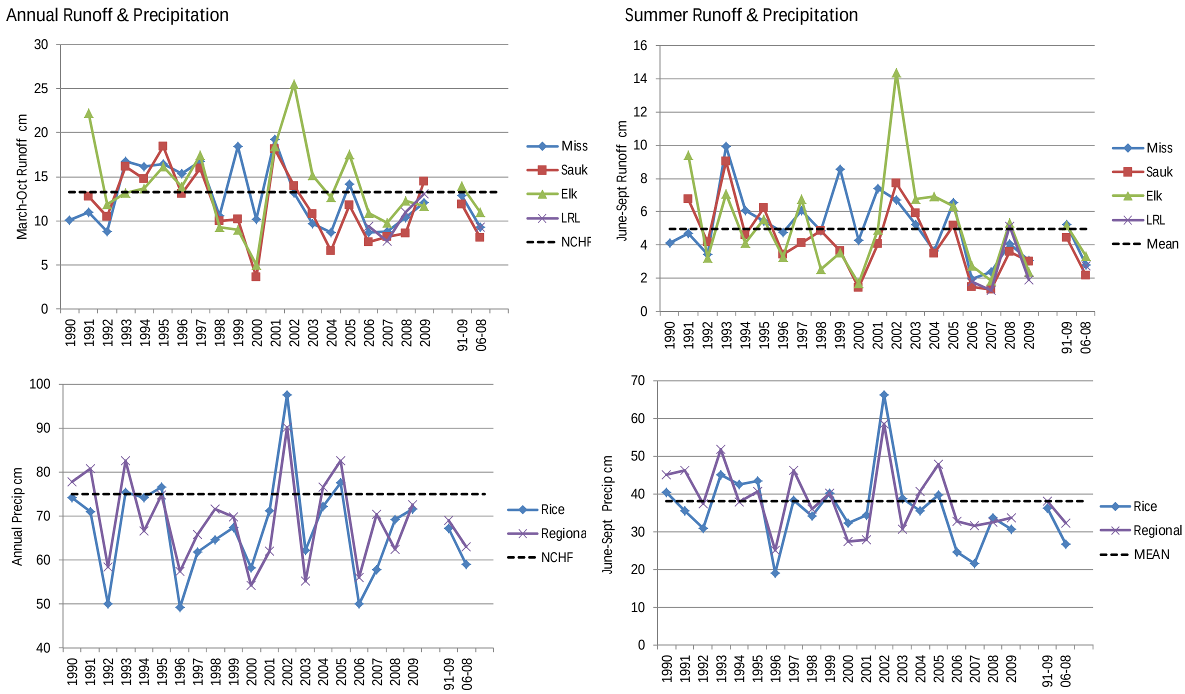
Figure 10 Long-Term Trends in Phosphorus, Chlorophyll-a & Transparency



Interpretation of the apparent trends is difficult because of variations in climatologic conditions and limitations in the data. Data collected in 1990 under the second MPCA diagnostic study (Heiskary, 1991) provide the best historical frame of reference. While the overall percentage of developed land apparently did not change between 1990 (~68%, Heiskary, 1991) and 2006-2008 (~70%, BSWCD, 2009), an increase in TP load could have occurred as a result of increases in the intensity and/or types of agricultural and/or urban land uses. Precipitation and runoff from other regional watersheds were well below long-term averages, particularly in the summers of 2006-2007 (Figure 11). The relatively high TP levels and heavy algal blooms observed in those years may partially reflect warm and dry summers relative to the 1970-2009 period of record (Figure 12).

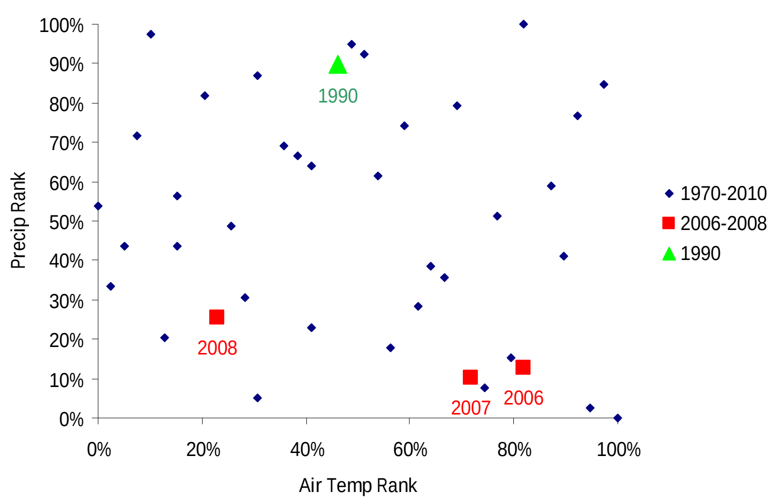
While external P loads would be higher in wet years, excessive algal blooms are more likely in shallow lakes during dry and hot summers, when lower base flows provide less dilution for P loads recycled from lake bottom sediments, algal growth rates and sediment decomposition rates are increased by warmer temperatures, and longer water residence times allow development of intense blooms. For example, summer chlorophyll-a levels are inversely correlated with flow in the Sauk River mainstem lakes, which are also in the NCHF ecoregion (Walker, 2009).

Figure 11 Regional Runoff and Precipitation Time Series



NCHF = Mean Runoff for NCHF Ecoregion (MINLEAP, Wilson & Walker, 1988); Regional = US Climatologic Database, Minnesota Region 5; Rice = NWS at Rice; Mean = Mean of Long-Term Datasets
Conditions were relatively dry during the TMDL study period (2006-2008).

Figure 12 Climatologic Conditions in Lake Study Years



US Long-TermTerm Climate Monitoring, Minn. Divison 5;   1970-2009, June-August

Figure 13 shows seasonal variations in water temperature and trophic state indicators in 1990 and 2006-2008. Lower TP and chlorophyll-a levels observed in 1990 are consistent with lower water and air temperatures in July and August. Relatively high water temperatures, TP levels, high Chl-a levels, and low Secchi depths were observed in June and July of 2007. Toxic bluegreen algae (Microcystis specie) and atmospheric hydrogen sulfide releases from anoxic bottom sediments were also reported (Lindon et al., 2007). Comparisons with data from other years indicate that severe conditions in 2007 were triggered by high tributary TP loads in March-April (see below) followed by summer low flow and high temperatures.

Figure 13 Seasonal Variations in LRL Water Quality During 1990 and 2006-2008

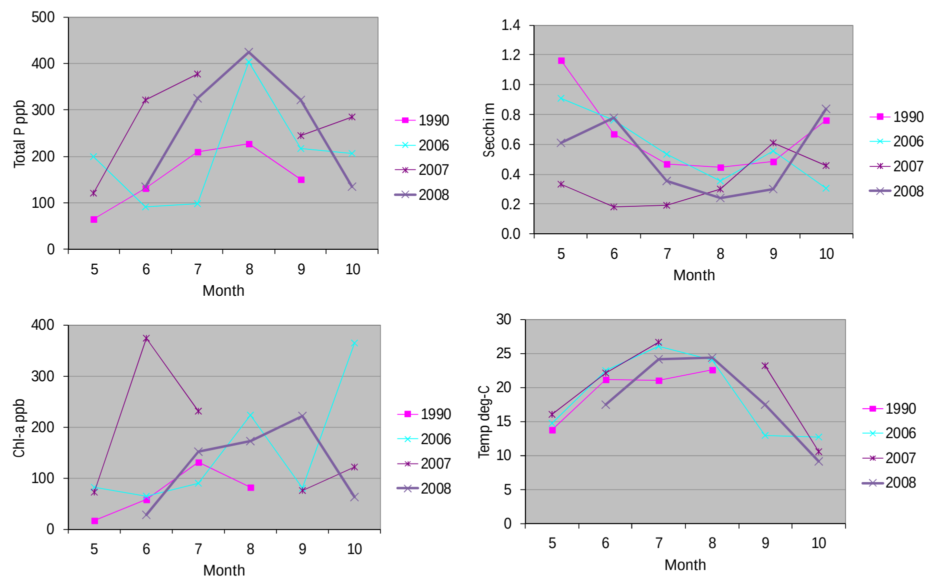
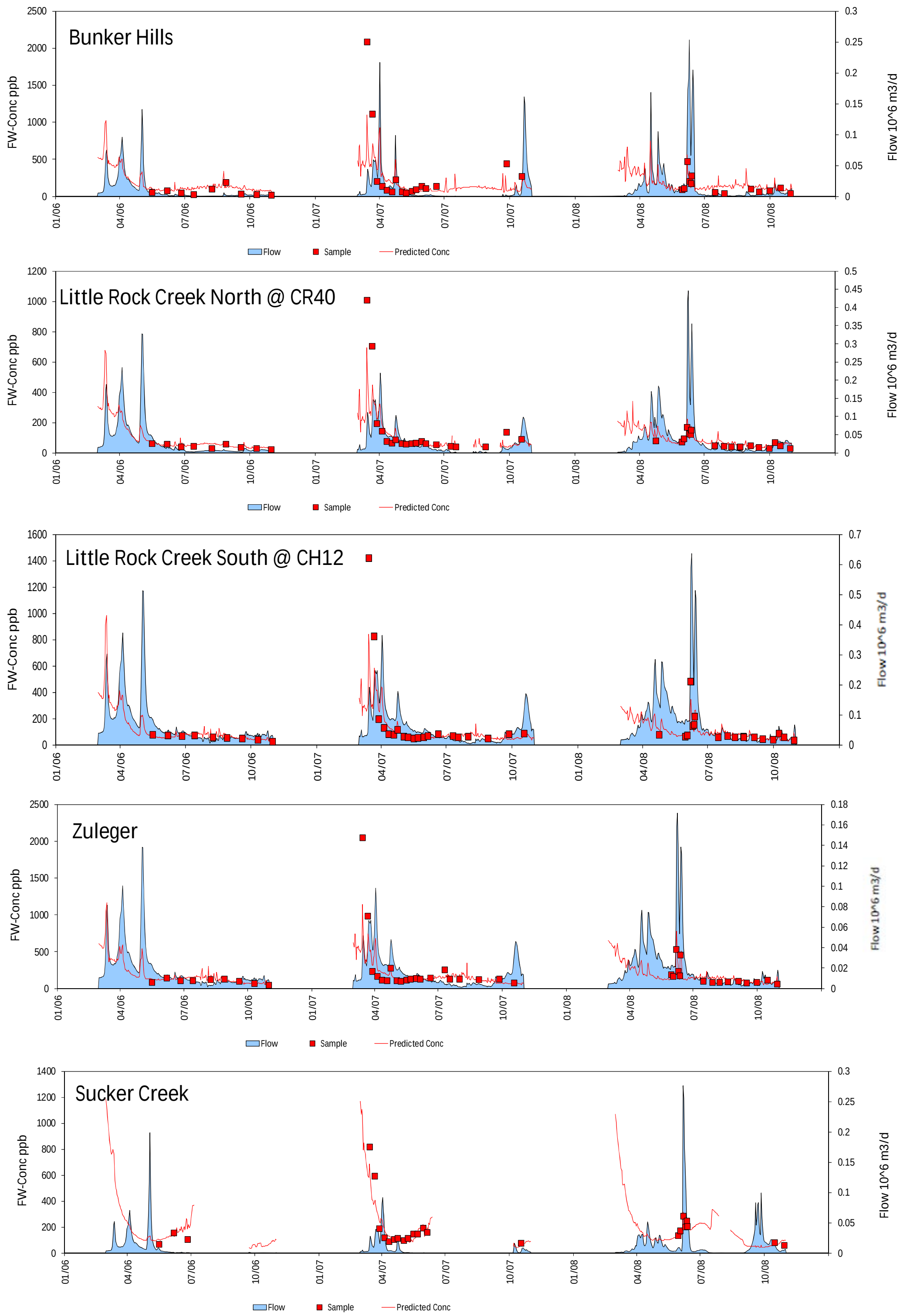


Figure 14 shows daily flows and TP concentrations in the tributaries over the 2006-2009 period. Appendix B contains more detailed displays and summaries of the data. Red lines show daily estimated TP concentrations predicted from regression equations relating sampled values to flow and season (Walker & Havens, 2003). Extremely high TP levels (~500-1000 ppb), as well as high concentrations of fecal coliforms and other nutrients indicative of animal waste, were measured in early spring runoff of 2007 (Appendix B). Concentration spikes also occurred during the June 2008 runoff event.

Early spring rains in 2007 would have promoted the transport of nutrients from watershed sources to the lake. LRC spring runoff peaked at 148 cfs in 2007 as compared with 583 cfs in 2009, when water quality sampling was not conducted. Lake water levels rose by 0.6 ft in spring of 2007 as compared with 2.5 ft in spring of 2009 (Appendix B). It is likely that the much larger spring runoff event in 2009 would have contributed substantially more phosphorus to the lake, as compared with spring runoff in 2006-2008.

Figure 14 Daily Flows & Flow-Weighted Mean Phosphorus Concentrations at Tributary Sites



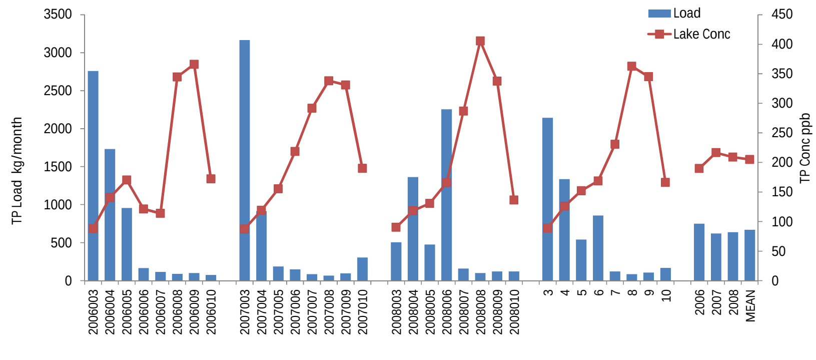
2.5 Water and Mass Balances

Estimated water and phosphorus mass balances for the March-October of 2006-2008 period of record are summarized in the Appendix B (A-1). These provide cornerstones for developing the TMDL using the methods described in the next section (see section 2.6). The assumptions and calculation results are listed in Appendix B (A-1). Components of the water and mass balances include the following:

1. Monitored Inflows in Port
    - Little Rock Creek above Lake Inflow (CH 12)
        - LRC North (above CR 8)
        - Bunker Hills
    - Zuleger Creek (Concentration Only)
    - Sucker Creek
    - Rainfall (measured at Rice, approximately 3 miles WNW from LRL)
2. Unmonitored Inflows
    - Areas the drain directly into the lake (lakeshed)
    - Wastewater disposal systems (septic tanks) on shoreline lots.
    - Atmospheric deposition
3. Unmonitored Outflows
    - Outflow volumes computed from water budget (inflow + precipitation – evaporation – increase in storage)
    - Outflow concentrations based upon data from the monitoring site at the south end of the lake (LRL-4) in 2008; estimated at 92% of the lake-mean concentration in other years, based upon calibration to the 2008 data.
    - Evaporation based upon regional data
4. Storage in Lake
    - Lake volume computed from surface area and stage.
    - Lake TP concentration

Gaps in the tributary flow and phosphorus data were filled using regression techniques, interpolation, and drainage area ratios. While data to evaluate groundwater inflows and outflows are not available, as typical of lake studies (Walker 1985), they are likely to be small relative to the surface TP loads, given the relatively large watershed and high concentrations of TP in the tributaries. Any contributions from the groundwater are assumed to be relatively unchanged and would not impact the calculation of the tributary TP loads under the TMDL. Several assumptions were also necessary to evaluate the unmonitored inflow and outflow components. Given the data limitations and assumptions required, the inflow loads and mass balances are considered approximations to be refined using future monitoring data.

Figure 15 Monthly TP Loads and Lake TP Concentrations



Monthly variations in TP load and lake concentration are shown in Figure 15. Despite uncertainty in the monthly values, the pattern is typical of P dynamics in shallow eutrophic lakes (Sheffer, 2004; Sondergaard, et al, 1999; Heiskary & Linton, 2005):

- The initial buildup in lake TP levels is triggered by spring runoff loads.

- The mid-summer P dynamics are dominated by P recycled from the bottom sediments, which is fueled by P deposited to the sediments earlier in the season and in previous years (Figure 6).

- The P buildup is accelerated by changes in hydrology and chemistry as the summer blooms develop. Mechanisms are related to decreases in flow (less dilution), increases in temperature, increases in sunlight, increases in pH, and decreases in dissolved oxygen levels at the sediment-water interface. Mass-balance calculations (Appendix B) indicate that rates of P buildup in the summer are reasonably consistent with laboratory studies of sediment cores collected in LRL and other lakes, when sensitivities to pH, temperature, and intermittent oxygen depletion are considered (James, 2008).

- Phosphorus decreases in the fall reflect die-off and sedimentation of algal blooms.

- As illustrated in Figure 6, P deposited to the sediments over the years is either recycled to the water column or buried below the sediment horizon that interacts with the water column (typically ~ 10 cm). The sediment accretion rate in LRL is estimated at 1-2 cm/yr (Garrison & LaLiberte, 2009).

- Data from other shallow lakes (Appendix B) indicate that P buildup over the summer is highly correlated with the initial TP concentrations in the winter and early spring. In lakes with spring TP concentrations < 50 ppb, the summer buildup is negligible; i.e. the spring and summer concentrations are equal. In lakes similar to LRL with spring TP levels of ~150 ppb, the summer means are ~ 300 ppb. The pattern is likely to reflect feedback loops that accelerate the rate of sediment P recycling as the lake becomes more eutrophic. The loops are driven by increases in pH, increases in organic matter production, and decreases in aquatic vegetation that otherwise stabilize the sediments. The linkage between spring and summer P indicates the importance of decreasing TP loads in spring runoff in order to achieve the summer TP standard.

Based upon review of the water quality and sediment data, P cycling mechanisms operating in LRL are likely similar to those observed in other lakes. Explicit mass-balance models of sediment-water interactions have been developed for other shallow-lake TMDL assessments supported by several years of data (Walker, 2000ab, 2001, 2009). These allow simulation of seasonal and year-to-year variations in lake conditions in response to variations in hydrology, climate, and reductions in P load. While additional monitoring data would be needed to support development of a similar model for LRL, the simpler empirical approach described below is sufficient for an initial TMDL assessment.

2.6 TMDL Derivation

Starting from the existing phosphorus loads derived in the previous section, load reductions sufficient to achieve the lake TP target are derived by applying an empirical phosphorus balance model, as described in detail below. Sufficient site-specific and regional data exist to support TMDL estimation using relatively simple, empirical models calibrated to data from other lakes. Generalized models of this type are robust to uncertainty in site-specific data and have been widely used in lake management for a few decades (Vollenweider, 1976; Canfield & Bachman, 1981; Wilson & Walker, 1988; Walker, 1984;2006). These models typically have uncertainties ranging from 30-40% of the predicted value, depending on dataset and model (Walker, 1985). Continued lake and watershed monitoring over the course of TMDL implementation will provide a basis for tracking progress, refining the model, and reducing uncertainty in the TMDL estimate (Walker, 2003).

The Canfield-Bachman (1981) model is widely applied in Minnesota lake P assessments and provides a robust basis for TMDL development when sufficient data are not available for developing site-specific models. The model predicts lake summer-mean TP concentration based upon average-annual inflow volume, TP load, lake mean depth, and lake surface area. It was originally developed from a nationwide dataset representing 290 lakes. A slightly different version was originally calibrated to reservoir data and subsequently tested against data from Corps of Engineer reservoirs and other large datasets (Walker, 1985). The model is used in the Minnesota Lake Eutrophication Analysis Procedure (MNLEAP, Wilson and Walker, 1988) to predict water quality conditions in relatively unimpaired lakes in each ecoregion of the state.

LRL water quality impairment is indicated by comparisons with data from MNLEAP predictions and calibration lakes (Appendix). Equations are listed in the Appendix B (A-3).

The TMDL can be defined as the long-term average TP load consistent with achieving the long-term-average TP target (summer mean = 60 ppb). As explained below, tributary runoff volumes for the 1991-2009 baseline period were applied to a range of assumed flow-weighed mean concentrations and the model was repeatedly run in order to estimate the runoff concentration required to achieve the lake TP target. Equations used in the derivation are listed in Appendix B. The derivation involves the following steps:

- To establish a hydrologic baseline, water and phosphorus loads measured in 2006-2008 are adjusted to reflect long-term-average (1991-2009) conditions using regional streamflow and precipitation data (Figure 11). Average tributary flows are increased by 37% based upon runoff data for the Sauk and Elk River watersheds. Application of data from another regional watershed was necessary in order to extend the hydrologic record because long-term hydrologic records are not available for the LRL watershed. The resulting average runoff (13 cm) is similar to that assumed for this ecoregion in MNLEAP (Wilson & Walker, 1988).

- Loading scenarios are constructed by applying a hypothetical flow-weighted-mean concentration limit to each tributary discharging directly into the lake (Little Rock, Zuleger, and Sucker). The scenarios cover a range of 40 to 200 ppb in runoff concentration (Figure 16). While the TMDL is independent of the allocation across sub-basins, the same concentration target could be applied to the LRC sub-basins (northern LRC and Bunker Hills) during implementation. Other allocations across tributaries could be used if they provide a more cost-effective method to achieve the same total tributary load. The predicted lake TP concentration is driven by the sum of the TP loads from all sources and is independent of how the loads are split among the individual tributaries or individual sub-basins.

- Total P loads are computed by applying the assumed flow-weighted mean March-October runoff concentration to the adjusted 1991-2009 baseline flow for each tributary.

- Direct discharge from septic systems is not permitted under MN state law; therefore the load allocation for septic systems is set to zero.

- TP concentrations in lakeshed runoff are assumed to equal the baseline values. These are conservative assumptions to the extent that additional measures are taken to reduce these sources over the course of TMDL implementation and hence provide a margin of safety in the TMDL allocation, as discussed below.

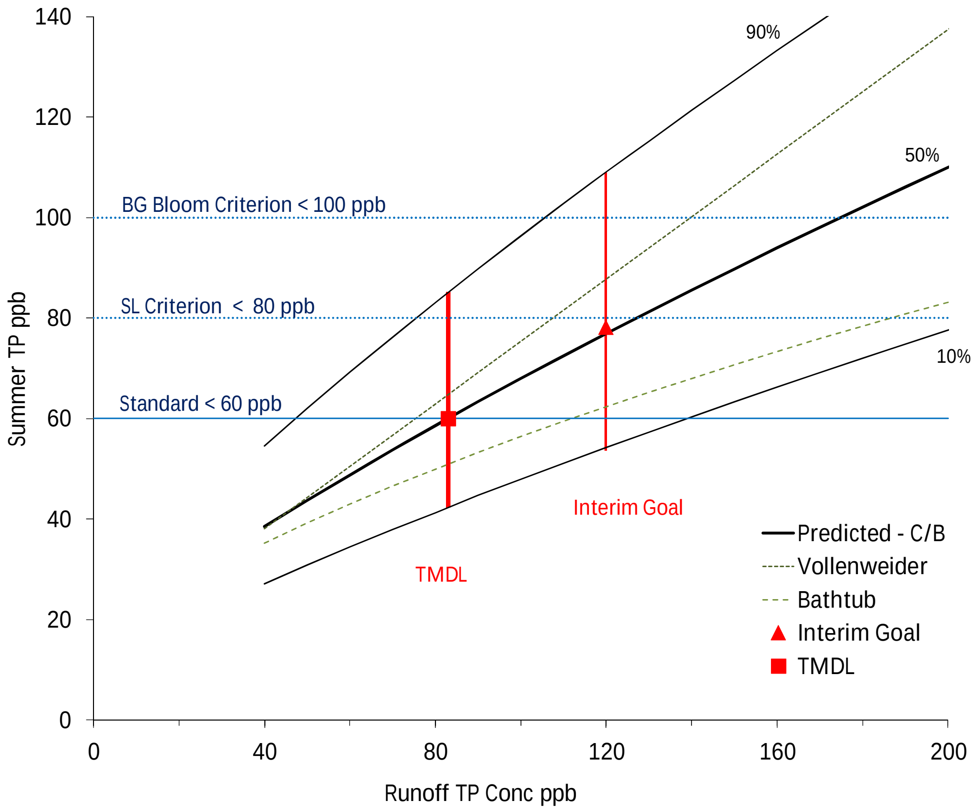
- The Canfield-Bachman model is applied to predict confidence intervals for lake TP concentration over a 40-200 ppb range in runoff concentration (Figure 16). Testing against large datasets indicates that empirical models of this type typically have log-normal error distributions and 80% confidence intervals (10^{th} to 90^{th} percentiles) ranging from approximately 70% to 140% of the predicted lake TP concentration (Walker, 1985).

- To evaluate sensitivity to modeling assumptions (Appendix B), other empirical models (Vollenweider, 1976; Walker, 2006) are also applied to predict lake P concentrations. These results generally fall within the confidence intervals predicted by the Canfield-Bachman model.

- Transparency and chlorophyll-a levels are predicted from lake TP concentrations using empirical equations developed by MPCA based upon data from other shallow lakes in this region of Minnesota (Heiskary & Lindon, 2005; Heiskary & Wilson, 2008) as listed in Appendix B (A-3).

Lake TP responses to variations in runoff concentration are shown in Figure 16. At a runoff concentration of 83 ppb uniformly applied to each gauged tributary, the predicted lake concentration is 60 ppb and the 80% confidence interval is 42 to 85 ppb. The estimated risk of exceeding the 80 ppb criterion (upper end of the 60-80 ppb range derived by Heiskary & Lindon (2005) is 15%. The estimated risk of exceeding the 100 ppb criterion for extreme bluegreen blooms (Sas, 1989) is 3%. At a runoff concentration of 120 ppb from each tributary, the estimated risks of exceeding the 80 ppb and 100 ppb levels, which might be considered as interim targets for the TMDL are 47% and 18%, respectively. This scenario could be considered as an interim target for implementation of the TMDL. The 83-120 range in runoff concentration is within the inter-quartile range of values measured in relatively unimpacted streams in the NCHF ecoregion (25th percentile = 70 ppb, 75th percentile = 120 ppb, Heiskary & Wilson, 2005).

Figure 16 Predicted Response to Variations in Runoff TP Concentration



Runoff TP	Lake Inflows from Gauged Tributaries (Little Rock Creek, Zuleger Creek, Sucker Creek)
Predicted TP	Canfield/Bachman (1981) Lake Model, Black Lines = 10th - 50th - 90th Percentiles
Vollenweider	Vollenweider (1976) Model
Bathtub	Bathtub Model 1 (Walker, 2006)
Runoff TP	Mean Runoff TP Conc for Gauged Tribs (Little Rock, Zuleger, Sucker) Adjusted to Achieve Standard
	Ungauged Sources (Lakeshed, Shoreline, Atmospheric) Assumed Constant
Lake TP Criteria	
60 ppb	Shallow Lake Standard (Heiskary & Wilson, 2008)
80 ppb	Upper End of 60-80 ppb Criterion Range for Clear-Water Shallow Lakes (Heiskary & Lindon, 2005)
100 ppb	Criterion for Extreme Bluegreen Algal Blooms (Sas, 1989).

Flow and load allocations across sources for the baseline, interim and TMDL scenarios are listed in Table 6. For an average March-October inflow of 37 hm^3, the TMDL estimate is 3,238 kg and the combined inflow concentration for all sources is 83 ppb. The corresponding daily-average TP load over the March-October runoff season is 13.2 kg/day. Load reductions relative to the baseline range from 54 to 69% for the individual tributaries discharging directly into the lake, although these estimates could vary considerably because of uncertainty in baseline loads derived from the 2006-2008 data. The net effects of internal P loads recycled from the lake sediments are not explicit in the allocation because they are implicit in the calibration of the Canfield/Bachman empirical model, which relates lake summer P concentration to external load.

It is assumed that the existing high rates of internal P recycling will decrease as the lake and sediments equilibrate to lower external P loads (Figure 6).

At a lake P concentration of 60 ppb, the regional regression models for shallow lakes (Heiskary & Lindon, 2005; Heiskary & Wilson, 2008) predict a chlorophyll-a concentration of 18 ppb and a mean Secchi depth of 1.08 meters (Log_{10} Chl-a = 1.08 Log_{10} TP - 0.66; $R^2 = 0.80$; n = 31) (Table 6). These results indicate that achieving the 60 ppb lake TP standard would provide compliance with the lake standards for chlorophyll-a and transparency (< 20 ppb and > 1.0 meters, respectively).

2.6.1- Load Allocation (LA)

The entire watershed load is from nonpoint sources with the exception of a small amount of discharge from regulated Municipal Separate Storm Sewer Systems (MS4s) in the Little Rock Creek subwatershed. Approximately 7 percent of the Little Rock Creek subwatershed consists of regulated MS4s. Thus, assuming area proportionality, 7 percent of the allocation for the subwatershed was placed into the WLA and the remaining 93 percent in the LA. Table 6 summarizes allocations for each subwatershed.

2.6.2. – Wasteload Allocation (WLA)

As stated above, 7 percent of the load for the Little Rock subwatershed was assigned to municipal stormwater. The WLA is expressed as a categorical allocation because of uncertainty in determining the loads from individual MS4s. The regulated MS4s are covered under the General Permit MNR040000 and include the following:

- Watab Township (ID = MS400161)
- Minnesota Department of Transportation – Outstate (ID = MS400180)
- Benton County (ID = MS400067)

There currently are no regulated industrial stormwater dischargers within the watershed. A WLA of 2 kg/year was assigned to construction activity to account for construction activities regulated under a NPDES permit. This amounts to 0.0006 percent of the total TMDL and is based on historical data on construction activity within the watershed.

In the event that additional stormwater discharges come under permit coverage within the watershed, WLA or LA will be transferred to these new entities based on the process used to set wasteload allocations in the TMDL. MS4s will be notified and will have an opportunity to comment on the reallocation.

Table 6 Load Allocations for Baseline, Interim, & TMDL Scenarios

	Baseline 1991-2009 Hydrology, March-Oct				Interim goal			TMDL Allocation (c)			
Source	Area km2	Flow hm3	Load kg	Conc ppb	Load kg	Conc ppb	Reduc %	Load kg	Load kg/d	Conc ppb	Reduc %
LRC Subwatersheds											
Bunker Hills	50.5	4.4	1267	287	529	120	58%	a			
LRC North	104.5	11.1	1766	160	1328	120	25%	a			
Lake Inflows – Load Allocation											
LR Creek – CH12	165.8	22	3763	184	2456	120	35%	1827	7	83	55%
Zuleger	48	5.9	1570	265	712	120	55%	492	2	83	69%
Sucker	11.2	3	551	182	364	120	34%	252	1	83	54%
Lake Inflows – Wasteload Allocation											
MS4 stormwater	12.5		283					128			
Construction stormwater					185			2	0.5		55%
Total Gauged	237.5	31	6167	199	3717	120	40%	2571	10.5	83	58%
Lakeshed	25.2	3.1	571	184	571	184	0%	571	2.3	184	0%
Total Watershed	262.6	34.1	6739	198	4288	126	36%	3142	12.8	92	53%
Shore. Septic tanks			90		90		0%	b			
Total External	262.6	34.1	6829	200	4379	128	36%	3144	12.8	92	54%
Rainfall	5.1	3.1	94	30	94	30	0%	94	0.4	30	0%
Total Inflow	267.7	37.2	6923	186	4473	120	35%	3238	13.2	87	53%

Predicted Lake	Standard	Mean	10%	90%	Mean	10%	**90%**
Total P ppb	< 60	78	55	111	60	42	**85**
Chlorophyll-a ppb	< 20	24	14	42	18	10	**32**
Secchi m	> 1.0	0.9	0.6	1.2	1.1	0.8	1.5

a TMDL allocations for little Rock Creek Subwatersheds are reflected in the total allocation for LR Creek at CH12
b Direct discharge from septic systems is not permitted under MN state law; therefore the allocation for septic systems is zero.
C The TMDL is the total inflow load (3238 kg)

2.7 Seasonal Variations

EPA regulatory guidelines (EPA, 2009; 40 C.F.R Part 130) require consideration of spatial and temporal water quality variations in formulating the TMDL. The 2008 monitoring data (Appendix B) indicate that spatial variations across the lake monitoring sites were not significant, especially in the context of the large seasonal and random variations. Given the strong correlation between chlorophyll-a and TP levels across individual sampling events, the lake TP concentrations achieved under TMDL conditions (Figure 8) would provide significant reductions in the magnitude and frequency of extreme algal blooms. Considerations of seasonal variations in water quality and critical conditions associated with severe mid-summer algal blooms and resulting use impairment are embedded in the derivation of the 60 ppb TP standard (Heiskary & Wilson, 2008).

2.8 Margin of Safety

Regulatory guidelines (EPA, 2009) also require that the TMDL include a margin of safety (MOS) to provide assurance that the lake water quality standards will be achieved. The following factors can be considered as MOS components:

- The load allocation (Table 6) assumes that there will be no reduction in runoff P load from ungauged lakeshed relative to baseline conditions. These sources are estimated to account for 18 % of the TMDL allocation (571 / 3236 kg). Implementing runoff P controls in the lakeshed similar to those implemented in the gauged watersheds would be expected to provide reductions in P load relative to baseline conditions that are slightly below those predicted for the gauged tributaries (58%, Table 6), but still significantly greater than the 0% assumed in the allocation.

- Achieving runoff total P load reductions would require greater percentage reductions in soluble reactive P (likely from animal waste & fertilizer), which has a greater impact on lake algal productivity, as compared with other forms of phosphorus that are less biologically available (Walker, 1985).

- Best Management Practices for reducing phosphorus loads from agriculture (Sharpley et al., 2006) and other sources could be conservatively designed in the process of implementation.

- The TMDL derivation was based upon data from relatively dry years which had high potential for phosphorus and algae buildup within the lake during the summer months because of low flushing rates. The highest tributary TP loads occurred in response to relatively intense early spring rains in 2007. These conditions indicate that the percentage reductions in tributary TP concentrations required to meet the TMDL goals expressed as a long-term averages may be lower than those estimated in the derivation.

- The 60 ppb lake standard is at the lower end of the 60-80 ppb range derived by Heiskary & Lindon (2005) as a TP criterion for shallow lakes. While this does not provide a margin of safety for achieving the lake P standard, it could be interpreted to provide a margin of safety for achieving the beneficial uses, upon which the lake P standard is conservatively based.

2.9 Monitoring and TMDL Implementation

Adaptive implementation of the TMDL is necessary given the uncertainties associated with predicting the effectiveness of management measures, as well as the time scales and ultimate responses of shallow lakes to load reductions. Continued monitoring is essential to improve the baseline and track responses to implementation of P loading controls over a range of climatologic conditions. Relevant responses include the tributary water quality and TP loads, lake water quality, vegetation, algae, fish, and user perception.

The monitoring plan for the lake TMDL can be integrated with the plan for the Little Rock Creek TMDL, the Citizens Monitoring Program, and MDNR surveys of fish and vegetation. The recommended design for the lake TMDL is similar to that designed for the 2008 monitoring of Little Rock Lake (BSWCD, 2008) with the following emphases and exceptions:

- Monitor the entire spring-summer-fall season in tributaries and lake. While tracking compliance with the lake standards requires June-September sampling, spring and fall data are needed to evaluate responses to watershed P controls, the lake phosphorus mass balance, and the buildup of phosphorus and blooms over the growing season.

- The number of lake sites can be decreased from five to three: LRL-1, LRL-2 (deepest point) and LRL-5 (representing outflow from the lake). The lake outlet can be sampled during spring runoff if ice cover precludes access to the lake.

- The lake can be sampled monthly and parameters should include at a minimum (every year) TP (surface & bottom at LRL-2), chlorophyll-a, transparency, field profiles, and user perception survey. The remaining parameters specified in the 2008 design can be monitored every third year (LRL-2 only).

- Monitoring of tributary flow and water quality should be performed each year and integrated with the creek TMDL plan. The plan should include sufficient samples to capture the rising and falling limbs of the spring runoff period (at least weekly frequency).

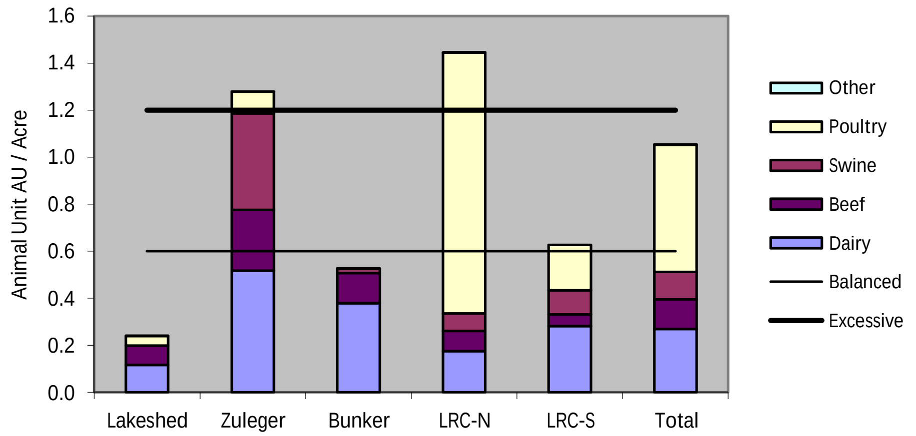
- The downstream sites at the LRC basin outlet and Mississippi River can be eliminated. Special sampling is recommended to document lake responses to extreme flooding events on the Mississippi and shoreline flooding.

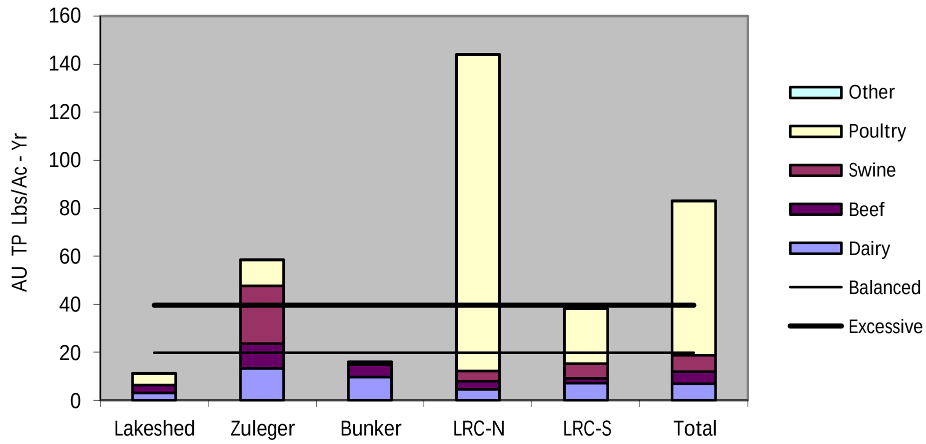
The results should be compiled and reported yearly to track progress. A comprehensive review of the data, mass balances, and modeling update should be performed after 3-5 years of continuous monitoring.

The extremely high concentrations, seasonal distribution, flow-dependence of several water quality constituents in spring runoff (fecal coliforms, BOD, ammonia-N, Kjeldahl-N, Total P, and soluble reactive P, Appendix B) indicate that animal waste is an important component of nutrient loads to the lake. Based upon watershed Animal Unit (1000 lbs live animal weight) estimates ranging from 25,471 (Felix, A., BSWCD, 2009) to 37,076 (GIS data) and unit waste loading factors ranging from 12 kg P / AU-year for dairy cows to 54 kg P/ AU-year for poultry (NRCS, 1995), the amount of phosphorus in animal waste generated and cycled on the farms is approximately 132-192 times the existing long-term-average P load reaching the lake (6,292 kg/yr, Table 6). Considering that this does not account for fertilizer P, only a small fraction of the P associated with agricultural operations would have to be transported in runoff to the lake in order to account for a significant portion of the total load. Figure 17 shows AU densities and manure P production expressed per unit of cropland in each watershed relative to guidance values developed for managing farm phosphorus balances in Vermont. These inventories can be refined with additional site-specific information on AU densities and manure management in each basin.

Phosphorus loading controls can be implemented on an incremental, cost-effective basis and tracked relative to the interim and TMDL goals developed above. Abundant technology, guidance, and statewide management programs exist to support design of BMPs for reducing phosphorus loads from cropland and feedlots (Sharpley et al., 2006; NRDC, 2010). The long-term strategy involves farm management to minimize excess phosphorus (fertilizer + animal feed – crop export – animal export), which eventually builds up on the soils or is transported to the lake. While transport is generally considered to occur primarily in surface runoff, sub-surface flows are expected to become increasingly important as soluble P concentrations build up in soils subject to excess P applications (Schippers et al., 2006; Sharpley et al, 2003). Farm-scale and watershed-scale phosphorus budgets guided by soil testing can be used as a basis for managing excess phosphorus and buildup of soluble P in the soils; this type of program could be coupled with traditional BMPs to reduce surface runoff and phosphorus transport from feedlots and cropland. As a component of the margin of safety, additional measures can be taken to reduce P sources in the lakeshed (septic tanks and runoff from shoreline lots, highways and other impervious surfaces).

Figure 17 Animal Unit Densities in LRL Watershed





Animal Unit data from GIS Layer (bmms_FL-P_mn009)
Animal Unit densities expressed per acre of total cropland.

NRCS (1995)	Dairy	Beef	Swine	Poultry	Other
Lbs - TP / AU - Yr	26	40	58	119	26

Guidance values for AU Densities to Manage Farm P Balance, Vermont
http://www.sera17.ext.vt.edu/Documents/BMP_phosphorus_balance.pdf

Farm Features	Farm Phosphorus Balance		
	Deficit	Balanced	Excess
Animal Density (Animal Units* per acre routinely manured)	Low <0.6	Medium 0.6 to 1.2	High >1.2
% of total feed from off-farm sources	<20	20 to 40	>40

* *1 Animal Unit = 1000 lbs live weight*

Construction stormwater activities are considered in compliance with provisions of the TMDL if they obtain a Construction General Permit under the NPDES program and properly select, install and maintain all BMPs required under the permit, including any applicable additional BMPs required in Appendix A of the Construction General Permit for discharges to impaired waters, or meet local construction stormwater requirements if they are more restrictive than requirements of the State General Permit. For road projects, pollutant loading reductions will occur as road reconstruction projects are implemented. This is accomplished through compliance with the Construction Stormwater general permit, which requires treatment of one inch of water for projects located within one mile of an impaired water. Treatment of the first inch of runoff typically achieves phosphorus reductions greater than required in this TMDL. Therefore road authorities such as MnDOT will meet TMDL requirements by following the construction stormwater permit as road reconstruction occurs. Permittees covered under the MS4 General Permit must review the adequacy of their Storm Water Pollution Prevention Programs (SWPPP) to meet the WLA. If necessary, permittees must modify their SWPPP to ensure compliance with the WLA.

If significant improvements in lake water quality are not achieved within a few years after significant reductions in P load are accomplished, application of alum or other chemicals would help to accelerate recovery by trapping historical P loads in the lake sediments. Incremental reductions in phosphorus and turbidity may promote growth of aquatic vegetation, which would help to stabilize the sediments and accelerate recovery (Heiskary & Lindon, 2005). Vegetation management programs should consider the possibility that excessive herbicide applications for aquatic plant management would make it more difficult to achieve water quality standards by promoting recycling of P loads from bottom sediments.

Depletion of stream base flow resulting from increased groundwater pumping for irrigation has been identified as a management concern for Little Rock Creek (BSWCD, 2009). Lower summer inflows resulting from drought and/or groundwater pumping could have adverse impacts on lake water quality through various mechanisms. Lower inflows would provide less dilution for P recycled from the lake bottom sediments and accelerate the buildup of P in the water column and algal blooms, as observed in 2007. Development of stagnant conditions could induce backflow and associated phosphorus loads from the outlet channel in periods when evaporation exceeds the total inflow from the tributaries and rainfall. The predominance of bluegreen algae could be enhanced by decreases in summer nitrate loads, potentially significant because of the high nitrate concentrations in summer base flows (NOX-N ~ 5 to 10 ppm). Nitrate loads could have beneficial impacts by oxidizing bottom sediments and decreasing P recycling. The mechanisms and scales are recommended for further evaluation supported by results of the ongoing watershed modeling study (BSWCD, 2009) and future monitoring.

The strategies listed in Table 7 and 8 are the result of Technical Advisory Committee meetings, Little Rock Lake Watershed Stakeholder committee meetings and public stakeholder meetings, all of which were led by Benton Soil and Water Conservation District staff. The costs portrayed in Table 7 and 8 are only for the actual cost of the project, not including design, project oversight, etc. An overall cost estimate for all implementation strategies is approximately 5.34 million dollars.

Table 7 First Priority Implementation Practices List

Practice	Unit Cost	Units	Note	Qty	Cost
Agricultural BMPs	-	-	-	-	**$2,328,894 – $3,728,894**
Nutrient Management	$14	acre		32,471	$454,594
Cover Crop	$40	acre		4,870	$194,800
Feedlot Projects	$30,000 - $100,000	farm/project	Unit Cost Varies	20	$600,000- $2,000,000
Residue and Tillage Management	$32	acre		10,000	$320,000
Filter Strip	$317	acre		1,000	$317,000
Irrigation Management	$5.80	acre		5,000	$29,000
Stream Crossing	$47	linear feet		500	$16,500
Contour Buffer Strips	$345	acre		1,000	$345,000
Prescribed Grazing	$52	acre		1000	$52,000
Other BMPs	-	-	-	-	**$899,275**
Lakeshore Native Buffers	$1440	acre		25	$36,000
Rain Gardens	$1075	garden		25	$26,875
Water and Sediment Control Basin	$13,000	basin		5	$65,000
Wetland Restoration	$7714	acre		100	$771,400
Miscellaneous	-	-	-	-	**$169,825**
SSTS Inspection Program	$135	septic system		295	$39,825
Education	$6,500	year	-	10	$130,000

*** Unit Cost is a derivative of the NRCS 2011 Minnesota EQIP Conservation Practice Payment) with the exception of Rain Gardens, and SSTS Inspection Program.**

Table 8 Second Priority Implementation Practices List

Practice	Unit Cost	Units	Note	Qty	Cost
Miscellaneous	-	-	-	-	**$545,640**
Lakeshore SSTS upgrades	$10,000	each		41	$410,000
Carp control	$25,000	per year	Fish trap	1	$25,000
Aluminum Sulfate Treatment	$800	acre	Recommended applying to zones 15 feet or deeper	50.8	$40,640
Aquatic Plant Management	$70,000	per year	Chemical or Mechanical removal of invasive aquatic plant species replacing with native aquatic plant species	1	$70,000

3.0 Reasonable Assurances

Reasonable assurances are to demonstrate the ability to reach and maintain the water quality goal. A number of factors impact reasonable assurance, including a thorough knowledge of the ability to implement BMPs. Benton and Morrison Soil and Water Conservation Districts will be critical to providing reasonable assurance that Little Rock Lake can meet the desired water quality endpoint and they have excellent track records in providing the required support.

Benton and Morrison Soil and Water Conservation Districts have a history of successfully installing Best Management Practices (BMPs) in the Little Rock Lake Watershed. Both Soil and Water Conservation Districts have formed many relationships over the years. Benton and Morrison SWCDs have continued to build successful relationships with multiple agencies across central Minnesota. Those agencies include, but are not limited to, Benton County officials, Morrison County officials, NRCS, MPCA, MN DNR Fisheries, MN DNR Waters, U.S. Fish and Wildlife Service, and BWSR. In addition to working with multiple agencies the SWCDs have also worked with the Little Rock Lake Association in developing a highly successful Native Buffer Program.

Benton and Morrison SWCDs strive to connect with the citizens of Little Rock Lake Watershed. In 2002, a survey was conducted to identify changes citizens have noticed in the watershed, identify citizens concerns and to identify what landowners would be willing to do to improve water quality. Over many years the SWCDs have formed solid relationships with citizens in the Little Rock Lake Watershed. The districts continue to build existing and new relationships with residents of the Little Rock Lake Watershed.

Benton SWCD formed a Little Rock Watershed Stakeholder Committee in 2010. This committee consists of 15 elected members, who live or work in the Little Rock watershed, including one citizen representative from the seven townships within the watershed, a County Commissioner from Benton and Morrison Counties, a SWCD Supervisor from Benton and Morrison County, as well as a representatives from the Little Rock Lake Association, Mid-Minnesota Trout Unlimited Association, East Central Irrigation Association and New Heights Dairy. The goal of this committee is to develop and implement management actions in the Little Rock Watershed related to the Little Rock Lake and Little Rock Creek TMDL projects. This committee will continue to meet after the completion of the TMDL projects.

Education and outreach is another important also strong reasonable assurance that Benton and Morrison SWCDs can provide. Education is a vital part of what Benton and Morrison Soil and Water Conservation District does. Benton SWCD has held biennial winter workshops on a wide range of conservation topics/programs. Benton SWCD has also worked diligently with the Little Rock Lake Association in educating lakeshore residents in the installation and maintenance of Native Buffers. Benton and Morrison SWCDs hold conservational tours demonstrating land use complexities, conservation solutions, controversies, and successes. Both districts provide technical assistance to landowners interested in conservational practices. Education plays a crucial role in protecting the natural resources of Benton and Morrison Counties and will continue to be incorporated to educate residents in the Little Rock Lake watershed about the lake's impairment and necessary improvements that need to take place.

On November 4, 2008, Minnesota voters approved a proposed Clean Water, Land and Legacy Amendment. Sales tax revenue is deposited in the state General Fund. The Amendment increased the general sales and use tax rate by three-eighths of one percentage point (0.375) to 6.875% and dedicated the additional proceeds to four categories, including a category to protect, enhance, and restore water quality in lakes, rivers, streams, and groundwater, drinking water sources (MN DNR). This is just one potential funding source for projects. Others include but not are limited to: Natural Resource Block Grants (NRBG) and State Cost Share (SCS) through the Board of Soil and Water Resources (BWSR), 319 Grants through Minnesota Pollution Control Agency (MPCA) as well as funding for individual projects through Natural Resources Conservation Service's (NRCS) multiple programs.

4.0 Public Participation

Little Rock Lake TMDL public participation began in 2008 with a public meeting held by Benton SWCD on July 29, 2008 at Sauk Rapids-Rice Middle School. This first public meeting covered an overview of the TMDL process, the importance of stakeholder participation, historical overview of Little Rock Lake, project workplan, schedule, goals and technical and financial assistance. 78 individuals attended this meeting, and a complete list of attendees is located in the Appendix C.

A Technical Advisory Committee (TAC) was created so that interested expert stakeholders could be involved in decisions during the TMDL process. These individuals provided feedback, and input into the project from their individual fields of expertise. The committee as a whole had a broad representation, all coming with different technical backgrounds. Table 9 highlights TAC members. Technical Advisory Committee meetings were held on June 24, 2008, March 10, 2009, and December 8, 2010.

Table 9 Technical Advisory Committee Members

Attendees	Area of Representation
Adam Birr	MDA
Bill James	ERDC Eau Galle Aquatic Ecology Laboratory
Bill Walker	Consultant (Modeler)
Bruce Wilson	MPCA
Chuck Johnson	MPCA
Dan Lais	Minnesota DNR
Gerry Maciej	Benton SWCD
Jeff Hrubes	BWSR
Katie Winkelman	Benton SWCD
Maggie Leach	MPCA
Mark Evenson	MPCA
Marshall Deters	Minnesota DNR
Nick Proulx	Minnesota DNR
Paul Garrison	Wisconsin DNR
Steve Marod	Minnesota DNR

A Little Rock Watershed Stakeholder Committee was established to develop and implement management actions in the Little Rock Watershed related to the Little Rock Lake and Little Rock Creek Total Maximum Daily Load (TMDL) projects. The Little Rock Watershed Committee consists of 15 members who live or work in the Little Rock Watershed, including one citizen representative from each township within the Little Rock Watershed boundary, a County Commissioner from Benton and Morrison Counties and one SWCD Supervisor from each county, as well as representatives from the Little Rock Lake Association, Mid-Minnesota Trout Unlimited Association, East Central Irrigation Association and New Heights Dairy. A complete list of members is illustrated in Table 10. Three meetings were held, July 27, 2010, August 31, 2010, and December 14, 2010.

Table 10 Little Rock Watershed Stakeholder Committee Members

Attendees	**Area of Representation**
Joe Wollak	Benton County Commissioner
Don Meyer	Morrison County Commissioner
Bernie Thole	Benton SWCD Supervisor Board Member
Marvin Stangl	Morrison SWCD Supervisor Board Member
Ed Popp	Langola Township – Benton County
Chuck Popp	Graham Township – Benton County
Diane Wojtanowicz	Watab Township – Benton County
Lawrence Thell	Mayhew Lake Township – Benton County
Ray Sieben	Buckman Township – Morrison County
Robert Stuckmayer	Morrill Township – Morrison County
Jeff Tiemann	Bellevue Township – Morrison County
Guy Spence	Little Rock Lake Association
Ken Nodo	Trout Unlimited Association
Rick Schlichting	East Central Irrigation Association
Brent Czech	New Heights Dairy

A second public stakeholder meeting took place on January 5, 2011 at the Sauk Rapids-Rice Middle School Community Art Center. Two sessions were held to reach maximum participation; the first session 1:30 – 3:30 PM, second session 6:00 – 8:00 PM. A total of 82 individuals attended these public meetings. A complete list of attendees can be located in the Appendix C. The meetings covered a brief overview of the TMDL process, history of Little Rock Lake TMDL Project, results of the modeling and the new goals of the lake and open discussion on implementation strategies.

In preparation for the second public stakeholder meeting Benton SWCD staff attended the meetings displayed in Table 11 to provide the public another opportunity to ask questions and give their input and advertise the upcoming public stakeholder meeting.

Table 11 Meetings Attended by Benton SWCD in Preparation to January 5, 2011 Public Meeting

Meeting Name	Date of Meeting
Benton County Board of Commissioners	12/09/2010
Little Rock Lake Association	12/11/2010
Graham Township	12/13/2010
Buckman Township	12/13/2010
Morrill Township	12/14/2010
Langola Township	12/15/2010
Morrison County Board of Commissioners	12/21/2010
Watab Township	01/04/2011
Mayhew Township	01/04/2011

Due to scheduling conflicts Benton SWCD will not be able to attend Bellevue Township meeting until 02/02/2011. This TMDL will go through the formal public notice process set forth by the Minnesota Pollution Control Agency and the Environmental Protection Agency, with assistance provided by Benton SWCD. The SWCD will respond to all comments received during the public notice process.

5.0 Conclusions

1. Historical data indicate that LRL summer mean TP concentrations increased from ~125 ppb in 1979-1981 to ~270 ppb in 2006-2008, as compared with the 60 ppb water quality standard. Corresponding increases in chlorophyll-a and decreases in transparency were observed. While it is clear that significant reductions in TP concentration are required to achieve the standard, interpretation of the historical water quality deterioration is complicated by climatologic variations, data limitations, potential long-term effects of P buildup in the lake sediments, and potential trends in land use types and intensities.

2. Lake TP concentrations are highly correlated with chlorophyll-a levels, Secchi depths, and user perceptions of aesthetic qualities and suitability for recreational use. Algal blooms in LRL are highly responsive to variations in watershed P loads, recycling of historical P loads from bottom sediments, and climate. Toxic bluegreen algal blooms and noxious hydrogen sulfide odors were observed in 2007, when spring runoff contained the highest TP concentrations and loads. High concentrations of other nutrients and fecal coliforms indicate that animal waste was an important source. The blooms were likely accelerated later in the summer by low inflows and warm temperatures.

3. Modeling results indicate that achieving the eutrophication water quality standards for TP, chl-a, and secchi depth would require reducing the tributary flow-weighted-mean concentrations to 83 ppb or less. Reductions in load relative to existing conditions range from 54% to 69% for the individual tributaries, although these estimates could vary considerably because of uncertainty in baseline loads derived from the 2006-2008 data.

4. Despite uncertainty in forecasting the ultimate lake responses to reducing external loads as prescribed by the TMDL, achieving incremental reductions in TP load and lake concentrations over the course of TMDL implementation are expected to provide incremental reductions in algal bloom severity and increases in transparency that would be perceptible by lake users.

5. Continued monitoring is essential to improve the TMDL baseline and track lake responses to implementation of P loading controls over a range of climatologic conditions.

6. Adaptive implementation of the TMDL is necessary, given the uncertainties associated with predicting the time scales and ultimate responses to load reductions. The opportunity to revise the lake goal and/or load allocation in the future based upon additional data and model refinements will reduce the uncertainties and provide greater assurance that lake management goals will eventually be achieved.

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7.0 Appendix

Appendix A – State of Minnesota Office Memorandum

Appendix B – Appendix Development of Phosphorus TMDL for Little Rock Lake, Minnesota

DEPARTMENT: POLLUTION CONTROL AGENCY

SF-00006-05 (4/86)

STATE OF MINNESOTA

Office Memorandum

DATE: July 31, 2007

TO: Shannon Lotthammer
Manager
Water Monitoring Section

FROM: Steve Heiskary
Research Scientist III
Water Monitoring Section
Environmental Analysis and Outcomes Division

PHONE: 651-296-7217

SUBJECT: Little Rock Lake (05-0013) Investigation and Recommendation for Inclusion on 2008 303(d) Draft List for Nutrient Impairment

Little Rock Lake experienced very severe algal blooms over the past few weeks in July and these blooms raised extensive concerns with lakeshore property owners and lake users. These concerns were forwarded to the Minnesota Pollution Control Agency (MPCA) and Minnesota Department of Natural Resources (MDNR). Multiple staff from the MPCA surveyed conditions on the lake during the week of July 23, 2007. This memorandum will focus primarily on sampling conducted by Harold Wiegner, David Tollefson (intern) and myself on July 25 but will also note an initial investigation by Matt Lindon and Kelly O'Hara on July 12, 2007.

Background

Little Rock is a relatively large (~1,270 acre) but shallow lake (mean depth = 8 feet and maximum depth = 19 feet) in Benton County that drains to the Mississippi River. It has a very large (~68,000 acre) agriculturally dominated watershed. It has been studied on at least two occasions by MPCA as reflected in a 1971 investigational report and a detailed Lake Assessment (LAP) study conducted in 1990. The LAP report may be found at http://www.pca.state.mn.us/publications/reports/lar-05-0013.pdf . Data from this and more recent efforts may be found at Environmental Data Access (EDA) at http://www.pca.state.mn.us/data/eda/STresults.cfm?stID=05-0013&stOR=MNPCA1&year=2007 . These data suggest hypereutrophic conditions for the lake. Findings from the LAP report and more recent data in EDA will be used to place 2007 in perspective.

July 25th sampling effort

Water samples and field measurements were collected at four sites on the lake: 1) beach/access at Benton County Park on the north side; 2) Little Rock Creek inflow bay; 3) west side of lake near 105th Avenue; and lake outlet at public access at US Highway 10 as noted in Figure 1 and the pictures of each site. At each site algal toxin samples were collected for microcystin and saxitoxin analysis. Field measures of dissolved oxygen, temperature, pH and conductivity were taken at all sites and total phosphorus and chlorophyll-a samples were collected at sites 1 and 4. Sites 1 and 4 represent actual "water" samples while sites 3 and 4 were collected amidst the algal blooms that had accumulated along the shoreline. Field and laboratory data are summarized in the following tables and data from July 30, 1990 are offered for perspective.

Table 1. Field data from July 25, 2007 and data from 1990 LAP study

Site	Dissolved oxygen (mg/L)	Temperature (C)	pH (SU)	Conductivity (µmhos/cm)
1. Beach	13.4	27.5	9.7	237
2. L. Rock Creek	0.2	29.2	8.1	368
3. West side	--	--	--	--
4. L. Rock outlet	13.3	28.9	9.9	239
July 30, 1990 (mid-lake sample)	10.1	21.0		250

Table 2. Lab data from July 25, 2007 and data from 1990 LAP study

Site	Total phosphorus (ppb)	Chlorophyll -a (ppb)	Pheophytin-a (ppb)
1. Beach	271	120	4.0
2. L. Rock Creek	---	----	
3. West side	---	---	
4. L. Rock outlet	431	127	5.5
July 30, 1990 (mid-lake sample)	210	126	2.4

Table 3. Algal toxin data from July 25, 2007 and July 12

Site	Microcystin (µg/L)	Saxitoxin (ng/L)
1. Beach	22	<0.02
2. L. Rock Creek	38,000	0.03
3. West side	>80,000	0.04
4. L. Rock outlet	17	<0.02
July 12 – south side	120	

Water temperatures were exceedingly warm on July 25, 2007 as compared to July 30, 1990. Dissolved oxygen was supersatured at sites 1 and 4 and is a direct reflection of algal productivity. pH values were elevated at these sites as well for the same reason. Conductivity (an indirect measure of dissolved minerals in the water) was rather similar in July 2007 as compared to July 1990.

Total phosphorus (TP) was high on July 25, 2007 (indicative of hypereutrophic conditions) and both samples were higher than the corresponding sample in 1990. TP at the outlet (site 4) was higher than site 1 and this may be an indication of internal recycling within the lake; however this is difficult to ascertain with a single sample. The 1990 LAP study indicated that TP increased from May through September, which often is an indication of internal phosphorus recycling.

Chlorophyll-a concentrations were exceedingly high on July 25, 2007 and indicative of severe nuisance blooms. These values though were quite comparable to the sample from July 30, 1990 (Table 2). The dominant alga on July 25, 2007 was the blue-green Microcystis -- a form noted for its ability to produce the toxin microcystin. Microcystis and another blue-green – Aphanizomenon (also a toxin-producer) were dominant in the July 30, 1990 sample.

Algal toxin samples were collected on July 25 and during an initial investigation by Matt Lindon and Kelly O'Hara on July 12, 2007 (Table 3). The World Health Organization (WHO) provides a basis for placing the microcystin concentrations in perspective in terms of human health risk as follows:
< 10 ppb – low risk; 10-20 ppb – moderate risk, 20-2,000 ppb – high risk and >2,000 – very high risk. Further details on blue-green algal toxins and levels of microcystin in Minnesota lakes may be found at:
http://www.pca.state.mn.us/water/clmp-toxicalgae.html and
http://www.pca.state.mn.us/publications/reports/wq-lar3-11.pdf respectively.

Based on the WHO categories the sample taken on July 12, 2007 is considered high risk. The two open water samples (site 1 and 4) on July 25th are considered moderate to high risk and the two samples taken amidst the blooms (sites 2 and 3) would be very high risk. The saxitoxin levels are below or just above detection, which is consistent with other work that suggests saxitoxin concentrations are typically quite low in freshwater algal blooms. The microcystin results support the recommendations to avoid contact with the water.

Impaired waters (303(d)) listing

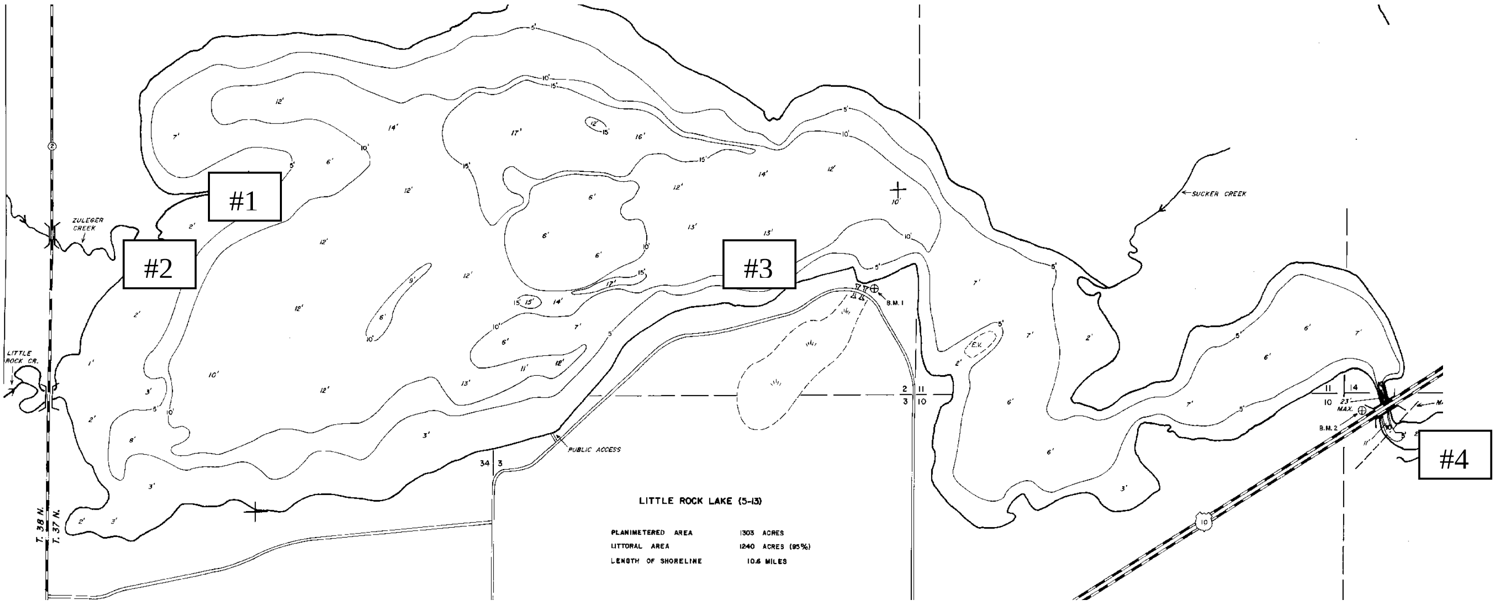
Because eutrophication criteria have not yet been adopted into standards the existing trophic status thresholds are the primary basis for the 2008 303(d) assessment; however for purposes of discussion the draft criteria have been included as well (Tables 5 and 6). When data was compiled for the current 2008 303(d) assessment (considers data collected from 1997 – 2006), in spring 2007, Little Rock Lake was not included because it had insufficient data. In fact no TP or chlorophyll-a data had been collected since the 1990 LAP study. Since that time data have been added to EDA for 2003 and 2006 and when combined with the 1990 LAP data this provides a good basis for assessing Little Rock Lake (Table 4).

Table 4. Little Rock trophic status. Summer (June to September) means. Number of sample dates noted.

	TP		**Chl-a**		**Secchi**	
	mean	N	**mean**	N	**mean**	N
1990	179	4	91	4	0.5	62
2003&2006	132	7	77	7	0.7	16
	ppb		**ppb**		**m**	

These values (Table 4) suggest that Little Rock is well above the TP, chlorophyll-a, and Secchi thresholds for North Central Hardwoods Forests Lakes (Table 5) and is also above recommended criteria for shallow lakes in that region as well (Table 6). In addition, algal toxin testing indicates elevated levels of microcystin relative to WHO thresholds, which is an additional factor to consider for 303(d) listing based on the most recent assessment guidance document (http://www.pca.state.mn.us/publications/wq-iw1-06.pdf page 66). Given this weight of evidence I am recommending that Little Rock Lake be included on the 2008 draft 303(d) list.

Figure 1. Little Rock map and sample sites.



← North

Site 1. Boat Access north side

Site 2. Little Rock Creek

.

Site 3. West side of lake

Site 4. Outlet of lake

Table 5. Trophic Status Thresholds for Determination of Use Support for Lakes. (Carlson's TSI Noted for Each Threshold.)

Ecoregion (TSI)	TP ppb	Chl ppb	Secchi m	TP Range ppb	TP ppb	Chl ppb	Secchi m
305(b):	Full Support			Partial Support to Potential Non-Support			
303(d):	Not Listed			Review	Listed		
NLF	< 30	<10	≥ 1.6	30 – 35	> 35	> 12	< 1.4
(TSI)	(< 53)	(< 53)	(< 53)	(53-56)	(> 56)	(> 55)	(> 55)
CHF	< 40	< 15	≥ 1.2	40 - 45	> 45	> 18	< 1.1
(TSI)	(< 57)	(< 57)	(< 57)	(57 – 59)	(> 59)	(> 59)	(> 59)
WCP & NGP	< 70	< 24	> 1.0	70 - 90	> 90	> 32	< 0.7
(TSI)	(< 66)	(< 61)	(< 61)	(66 – 69)	(> 69)	(> 65)	(> 65)

TSI = Carlson trophic state index; Chl = Chlorophyll-a; ppb = parts per billion or µg/L; m = meters

Table 6. Proposed eutrophication criteria by ecoregion and lake type.

Ecoregion	TP	Chl-a	Secchi
	ppb	ppb	meters
NLF – Lake trout (Class 2A)	**< 12**	**< 3**	**> 4.8**
NLF – Stream trout (Class 2A)	**< 20**	**< 6**	**> 2.5**
NLF – Aquatic Rec. Use (Class 2B)	**< 30**	**< 9**	**> 2.0**
CHF – Stream trout (Class 2a)	**< 20**	**< 6**	**> 2.5**
CHF – Aquatic Rec. Use (Class 2b)	**< 40**	**< 14**	**> 1.4**
CHF – Aquatic Rec. Use (Class 2b) Shallow lakes	**< 60**	**< 20**	**> 1.0**
WCP & NGP – Aquatic Rec. Use (Class 2B)	**< 65**	**< 22**	**> 0.9**
WCP & NGP – Aquatic Rec. Use (Class 2b) Shallow lakes	**< 90**	**< 30**	**> 0.7**

Appendix B

Development of Phosphorus TMDL for Little Rock Lake, Minnesota

Page	Contents

A-1   # Approximate Water & Mass Balances, March-October 2006-2008

Term	Area km^2	Flow hm^3	Load kg	Flow-Weighted Conc ppb	Std Error	Samples	Runoff cm	Unit Area Load kg/km^2	Percent of Total Lake Inflow % Area	% Flow	% Load	Flow cfs
Little Rock Creek Gauged Sub-Basins												
Bunker Hills	50.51	3.2	927	287	0.20	38	6.4	18	19%	12%	18%	8.1
LRC North - CR40	104.50	8.1	1292	160	0.13	46	7.7	12	39%	29%	25%	20.3
Sum of Gauged	155.01	11.3	2218	196		84	7.3	14	58%	41%	44%	28.4
Lake Inflows												
LR Creek - CH12	178.25	16.1	2958	184	0.18	47	9.0	17	67%	58%	58%	40.4
Zuleger	48.03	4.3	1148	265	0.16	44	9.0	24	18%	16%	23%	10.9
Sucker **	11.20	2.2	403	182	0.08	25	19.8	36	4%	8%	8%	5.6
Total Gauged	237.48	22.7	4510	199	0.12	116	9.5	19	89%	82%	88%	56.9
Ungauged Local	25.17	2.3	418	184	0.25		9.0	17	9%	8%	8%	5.7
Total Watershed	262.64	24.9	4927	198	0.16		9.5	19	98%	90%	97%	62.6
Shoreline Septic Tanks			90		0.50						2%	
Total External	262.64	24.9	5018	201	0.16		9.5	19	98%	90%	98%	62.6
Rainfall	5.10	2.7	81	30	0.30		53.0	16	2%	10%	2%	6.8
Total	267.74	27.6	5099	185	0.16	116	10.3	19	100%	100%	100%	69.4
Evaporation		3.8					75.2			14%		9.6
Net Inflow	267.74	23.8	5099	214	0.16	116		19			100%	59.7
Outflow	267.74	23.6	3195	135	0.13	26	8.8	12	100%	85%	63%	59.2
Net Inflow - Outflow		0.21	1904		0.47						37%	
Initial Storage		11.51	1151	100								
Final Storage		11.72	1485	127								
Mean Storage		11.85	2416	204								
Storage Increase		0.21	334									
Net Retention		0.00	1570		0.57						31%	

Red Cells Are Input Values

Lake Area	5.1	km^2
Lake Mean Depth	2.4	m
Rainfall P	30	ppb
Length of Averaging Period	0.67	March-October
Hydraulic Resid Time	127	days

RSE *	Relative Std Error of Load & FWM estimate
Ungauged (Lakeshed)	Drainage Area Ratio; Flow & Load = 0.14 x LRC
Zuleger Flow (Ungauged)	Drainage Area Ratio; Flow = 0.27 x LRC
Net Inflow	Inflow + Rainfall - Evaporation
Lake Outflow Volume	Water Balance
Storage	Computed from lake volume and lake-mean concentrations
Lake Outlet P Conc	0.92 x Lake Mean Conc (Calibrated to 2008 data)
Net Retention	Net Inflow - Outflow - Increase in Storage
Precipitation	http://climate.umn.edu; NWS stations Near Rice
Evaporation	Regional monthly means. Van der Leen at al, Water Encyclopedia. 1990.
Missing Flows	< July 2006; Regression vs. LRC_CH40;
Load Calculations	Gauged Sites; Daily Time Step; Regress Conc vs. Flow & Season; Interpolate Residuals; Walker & Havens, 2003.

Computation of Shoreline Septic Tank Loads

Septic Tanks	300	
People/Tank	3	
Seasonal Load Factor	1	
Unit Load To Tank	0.66	kg/cap-yr
Total Source Load	475.2	kg
Functioning Tank Reduc	90%	
Percent Failing Tanks	10%	
Load to Lake Per Tank	0.30	kg
Total Load to Lake	90.3	kg/yr

* Relative standard error = standard error / predicted value; estimates do not reflect uncertainty resulting from data gaps, flow estimates, ungauged watersheds, and drought conditions
Loads and mass balances are at best approximations and not representative of long-term averages; additional data needed to refine estimates and provide baseline for TMDL implementatior

** Runoff from Sucker Creek exceeds values measured in other watersheds (20 cs. 6-9 cm/yr). It is possible that this reflects inflow from the adjacent Mayhew Creek basin
Aerial photography and GIS hydrography layer indicate that these basins are connected by a drainage ditch, which is not reflected in the hydrologic unit boundary.

A-2 Water & Mass Balances for 2006-2008 & 1991-2009 Baseline Scenarios

2006-2008							Load
Source	Area km^2	Flow hm^3	Load kg	Conc ppb	Runoff cm	Load kg/km^2	% Total
Bunker Hills	50.5	3.2	927	287	6.4	18.3	18%
LRC North - CR40	104.5	8.1	1292	160	7.7	12.4	25%
Lake Inflows							
LR Creek - CH12	178.2	16.1	2958	184	9.0	16.6	58%
Zuleger	48.0	4.3	1148	265	9.0	23.9	23%
Sucker	11.2	2.2	403	182	19.8	36.0	8%
Total Gauged	237.5	22.7	4510	199	9.5	19.0	88%
Ungauged Local	25.2	2.3	418	184	9.0	16.6	8%
Total Watershed	262.6	24.9	4927	198	9.5	18.8	97%
Shoreline Septic Tanks			90				2%
Total External	262.6	24.9	5018	201	9.5	19.1	98%
Rainfall	5.1	2.7	81	30	53.0	15.9	2%
Total	267.7	27.6	5099	185	10.3	19.0	100%
Evaporation		3.8					
Net Inflow	267.7	23.8	5099	214	8.9	19.0	100%

TMDL Baseline Conditions, 1991-2009 Hydrology							Load
Source	Area km^2	Flow hm^3	Load kg	Conc ppb	Runoff cm	Load kg/km^2	% Total
Bunker Hills	50.5	4.4	1267	287	8.7	25.1	18%
LRC North - CR40	104.5	11.1	1766	160	10.6	16.9	26%
Lake Inflows							
LR Creek - CH12	178.2	22.0	4046	184	12.3	22.7	58%
Zuleger	48.0	5.9	1570	265	12.3	32.7	23%
Sucker	11.2	3.0	551	182	27.1	49.2	8%
Total Gauged	237.5	31.0	6167	199	13.0	26.0	89%
Ungauged Local	25.2	3.1	571	184	12.3	22.7	8%
Total Watershed	262.6	34.1	6739	198	13.0	25.7	97%
Shoreline Septic Tanks			90				1%
Total External	262.6	34.1	6829	200	13.0	26.0	99%
Rainfall	5.1	3.1	94	30	61.6	18.5	1%
Total	267.7	37.2	6923	186	13.9	25.9	100%
Evaporation		3.8					
Net Inflow	267.7	33.4	6923	207	12.5	25.9	100%

Adjustment of 2006-2008 Hydrology to 1991-2009 Baseline

March-October	2006-2008	1991-2009	Ratio	
Elk River Runoff cm	8.1	11.9	1.46	
Sauk River Runoff cm	11.0	14.0	1.28	Mean of Elk & Sauk = 1.37
LRL Runoff cm	9.5	13.0	1.37	
Precipitation @ Rice cm	53.0	61.6	1.16	

A-3 Water & Mass Balances for TMDL & Interim Scenarios

TMDL Conditions	Tributary TP = 83 ppb					Unit Area	Load	Load
Source	Area km^2	Flow hm^3	Load kg	Conc ppb	Runoff cm	Load kg/km^2	% Total	% Reduc
Bunker Hills	50.5	4.4	366	83	8.7	7.2	11%	71%
LRC North - CR40	104.5	11.1	919	83	10.6	8.8	28%	48%
Direct Lake Inflows								
LR Creek - CH12	178.2	22.0	1827	83	12.3	10.2	56%	55%
Zuleger	48.0	5.9	492	83	12.3	10.2	15%	69%
Sucker	11.2	3.0	252	83	27.1	22.5	8%	54%
Total Gauged	237.5	31.0	2571	83	13.0	10.8	79%	58%
Lakeshed	25.2	3.1	571	184	12.3	22.7	18%	0%
Total Watershed	262.6	34.1	3142	92	13.0	12.0	97%	53%
Shoreline Septic Tanks *			0				0%	
Stormwater **			2				0%	
Total External	262.6	34.1	3144	92	13.0	12.0	97%	54%
Rainfall	5.1	3.1	94	30	61.6	18.5	3%	0%
Total	267.7	37.2	3238	87	13.9	12.1	100%	53%
Evaporation		3.8						
Net Inflow	267.7	33.4	3238	97	12.5	12.1	100%	53%
Outflow	267.7	33.4	2271	68	12.5	8.5	70%	53%

Predicted Lake Water Quality	Predicted	10%	90%	Standard
Total Phosphorus ppb	60	42	85	60
Chlorophyll-a ppb	18	10	32	20
Secchi Depth m	1.08	0.79	1.47	1.0

Interim Goal	Tributary TP = 120 ppb					Unit Area	Load	Load
Source	Area km^2	Flow hm^3	Load kg	Conc ppb	Runoff cm	Load kg/km^2	% Total	% Reduc
Bunker Hills	50.5	4.4	529	120	8.7	10.5	12%	58%
LRC North - CR40	104.5	11.1	1328	120	10.6	12.7	30%	25%
Direct Lake Inflows								
LR Creek - CH12	178.2	22.0	2641	120	12.3	14.8	59%	35%
Zuleger	48.0	5.9	712	120	12.3	14.8	16%	55%
Sucker	11.2	3.0	364	120	27.1	32.5	8%	34%
Total Gauged	237.5	31.0	3717	120	13.0	15.7	83%	40%
Lakeshed	25.2	3.1	571	184	12.3	22.7	13%	0%
Total Watershed	262.6	34.1	4288	126	13.0	16.3	96%	36%
Shoreline Septic Tanks			90				2%	
Total External	262.6	34.1	4379	128	13.0	16.7	98%	36%
Rainfall	5.1	3.1	94	30	61.6	18.5	2%	0%
Total	267.7	37.2	4473	120	13.9	16.7	100%	35%
Evaporation		3.8		0				
Net Inflow	267.7	33.4	4473	134	12.5	16.7	100%	35%
Outflow	267.7	33.4	3137	94	12.5	11.7	70%	35%

Predicted Lake Water Quality	Mean	10%	90%	Standard
Total Phosphorus ppb	78	55	111	60
Chlorophyll-a ppb	24	14	42	20
Secchi Depth m	0.88	0.64	1.19	1.0

Model Equations:

Q = Net Inflow hm^3 L = TP Load kg PI = Avg Inflow Conc ppb = L / Q f = fraction of year, march-oct = 0.67

A = Lake Area = 5.1 km^2 Z = Mean Depth = 2.4 m T = Hydraulic Resid Time years = A Z f / Q

SE = prediction standard error, ln-transformed, typical value for empirical models (Walker,1985)

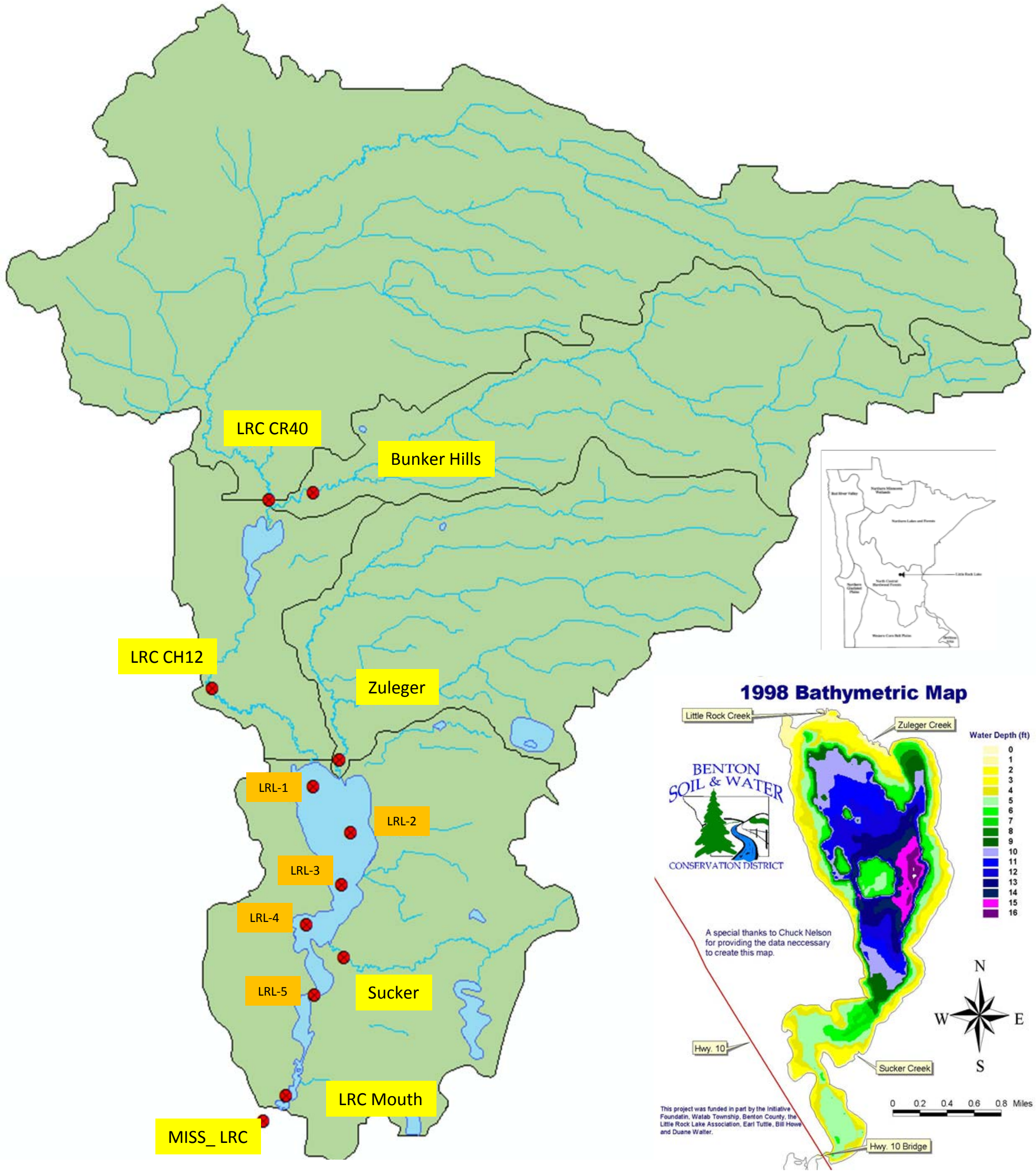
F10 = Scale Factor, 10th Percentile = EXP (-1.28 SE) F90 = ErrorScale Factor, 90th Percentile = EXP (+ 1.28 SE)

Predicted Values	Equation	SE	F10	F90	Reference
P = Lake TP ppb	$PI \,/\, [\,1 + 0.162\, T^{0.542}\, PI^{0.458}\,]$	0.272	0.71	1.42	Canfield/Bachman (1981) Lake Model
Chla = Chlorophyll-a ppb	log10(Chl-a) = 1.08 log10 (TP) - 0.66	0.437	0.57	1.75	Shallow Lakes (Heiskary & Wilson, 2008, Eq 4)
S = Secchi Depth m	$26.985\ P^{-0.7861}$	0.242	0.73	1.36	Shallow Lakes (Heiskary & Lindon, 2005, Fig 13)

* Direct discharge from septic systems is not permitted under MN state law; therefore the TMDL allocation for septic systems is set to zero .

** Allowance for stormwater loads associated with future urban development set a 0.05% of the TMDL (2 kg)

A-4 Lake & Watershed Monitoring Sites



ALIAS	STORET	DESCRIPTION	LAT	LONG	TYPE
BUNKER	S004-063	BUNKER HILL CR AT CR 56, 4 MI NE OF RICE, MN	45.803	-94.176	Stream
LRCR_CR40	S004-062	LITTLE ROCK CR AT CR 40, 3.5 MI NE OF RICE, MN.	45.801	-94.189	Stream
LRCR_CH12	S004-061	LITTLE ROCK CR AT CSAH 12, 1 MI NE OF RICE, MN	45.764	-94.205	Stream
SUCKER	S004-064	SUCKER CR AT SUCKER CR RD, 3.8 MI SE OF RICE, MN	45.711	-94.165	Stream
ZULEGER	S002-447	ZULEGER CR AT CSAH-2. 2.5 MI E OF RICE, MN	45.750	-94.167	Stream
LRC_MOUTH	S005-004	LITTLE R CK AT HARRIS CHANNEL, 4.5 MI NE OF SARTELL	45.684	-94.182	Stream
MISS_LRC	S004-320	MISSISSIPPI RIVER ABOVE LRC	45.679	-94.188	Stream
LRL_1	205	LITTLE ROCK LAKE (05-0013)	45.745	-94.174	Lake
LRL_2	204	LITTLE ROCK LAKE (05-0013) Deepest Point	45.736	-94.163	Lake
LRL_3	209	LITTLE ROCK LAKE (05-0013)	45.726	-94.166	Lake
LRL_4	211	LITTLE ROCK LAKE (05-0013)	45.718	-94.176	Lake
LRL_5	212	LITTLE ROCK LAKE (05-0013) Above Lake Outlet	45.704	-94.173	Lake
LRL_DS	05-0012	UNNAMED (LITTLE ROCK CHAIN) 4.3 MI SE OF RICE	45.699	-94.176	Lake

A-5 Monthly Mean Water Quality Data by Site and Parameter, 2006-2008

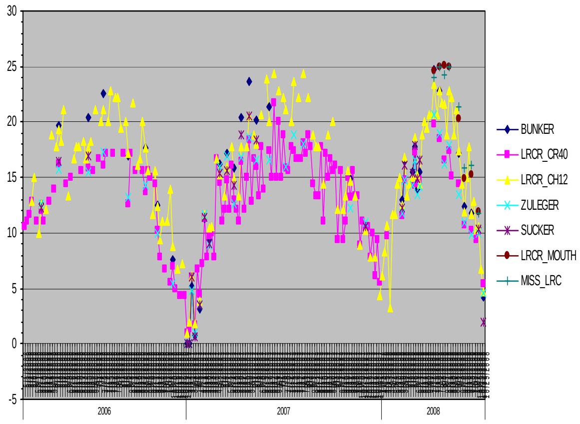
		Month								Spring	Summer	Year
Data	SITE	3	4	5	6	7	8	9	10	3-5	6-9	3-10
TP Samples	LRC_CR40	3	5	7	9	6	6	5	6	15	26	47
	BUNKER_HILL	3	4	7	9	3	2	5	5	14	19	38
	LRC_CH12	3	5	7	9	6	6	5	6	15	26	47
	ZULEGER	3	4	7	9	6	5	5	5	14	25	44
	SUCKER	3	4	7	8				3	14	8	25
	LAKE		1	2	3	14	13	16	11	3	46	60
	LRC_MOUTH					2	2	3	1	0	7	8
	MISS_LRC					2	2	3	1	0	7	8
TP ppm	LRC_CR40	0.64	0.09	0.07	0.10	0.05	0.04	0.06	0.05	0.26	0.06	0.14
	BUNKER_HILL	1.13	0.13	0.08	0.18	0.04	0.14	0.14	0.09	0.45	0.13	0.24
	LRC_CH12	0.81	0.10	0.06	0.15	0.07	0.06	0.06	0.06	0.32	0.08	0.17
	ZULEGER	1.09	0.17	0.13	0.23	0.14	0.11	0.10	0.07	0.46	0.14	0.25
	SUCKER	0.54	0.11	0.13	0.19				0.07	0.26	0.19	0.21
	LAKE		0.12	0.16	0.18	0.32	0.42	0.31	0.15	0.14	0.31	0.24
	LRC_MOUTH					0.16	0.16	0.17	0.09		0.16	0.14
	MISS_LRC					0.05	0.05	0.03	0.03		0.04	0.04
SRP ppm	LRC_CR40	0.44	0.04	0.03	0.04	0.03	0.03	0.04	0.03	0.17	0.03	0.08
	BUNKER_HILL	0.73	0.08	0.04	0.06	0.02	0.12	0.11	0.07	0.28	0.08	0.15
	LRC_CH12	0.54	0.04	0.02	0.04	0.04	0.03	0.03	0.03	0.20	0.04	0.10
	ZULEGER	0.77	0.11	0.08	0.11	0.09	0.08	0.07	0.06	0.32	0.09	0.17
	SUCKER	0.46	0.04	0.07	0.11				0.05	0.19	0.11	0.15
	LAKE		0.02	0.01	0.03	0.13	0.17	0.09	0.03	0.01	0.10	0.07
	LRC_MOUTH					0.03	0.06	0.01	0.01		0.03	0.03
	MISS_LRC					0.02	0.01	0.01	0.01		0.01	0.01
TKN ppm	LRC_CR40	5.86	1.67	0.89	1.18	0.42	0.41	0.50	0.82	2.80	0.63	1.47
	BUNKER_HILL	7.10	1.89	1.48	1.56	0.89	1.05	1.09	1.38	3.49	1.15	2.05
	LRC_CH12	6.26	1.54	0.92	1.34	0.53	0.65	0.59	0.88	2.91	0.78	1.59
	ZULEGER	6.63	1.79	1.19	1.54	0.49	0.45	0.38	0.72	3.20	0.71	1.65
	SUCKER	3.73	1.67	1.08	1.53				0.45	2.16	1.53	1.69
	LAKE					2.86	2.97	2.97	1.99		2.93	2.70
	LRC_MOUTH					1.79	1.56	1.70	1.20		1.68	1.56
	MISS_LRC					0.74	0.72	1.41	0.60		0.95	0.87
NH4-N ppm	LRC_CR40	2.14	0.06	0.01	0.03	0.01	0.01	0.02	0.02	0.74	0.02	0.29
	BUNKER_HILL	2.25	0.07	0.02	0.04	0.01		0.02	0.03	0.78	0.02	0.35
	LRC_CH12	2.07	0.09	0.02	0.10	0.01	0.01	0.01	0.06	0.73	0.03	0.30
	ZULEGER	2.19	0.17	0.04	0.09	0.02	0.01	0.01	0.01	0.80	0.03	0.32
	SUCKER	1.13	0.16	0.02	0.07				0.04	0.44	0.07	0.28
	LAKE		0.10			0.11	0.10	0.13	0.18	0.10	0.12	0.13
	LRC_MOUTH					0.01	0.03	0.01	0.01		0.02	0.02
	MISS_LRC					0.01	0.03	0.02	0.01		0.02	0.02
NOX-N ppm	LRC_CR40	2.43	2.82	5.29	4.03	10.71	10.48	7.77	6.12	3.51	8.25	6.21
	BUNKER_HILL	1.22	2.78	3.77	4.22	1.58	3.47	6.43	6.21	2.59	3.92	3.71
	LRC_CH12	2.43	3.12	4.84	3.47	6.06	6.27	6.41	5.70	3.47	5.55	4.79
	ZULEGER	1.47	3.03	4.31	4.46	4.28	3.55	3.66	5.37	2.94	3.99	3.77
	SUCKER	0.84	0.70	0.21	0.87				0.03	0.58	0.87	0.53
	LAKE		1.50			0.02	0.02	0.03	0.22	1.50	0.02	0.36
	LRC_MOUTH					0.05	0.01	0.01	0.01		0.02	0.02
	MISS_LRC					0.19	0.09	0.09	0.18		0.12	0.14
TSS ppm	LRC_CR40	16.93	3.47	3.40	2.27	3.30	1.65	2.32	1.84	7.93	2.38	4.40
	BUNKER_HILL	14.87	5.33	4.40	3.07	1.47	9.00	3.12	5.52	8.20	4.16	5.85
	LRC_CH12	20.17	6.27	4.02	4.27	2.07	2.25	2.56	1.72	10.15	2.79	5.41
	ZULEGER	19.93	11.73	2.30	3.20	2.13	2.50	4.52	1.54	11.32	3.09	5.98
	SUCKER	6.13	3.00	2.83	2.10				1.27	3.99	2.10	3.07
	LAKE					44.00	66.75	58.50	21.00		56.42	47.56
	LRC_MOUTH					21.50	24.00	31.00	12.00		25.50	22.13
	MISS_LRC					4.60	4.60	3.07	3.20		4.09	3.87
BOD ppm	LRC_CR40	18.43	1.25	0.88	0.77	1.00	1.00	1.35	1.00	6.85	1.03	3.21
	BUNKER_HILL	24.47	1.45	1.22	2.13	1.00	1.00	1.75	1.30	9.05	1.47	4.29
	LRC_CH12	22.97	1.50	2.62	1.38	0.95	1.25	1.20	1.03	9.03	1.20	4.11
	ZULEGER	20.50	1.65	0.90	0.87	0.80	1.00	1.05	0.97	7.68	0.93	3.47
	SUCKER	11.37	1.63	1.84	0.95				1.10	4.94	0.95	3.38
	LAKE											
	LRC_MOUTH											
	MISS_LRC											

A-5 Monthly Mean Water Quality Data by Site and Parameter, 2006-2008

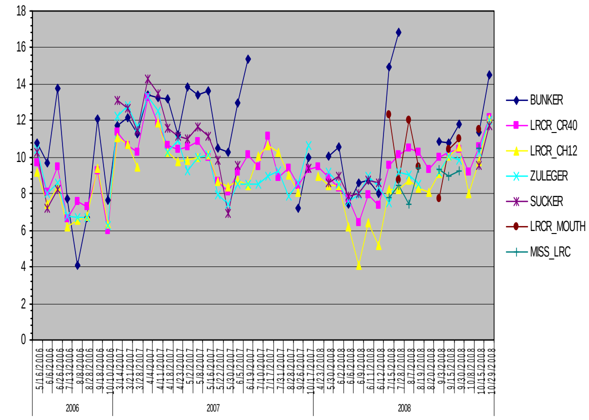
		Month								Spring	Summer	Year
Data	SITE	3	4	5	6	7	8	9	10	3-5	6-9	3-10
Turbidity NTU	LRC_CR40	9.80	4.74	3.47	6.01	3.63	1.73	1.59	2.91	6.00	3.24	4.24
	BUNKER_HILL	5.15	1.65	1.00	11.99	1.14	1.30	1.61	1.84	2.60	4.01	3.21
	LRC_CH12	11.23	5.54	7.07	5.08	1.68	2.52	2.17	3.53	7.95	2.86	4.85
	ZULEGER	10.23	3.20	3.31	19.69	1.96	2.16	2.13	1.76	5.58	6.48	5.56
	SUCKER	3.77	1.43	1.54	10.48				0.87	2.24	10.48	3.62
	LAKE			15.05	63.29	57.07	77.85	64.46	21.88	15.05	65.67	49.93
	LRC_MOUTH					25.04	26.43	22.50	8.72		24.66	20.67
	MISS_LRC					4.11	6.18	2.52	2.58		4.27	3.85
FCOLI cfu/100 ml	LRC_CR40	1215.33	25.00	146.67	440.00	234.00	656.67	260.00	75.00	462.33	397.67	381.58
	BUNKER_HILL	2016.67	2107.25	70.83	202.67	230.00	185.00	390.00	3220.00	1398.25	251.92	1052.80
	LRC_CH12	1654.33	1395.50	36.42	65.33	135.00	300.00	101.50	119.33	1028.75	150.46	475.93
	ZULEGER	876.67	256.25	274.00	233.33	262.50	270.00	321.00	80.67	468.97	271.71	321.80
	SUCKER	457.33	47.00	96.33	93.00				90.00	200.22	93.00	156.73
	LAKE											
	LRC_MOUTH											
	MISS_LRC											
CL ppm	LRC_CR40	13.33	15.75	13.75	11.27	12.65	12.88	13.06	12.75	14.28	12.47	13.18
	BUNKER_HILL	19.33	30.33	28.50	24.83	20.07	27.00	27.54	32.54	26.06	24.86	26.27
	LRC_CH12	16.00	17.83	15.00	12.43	13.05	13.32	13.50	14.97	16.28	13.08	14.51
	ZULEGER	19.00	28.67	20.25	16.07	11.25	11.28	13.36	18.31	22.64	12.99	17.27
	SUCKER	13.00	16.67	11.28	7.40				8.63	13.65	7.40	11.39
	LAKE		11.80			14.53	14.98	14.37	14.22	11.80	14.62	13.98
	LRC_MOUTH					9.01	10.50	12.23	12.60		10.58	11.08
	MISS_LRC					6.72	7.69	9.60	9.11		8.00	8.28
Temp deg-C	LRC_CR40	2.81	8.46	12.92	15.53	17.32	15.69	12.92	8.09	8.06	15.37	11.72
	BUNKER_HILL	1.71	6.17	16.98	17.85	23.39	17.30	13.75	8.17	8.28	18.07	13.16
	LRC_CH12	2.98	8.35	14.68	18.04	21.75	19.38	14.31	9.10	8.67	18.37	13.57
	ZULEGER	1.64	6.27	15.06	15.29	18.28	15.43	11.29	7.74	7.65	15.07	11.37
	SUCKER	2.01	6.14	15.59	16.58				7.62	7.91	16.58	9.59
	LAKE		11.64	15.35	20.69	24.80	24.30	17.52	9.89	13.49	21.83	17.74
	LRC_MOUTH					24.79	24.99	16.81	11.94		22.20	19.63
	MISS_LRC					24.45	24.61	17.79	11.82		22.28	19.67
DO ppm	LRC_CR40	10.75	11.11	9.56	8.29	9.31	9.07	9.69	9.44	10.47	9.09	9.65
	BUNKER_HILL	11.75	12.79	11.78	10.57	13.19	5.41	10.56	10.87	12.10	9.93	10.86
	LRC_CH12	10.44	10.24	9.24	7.03	8.94	7.93	9.45	9.07	9.97	8.34	9.04
	ZULEGER	12.23	11.77	9.18	8.34	8.36	7.76	9.41	9.80	11.06	8.47	9.61
	SUCKER	12.43	12.62	9.91	8.40				10.22	11.65	8.40	10.72
	LAKE		13.80	11.24	9.16	9.48	8.79	8.81	11.37	12.52	9.06	10.38
	LRC_MOUTH					10.54	10.75	9.70	11.54		10.33	10.63
	MISS_LRC					8.14	8.42	9.19	10.51		8.58	9.07
Cond umhos/cm	LRC_CR40	266.33	311.80	384.57	338.56	418.00	415.83	406.80	397.20	320.90	394.80	367.39
	BUNKER_HILL	262.00	359.25	461.86	369.89	394.67	456.50	476.20	501.50	361.04	424.31	410.23
	LRC_CH12	282.00	323.40	396.86	338.78	401.67	415.33	419.80	412.60	334.09	393.89	373.80
	ZULEGER	275.67	372.75	419.43	368.44	395.67	391.00	409.40	456.00	355.95	391.13	386.04
	SUCKER	202.00	268.75	291.71	259.50				315.00	254.15	259.50	267.39
	LAKE		260.00	260.50	268.50	292.66	291.12	319.57	305.85	260.25	292.96	285.46
	LRC_MOUTH					314.08	317.00	335.08	317.00		322.06	320.79
	MISS_LRC					375.25	335.92	360.50	353.00		357.22	356.17
pH	LRC_CR40	7.53	7.79	8.06	7.66	8.10	7.97	7.88	7.86	7.79	7.90	7.86
	BUNKER_HILL	7.43	7.94	8.40	8.01	8.73	7.68	7.83	7.89	7.92	8.06	7.99
	LRC_CH12	7.46	7.74	8.05	7.51	8.15	7.91	7.83	7.89	7.75	7.85	7.82
	ZULEGER	7.55	7.83	8.01	7.60	8.34	7.85	7.77	7.92	7.79	7.89	7.86
	SUCKER	7.49	7.89	7.81	7.27				7.40	7.73	7.27	7.57
	LAKE		9.22	9.30	8.85	9.24	9.26	8.76	8.92	9.26	9.03	9.08
	LRC_MOUTH					8.73	8.78	8.65	8.70		8.72	8.71
	MISS_LRC					8.15	8.26	8.29	8.04		8.23	8.19
Flow cfs	LRC_CR40	24.89	31.70	20.73	18.36	2.55	1.87	2.35	10.00	25.78	6.28	14.06
on Sample Day	BUNKER_HILL	11.33	16.91	2.57	25.28	0.34	0.35	0.79	1.61	10.27	6.69	7.40
	LRC_CH12	30.31	58.86	40.06	36.19	10.51	7.22	8.60	18.28	43.08	15.63	26.25
	ZULEGER	14.28	14.94	6.75	18.90	2.41	2.04	2.26	5.28	11.99	6.40	8.36
	SUCKER	6.83	8.05	1.05	26.83				2.94	5.31	26.83	9.14
Computed	LAKE		129.35	53.29	123.00	9.57	3.88	24.03	25.52	91.32	40.12	52.66
Computed	LRC_MOUTH					13.52	4.03	25.28	34.88		14.28	19.43
	MISS_LRC											

A-6 Stream Water Quality by Site & Date, 2006-2008

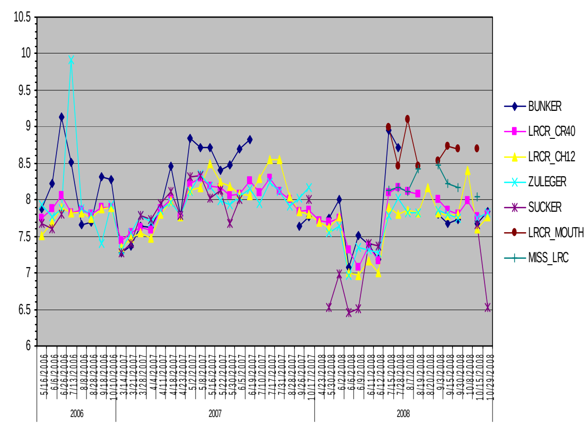
Temperature, water deg C



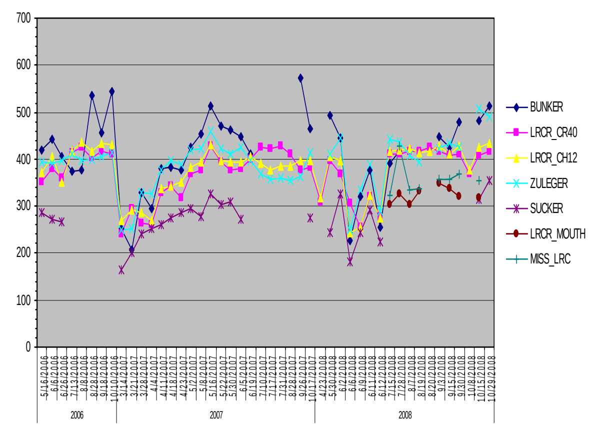
Dissolved oxygen (DO) mg/l



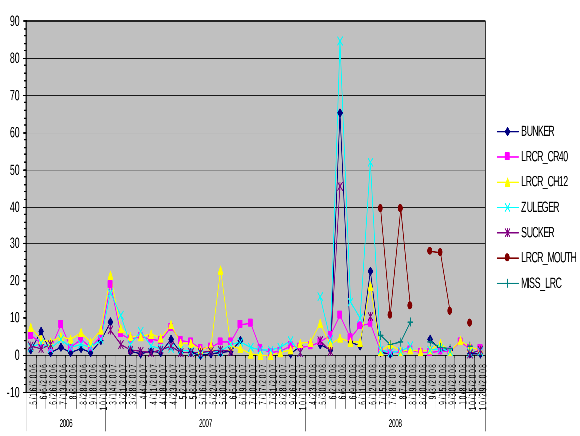
pH None



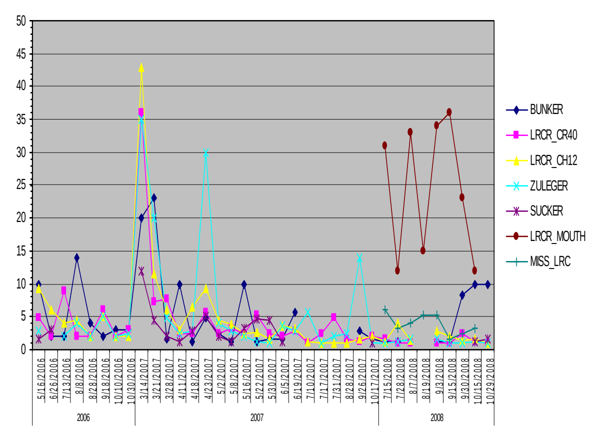
Specific conductance uS/cm



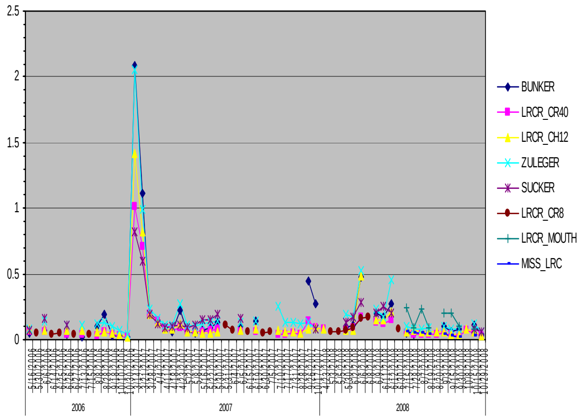
Turbidity NTRU



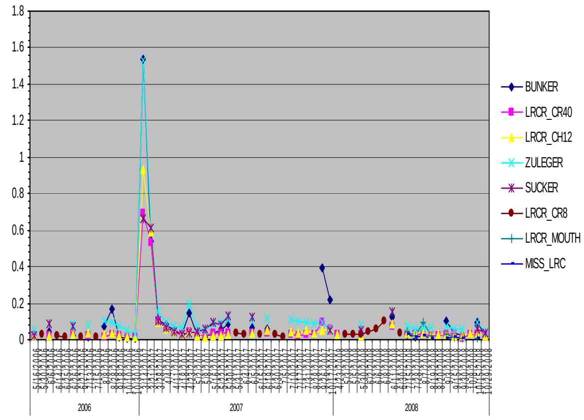
Solids, Total Suspended (TSS) mg/l



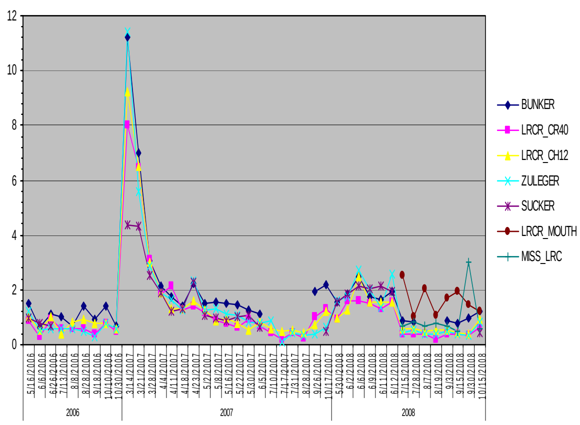
Phosphorus as P mg/l



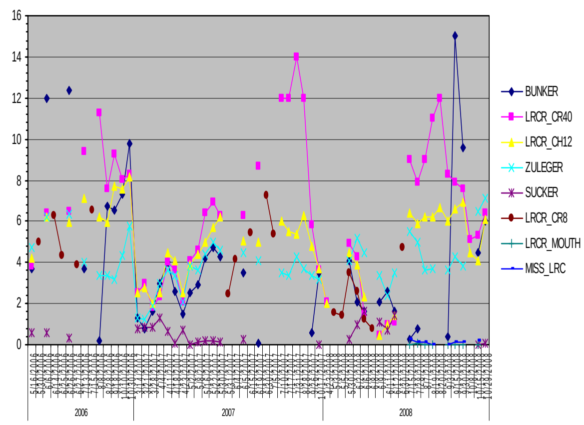
Phosphorus, orthophosphate as P mg/l



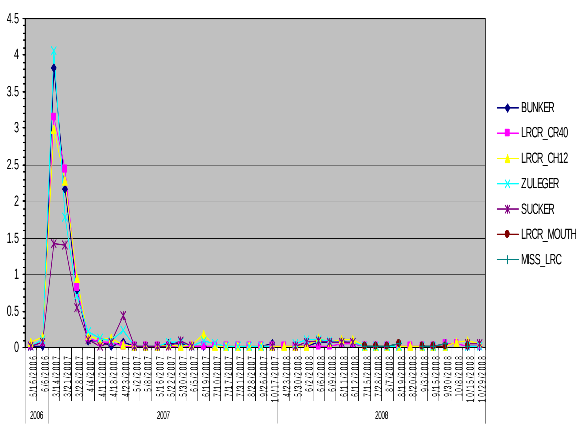
Nitrogen, Kjeldahl mg/l



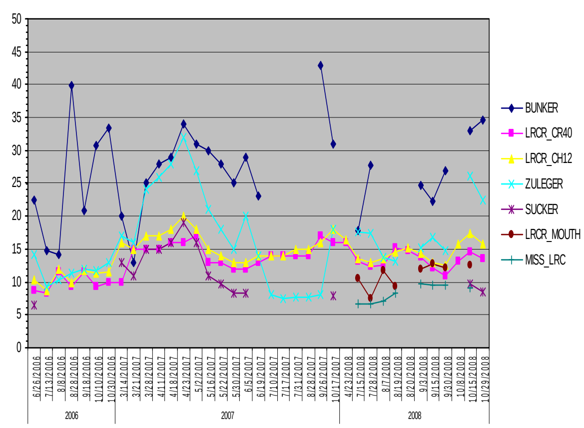
Nitrogen, Nitrite (NO2) + Nitrate (NO3) as N mg/l



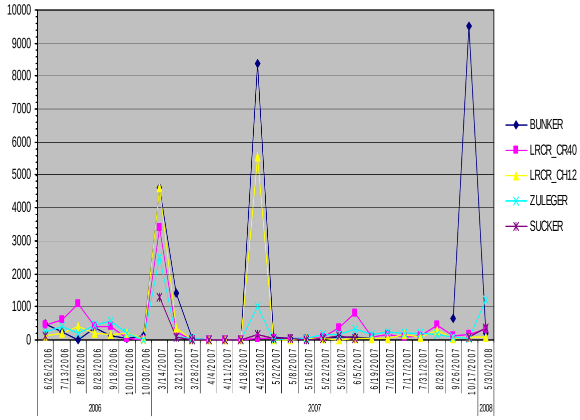
Nitrogen, ammonia (NH3) + ammonium (NH4) mg/l



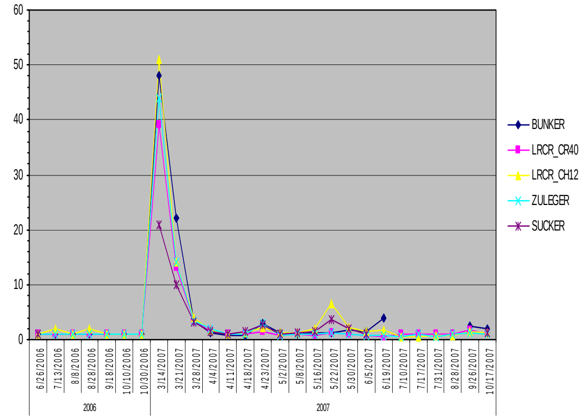
Chloride mg/l



Fecal Coliform cfu



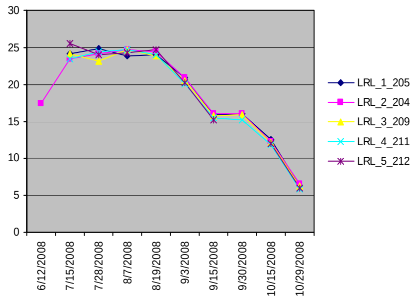
BOD, Biochemical oxygen demand mg/l



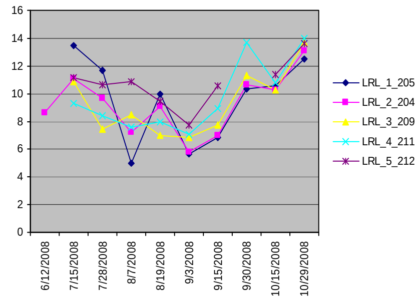
A-7 LRL Water Quality Time Series by Variable & Site, 2008

Surface Samples Stations Sorted in Downstream Order 2008

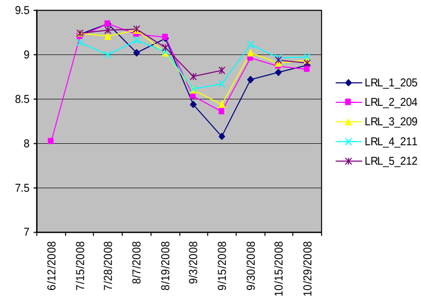
Temperature, water deg C Year: 2008



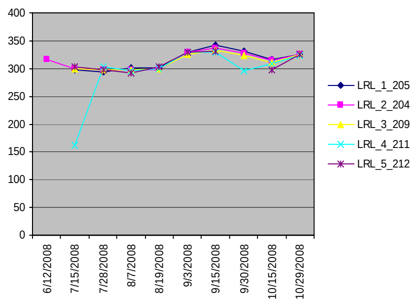
Dissolved oxygen (DO) mg/l Year: 2008



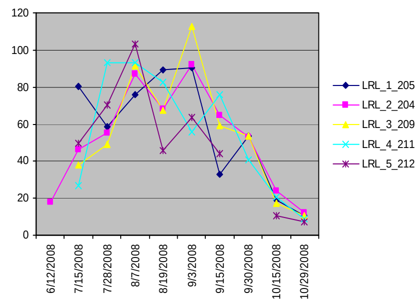
pH None Year: 2008



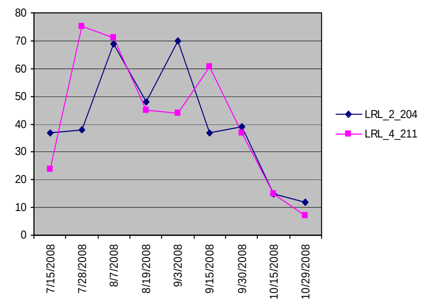
Specific conductance uS/cm Year: 2008



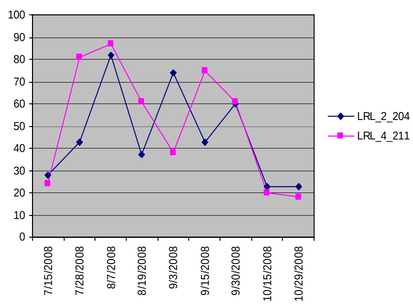
Turbidity - Probe FNU Year: 2008



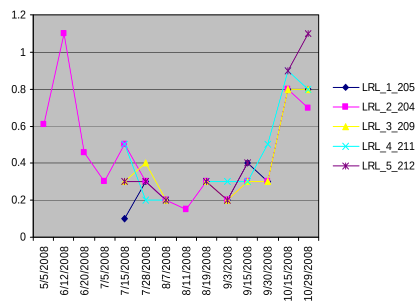
Turbidity NTRU Year: 2008



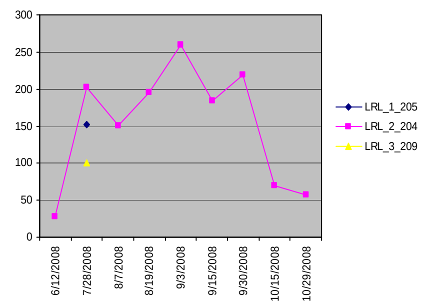
Solids, Total Suspended (TSS) mg/l Year: 2008



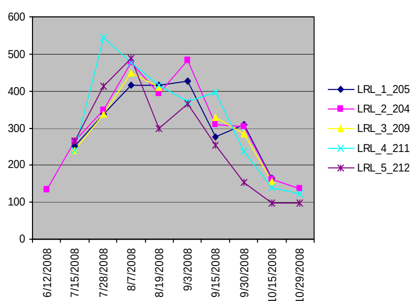
Depth, Secchi Disk Depth m Year: 2008



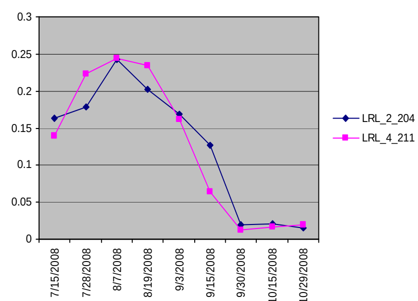
Chlorophyll a, corrected for pheophytin ug/l Year: 2008



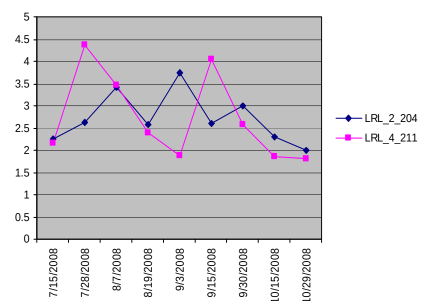
Phosphorus as P ppb Year: 2008



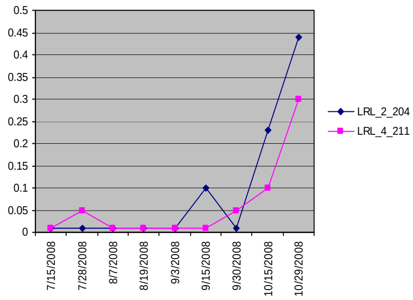
Phosphorus, orthophosphate as P mg/l Year: 2008



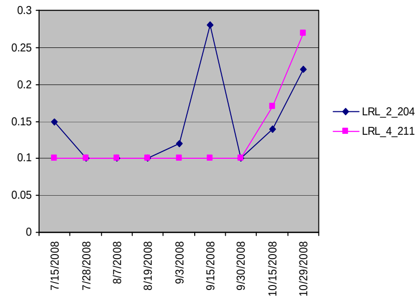
Nitrogen, Kjeldahl mg/l Year: 2008



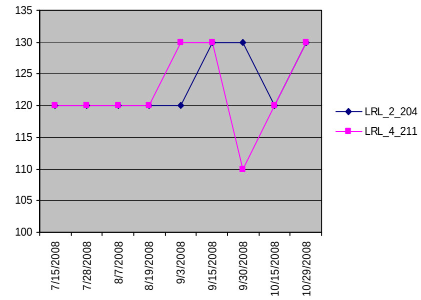
Nitrogen, Nitrite (NO2) + Nitrate (NO3) a mg/l Year: 2008



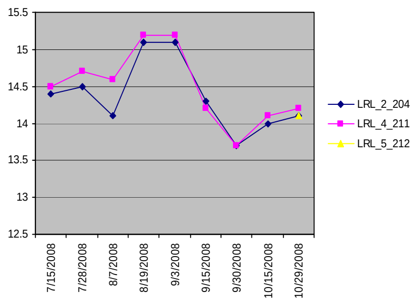
Nitrogen, ammonia (NH3) + ammonium mg/l Year: 2008



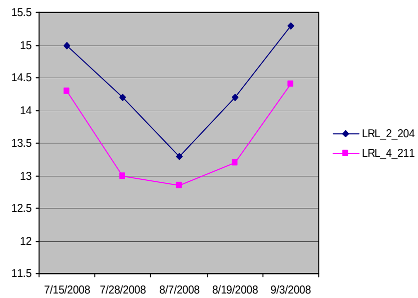
Alkalinity, Total (total hydroxide+carbona mg/l CaC Year: 2008



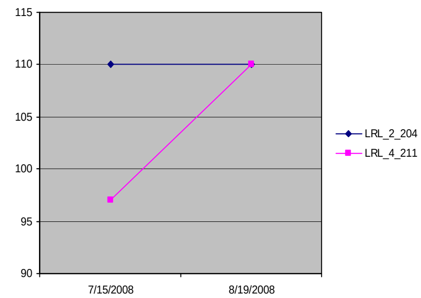
Chloride mg/l Year: 2008



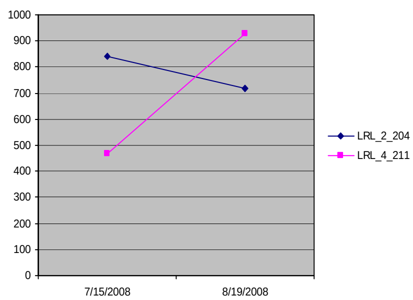
Sulfur, sulfate (SO4) as SO4 mg/l Year: 2008



Calcium mg/l Year: 2008

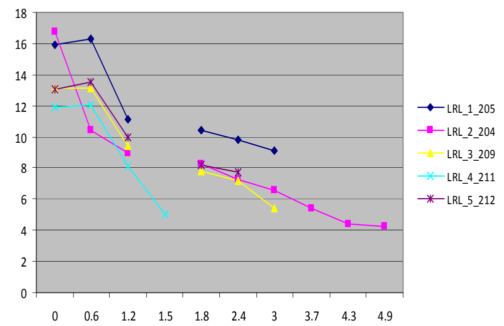


Iron ug/l Year: 2008

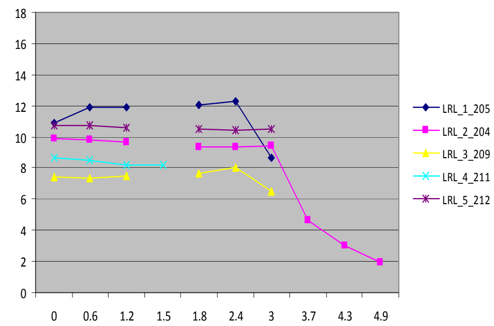


A-8 Vertical Profiles by Date & Lake Site, 2008 X-Axis = Depth meters Dissolved Oxygen (ppm)

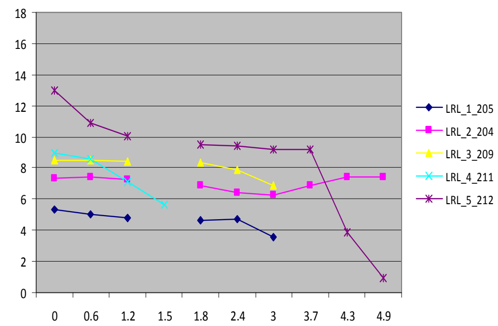
7/15/2008



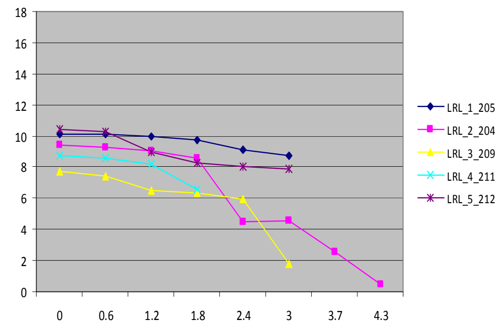
7/28/2008



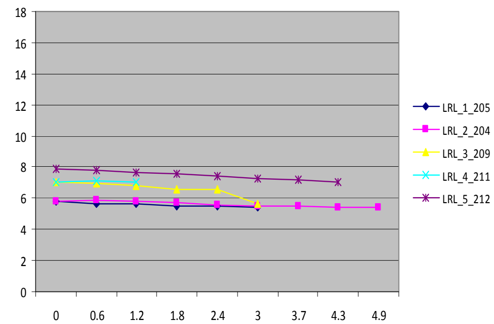
8/7/2008



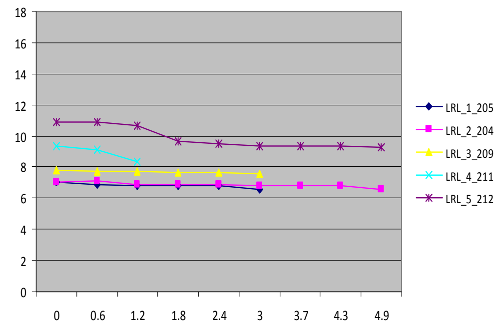
8/19/2008



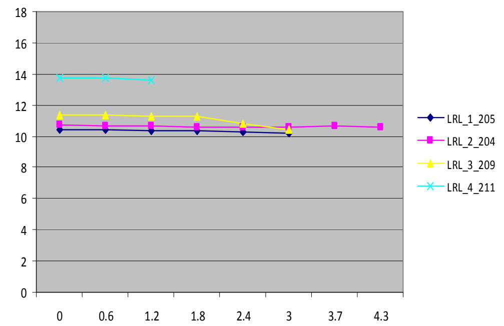
9/3/2008



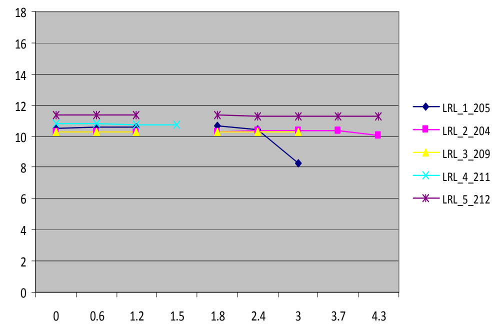
9/15/2008



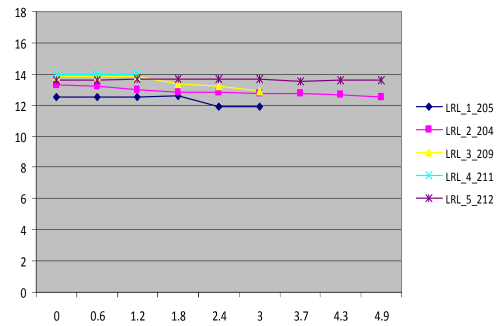
9/30/2008



10/15/2008

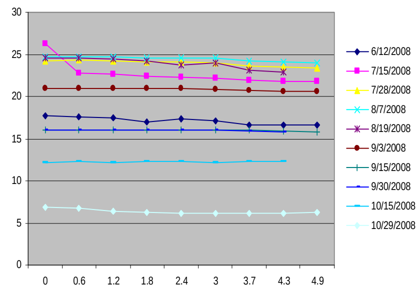


10/29/2008

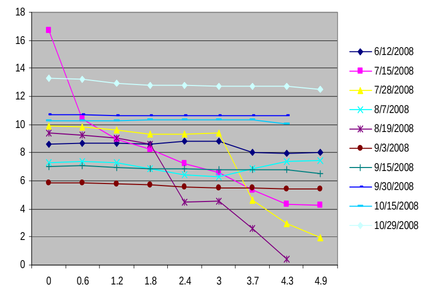


A-9 Vertical Profiles by Date & Parameter, 2008, Site 204 X-Axis = Depth (meters)

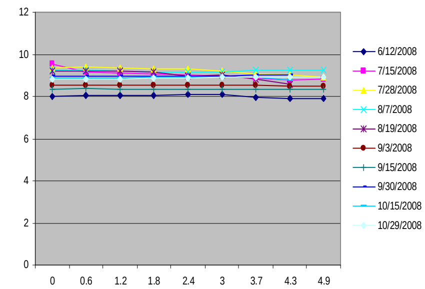
Temperature, water deg C



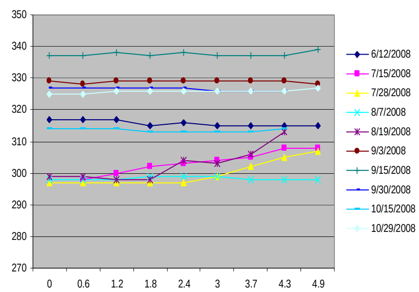
Dissolved oxygen (DO) mg/l



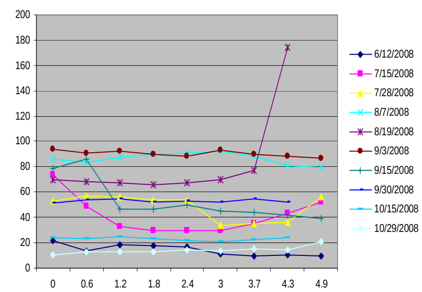
pH None



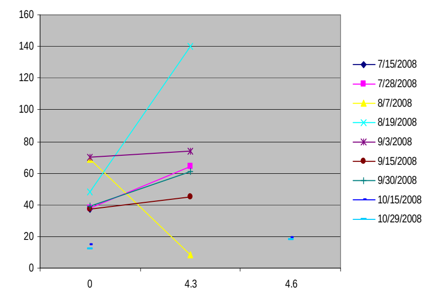
Specific conductance uS/cm



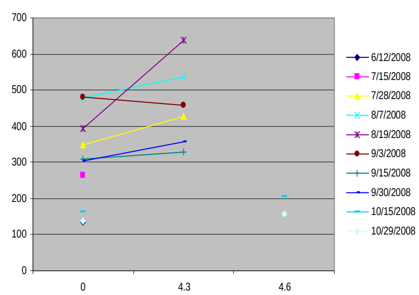
Turbidity - Probe FNU



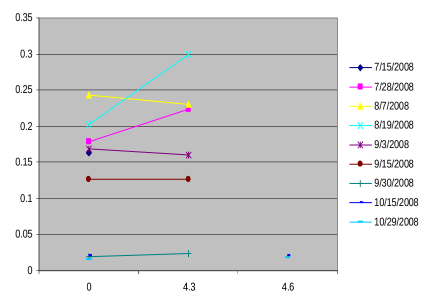
Turbidity NTRU



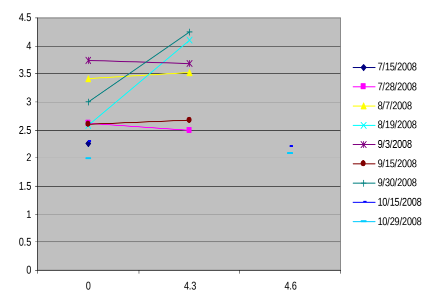
Phosphorus as P ppb



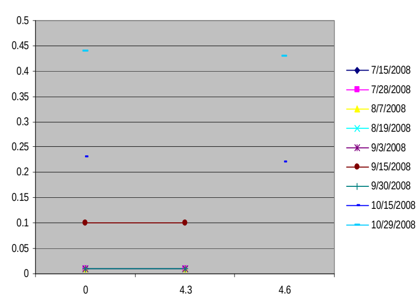
Phosphorus, orthophosphate as P mg/l



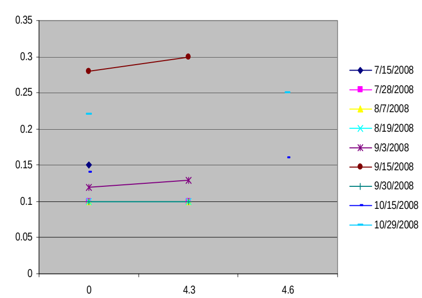
Nitrogen, Kjeldahl mg/l



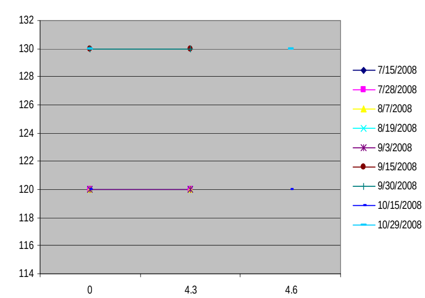
Nitrogen, Nitrite (NO2) + Nitrate (NO3) as N mg/l



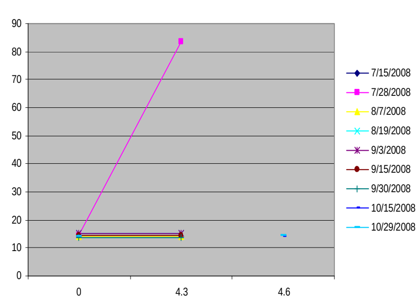
Nitrogen, ammonia (NH3) + ammonium (NH4) mg/l



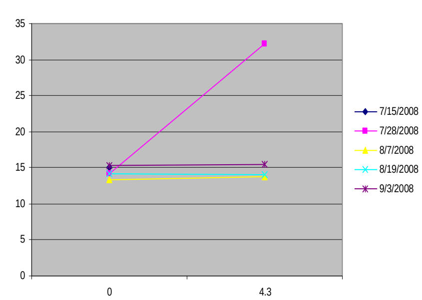
Alkalinity, Total (total hydroxide+carbonate+bic mg/l CaCO3



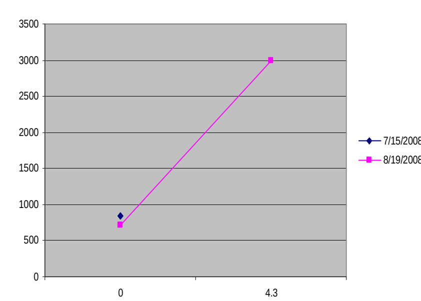
Chloride mg/l



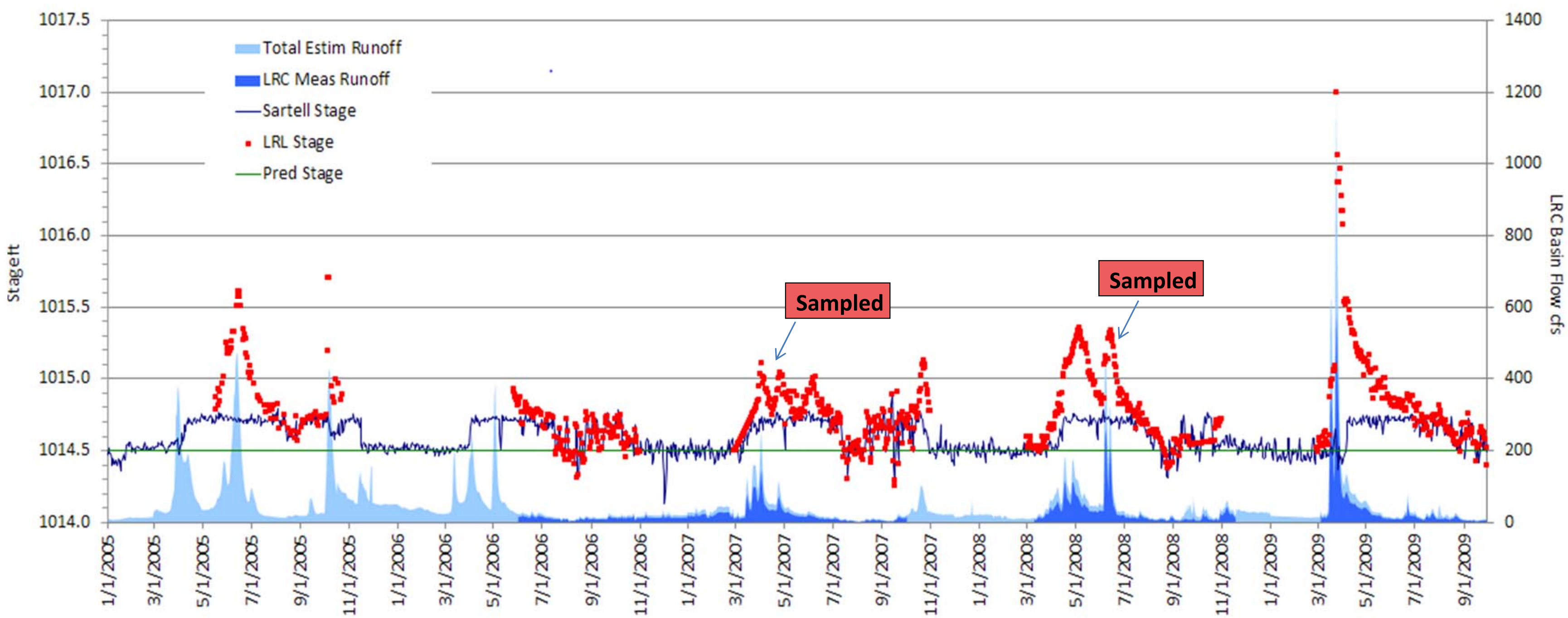
Sulfur, sulfate (SO4) as SO4 mg/l



Iron ug/l



A-10 Daily Stage & Flow Data for Mississippi River and Little Rock Lake, 2005-2009



Sartell & Little Rock Lake stage data provided by MDNR (D. Heneley, D. Lais) & MPCA (M. Evenson).

Little Rock Lake stage shown for March - October; datums adjusted to fit Sartell stage on days with low runoff (< 10 cfs, $r^2 > 0.95$) in 2005-2009.

MDRN lake stage data from lake water quality monitoring database; datum adjustment = -0.18 feet.

MPCA lake stage data from continuous monitor at Hwy 10 bridge in July 2006 - October 2009; datum adjustment = -0.53 feet.

LRC Basin total runoff to Little Rock Lake estimated from measured flows LRC CH12 & Sucker Creek (dark blue); missing values filled by correlations with LRC CR8 or Platte River.

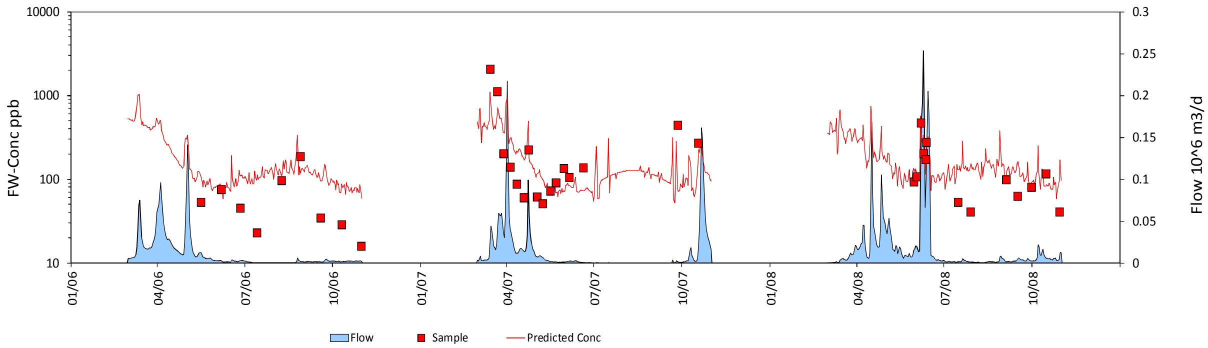
Runoff from ungauged watersheds (Zuleger, lakeshed) estimated based upon drainage area ratios relative to LRC CH12

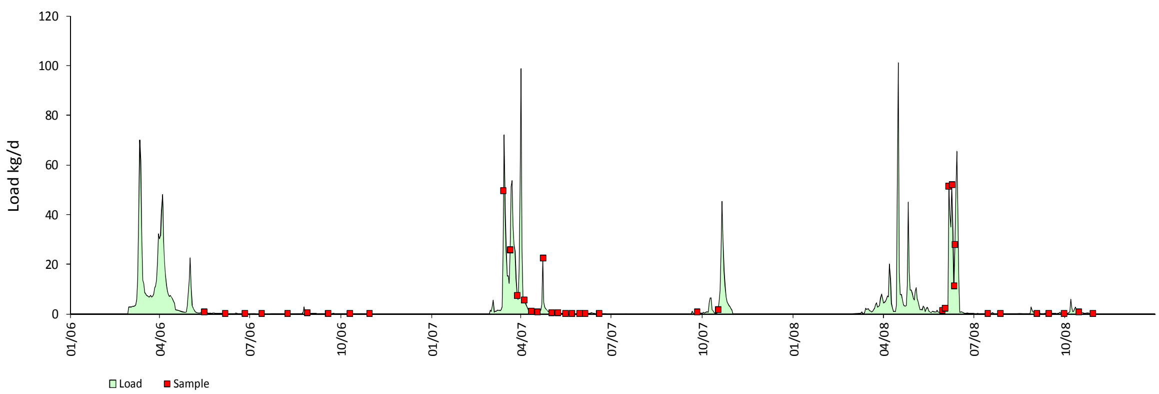
Red boxed indicate high-flow events when water quality samples were collected.

A-11 Flow & TP Load Time Series - Bunker Hills Creek

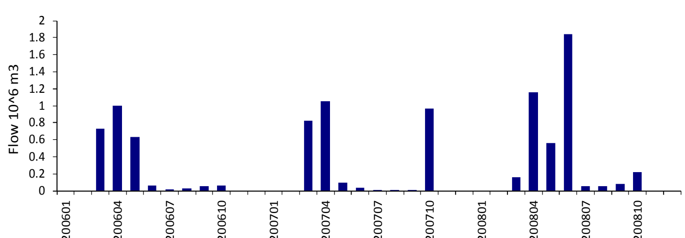
Site:	BUNKER_HILL	Bunker Hill Crk	Variable:	TP	Total P ppb	Months: 3 10		Dates: 01/01/2006 - 12/31/2008
Flow Data:	BUNKER_HILL	Flow 10^6 m3/yr =	3.224	Load kg/yr =	926.7	FW-Conc ppb = 287.4	RSE = 20%	Method Used= 5

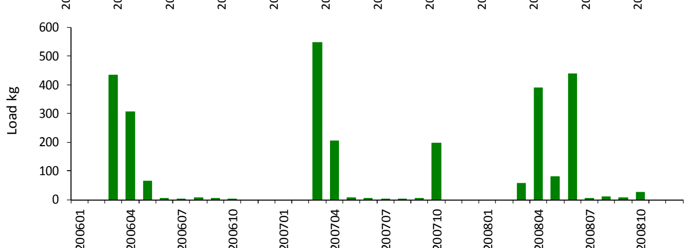
Daily Time Series:

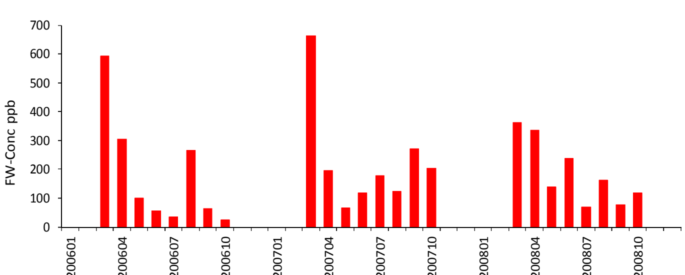




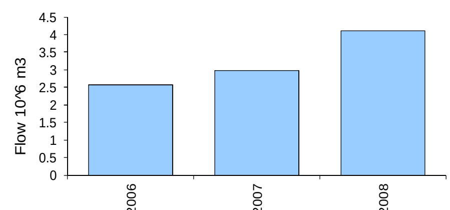
Monthly Time Series:

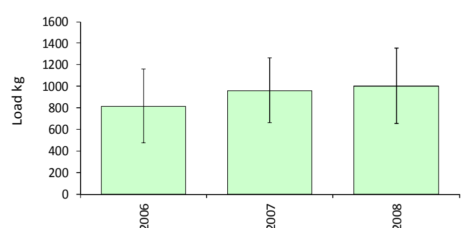


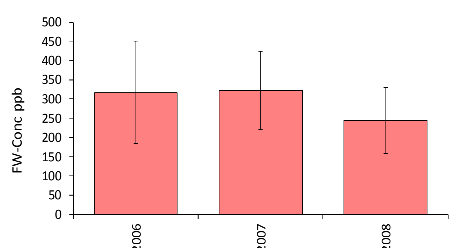




Yearly Time Series:



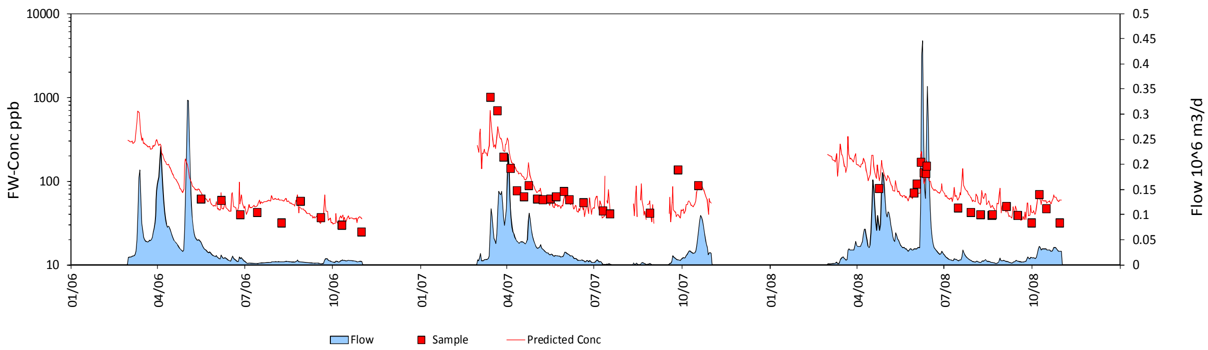


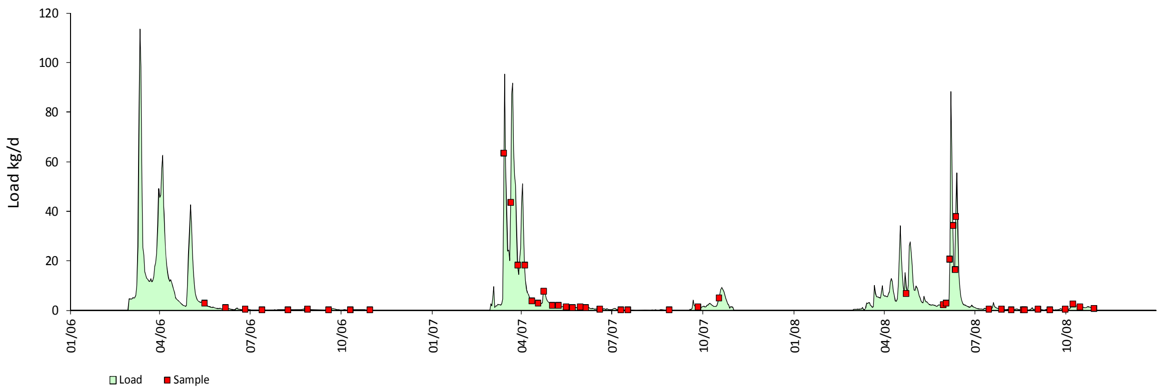


A-12 Flow & TP Load Time Series - Little Rock Creek North

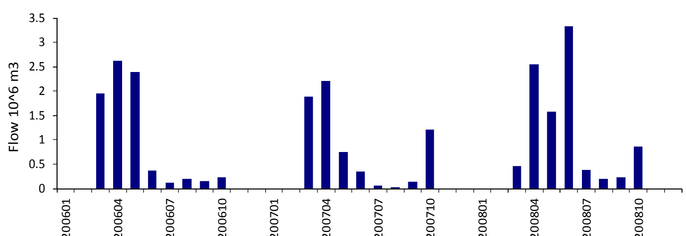
Site:	LRC_CR40	LRC at CR 40	Variable:	TP	Total P ppb	Months:	3	10	Dates:	01/01/2006 - 12/31/2008
Flow Data:	LRC_CH40	Flow 10^6 m3/yr =	8.094	Load kg/yr =	1291.7	FW-Conc ppb =	159.6	RSE =	13%	Method Used= 5

Daily Time Series:

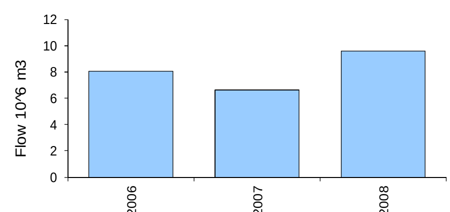


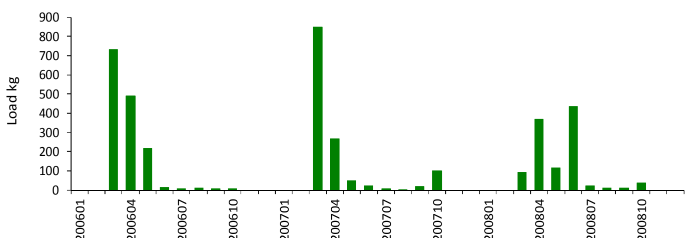


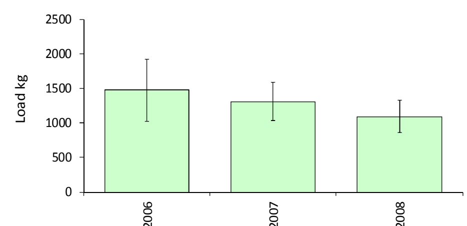
Monthly Time Series:

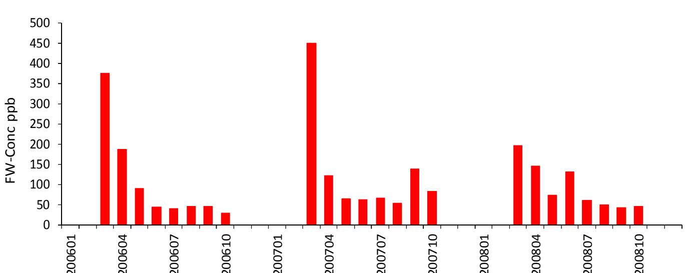


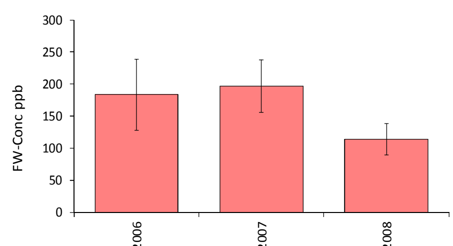
Yearly Time Series:







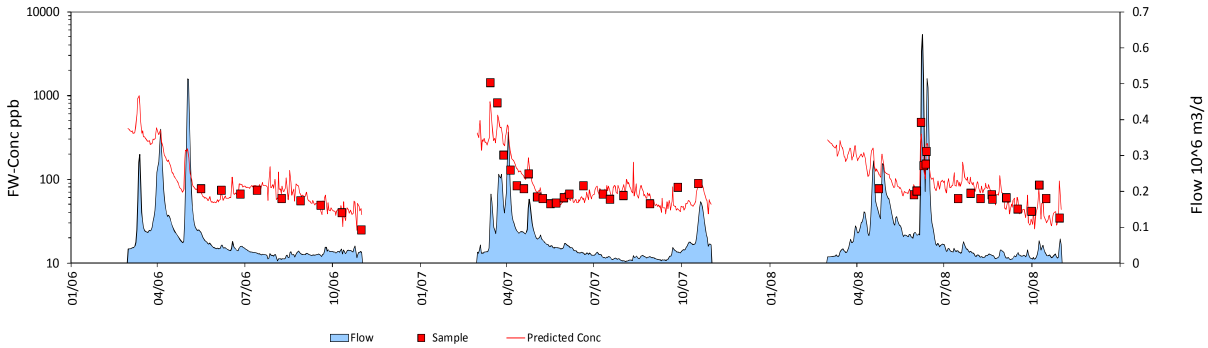


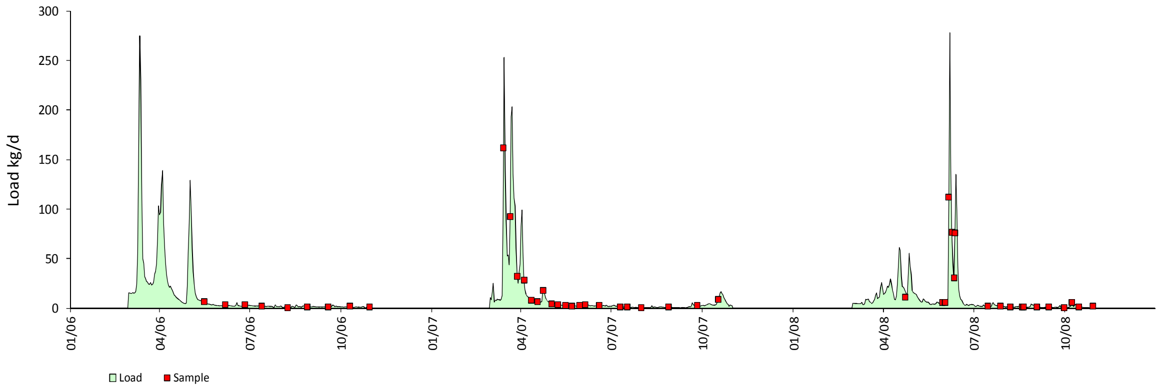


A-13 Flow & TP Load Time Series - Little Rock Creek @ CH12, Lake Inflow

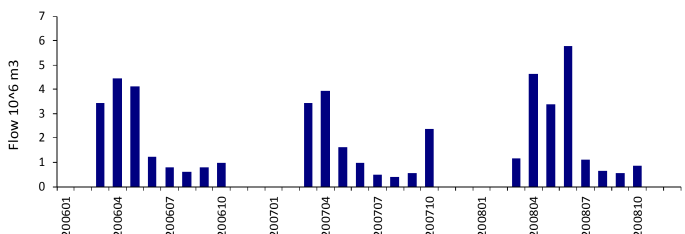
Site:	LRC_CH12	LRC at CH12 Inflow to LRL	Variable:	TP	Total P ppb		Months:	3	10	Dates:	01/01/2006 - 12/31/2008	
Flow Data:	LRC_CH12	Flow 10^6 m3/yr =	16.096	Load kg/yr =	2958.4	FW-Conc ppb =	183.8	RSE =	18%	Method Used=	5	

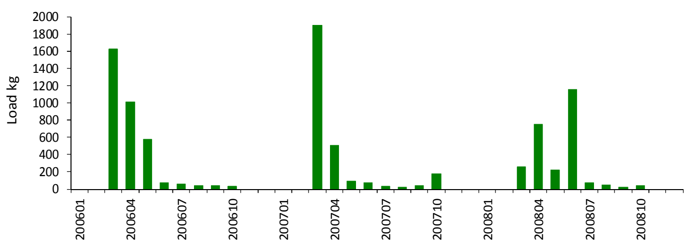
Daily Time Series:

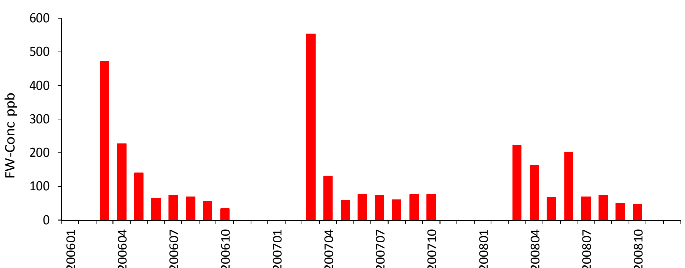




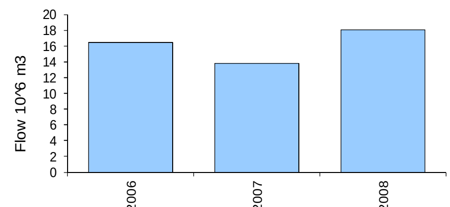
Monthly Time Series:

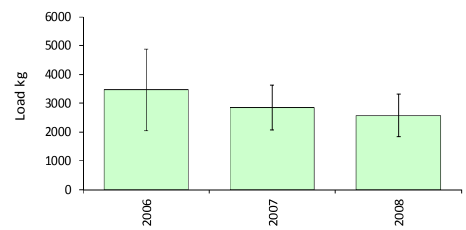


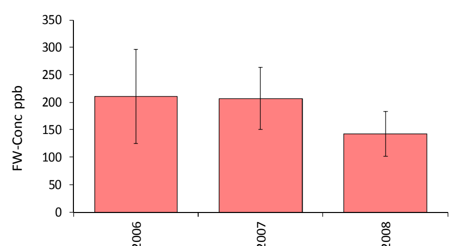




Yearly Time Series:







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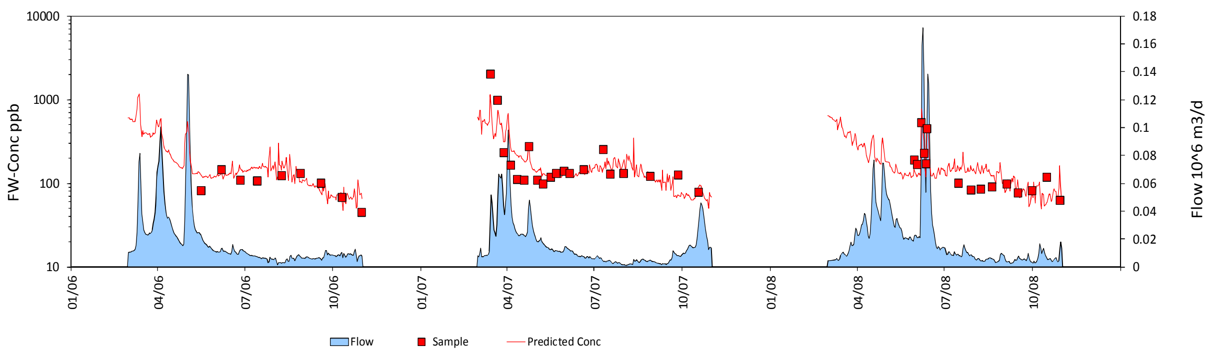
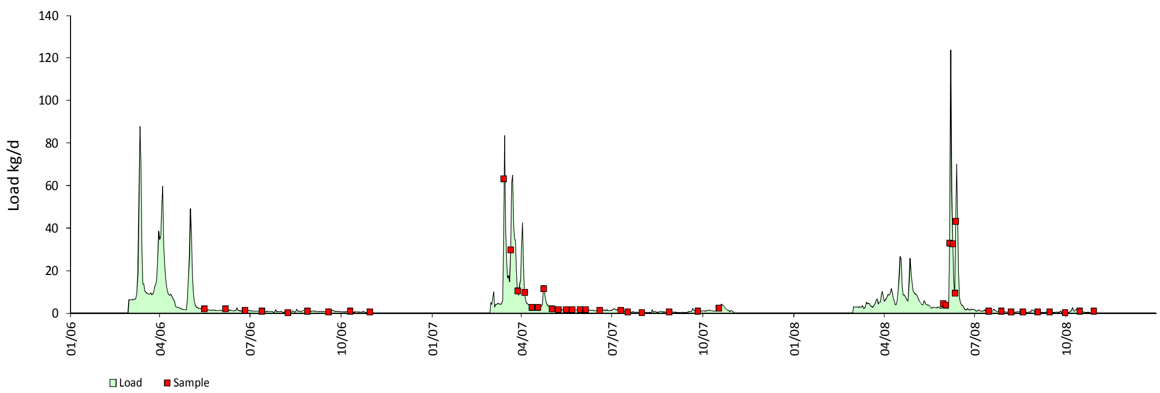
A-14 Flow & TP Load Time Series - Zuleger Creek

Site: ZULEGER Zuleger Creek Inflow to LRL Variable: TP Total P ppb Months: 3 10 Dates: 01/01/2006 - 12/31/2008

Flow Data: ZULEGER Flow 10^6 m3/yr = 4.337 Load kg/yr = 1148.4 FW-Conc ppb = 264.8 RSE = 16% Method Used= 5

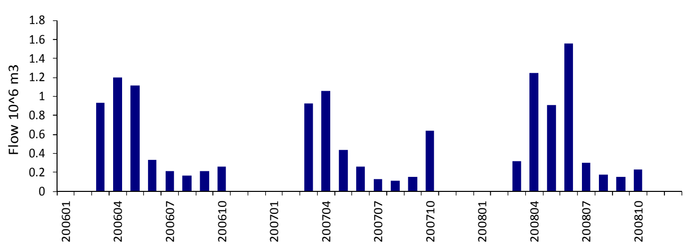
Daily Time Series:

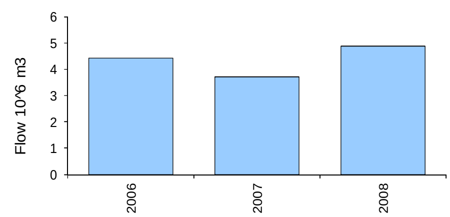


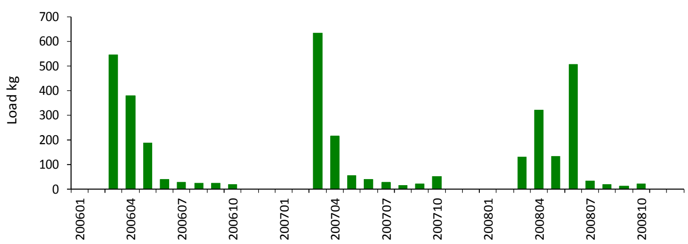


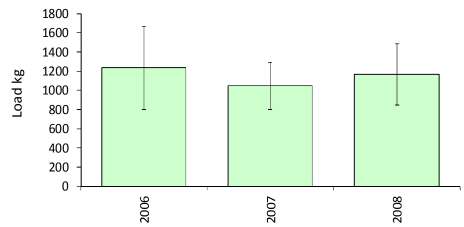
Monthly Time Series:

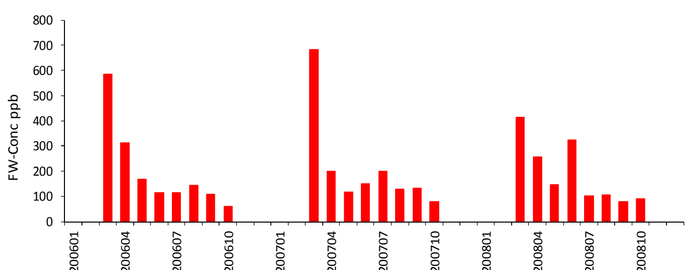
Yearly Time Series:

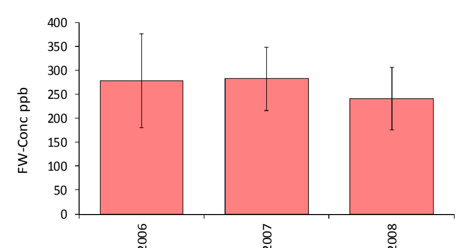












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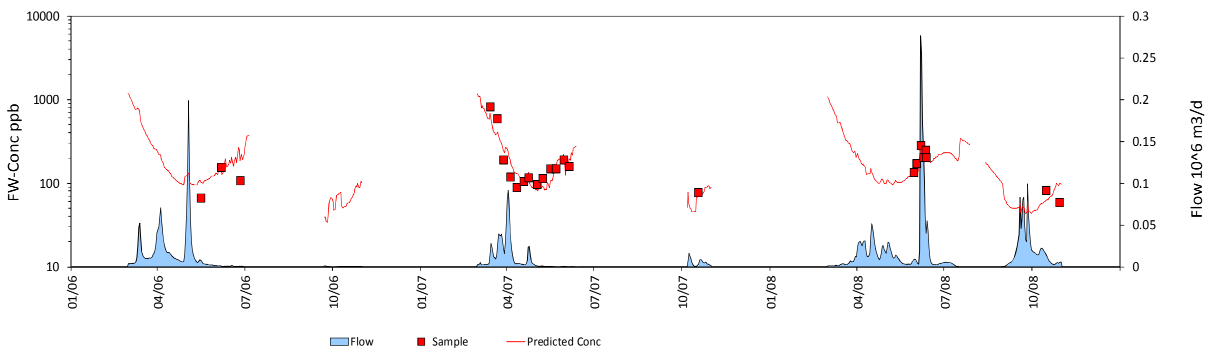
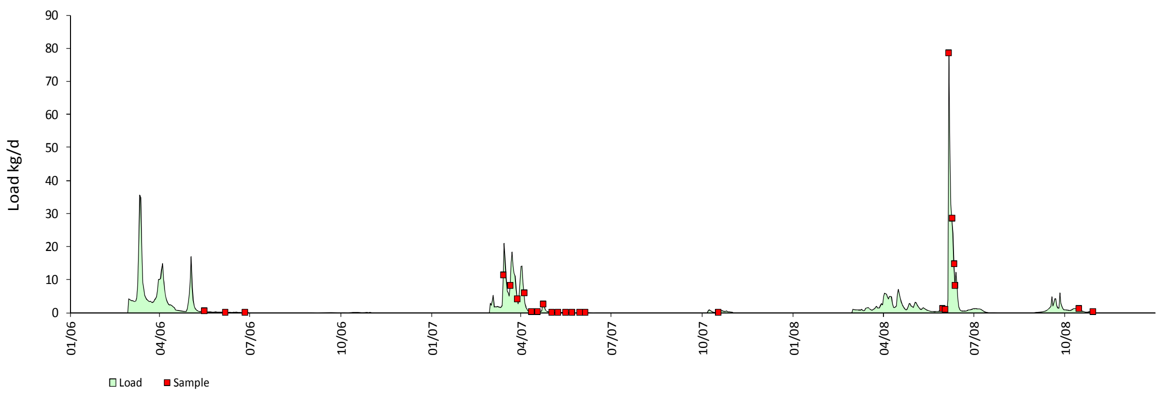
A-15 Flow & TP Load Time Series - Sucker Creek

Site:	SUCKER	Sucker Creek Inflow to LRL	Variable:	TP	Total P ppb		Months:	3	10	Dates: 01/01/2006 - 12/31/2008
Flow Data:	SUCKER	Flow 10^6 m3/yr =	2.218	Load kg/yr =	403.0	FW-Conc ppb =	181.6	RSE =	8%	Method Used= 5

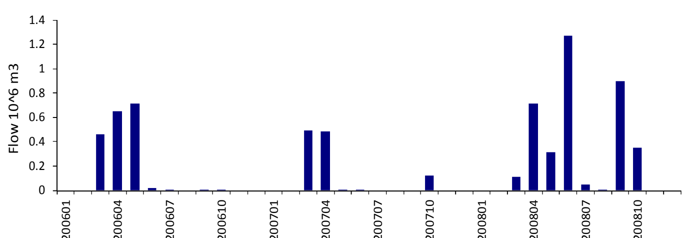
Daily Time Series:

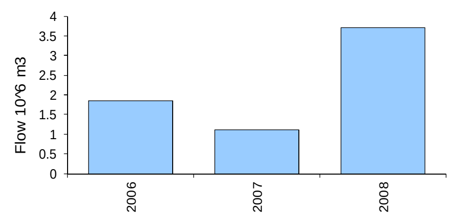


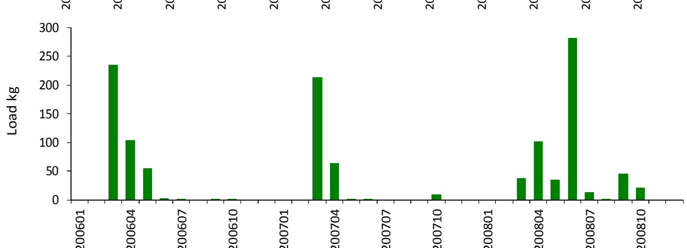


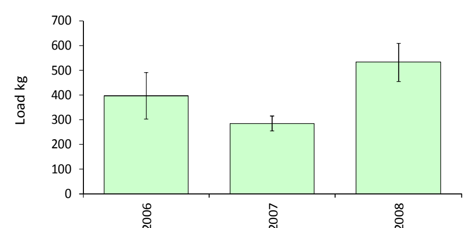
Monthly Time Series:

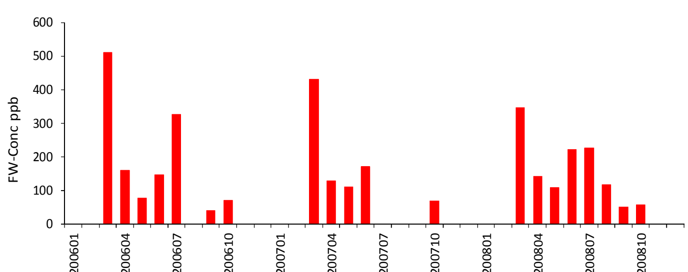
Yearly Time Series:

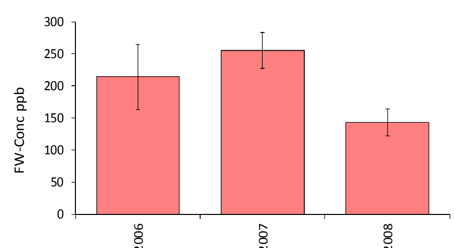








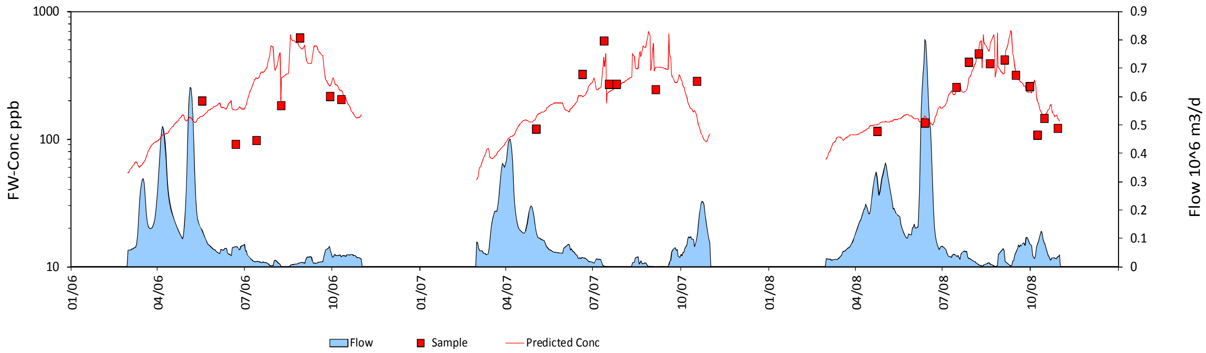


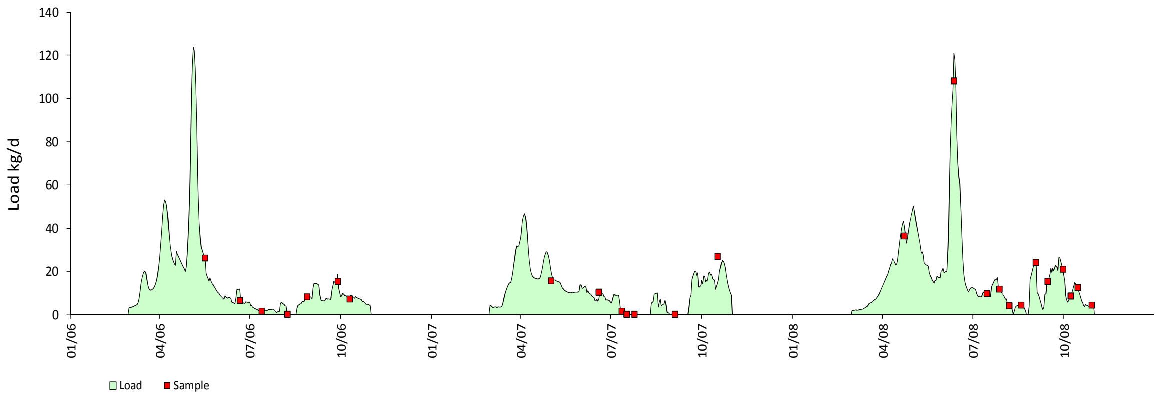


A-16 Flow & TP Load Time Series - Lake Outflow

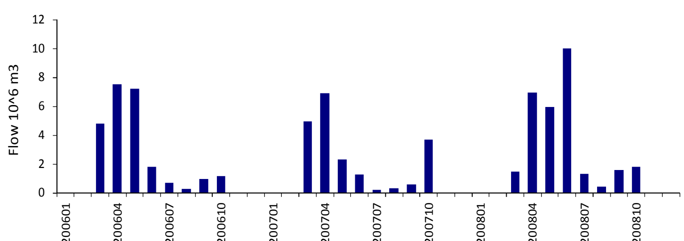
Site:	LAKE	All Lake Sites	Variable:	TP	Total P ppb	Months:	3	10	Dates: 01/01/2006 - 12/31/2008
Flow Data:	OUTFLOW_7	Flow 10^6 m3/yr =	24.699	Load kg/yr =	3637.7	FW-Conc ppb =	147.3	RSE = 9%	Method Used= 5

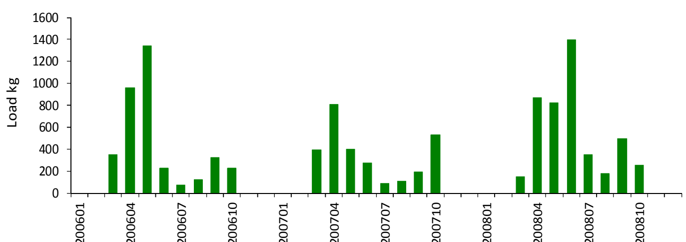
Daily Time Series:

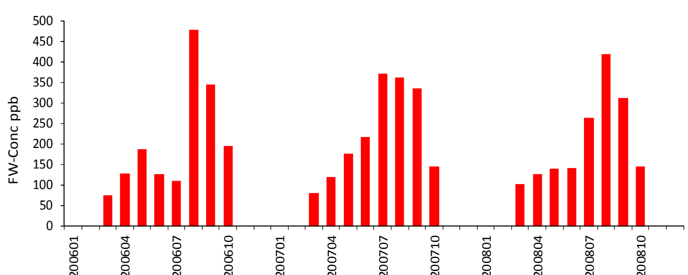




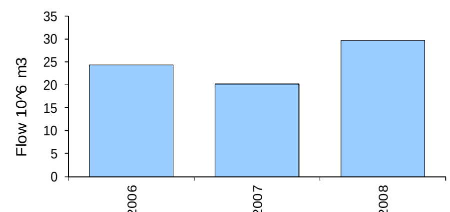
Monthly Time Series:

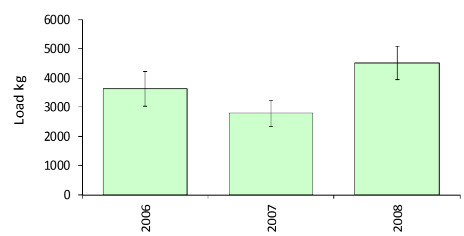


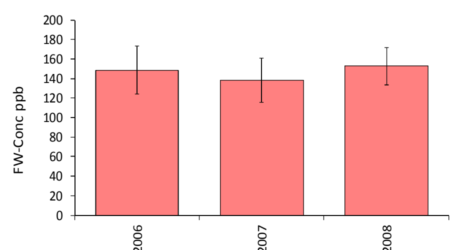




Yearly Time Series:







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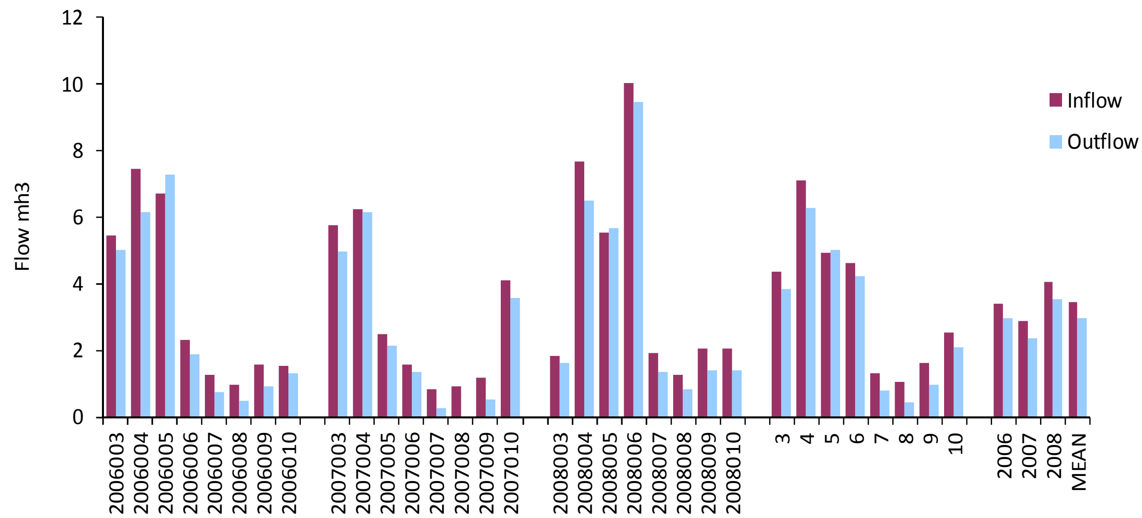
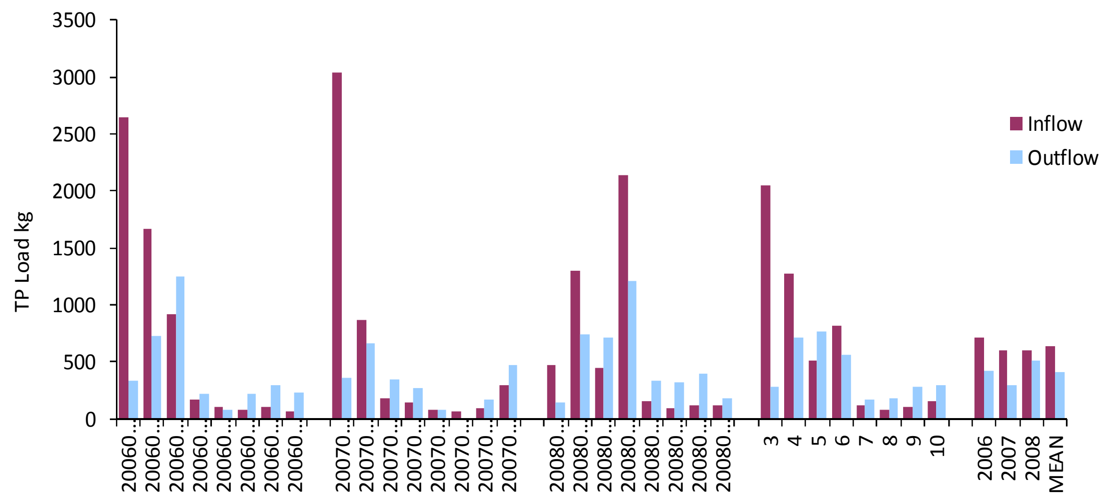
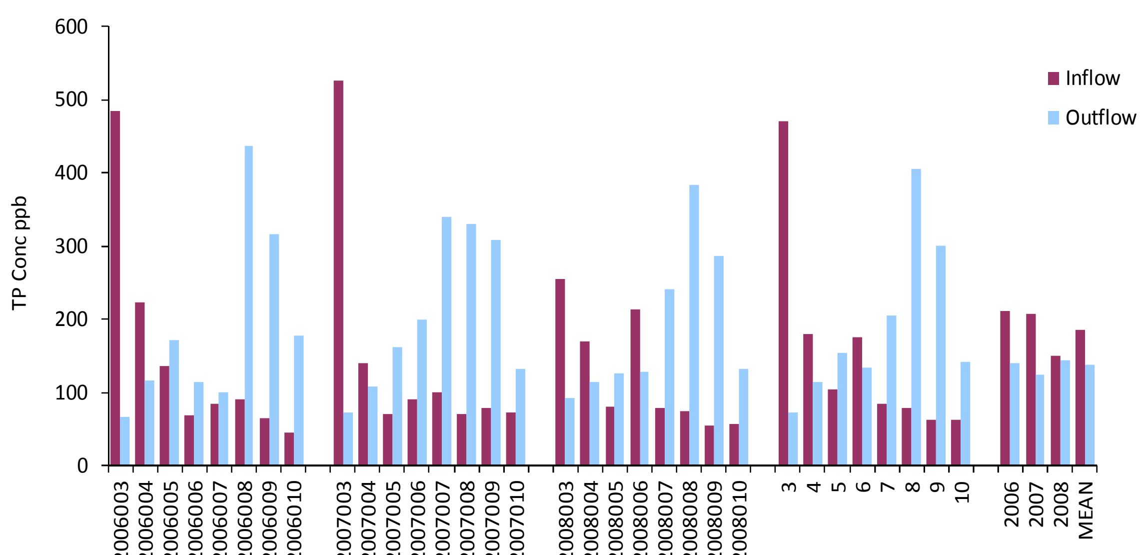
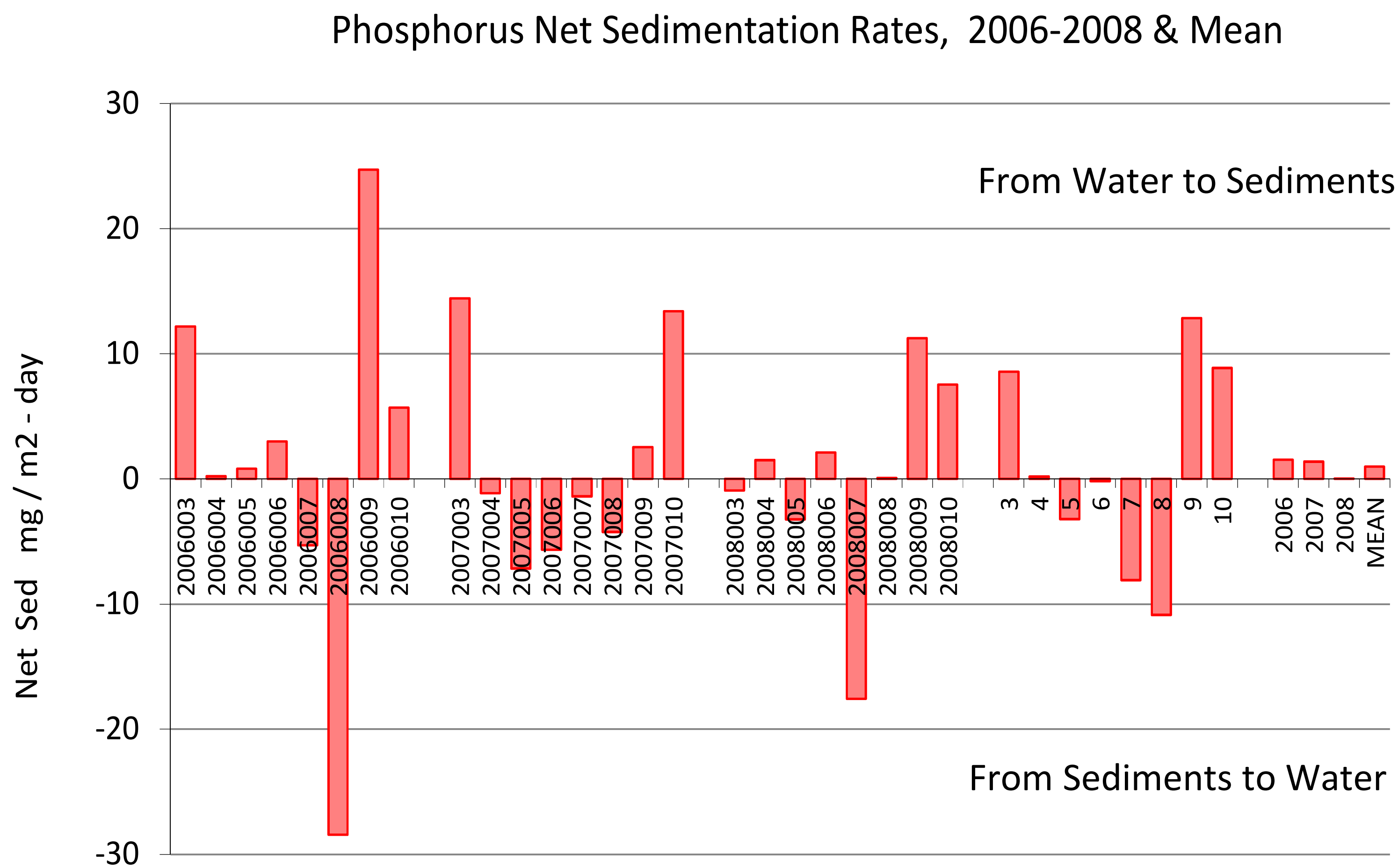
A-17 Monthly Inflows and Outflows







A-18 Monthly & Yearly Phosphorus Net Sedimentation Rates



Net Sedimentation Rate = (Inflow - Outflow - Storage Increase) / Lake Area

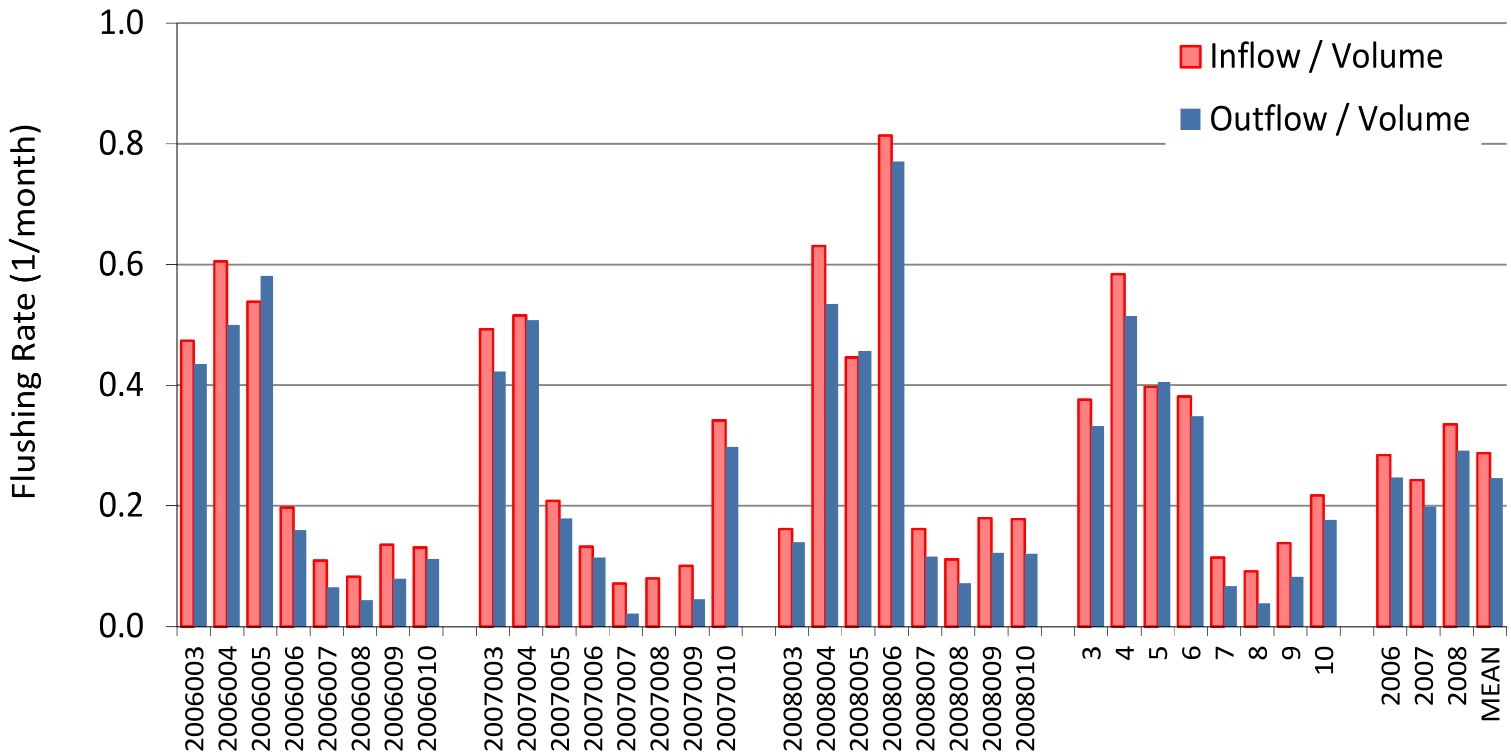
Positive values reflect deposition to sediments; negative values are releases from sediments to water column (internal load)

Positive sedimentation rates in fall reflect dieoff and settling of algal blooms.

Sedimentation rates in March-April are relatively uncertain because of limited watershed and lake data.

Internal loading rates in July-August comparable to values measured by James (2008) under anaerobic conditions.

A-19 Monthly Flushing Rates



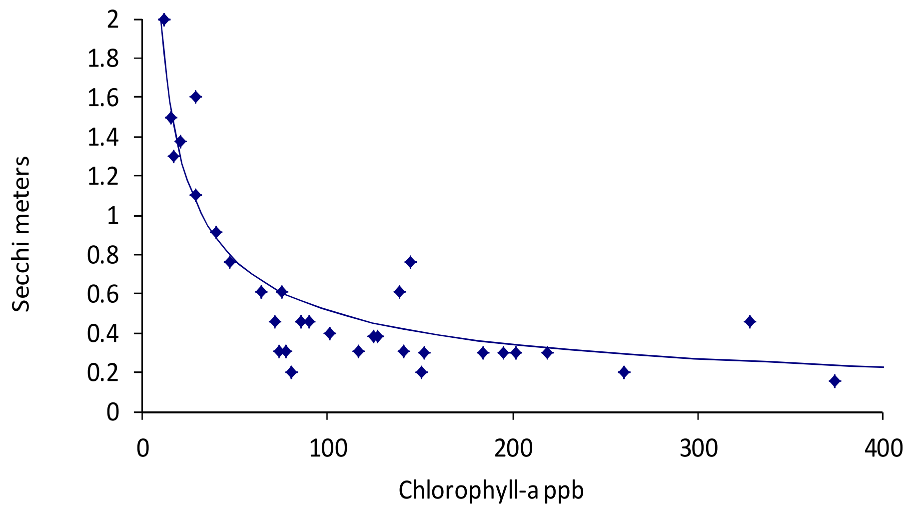
Flushing Rate = Flow / Volume = 1 / Hydraulic Residence Time

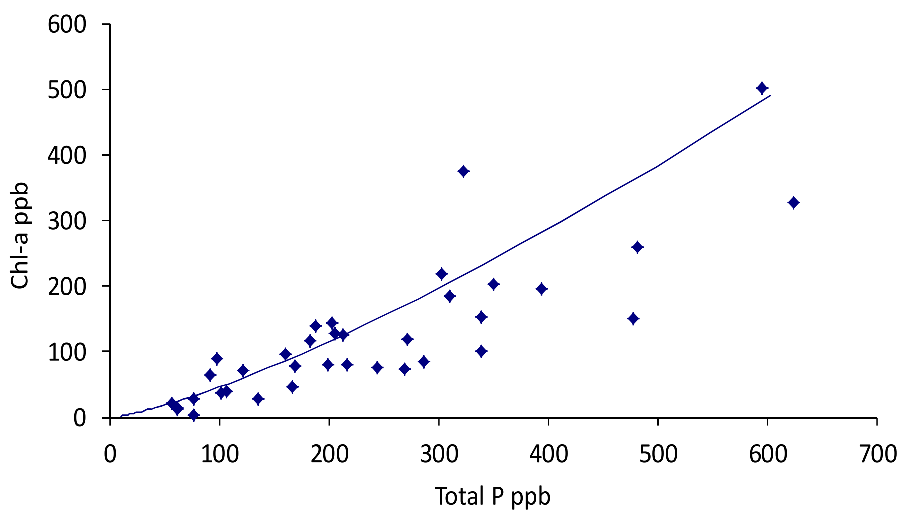
Stagnant conditions (no outflow) occurred in July-August 2007, when toxic bluegreen blooms were observed.

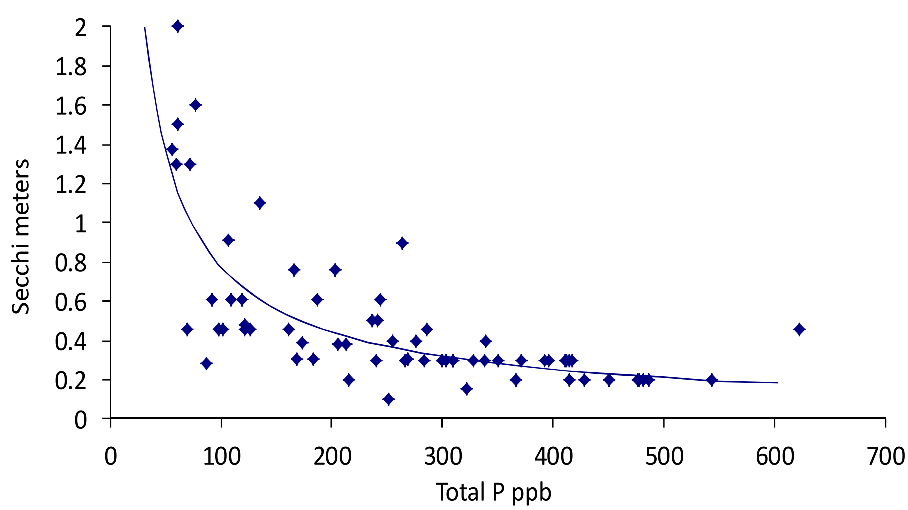
Lake TP concentration increases from ~100 to >300 ppb in summer due to low flushing rate and high sediment P release rates.

Lake TP buildup is enhanced by drought and depletion of stream base flows due to groundwater pumping for irrigation.

TSI Correlations vs. MPCA Statewide Regressions







All LRL Data, May-Sept, 1990-2008; Each point represents a paired sample.
Lines are regressions of summer-mean values; state-wide data (Heiskary & Wilson, 2008)

LRL Water Quality vs. MINLEAP Predictions

LAKE AND RESERVOIR MANAGEMENT, 1989 5(2): 11-22

Development of Lake Assessment Methods Based Upon the Aquatic Ecoregion Concept

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ABSTRACT

The development of practical lake management strategies in Minnesota has been greatly facilitated by using the aquatic ecoregion approach and standard assessment methodologies (models). Previous studies have shown the significance of the aquatic ecoregion in determining lake water quality patterns, water quality attainability, and development of nutrient criteria (Heiskary et al. 1987; Heiskary and Walker, 1988). This paper focuses upon the use of ecoregion data for modeling purposes. The Minnesota Lake Eutrophication Analysis Procedure (MINLEAP) is a computer program designed to predict eutrophication indices in Minnesota lakes based upon area watershed, depth, and ecoregion. Ecoregion is used to predict runoff and average stream phosphorus concentration. The program formulates water and phosphorus balances and uses a network of empirical models to predict lake phosphorus, chlorophyll a, and transparency values. The program is intended primarily as a screening tool for estimating lake conditions with minimal input data and for identifying "problem" lakes. Included in the program output are: (1) statistical comparisons of observed and predicted phosphorus, chlorophyll a, and transparency values; (2) uncertainty estimates; and (3) estimates of chlorophyll a interval frequencies (nuisance frequencies), for observed and predicted conditions. These expressions of lake condition may be calibrated to citizen preferences using observer surveys (Heiskary and Walker, 1988) to define swimmable and nonswimmable conditions in a locally meaningful manner. The model should be used to approximate lake water quality expectations acknowledging that individual lakes may deviate greatly from regionally defined patterns.

LRL Historical Range

MINLEAP Forecasts 90% Conf Intervals

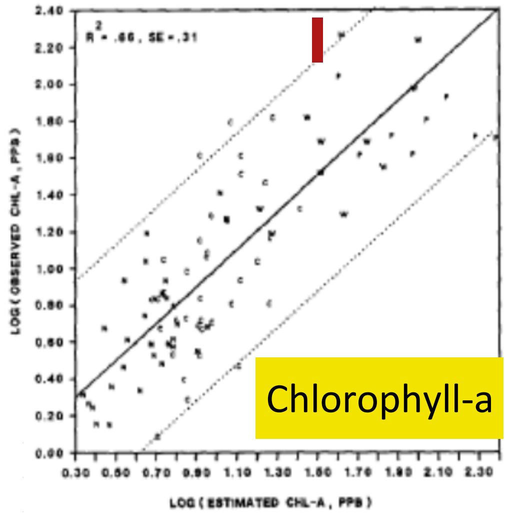

Figure 4.—Observed verus predicted chlorophyll a mean + 2 standard errors by ecoregion. Legend: base-10 logarithmic scales. Symbols: N = Northern Lakes and Forests, C = Northern Central Hardwood Forests, P = Northern Glaciated Plains, W = Western Corn Belt Plains.

With one exception, MINLEAP provides unbiased predictions (mean residual not significantly different from zero) for each ecoregion and lake response variable. The average chlorophyll a residual for Northern

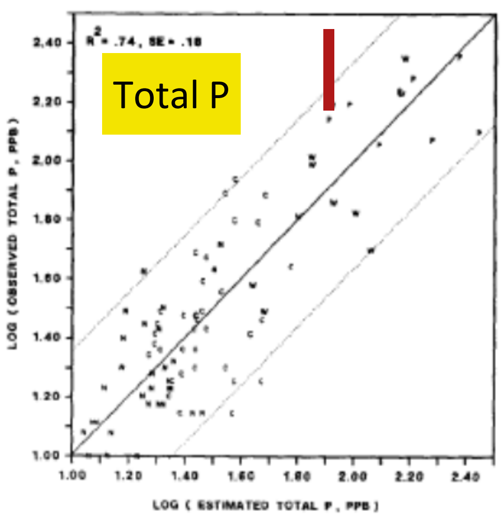

Figure 3.—Observed versus predicted total phosphorus mean + 2 standard errors by ecoregion. Legend: Base-10 logarithmic scales. Symbols: N = Northern Lakes and Forests, C = Northern Central Hardwood Forests, P = Northern Glaciated Plains, W = Western Corn Belt Plains.

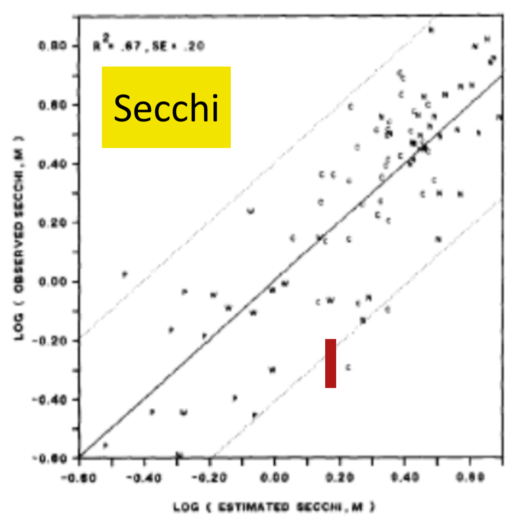

Figure 5.—Observed versus predicted Secchi transparency mean + 2 standard errors by ecoregion. Legend: base-10 logarithmic scales. Symbols: N = Northern Lakes and Forests, C = Northern Central Hardwood Forests, P = Northern Glaciated Plains, W = Western Corn Belt Plains.

MINLEAP predicted Trophic State Indicators in Minimially impacted lakes.
TP values exceeding predicted values likely to reflect excessive P loads and/or limited assimilative capacity due to internal P cycling mechanisms.

Net P Retention vs. Flow in Lake Pepin

Establishing a Chlorophyll *a* Goal for a Run-of-the-river Reservoir

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520 Lafayette RoadSt. Paul, MN 55155

William W. Walker, Jr.,
1127 Lowell Road Concord, MA 01742

ABSTRACT

Heiskary, Steven A. and William W. Walker, Jr. 1995. Establishing a chlorophyll *a* goal for a run-of-the-river reservoir. Lake and Reserv. Manage. 11(1):67-76.

Lake Pepin, a 100 km^2 run-of-the-river reservoir, is located on the Mississippi River about 80 km downstream of the Twin Cities metropolitan area on the border between Wisconsin and Minnesota. A major inter-agency study of Lake Pepin and the Mississippi River has been underway since 1990 for the purposes of determining the impacts of the effluent from the Metropolitan Waste Control Commission's Metropolitan Wastewater Treatment Facility on Lake Pepin and to predict the benefits of reducing effluent phosphorus levels to 1 mg L^{-1} or lower. Severe nuisance algal blooms and fish kills during the low flows of 1988 prompted this study.

Understanding the reservoir limnology and factors contributing to user perception of "nuisance algal blooms" (in terms of chlorophyll *a* concentration or phytoplankton species composition), are important steps in developing a chlorophyll *a* goal for Lake Pepin. Based upon analyses of chlorophyll *a* data, phytoplankton composition, and user perception information, a summer mean chlorophyll *a* concentration of 30 mg m^{-3} is recommended as a water quality goal for Lake Pepin. Nutrient-mass balance modeling suggests that a dramatic reduction in the inflow phosphorus concentration and in the overall in-lake phosphorus concentration (including internal loading) will be required to achieve this goal during low-flow summers.

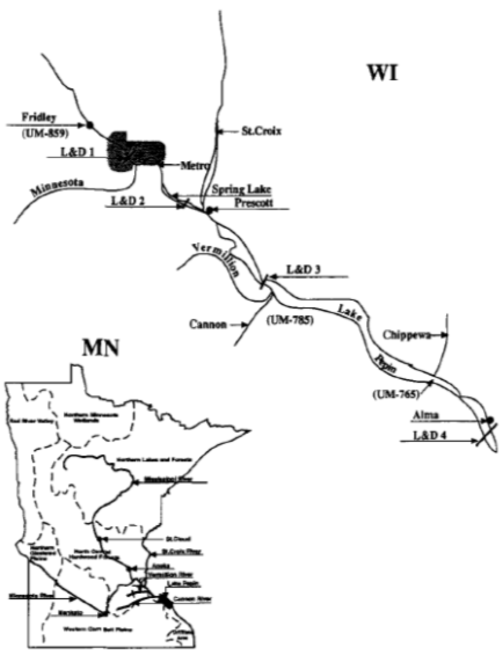
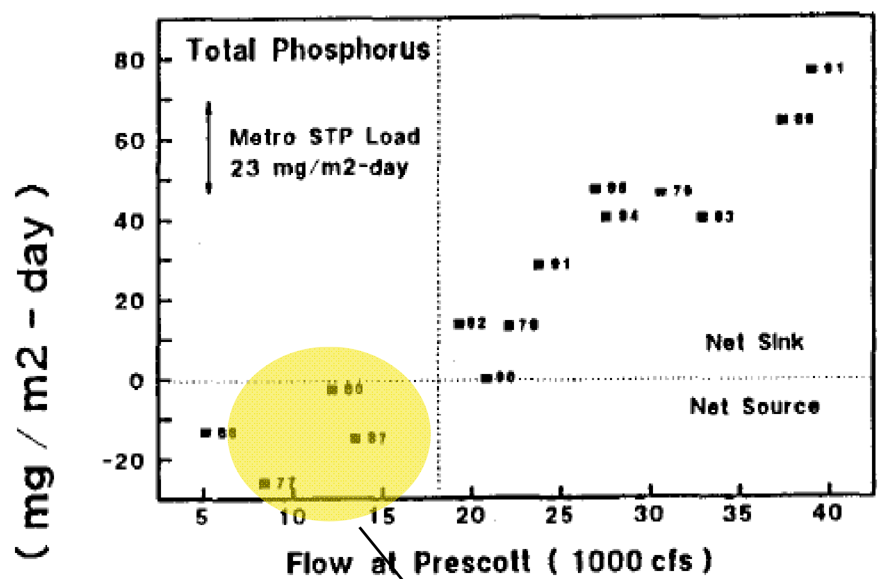
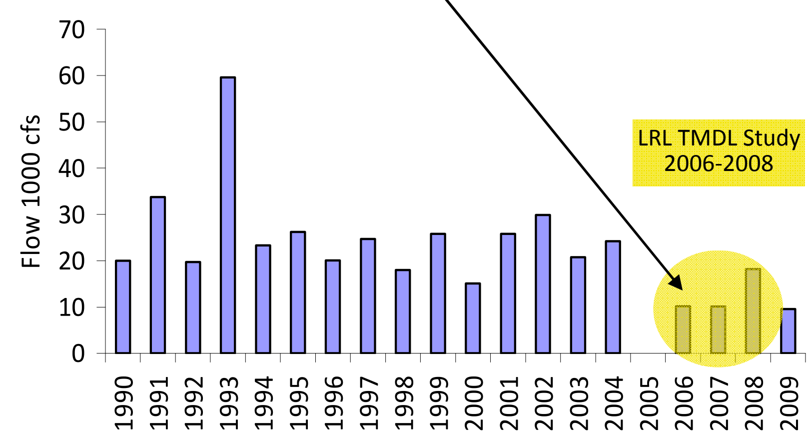


Figure 1.—Mississippi River phosphorus study area.

June-September Flow-Wtd Means



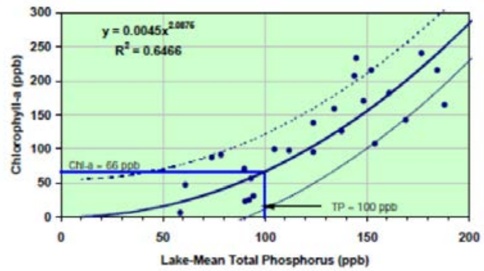
Mississippi River Flow @ Prescott - LRL Period of Record

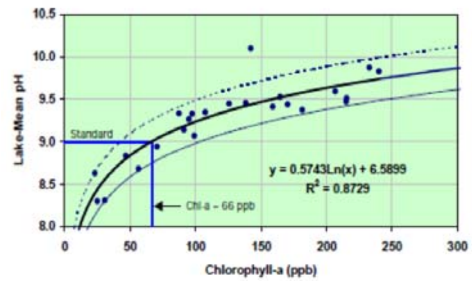


Lake Pepin is a TP Source in dry years similar to LRL Study Period (2006-2008) & Net Sink in Average-Wet Years

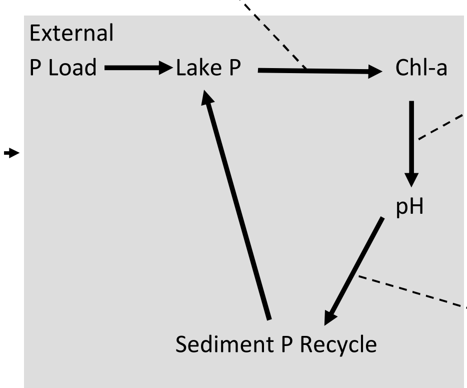
The LRL TP Mass Balances in the 2006-2008 drought are not likely to reflect of Long-Term Average Conditions

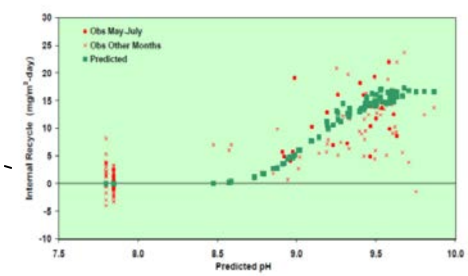
Feedback Loops Accelerating Internal P Recycling in Upper Klamath Lake, Oregon



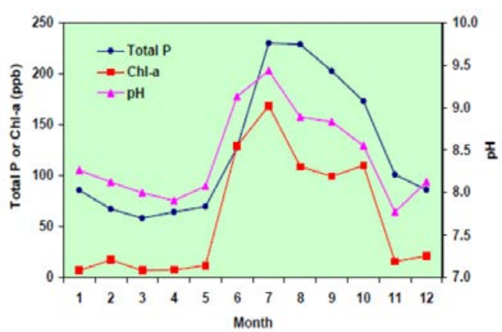


Perturbations Accelerating Cycle
- High Temperature - Low Flow / Dilution - Wind - Depth Fluctuations





Monthly Variations - UKL



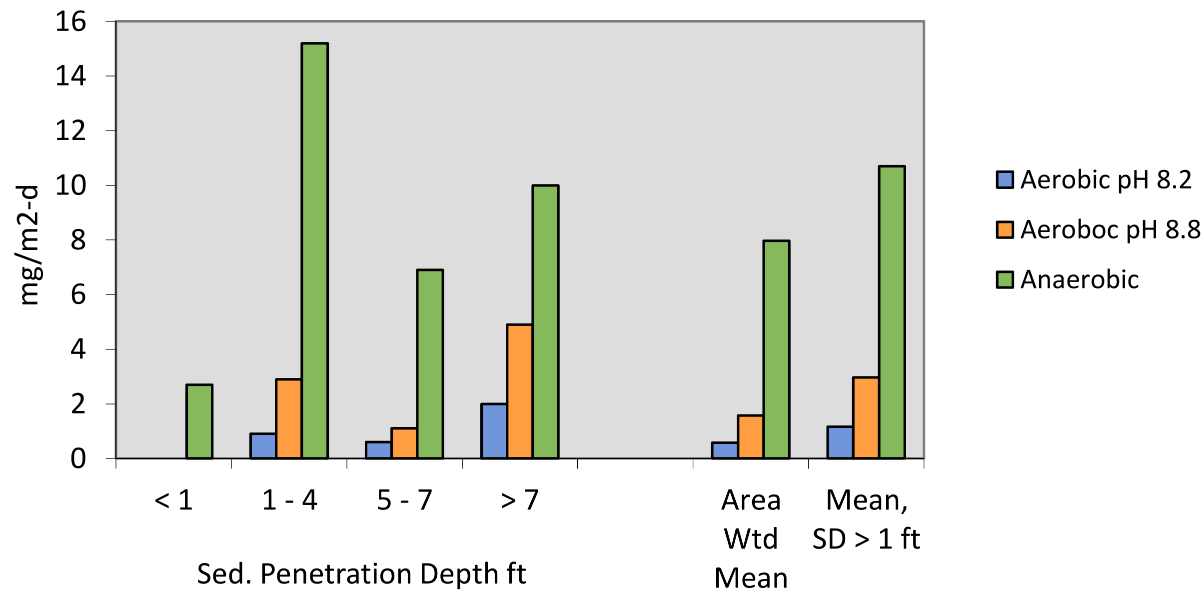
Biweekly Mean Values

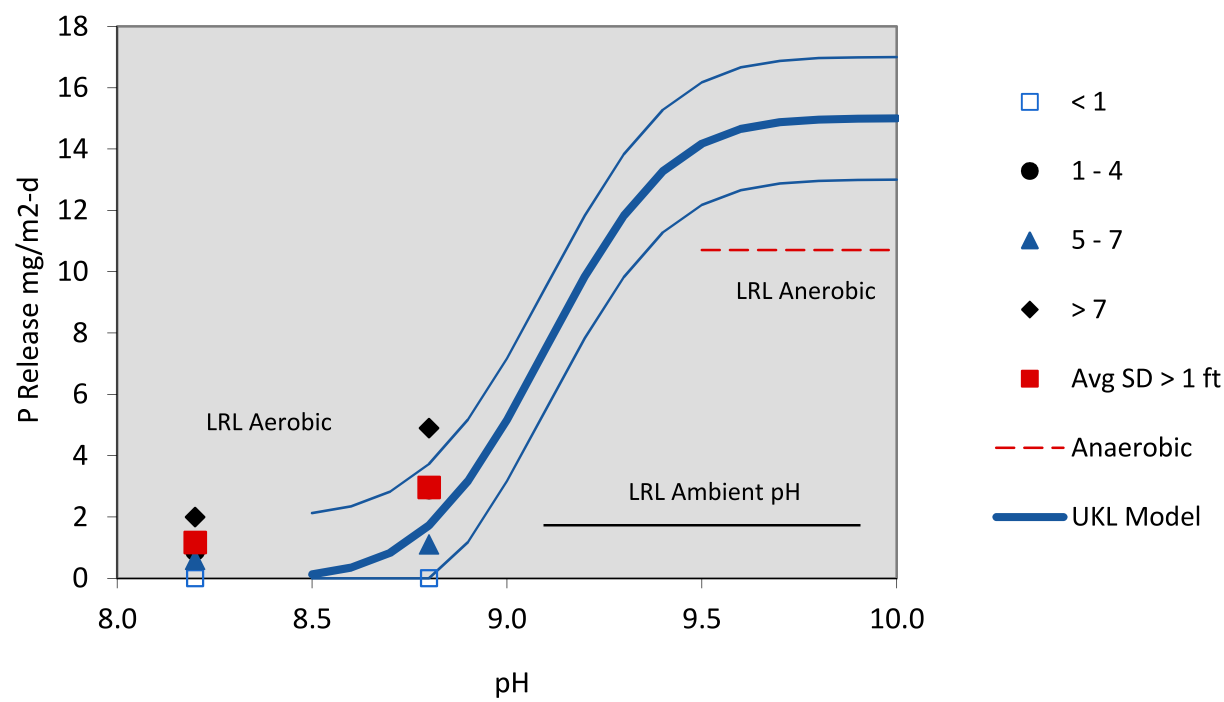
Period of Peak Algal Growth Rates (June-July)

Upper Klamath Lake TMDL Model

Ref: Walker, 2001

A-24 Sediment P Release Rates in LRL vs. Upper Klamath Lake Model

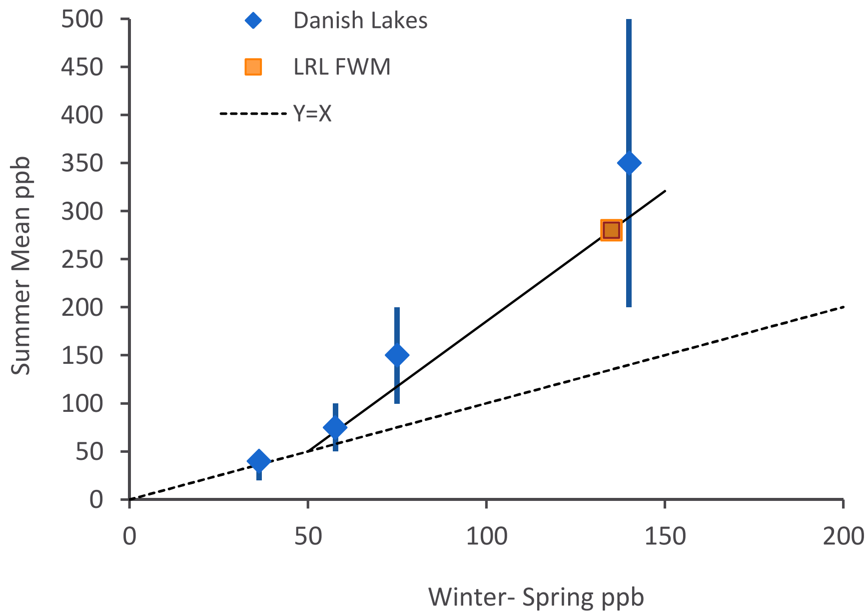




LRL Sediment P Release Rates Measured by James (2008)

UKL = Upper Klamath Lake Model (Walker, 2001)

A-25 Summer TP vs. Spring TP for Shallow Lakes in Denmark



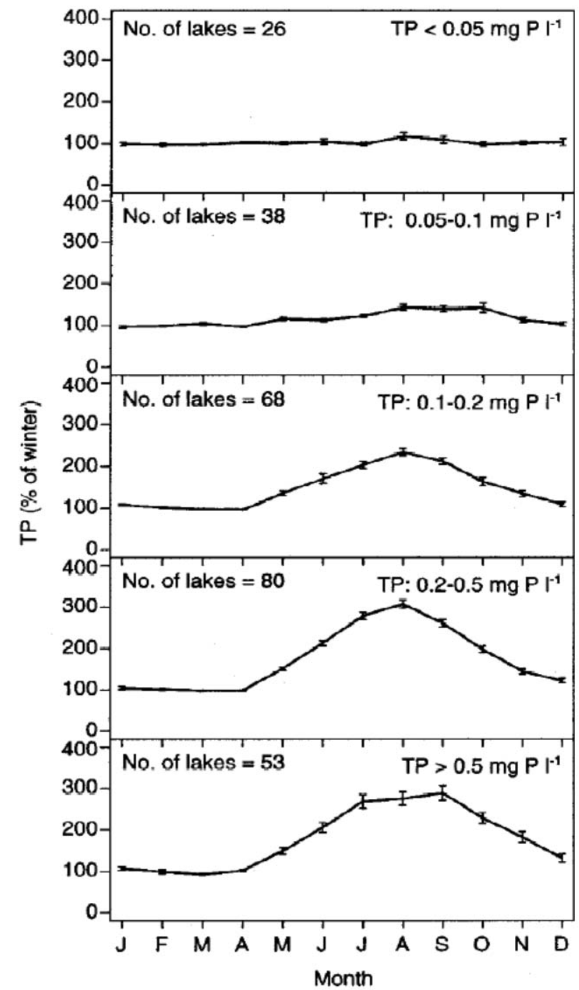


Figure 1. Seasonal variation in TP (monthly mean ± SD) as pe cent of winter values (1 Jan. – 31 March) in different categorie of TP_{sum} (number of lakes = 265). Modified from Jeppesen et a (1997).

Values for Danish Lakes Inferred from Figure 1 (Sondergaard et al, 1999), Shown on Right

X- Axis: Values Approximating TP Concentration at Start of Growing Season
December-April Means, Danish Lakes

Y Axis: Summer Mean (June - Sept)

Hypothesis: Internal Recycling Feedback Loops Triggered at Spring TP > 50 ppb: (TP -> Chla -> High pH/Anoxic Sediments - > Internal Load -> TP)