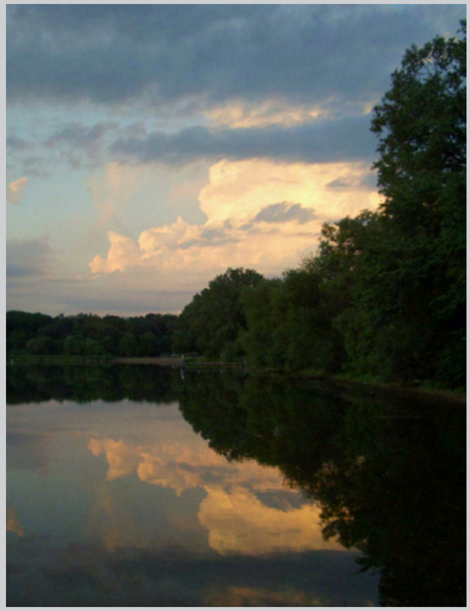
Medicine Lake Excess Nutrients Total Maximum Daily Load



Prepared for:

**Minnesota Pollution Control Agency
and the
Bassett Creek Watershed Management Commission**

November 8, 2010

LimnoTech
Water | Environment | Scientists | Engineers

wq-iw8-19e

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Required TMDL Element	**Summary Description**	**TMDL Report Location**
Location	Upper Mississippi Drainage Basin, City of Plymouth, Minnesota, Hennepin County	Page 1
303(d) Listing Information	Waterbody: Medicine Lake Lake Assessment Unit ID: 27-0104-00 Affected Use: aquatic recreation Pollutant or Stressor: nutrient/eutrophication biological indicators (phosphorus) Original Listing Year: 2004, Category 5A Subsequent Changes: 2008, Category 5B Priority Ranking: 2008 Target Start, 2010 Target Completion	Page 7
Applicable Water Quality Standards/Numeric Targets	Class 2B Eutrophication Standards (Lakes and Reservoirs in North Central Hardwood Forest Ecoregion): Phosphorus, total (TP): 40 µg/L Chlorophyll-a: 14 µg/L Secchi disc transparency: not less than 1.4 m The above are averages for June-September Source: Minnesota Rule 7050.0222 Subp. 4.	Page 7
Loading Capacity	Loading Capacity: 10.3 lbs/day TP Critical Condition: 2006 Water Year (Oct. 1, 2005 – Sep. 30, 2006)	Page 20

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<tr><th>Required TMDL Element</th><th>Summary Description</th><th>TMDL Report Location</th></tr>
<tr><td>Wasteload Allocation (WLA)</td><td>Total WLA = 8.84 lbs/day TP
<table>
<tr><th>Source</th><th>Permit #</th><th>WLA (lbs/day TP)</th></tr>
<tr><td>Permitted Stormwater (Plymouth MS4)</td><td>MS400112</td><td rowspan="5">8.44 lbs/day (categorical)</td></tr>
<tr><td>Permitted Stormwater (Medicine Lake MS4)</td><td>MS400104</td></tr>
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<tr><td>Permitted Stormwater (Hennepin County MS4)</td><td>MS400138</td><td>0.132 lbs/day</td></tr>
<tr><td>Permitted Stormwater (Mn/DOT MS4)</td><td>MS400170</td><td>0.26 lbs/day</td></tr>
<tr><td>Permitted Stormwater (construction)</td><td>Various</td><td rowspan="2">Implicit in MS4 WLAs</td></tr>
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<tr><td>Permitted Wastewater (Honeywell)</td><td>MN0063266</td><td>0.074[+]</td></tr>
<tr><td>Permitted Wastewater (Minntech)</td><td>MN0063541</td><td>0.63[+]</td></tr>
</table>
[+]Represents end-of-pipe discharge WLA. Contribution to total WLA for TMDL is smaller due to assimilation.</td><td>Page 22</td></tr>
<tr><td>Load Allocation (LA)</td><td>
<table>
<tr><th>Source</th><th>LA (lbs/day TP)</th></tr>
<tr><td>Atmospheric deposition</td><td>0.69</td></tr>
<tr><td>Internal load from lake sediment and curlyleaf pondweed die-off/ senescence above background (defined as 2006 conditions)</td><td>0.0</td></tr>
</table></td><td>Page 24</td></tr>
<tr><td>Margin of Safety (MOS)</td><td>Explicit MOS = 0.74 lbs/day

MOS established to achieve an in-lake TP level of 38 μg/L</td><td>Page 25</td></tr>
<tr><td>Reserve Capacity (RC)</td><td>RC = 0 lbs/day TP

Majority of watershed is developed.</td><td>Page 25</td></tr>
<tr><td>Seasonal Variation</td><td>TP loadings to Medicine Lake vary seasonally. Medicine Lake water quality responds to loadings on an annual or longer term basis. Therefore, the TMDL has been developed to achieve an annual average daily load.</td><td>Page 26</td></tr>
</table>

Required TMDL Element	Summary Description	TMDL Report Location
Reasonable Assurance	MS4 entities and the Bassett Creek Watershed Management Commission have on-going projects and planning which will continue to have a positive impact on Medicine Lake. Implementation includes extensive monitoring to track progress and attainment of TMDL goals. Upon approval of this TMDL by USEPA, MS4 entities must review the adequacy of their Storm Water Pollution Prevention Program (SWPPP) to meet their respective WLA. If the SWPPP is not meeting the applicable requirements, schedules and objectives of this TMDL, MS4 entities must modify their SWPPP consistent with the requirements of their permit and this TMDL.	Page 27
Monitoring	A comprehensive monitoring program has been developed to assess progress towards TMDL goals and attainment of beneficial uses.	Page 29
Public Participation	Extensive stakeholder involvement was conducted including organization of a steering committee with multiple meetings throughout the TMDL development process.	Page 31
Implementation	The Implementation Strategy includes an assessment of potential projects to reduce TP loads, demonstrates the feasibility of achieving the TMDL goals, and presents estimates of costs for implementation.	Page 37

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EXECUTIVE SUMMARY

REQUIREMENT FOR A MEDICINE LAKE TOTAL MAXIMUM DAILY LOAD

Medicine Lake is located within the City of Plymouth, Hennepin County, Minnesota. The watershed is located in the metropolitan area of the Upper Mississippi River Basin and includes portions of the cities of Plymouth, Medicine Lake, Minnetonka, Golden Valley, New Hope, and Medina. The outlet of Medicine Lake is the headwater of Bassett Creek. Medicine Lake is the second largest lake in Hennepin County and is considered the most important recreational water body in the City of Plymouth.

The Medicine Lake watershed (nearly 12,000 acres) is fully developed. Runoff from the watershed enters the lake from creeks, storm sewer outfalls, and culverts at various points along the lakeshore. The volume and pollutant levels of storm water runoff from the watershed, combined with releases of phosphorus from sediments and plants in the lake, result in periods of poor lake water quality. Available data indicates that Medicine Lake violates the State's water quality standards. The combination of high phosphorus and high chlorophyll-*a* (a measurement of algae growth) supports including Medicine Lake on the Minnesota Pollution Control Agency's (MPCA) impaired waters list.

The Clean Water Act and Environmental Protection Agency (EPA) regulations require states to develop Total Maximum Daily Loads (TMDLs) for water bodies that are not meeting water quality standards. The TMDL process establishes the allowable loading of pollutants for a water body. By following the TMDL process, states can establish controls to reduce pollution and restore and maintain the quality of the water resource. Therefore, a TMDL was designed to allow Medicine Lake to meet water quality goals.

The primary water quality target for this TMDL is the average growing season total phosphorus concentration in Medicine Lake. The State standard is 40 μg/L. The City of Plymouth has established a goal of 38 μg/L for Medicine Lake. This TMDL has been developed to meet the 38 μg/L target. The more conservative target of 38 μg/L is considered an explicit Margin of Safety (MOS) for this TMDL.

DEVELOPMENT OF THE MEDICINE LAKE TMDL

Extensive monitoring data and computer models were used to understand the relationship between pollutant sources and water quality conditions in Medicine Lake. The P8 Urban Catchment Model and the BATHTUB lake model were selected to support the development of this TMDL. The Medicine Lake TMDL process also engaged stakeholders to provide value-based feedback and prioritization to complement the modeling and scientific analysis.

All known sources of phosphorus to Medicine Lake were considered in the development of the TMDL. These sources include:

- Stormwater runoff from Municipal Separate Storm Sewer Systems (MS4);
- Permitted point sources other than MS4s;
- Atmospheric deposition; and
- Internal loading.

The TMDL represents the total mass of phosphorus that can be assimilated into Medicine Lake while continuing to meet the state water quality standards. The TMDL is described as the sum of four different components: Wasteload Allocation (WLA); Load Allocation (LA); Margin of Safety (MOS); and Reserve Capacity (RC). The WLA represents phosphorus loading from point sources such as permitted stormwater discharge from the various MS4s. The LA represents phosphorus from nonpoint sources such as atmospheric deposition and internal loading. No reductions are being called for from atmospheric deposition or internal loads. A portion of the TMDL is allocated to the MOS to account for uncertainty. The RC represents the portion of the load that is set aside to account for future development.

The Medicine Lake TMDL for total phosphorus (TP) is presented as:

	TMDL	=	∑WLA	+	∑LA	+	MOS	+	RC
(lbs/day TP)	**10.3**	=	**8.84**	+	**0.69**	+	**0.74**	+	**0**
(lbs/yr TP)	**3,753**	=	**3,230**	+	**253**	+	**270**	+	**0**

ALLOCATION OF THE TMDL

The WLA of 3,230 lbs/yr is 1,287 lbs/yr less than loadings estimated for watershed conditions in 2007, or a 28% reduction. Therefore, point source discharges will need to be reduced by 1,287 lbs/yr to comply with the TMDL. Two permitted wastewater discharges are located within the watershed. These include Minntech Corporation and Honeywell, Inc. The Minntech discharge is assumed to contribute negligible phosphorus to Medicine Lake. The Honeywell discharge is assumed to contribute 6 lbs/yr of phosphorus to Medicine Lake. Neither wastewater discharge is being asked, at this time, to reduce phosphorus in their discharge.

The remaining WLA of 3,224 lbs/yr TP was assigned to MS4s. The municipal MS4s have decided to approach this in a coordinated fashion and have agreed to a categorical WLA. These municipal MS4s include the City of Plymouth, City of Medicine Lake, City of Minnetonka, City of Golden Valley, and the City of New Hope. The Bassett Creek Watershed Management Commission (BCWMC) will serve as the convener of action for the categorical WLA, but not as a responsible entity. Additional MS4 entities which have individual WLAs include Hennepin County and Mn/DOT. WLAs were developed based on the percent of the watershed area occupied and are summarized in the table below.

TMDL and Allocation Summary.

Point Sources	Permit #	Gross WLA (i.e. loading to Medicine Lake) (lbs/year TP)
Categorical WLA		
City of Plymouth	MS400112	3,082
City of Medicine Lake	MS400104	
City of Minnetonka	MS400035	
City of Golden Valley	MS400021	
City of New Hope	MS400039	
Construction Stormwater	Various	
Industrial Stormwater	Various	
Individual WLAs		
Hennepin County	MS400138	48
Mn/DOT	MS400170	94
Honeywell*	MN0063266	6
Minntech*	MN0063541	0
Total WLA		3,230
Load Allocation		253
Margin of Safety (MOS)		270
TOTAL		**3,753**

*The actual "end-of-pipe" allocation for Honeywell and Minntech is greater than the value presented in this table.

IMPLEMENTATION OF THE TMDL

An Implementation Strategy was developed to achieve and maintain the required load reductions for the Medicine Lake TMDL. The Implementation Strategy focuses on reducing phosphorus loads from the surrounding watershed and maintaining background levels of internal loads. The Implementation Strategy for the Medicine Lake TMDL includes:

- Continued maintenance of existing stormwater ponds and assessment and implementation of retrofits for improved performance;
- Continued curlyleaf pondweed control to maintain densities equal to or less than that experienced in 2006;
- Construction of the West Medicine Lake Water Quality Ponds in the City of Plymouth (scheduled for completion in the fall of 2010);
- Continued educational efforts that promote stewardship;
- Continued streambank stabilization efforts;
- Continued shoreline restoration efforts;
- Assessment and implementation of best management practices (BMPs) that reduce runoff, such as reduced impervious area (e.g. smaller parking areas),

increased storage (e.g. rain barrels and increased tree cover); and increased infiltration (e.g. rain gardens and soil amendments); and

- Continued monitoring, assessment and adaptive management.

A combination of these efforts can be expected to achieve the reductions in watershed TP loads required to meet the TMDL and maintain or reduce existing internal loads. To ensure effectiveness and efficiency of TMDL implementation, ongoing monitoring will be conducted.

Attaining 1,287 lbs/yr TP reduction in the watershed load could cost between $2,500/lb and $5,000/lb, for a total cost between $3,217,500 and $6,435,000. This cost could be less considering BMPs implemented since 2007 have not been accounted for in the 1,287 lbs/yr TP reduction estimate. The continued combined efforts of the Bassett Creek Watershed Management Commission (BCWMC), the Three Rivers Park District (TRPD), the Association of Medicine Lake Area Citizens (AMLAC), the Minnesota Pollution Control Agency (MPCA), and the individual MS4 permit holders (primarily the City of Plymouth) will be critical to the success of the TMDL implementation efforts. An Implementation Plan will be developed and provide information to be used to guide implementation activities. The specific activities to be taken to achieve the required load reductions will be left to the discretion of the BCWMC and MS4 permit holders, including Mn/DOT and Hennepin County.

1. INTRODUCTION

1.1 PURPOSE

Section 303(d) of the Clean Water Act and Environmental Protection Agency's (EPA) Water Quality Planning and Management Regulations (40 CFR Part 130) require states to develop Total Maximum Daily Loads (TMDLs) for water bodies that are not meeting designated uses under technology-based controls. The TMDL process establishes the allowable loading of pollutants or other quantifiable parameters for a water body based on the relationship between pollution sources and instream conditions. By following the TMDL process, states can establish water quality-based controls to reduce pollution from both point and non-point sources and restore and maintain the quality of their water resources (USEPA, 1991).

Medicine Lake is listed on the 2008 Minnesota Section 303(d) List of Impaired Waters due to impairment of aquatic recreation by excess nutrients (phosphorus). It was originally listed in 2004. Therefore, the development of a TMDL is required. The Minnesota Pollution Control Agency (MPCA) projected schedule for TMDL report completion, as indicated on the 303(d) list, implicitly reflects Minnesota's priority ranking of these TMDLs. The MPCA assigned a target start date of 2008 and a target completion date of 2010 for the development of the Medicine Lake TMDL. Ranking criteria for scheduling TMDL projects include, but are not limited to: impairment impacts on public health and aquatic life; public value of the impaired water resource;likelihood of completing the TMDL in an expedient manner, including a strong base of existing data and restorability of the water body; technical capability and willingness locally to assist with each TMDL; and appropriate sequencing of TMDLs within a watershed or basin. This document presents the TMDL designed to allow Medicine Lake to fully support its designated uses. The report covers each required component of the TMDL development process. The TMDL has been developed following a Work Plan developed by the MPCA (MPCA, 2008).

Extensive studies and reports related to Medicine Lake and its watershed have been produced by various entities and are referenced in this report. When more detailed information is desired than what is presented in this TMDL report, please refer to the referenced reports.

1.2 CHARACTERIZATION OF STUDY AREA

Medicine Lake (Lake Assessment Unit ID: 27-0104-00) is located within the City of Plymouth, Hennepin County, Minnesota (Figure 1-1). The watershed is located in the metropolitan area of the Upper Mississippi River Basin and includes portions of the cities of Plymouth, Medicine Lake, Minnetonka, Golden Valley, New Hope, and Medina. The outlet of Medicine Lake is the headwater of Bassett Creek. The current emphasis of the Bassett Creek Watershed Management Commission (BCWMC) is to improve surface water quality, including Medicine Lake (http://www.bassettcreekwmo.org/).

Medicine Lake is the second largest lake in Hennepin County and is considered the most important recreational water body in the City of Plymouth (Barr, 2000). Recreational opportunities in and around the lake include fishing, boating, swimming, water-skiing and aesthetic enjoyment. Multiple parks are adjacent to the lake and provide public access. The Association of Medicine Lake Area Citizens (AMLAC) has been organized to "To preserve, protect and promote the water quality in and surrounding Medicine Lake for present citizens and future generations to enjoy" (http://www.amlac.org/).

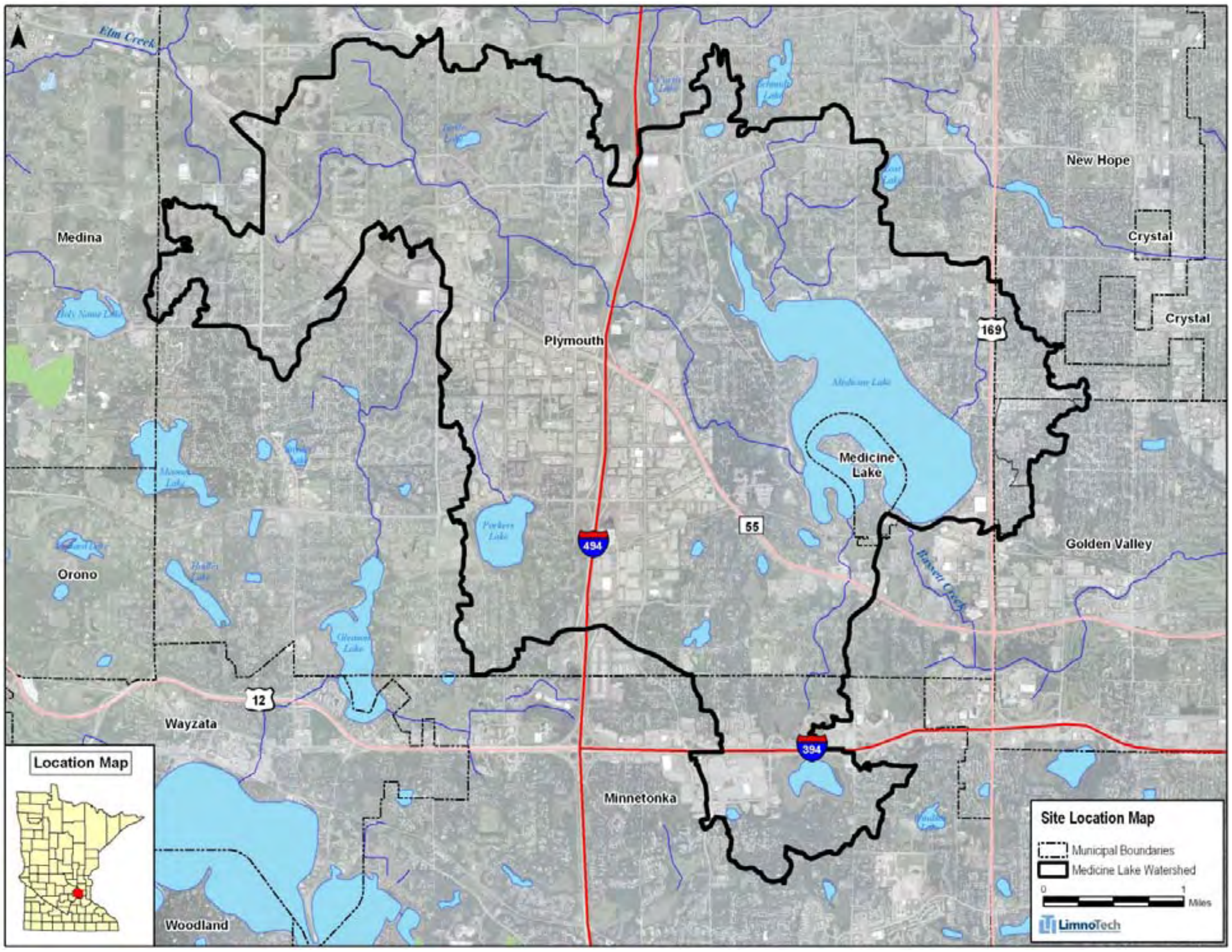


Figure 1-1. Site Location.

1.2.1 Medicine Lake

Medicine Lake is approximately 900 surface acres in size, with a maximum depth of 11 meters (Figure 1-2 and Table 1-1). The lake littoral area (< 15 ft in depth) comprises approximately 33% of the entire surface acreage. Medicine Lake meets the State's deep lake criteria. Medicine Lake has a large fetch (3-km) that is oriented from the northwest to the southeast. The lake typically stratifies during the summer at approximately 5 meters in depth (Vlach et al., 2007). However, prolonged winds from the north and/or south often initiate complete or partial turnover events (in addition to the spring and fall turnover) that potentially exacerbate the internal loading of phosphorus (USEPA, 2000).

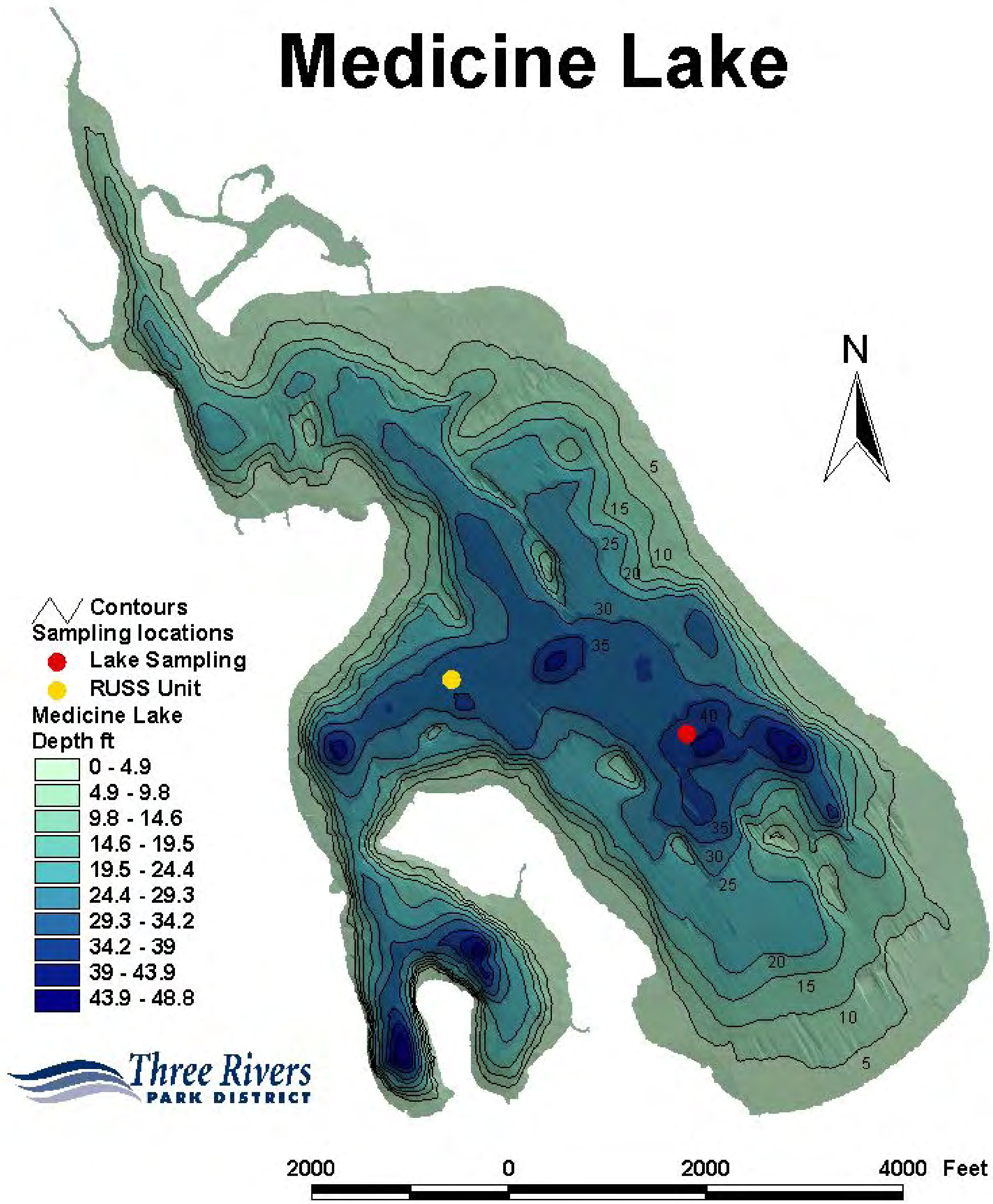


Figure 1-2. Medicine Lake Bathymetry.

Table 1-1. Medicine Lake Bathymetry.

Morphometry Characteristics	
Surface Area	3.83 km^2
Mean Depth	5.3 m
Length	3 km
Mixed Layer Depth	5 m
Hypolimnetic Depth	7 m

1.2.2 Medicine Lake Watershed

The Medicine Lake watershed (nearly 12,000 acres) drains land from six different municipalities (Plymouth, City of Medicine Lake, New Hope, Golden Valley, Minnetonka, and Medina) and two transportation agencies (Hennepin County and Minnesota Department of Transportation) that are served by Municipal Separate Storm Sewer Systems (MS4). The watershed has been delineated into 3 primary watersheds and 11 major subwatersheds (Figure 1-3) based on monitoring locations and MS4 boundaries.

The watershed was primarily agriculture in the early 1900s. Residential development of the watershed began in the 1930s. The watershed experienced increased rates of residential and industrial development in the 1960s and 1970s. By the end of the 1990s the watershed was fully developed. Nearly 60% of the watershed is assigned a land cover of 25% impervious area or greater (Figure 1-4). Runoff from the watershed enters the lake from creeks, storm sewer outfalls, and culverts at various points along the lakeshore. Stormwater from approximately 90 percent of the Medicine Lake watershed currently drains through some form of wet detention before it enters Medicine Lake.

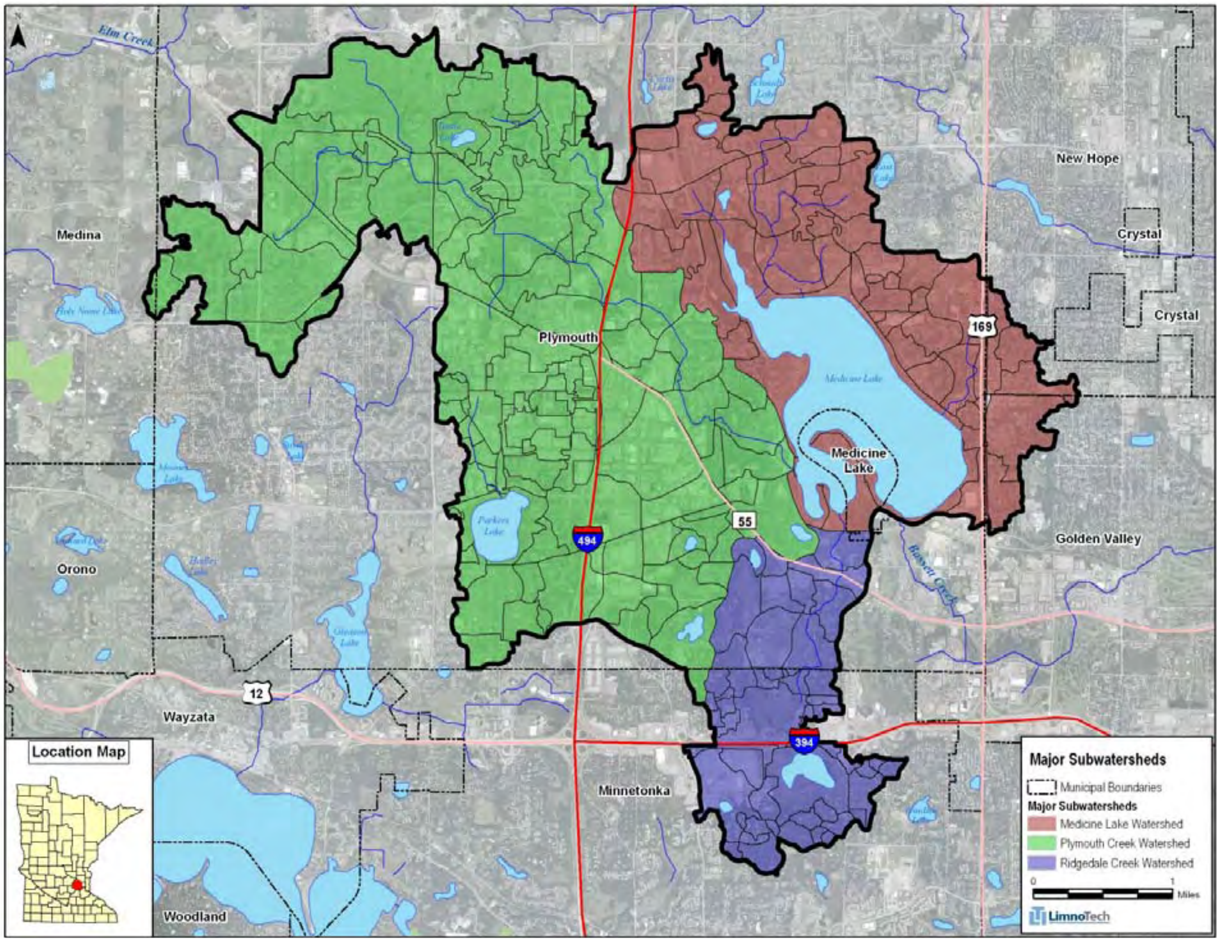
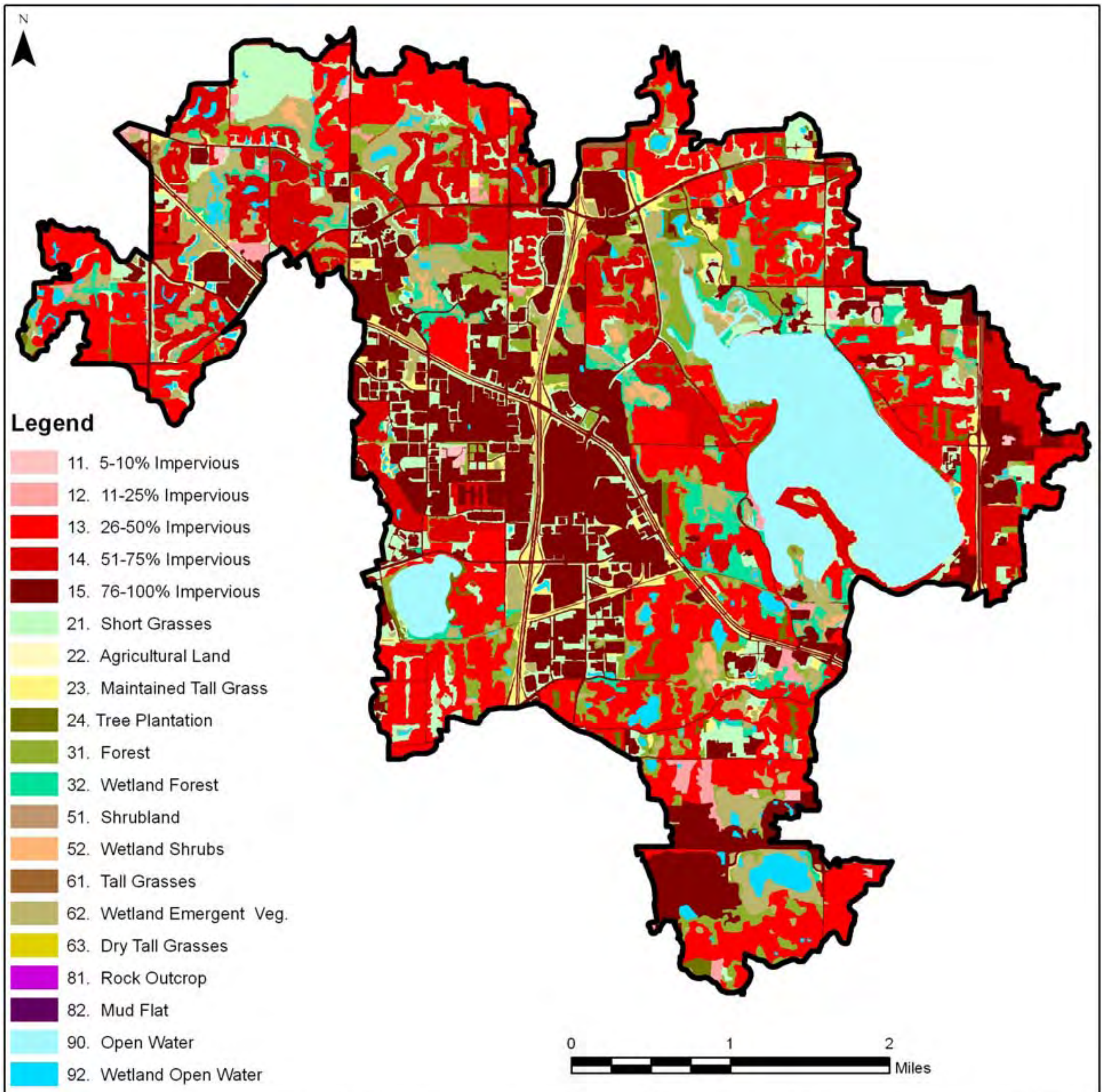


Figure 1-3. Medicine Lake Subwatersheds.



	City Land Cover (acres)							City Land Cover percentage						
Land Cover Type	Golden Valley	Medicine Lake	Medina	Minnetonka	New Hope	Plymouth	Grand Total	Golden Valley	Medicine Lake	Medina	Minnetonka	New Hope	Plymouth	Grand Total
5-10% Impervious	0.5	0.0	0.0	7.9	2.4	33.5	44.3	0.22%	0.00%	0.00%	0.88%	1.46%	0.33%	0.38%
11-25% Impervious	0.1	0.0	0.4	39.4	0.0	67.4	107.3	0.05%	0.00%	3.75%	4.37%	0.00%	0.67%	0.92%
26-50% Impervious	53.1	12.2	0.0	331.9	0.0	2,319.0	2,716.1	24.39%	5.31%	0.00%	36.81%	0.00%	22.97%	23.38%
51-75% Impervious	67.2	48.6	0.0	1.7	111.3	1,209.5	1,438.4	30.89%	21.20%	0.00%	0.19%	69.24%	11.98%	12.38%
76-100% Impervious	56.5	0.5	0.0	258.4	42.2	2,122.8	2,480.4	25.96%	0.24%	0.00%	28.66%	26.28%	21.03%	21.35%
Short Grasses	16.2	17.1	0.6	2.1	3.5	1,001.6	1,041.2	7.46%	7.46%	5.01%	0.23%	2.18%	9.92%	8.96%
Agricultural Land	0.0	0.0	0.1	0.0	0.0	0.0	0.1	0.00%	0.00%	0.62%	0.00%	0.00%	0.00%	0.00%
Maintained Tall Grass	4.4	0.0	0.0	2.3	1.4	342.1	350.1	2.02%	0.00%	0.00%	0.26%	0.84%	3.39%	3.01%
Tree Plantation	0.0	0.0	3.0	11.2	0.0	141.6	155.9	0.00%	0.00%	25.30%	1.24%	0.00%	1.40%	1.34%
Forest	8.8	0.0	4.9	75.4	0.0	644.1	733.2	4.06%	0.00%	41.05%	8.36%	0.00%	6.38%	6.31%
Wetland Forest	2.2	10.9	0.0	3.2	0.0	301.9	318.2	0.99%	4.76%	0.00%	0.36%	0.00%	2.99%	2.74%
Shrubland	0.0	0.0	0.0	0.0	0.0	0.7	0.7	0.00%	0.00%	0.00%	0.00%	0.00%	0.01%	0.01%
Wetland Shrubs	0.0	0.0	0.0	0.0	0.0	57.1	57.1	0.00%	0.00%	0.00%	0.00%	0.00%	0.57%	0.49%
Tall Grasses	1.4	0.0	0.0	0.0	0.0	11.4	12.8	0.62%	0.00%	0.00%	0.00%	0.00%	0.11%	0.11%
Wetland Emergent Veg.	4.6	8.7	2.3	106.9	0.0	743.0	865.4	2.11%	3.81%	18.93%	11.86%	0.00%	7.36%	7.45%
Dry Tall Grasses	0.7	0.0	0.0	0.0	0.0	0.0	0.7	0.31%	0.00%	0.00%	0.00%	0.00%	0.00%	0.01%
Open Water	0.0	131.2	0.0	0.0	0.0	915.2	1,046.5	0.00%	57.22%	0.00%	0.00%	0.00%	9.07%	9.01%
Wetland Open Water	2.0	0.0	0.6	61.2	0.0	184.1	248.0	0.94%	0.00%	5.35%	6.79%	0.00%	1.82%	2.13%
Grand Total	217.6	229.3	12.0	901.6	160.7	10,095.1	11,616.3							

Figure 1-4. Medicine Lake Watershed Land Cover.

2. PROBLEM IDENTIFICATION

In 2004, Medicine Lake was placed on the MPCA's impaired waters list as the available data indicated that Medicine Lake exceeded the State's narrative criteria for nutrients (based on total phosphorus, chlorophyll-a and Secchi disc transparency) for the growing season mean. Similarly, Medicine Lake has typically not met the BCWMC water quality goals.

Medicine Lake water quality conditions are typical of lakes in highly urbanized settings. The volume and pollutant levels of storm water runoff from the watershed, combined with internal sources of phosphorus, result in periods of poor lake water quality.

2.1 APPLICABLE WATER QUALITY STANDARDS

Medicine Lake (Lake Assessment Unit ID: 27-0104-00) is in the North Central Hardwood Forest Ecoregion (ecoregion map included in Minnesota Rule 7050.0467). Medicine Lake is designated as a Class 2B water in Minnesota Rule 7050.0430. Minnesota Rule 7050.0140 defines the beneficial use of Class 2 waters, aquatic life and recreation, as:

> *Aquatic life and recreation includes all waters of the state that support or may support fish, other aquatic life, bathing, boating, or other recreational purposes and for which quality control is or may be necessary to protect aquatic or terrestrial life or their habitats or the public health, safety, or welfare.*

Minnesota Rule 7050.0222 Subp 4 includes the applicable numeric criteria for Deep Lakes and Reservoirs in the North Central Hardwood Forest Ecoregion. These include:

- Phosphorus, total: 40 μg/L
- Chlorophyll-a: 14 μg/L
- Secchi disc transparency: not less than 1.4 m

Minnesota Rule 7050.0222 Subp. 4a. B defines conditions for impairment based on these criteria:

> *Eutrophication standards are compared to data averaged over the summer season (June through September). Exceedance of the total phosphorus and either the chlorophyll-a or Secchi disk standard is required to indicate a polluted condition.*

2.2 HISTORICAL WATER QUALITY DATA

Figure 2-1 presents annual growing season total phosphorus concentrations for Medicine Lake from 1995 through 2009. Figure 2-2 presents annual growing season secchi depth and chlorophyll-a concentrations for Medicine Lake from 1995 through 2009. Table 2-1 includes average water quality conditions for 2004 through 2009.

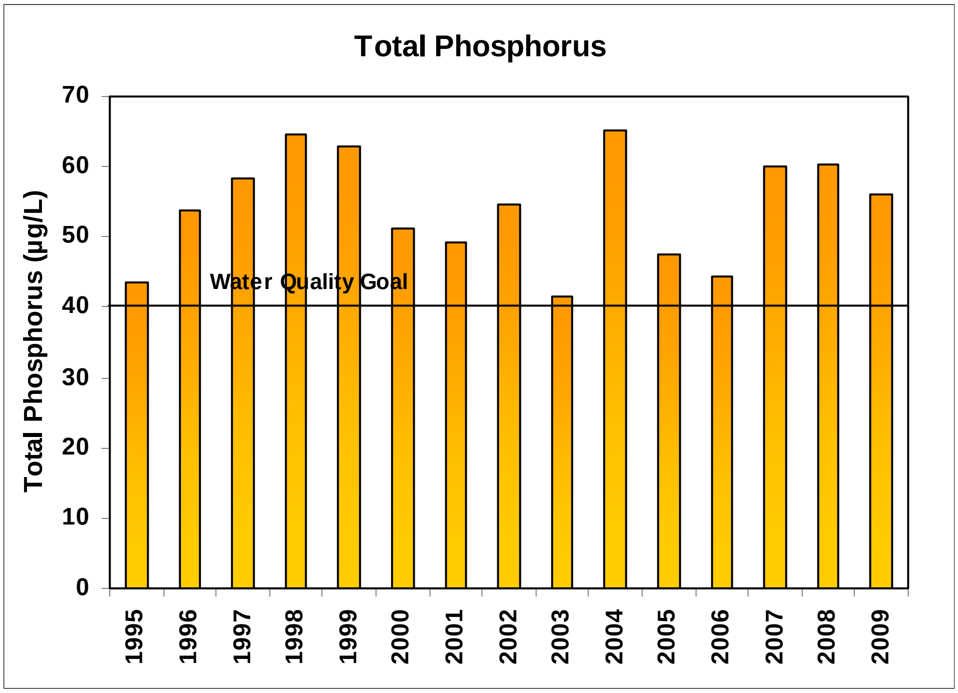


Figure 2-1. Historical Phosphorus Concentrations.

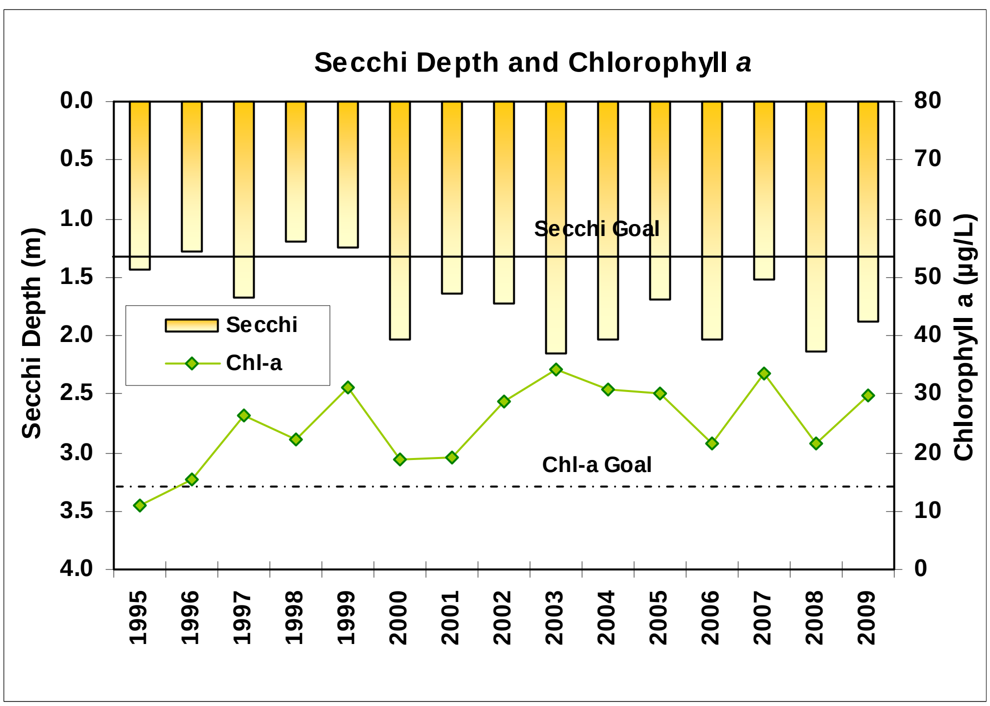


Figure 2-2. Historical Secchi Depth and Chlorophyll-a.

Table 2-1. Water Quality Conditions for Medicine Lake from 2004 through 2009.

Average Water Quality Conditions			
Year	TP (µg/L)	Chl-a (µg/L)	Secchi (m)
2004	65.1	30.6	2.04
2005	47.6	30.0	1.70
2006	45.0	21.6	2.04
2007	60.0	33.3	1.52
2008	60.4	21.7	2.13
2009	56.1	29.9	1.88

The historical water quality data indicate annual variations in average growing season phosphorus concentrations but consistent non-compliance with the applicable numeric criterion of 40 µg/L. While secchi depth values generally attain the applicable numeric criterion of a minimum of 1.4 m, chlorophyll-*a* concentrations are generally substantially greater than the allowable level of 14 µg/L. The combination of high phosphorus and high chlorophyll-*a* support listing Medicine Lake as impaired. Additional information on historical data can be found in the City of Plymouth Water Quality Monitoring Report for 2005-2007 (Vlach et al., 2007).

2.3 TMDL TARGETS

The primary numerical water quality target for this TMDL is the average growing season total phosphorus concentration in Medicine Lake. The State standard is 40 µg/L. The City of Plymouth established a goal of 38 µg/L in their Medicine Lake Watershed Implementation and Management Plan (City of Plymouth, 2004). This TMDL has been developed to meet the 38 µg/L target. The more conservative target of 38 µg/L is considered an explicit Margin of Safety (MOS) for this TMDL.

The secondary numerical water quality target for this TMDL is the average growing season secchi depth criterion of 1.4 m. Historical water quality data indicate that this criterion is generally being met currently. Compliance with the total phosphorus target and the secchi depth target would constitute compliance with the applicable water quality standards and attainment of the beneficial uses.

While attainment of the chlorophyll-*a* criterion of 14 µg/L is not a numerical target for this TMDL, making progress towards the attainment of the total phosphorus target is expected to contribute to lower chlorophyll-*a* levels in Medicine Lake. Continued monitoring will track progress towards all three parameters.

2.4 TMDL TARGET CONDITIONS

Concurrent with the selection of a numeric target, TMDL development must also define the environmental conditions that will be used when defining allowable loads.

Selection of these conditions must consider both the appropriate duration and the severity of the condition. The duration of the TMDL environmental conditions must consider the response time of the water quality impairment and the residence time of the pollutant in the waterbody.

For this TMDL, climatic conditions, including precipitation and temperature, experienced in the 2006 water year (October 1, 2005 through September 30, 2006) have been selected as the appropriate conditions with which to define allowable total phosphorus loads on an annual basis. An annual basis for TMDL development is consistent with the hydraulic residence time of Medicine Lake, which exceeds one year. 2006 conditions were selected because they represent typical annual precipitation amounts and patterns as well as typical phosphorus loadings. In addition, internal phosphorus loading from curlyleaf pondweed die-off/senescence and multiple mixing events was minimal in 2006.

3. SOURCE ASSESSMENT AND LINKAGE TO TMDL TARGETS

All known sources of phosphorus to Medicine Lake were considered in the development of the TMDL. These sources include:

- Stormwater runoff from MS4s;
- Permitted point sources other than MS4s;
- Atmospheric deposition; and
- Internal loading.

The Medicine Lake watershed is essentially fully developed. Runoff from the watershed enters the lake from creeks, storm sewer outfalls, and culverts at various points along the lakeshore. Stormwater from approximately 90 percent of the Medicine Lake watershed currently drains through some form of wet detention before it enters Medicine Lake. There are no permitted discharges directly to Medicine Lake other than the MS4s.

There are two known permitted wastewater discharges within the watershed but these are not expected to be significant contributors of phosphorus to Medicine Lake. These permitted wastewater discharges are discussed further in development of the TMDL but are not explicitly included in the watershed modeling.

Atmospheric deposition is a significant contributor of phosphorus to Medicine Lake and is accounted for in the water quality modeling.

There are two primary sources of internal loading of phosphorus in Medicine Lake - sediment release of phosphorus and curlyleaf pondweed die-off/senescence. These have been considered in the water quality modeling.

3.1 MODELING APPROACH

The P8 Urban Catchment Model and the BATHTUB lake model were selected to support the development of this TMDL. Key considerations in selecting these models included:

- Availability of existing models;
- Ability to simulate relevant water quality parameters and processes;
- Spatial and temporal resolution consistent with response of Medicine Lake to loadings;
- Sufficient data available to support parameterization and calibration of models; and
- Availability of resources to develop and apply models.

P8 was chosen to simulate stormwater runoff volumes and watershed loadings of phosphorus to Medicine Lake. P8 is a useful tool for simulating rainfall-runoff relationships and transport of pollutants in urban watersheds, including the effectiveness of stormwater detention ponds. P8 has extensive applications and is a readily accepted model.

A BATHTUB model (Army Corps of Engineers Version 6.1) was developed to describe water quality conditions and estimate the assimilative capacity in Medicine Lake. BATHTUB is an empirical model that estimates lake and reservoir eutrophication using several different algorithms. The model estimates in-lake water quality conditions based on the lake morphological characteristics and a mass-balance of nutrient loading to the lake. Nutrient sources included in the model are atmospheric deposition, and both internal and watershed loading. The BATHTUB model was developed to simulate the average, growing-season, water-quality conditions for total phosphorus, chlorophyll-*a*, and secchi depth.

The P8 model was developed and applied to generate annual stormwater runoff volumes and associated total phosphorus loads in the Medicine Lake watershed. These flows and loads were used in the BATHTUB model of Medicine Lake to simulate the response of in-lake total phosphorus, chlorophyll-*a*, and secchi depth to the watershed loadings. Once calibrated, the BATHTUB model was applied to define the allowable watershed loading of total phosphorus to meet the in-lake TMDL target for total phosphorus of 38 μg/L. Once this allowable loading was determined, the P8 model was applied to assess the feasibility of reducing watershed loadings to meet the target. These results were used to inform the Implementation Plan.

For this TMDL, MPCA contractors were used to conduct the modeling. LimnoTech conducted the P8 modeling and Three Rivers Park District (TRPD) conducted the BATHTUB modeling. Detailed descriptions of the modeling efforts are included in Appendices A and B. A summary of model development, calibration, and application to support the TMDL is presented in Sections 3.2 and 3.3 below.

3.2 WATERSHED LOADING MODEL

The most recent P8 modeling files for the Medicine Lake watershed were converted to the Windows-based version of P8 (Version 3.4). Model inputs were reviewed with the cities of New Hope, Golden Valley, Plymouth, and Minnetonka, as well as Mn/DOT. Model inputs were updated with the most recent information. Model inputs were also reviewed to identify any inconsistencies in model parameterization throughout the watershed and minor revisions were made to improve consistency. These included minor adjustments to runoff coefficients in impervious areas and infiltration rates in stormwater ponds.

Hourly precipitation and daily temperature files were developed to represent the period from 2004 through 2008. A summary of the annual precipitation based on water years is presented in Table 3-1.

Table 3-1. Summary of Precipitation Inputs to P8 Model.

Water Year	Period	Precipitation (inches)
2004	10/1/2003-9/30/2004	33.8
2005	10/1/2004-9/30/2005	27.9
2006	10/1/2005-9/30/2006	29.7
2007	10/1/2006-9/30/2007	27.3
2008	10/1/2007-9/30/2008	25.6

P8 was run to simulate the monitoring period in 2006 for calibration purposes. TRPD provided assessments of the monitoring data for each of the eleven sampling sites within the Medicine Lake watershed. TRPD used the United States Army Corps of Engineers' FLUX program to develop pollutant loading rates. The FLUX program applies five different estimation methods to calculate loading rates from periodic concentration data and flow monitoring records. Adjustments of model parameters were made to achieve a reasonable match to the FLUX results. Consideration was first given to model-data comparisons for flow rates, then solids loads, and finally total and dissolved phosphorus loads. Final calibration results for flow and total phosphorus are presented in Figures 3-1 and 3-2. Confidence intervals for the P8 results are represented as ±25% on flow and ±35% on TP based on current best professional judgment for watershed modeling. Uncertainty bars on the FLUX results for TP were included representing two standard deviations as calculated by the FLUX program. The adequacy of the calibration was assessed by evaluating the overlap of the confidence intervals and uncertainty bars. For additional discussion of the calibration of the P8 model, see Appendix A.

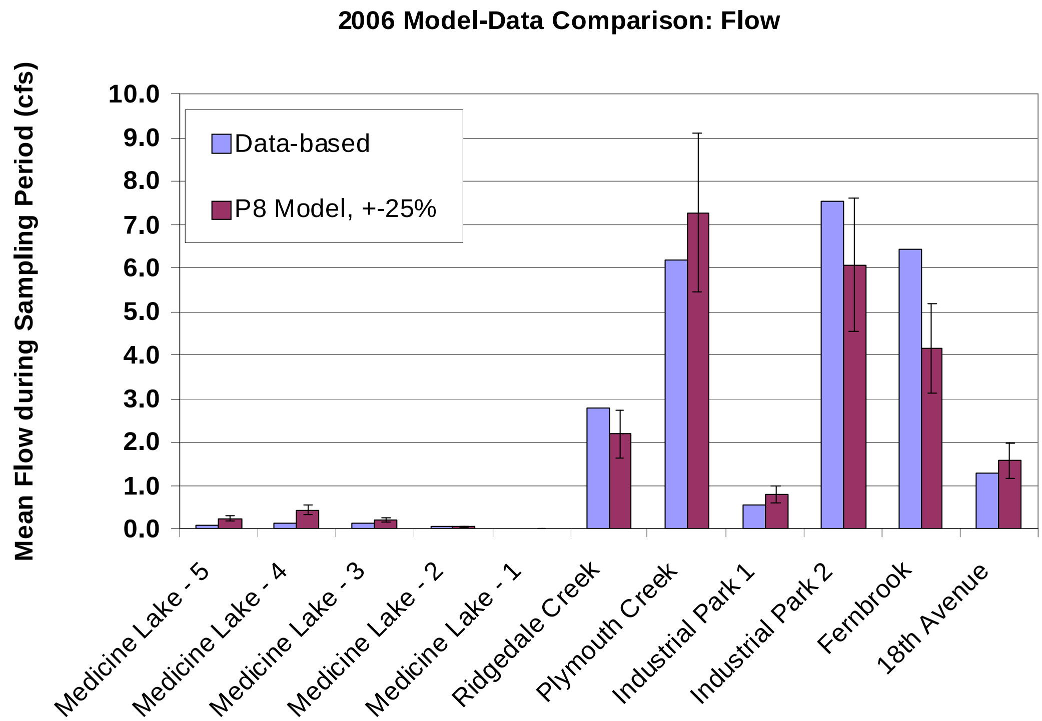


Figure 3-1. Model-Data Comparison for Flow for Calibration Year 2006.

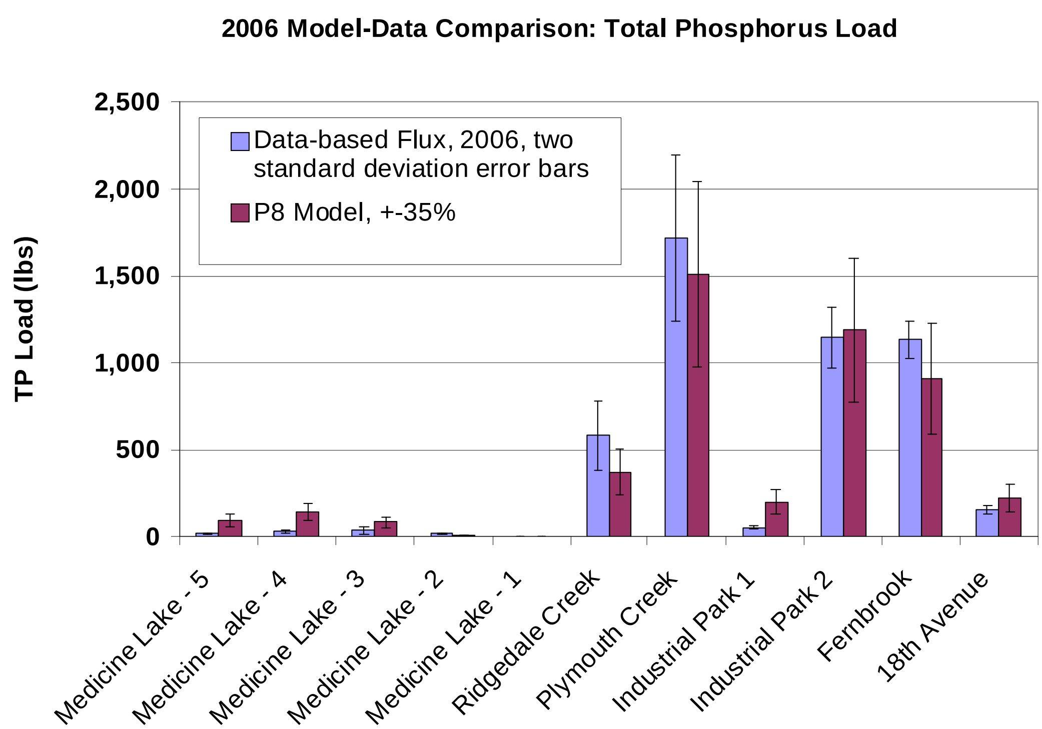


Figure 3-2. Model-Data Comparison for TP for Calibration Year 2006.

Following the calibration of the model to the 2006 monitoring data, the model was applied to simulate monitoring periods in 2004, 2005, and 2007 for validation purposes. Model-data comparisons for all years at all locations are presented in Appendix A.

Overall, the model-data comparisons demonstrate that the P8 model adequately simulates the temporal and spatial variation in phosphorus loads on a major subwatershed basis and does not show a strong bias in either over-predicting or under-predicting flows or phosphorus loads at any given site.

The P8 model, given its general ability to simulate flows and phosphorus based on the model-data comparisons, is an acceptable tool to be applied to inform decisions related to achieving phosphorus reductions needed to meet this TMDL. However, during implementation of the TMDL, prior to making decisions on significant investments for specific BMPs, additional monitoring data and model refinement should be considered.

3.3 LAKE WATER QUALITY MODEL

The BATHTUB model was developed to simulate the average, growing-season, water-quality conditions (May through September) from 2004 through 2007. Ideally, the averaging period of the model and the timeframe that the standards apply (June-September) would be the same. However, BATHTUB is a steady-state model, and use of a steady state framework requires that model inputs be averaged over a sufficient duration such that lake concentrations will fully respond to changes in load that occur during the averaging period. The BATHTUB documentation (Walker, 2006) is explicit that annual averaging periods are most appropriate for lakes such as Medicine Lake with nutrient resident times longer than three months. This TMDL accounts for the necessary disconnect between the averaging period used to describe loads and the seasonal averaging period reflected in the water quality standard by calibrating and validating the phosphorus loss rate to phosphorus data from the May-September time period. Use of these model results to inform the TMDL is therefore expected to be protective of the June-September period during which standards apply. The morphometry and observed water quality conditions for Medicine Lake were represented within the BATHTUB model as a spatially-averaged single segment. Although Medicine Lake has two geographically distinct areas, Medicine Lake and Medicine Bay, it was modeled as a single segment because the results from comparative sampling efforts suggested that there was not a significant difference in water quality between the two bays.

Atmospheric depositional loading was estimated using the BATHTUB model default value for atmospheric deposition of 0.27 lbs/acres-year (30 mg/m^2-yr). The total surface area of Medicine Lake is approximately 946 acres. Consequently, total atmospheric deposition was estimated to be 253 lbs/year for Medicine Lake.

There are two primary sources of internal loading in Medicine Lake – sediment release of phosphorus and curlyleaf pondweed die-off/senescence. Internal loads of phosphorus from these two sources were estimated as a part of the BATHTUB calibration process, described further below and in Appendix B.

The BATHTUB model, similar to P8, was calibrated to observed water quality data from 2006, and validated against water quality data from three additional years (2004, 2005, and 2007). The watershed load entered into the BATHTUB model was derived from the P8 modeling effort. P8 modeling estimates were used in the BATHTUB model (instead of direct monitoring data) to include load estimates from unmonitored subwatersheds. Annual watershed loads were input into BATHTUB as annual flow volumes and average phosphorus concentrations (Table 3-2) and were derived from the P8 model simulations using precipitation data corresponding to the water year time period (October through September).

The Canfield and Bachmann General Lakes TP sedimentation equation (option 9 in BATHTUB) was used for the model simulations because it best predicted the observed water quality conditions in Medicine Lake. The Canfield and Bachmann algorithm has been used successfully in previous lake nutrient TMDLs throughout the region. The BATHTUB model accurately predicted in-lake total phosphorus concentrations without adjusting the internal loading rates or calibration coefficients in 2006 (Table 3-3).

The calibrated BATHTUB model was validated using in-lake water quality data and P8 loadings from three additional years (2004, 2005, and 2007). In the process of validating the BATHTUB model, two distinct patterns emerged for Medicine Lake. The BATHTUB model reliably predicted water quality conditions during years (2005 and 2006) when internal loading from curlyleaf pondweed and/or multiple mixing events was limited. However, the BATHTUB model underpredicted in-lake water quality conditions for years where high curlyleaf pondweed densities and/or multiple mixing events were observed (2004 and 2007 in Figure 3-3). To account for the underprediction of total phosphorus concentration in years 2004 and 2007, the average internal loading rates within the BATHTUB model were increased to 1.55 P/m^2-day in 2004 and 1.2 mg P/m^2-day in 2007. The adjustment of internal loading rates resulted in an addition of 4770 pounds and 3693 pounds of phosphorus to the overall respective mass balance of phosphorus in 2004 and 2007. With this adjustment, the BATHTUB model accurately predicted in-lake total phosphorus concentrations in 2004 and 2007 (Figure 3-4). For further discussion of this, see Appendix B.

Table 3-2. Annual Flow and Total Phosphorus Concentration Simulated by P8.

Tributary	2004		2005		2006		2007	
	Flow (hm^3/yr)	TP (µg/L)	Flow (hm^3/yr)	TP (µg/L)	Flow (hm^3/yr)	TP (µg/L)	Flow (hm^3/yr)	TP (µg/L)
Plymouth Creek	5.83	202	5.26	211	5.83	184	5.38	210
18th Avenue	1.31	135	1.14	137	1.27	128	1.15	140
Ridgedale Creek	1.84	122	1.53	122	1.70	131	1.55	121
West Medicine Lake	0.16	206	0.13	216	0.15	258	0.26	202
North Medicine Lake	0.56	199	0.47	207	0.53	225	0.47	210
Northeast Medicine Lake	0.54	84	0.46	85	0.52	98	0.43	81
North Bassett Creek	0.20	298	0.17	312	0.19	340	0.17	314
Middle Bassett Creek	0.13	280	0.11	295	0.12	327	0.11	294
South Bassett Creek	0.62	157	0.47	161	0.59	185	0.52	156
East Medicine Lake Park	0.17	216	0.14	220	0.16	239	0.15	228
City of Medicine Lake	0.32	352	0.27	369	0.32	419	0.26	365

Table 3-3. BATHTUB Model Calibration to Existing Conditions in 2006.

Water Quality Parameters	Medicine Lake			
	Observed	BATHTUB Predicted	BATHTUB	
			Model Selection	Calibration Coefficients
TP (µg/L) Mean	46.0	45.9	9-Canfield Bachmann, Lakes	1
Chl-a (µg/L) Mean	21.5	21.6	5-P,Jones and Bachmann	1
SD (m) Mean	2.0	1.9	1-vs. Chl-a & Turbidity	1.2

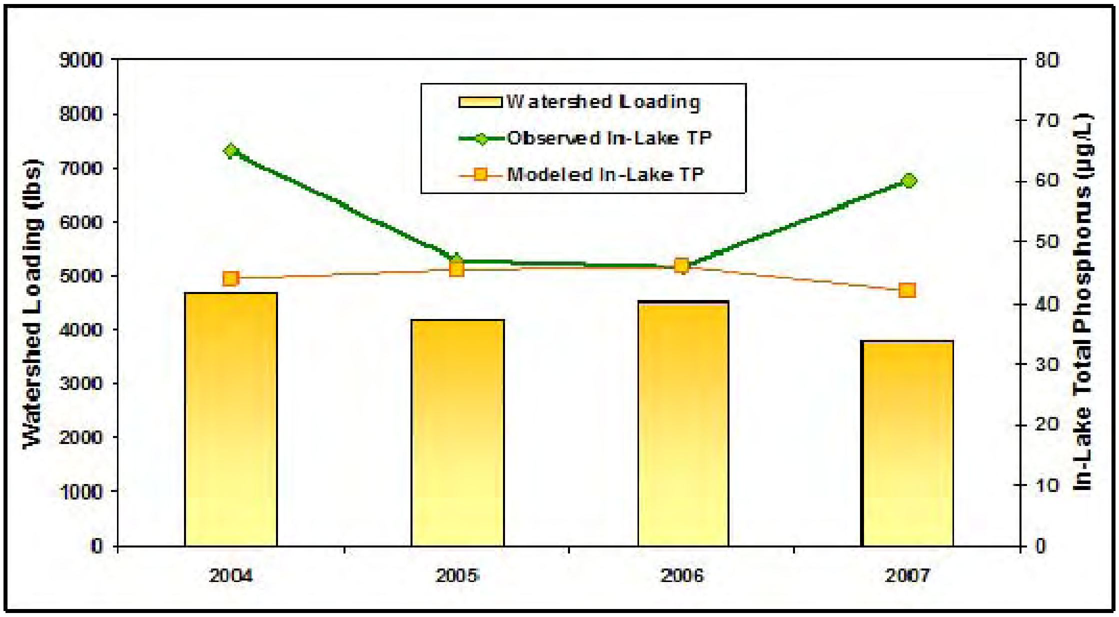


Figure 3-3. BATHTUB Results Prior to Internal Load Adjustments.

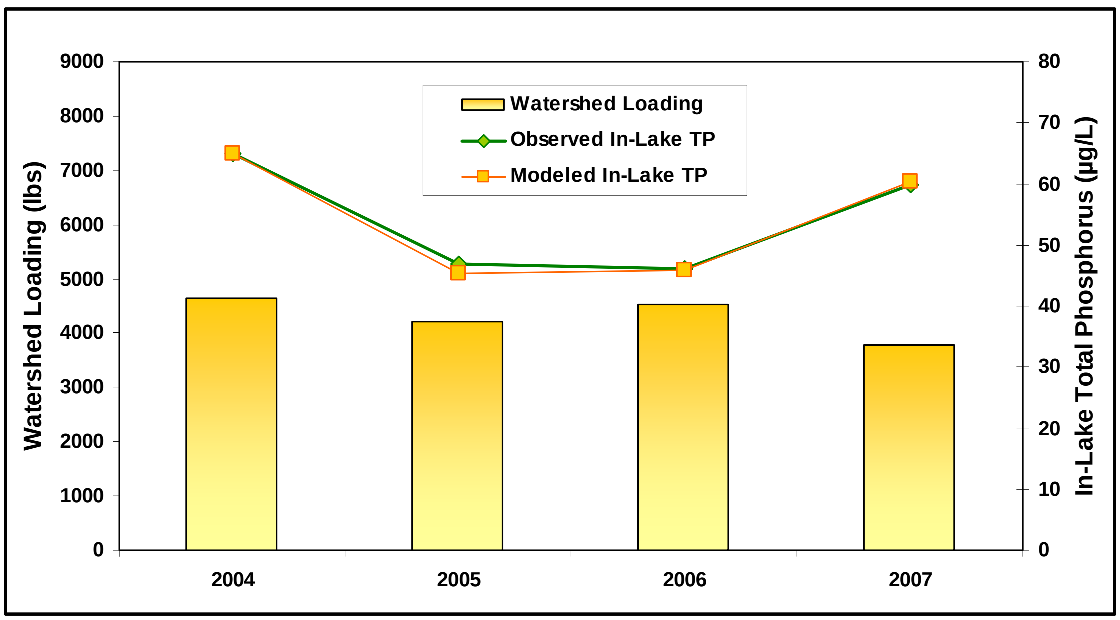


Figure 3-4. Final BATHTUB Calibration and Validation Results.

4. TMDL COMPONENTS

The TMDL represents the total mass of phosphorus that can be assimilated into Medicine Lake while continuing to meet the state water quality standards. For purposes of implementation, the TMDL equation is described as four different components: Wasteload Allocation (WLA); Load Allocation (LA); Margin of Safety (MOS); and Reserve Capacity (RC). The WLA represents phosphorus loading from point sources such as permitted stormwater discharge from the various MS4s. The LA represents phosphorus from nonpoint sources such as atmospheric deposition and internal loading. A portion of the TMDL is allocated to the MOS to account for uncertainty associated with modeling estimates and environmental variation. The RC represents the portion of the load that is set aside to account for future development.

$$TMDL = \sum WLA + \sum LA + MOS + RC$$

WLA = Wasteload Allocations

LA = Load Allocations

MOS = Margin of Safety

RC = Reserve Capacity

The BATHTUB model load-response function was used to evaluate the in-lake water quality response to varying phosphorus loads from the watershed and establish the TMDL. The TMDL and its components are presented as:

	TMDL	=	∑WLA	+	∑LA	+	MOS	+	RC
(lbs/day)	**10.3**	=	**8.84**	+	**0.69**	+	**0.74**	+	**0**
(lbs/year)	**3,753**	=	**3,230**	+	**253**	+	**270**	+	**0**

The annual loading rate is the relevant time scale for considering the water quality impacts of excess phosphorus loads to Medicine Lake and compliance with applicable water quality standards. However, EPA requires TMDLs be written with daily loads. Therefore, both time scales will be presented. Table 4-1 presents a summary of the TMDL components and percent reductions needed from watershed conditions existing in 2007. BMPs implemented following 2007 have not been accounted for in the assessment of reductions needed to meet the WLA. If monitoring or modeling of BMPs implemented since 2007 can demonstrate reduced loadings, those should be considered in the required reductions needed to meet the WLA. This TMDL report is a dynamic document and can be revised to address future findings. Further explanation of each component of the TMDL is presented in the following sections. A complete description of the BATHTUB application and assumptions used to arrive at these values is presented in Appendix B.

Table 4-1. Medicine Lake TMDL, Components and Percent Reductions.

TP Source	TP Load			% Reduction
	Current	TMDL	Reduction	
Watershed (WLA) (lbs/day)	12.4	8.84	3.56	28%
(lbs/year)	4,517	3,230	1,287	
Atmospheric (LA) (lbs/day)	0.69	0.69	0	0%
(lbs/year)	253	253	0	
Internal (LA) (lbs/day)	0*	0*	0	0%
(lbs/year)				
Margin of Safety (MOS) (lbs/day)	-	0.74	-	-
(lbs/year)	-	270	-	
Reserve Capacity (RC) (lbs/day) (lbs/year)	-	0	-	-
Total (lbs/day)	13.1	10.3	3.53	27%
(lbs/year)	4,770	3,753	1,287	

* Represents background levels of internal loading implicitly accounted for in the BATHTUB model for 2006 conditions. See Sections 4.1 and 4.3 and Appendix B for further discussion.

4.1 LOADING CAPACITY

The BATHTUB load-response analysis was conducted for 2006 conditions to describe the watershed load reductions necessary to meet in-lake goals. The water quality standard for Medicine Lake is a growing-season average, in-lake total phosphorus concentration of 40 µg/L. Based on the load-response simulation, the total annual watershed phosphorus load must not exceed 3,500 lbs TP/year to achieve the in-lake water quality goal (Figure 4-1). Note that this is in addition to atmospheric loadings of phosphorus of 253 lbs TP/year, for a total external load of 3,753 lbs TP/year. An internal load is also implicitly accounted for in the BATHTUB model. Therefore, the external loading capacity of 3,753 lbs TP/year is in addition to the “background” internal load under 2006 conditions. Conditions may be experienced in any given year that lead to higher levels of internal loading than what was experienced in 2006 and accounted for in this TMDL. Such conditions include multiple wind-driven mixing events and increased curlyleaf pondweed densities. Compliance with water quality standards, even if the external loading capacity of 3,753 lbs TP/year is met, may not be achieved during years of internal loading at levels above that experienced in 2006. Should long-term monitoring demonstrate continued impairment even with reductions in the external loads, adaptive management will be required to assess and identify additional actions that will result in attainment of water quality standards.

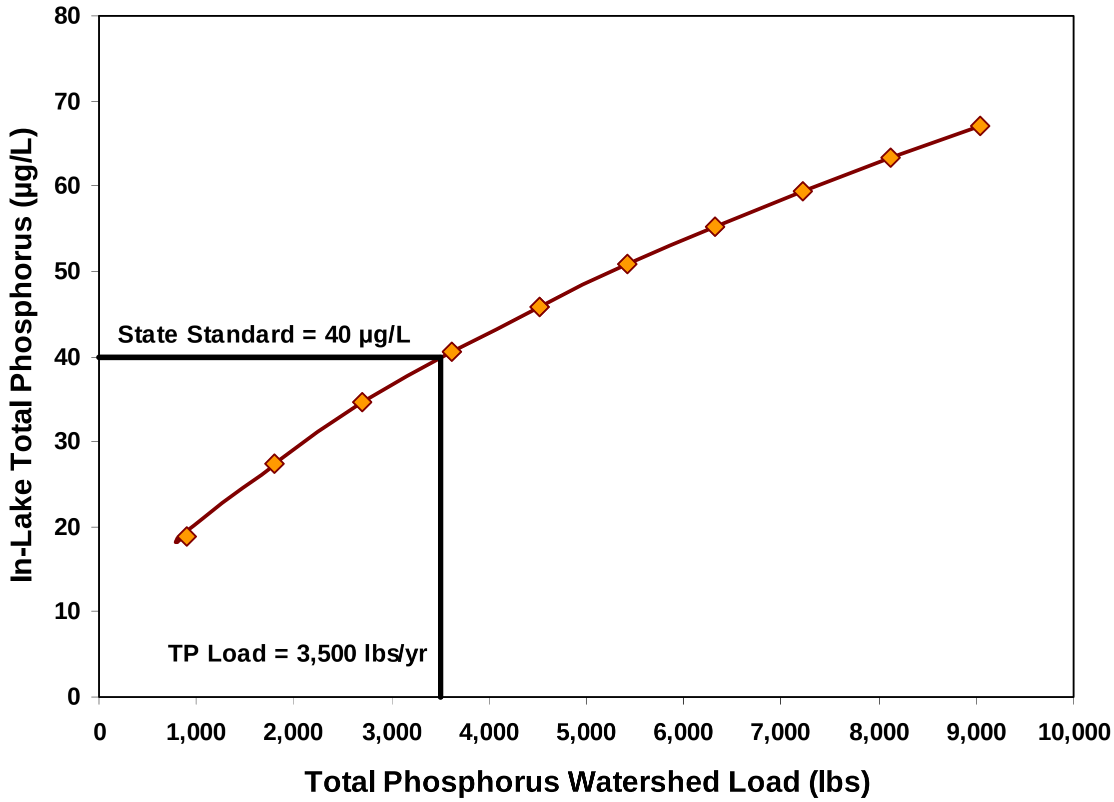


Figure 4-1. BATHTUB Application to Determine Loading Capacity.

The BATHTUB model was also used to predict the change in chlorophyll-*a* concentration and secchi-depth transparency that will correspond to the TMDL loading scenario. With phosphorus loading at levels prescribed by the TMDL, secchi depth in Medicine Lake will increase to 2.4 m (Table 4-2) – meeting the state standard of 1.4 meters. However, the chlorophyll-*a* water quality standard will not be achieved with the load reductions prescribed by the TMDL. The BATHTUB model predicts that chlorophyll-*a* concentration will decrease to 16.2 µg/L, which is above the chlorophyll-a water quality standard of 14 µg/L. Assuming that the total phosphorus and secchi-depth transparency water quality standards are achieved, Medicine Lake will not be considered impaired due to excess nutrients.

Table 4-2. Predicted Water Quality Response to TMDL.

Parameters	Loading Scenario		Water Quality Standard
	Existing Conditions	TMDL Modeled	
TP (µg/L)	46.0	38.0	40.0
Chl-a (µg/L)	21.5	16.2	14.0
Secchi (m)	2.0	2.4	1.4

4.2 WASTELOAD ALLOCATIONS

The wasteload allocation (WLA) component of the TMDL addresses all point sources. Two permitted wastewater discharges are located within the watershed. These include Minntech Corporation and Honeywell, Inc. Additional description of these discharges and their inclusion in the TMDL and WLA is described below.

- Minntech, Corp (MN0063541), in the City of Plymouth, direct discharge to Parkers Lake. The discharge consists of reject water from a reverse osmosis system at an approximate rate of 150,000 gallons per day and an estimated 230 lbs/yr TP into Parkers Lake. The TP in the discharge from Parkers Lake is relatively small and the actual amount that makes it to Medicine Lake is estimated to be negligible based on P8 results. Therefore, the TP load from this facility to Medicine Lake is considered negligible and no reduction in loading is required to be in compliance with this TMDL.
- Honeywell, Inc. (MN0063266) in the City of Plymouth, Ridgedale Creek drainage area, subwatershed BC75A. The discharge consists of reject water from a reverse osmosis system at an average rate of 50,000 gallons per day and an estimated 27 lbs/yr TP. The discharge is into a wetland system before flowing to Ridgedale Creek and eventually Medicine Lake. The discharge flows through the following devices represented in the P8 model before discharging into Medicine Lake: BC-P32A, BC-P32B, BC-P32, and SShoreWt. The estimated percent removal of phosphorus from this discharge, as simulated by P8, before it reaches Medicine Lake is 78%, resulting in 6 lbs/yr TP discharged to Medicine Lake. This estimate assumes the discharge from Honeywell experiences similar removal in ponds as watershed runoff contributions. Therefore, this discharge will be given an individual end-of-pipe WLA of 27 lbs/yr (0.074 lbs/day) and no reduction in loading is required to be in compliance with this TMDL. However, monitoring of TP in the discharge may be included in the NPDES permit upon permit renewal. Should additional monitoring of the discharge and assessment of its transport and fate indicate greater than 6 lbs/year of total phosphorus is contributed to Medicine Lake from the facility, mitigation may be required.

The remaining WLA was assigned to MS4s. The municipal MS4s have decided to approach this in a coordinated fashion and have agreed to a categorical WLA. These municipal MS4s include the City of Plymouth, City of Medicine Lake, City of Minnetonka, City of Golden Valley, and the City of New Hope. The BCWMC will serve as the convener of action for the categorical WLA, but not as a responsible entity. The City of Medina has a negligible area along the western watershed boundary (12 acres or 0.1% of the watershed) at the far upstream edge of the Plymouth Creek drainage area. The loading of phosphorus from the City of Medina drainage area to Medicine Lake was determined to be of minimum importance. Therefore, the City of Medina was not included in the TMDL and was not assigned a WLA. Additional MS4 entities which have individual WLAs include Hennepin County and Mn/DOT. The MS4s boundaries are presented in Figure 4-2. Table 4-3 presents a summary of the land area of each MS4. Note that municipal MS4s have transportation right-of-ways subtracted from their total area. Areas for the transportation right-of-ways for Hennepin County and Mn/DOT were calculated from GIS coverage using roadway lengths and right-of-way widths for each road in the respective jurisdiction.

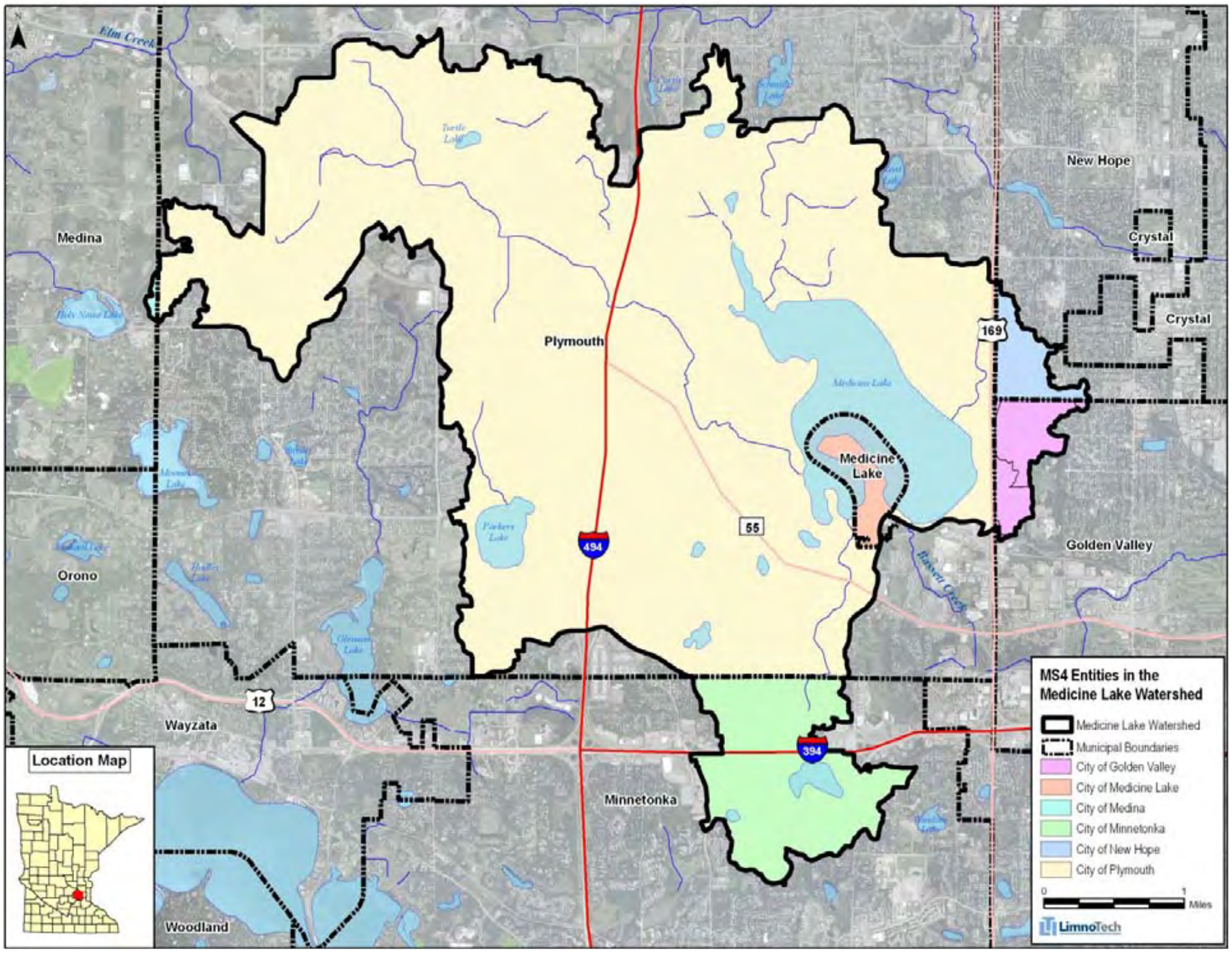


Figure 4-2. MS4 Boundaries.

Table 4-3. MS4 Areas within the Medicine Lake Watershed.

MS4	Area (acres)	% of Watershed Area
Categorical Municipal MS4 (sum of cities listed below)	11,066	95.6%
City of Plymouth	9,613	83.1%
City of Medicine Lake	229	2.0%
City of Minnetonka	887	7.5%
City of Golden Valley	202	1.7%
City of New Hope	145	1.2%
Hennepin County	171	1.5%
Mn/DOT	379	2.9%

The WLA remaining after the 6 lb/yr for the Honeywell discharge is subtracted is 3,224 lb/yr. When applying the land area percentages in Table 4-3 to the remaining WLA, the categorical and individual WLAs are as follows:

- Categorical Municipal MS4 WLA: 3,082 lbs/yr (8.44 lbs/day);
- Hennepin County: 48 lbs/yr (0.132 lbs/day); and
- Mn/DOT: 94 lbs/yr (0.26 lbs/day).

The categorical municipal WLA implicitly includes allocations for Construction General Permit applicants and Industrial Stormwater General Permit applicants. Loads from construction stormwater are considered to be a small percent of the total WLA and are difficult to quantify. Construction stormwater activities are therefore 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 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. Industrial storm water activities are considered in compliance with provisions of the TMDL if they obtain an industrial stormwater general permit or General Sand and Gravel general permit (MNG49) under the NPDES program and properly select, install and maintain all BMPs required under the permit. Stormwater activities from individually permitted, non-MS4 NPDES/SDS stormwater discharges will be considered in compliance with provisions of the TMDL if they follow conditions of the individual permit and implement the appropriate BMPs.

In the event that additional stormwater discharges come under permit coverage within the watershed, or if additional information becomes available, the WLA may be transferred based on the process used to set wasteload allocations in the TMDL. Affected MS4s will be notified and will have an opportunity to comment on the reallocation. A formal public notice is not required.

4.3 LOAD ALLOCATIONS

The Load Allocation (LA) explicitly represented in the BATHTUB model was 253 lbs/year TP from atmospheric deposition. The BATHTUB model and TMDL also include an implicit amount of internal loading for 2006 conditions when mixing events and curlyleaf pondweed die-off/senescence were limited. The implicit internal load is an inherent feature of the empirical nature of the BATHTUB model. Acknowledging this implicit internal load in the TMDL implies that water quality goals will be met when internal loads are no higher than the background levels represented in the BATHTUB model for conditions experienced in 2006 (see Appendix B for additional discussion). To meet water quality goals in all years (particularly those with multiple mixing events and/or high densities of curlyleaf pondweed), internal loads may need to be reduced along with the watershed load reductions specified in Section 4.2. In-lake management of the internal load is discussed further in the Implementation Strategy, Section 7.

4.4 MARGIN OF SAFETY

An explicit Margin of Safety (MOS) of 270 lbs/year TP was included in the TMDL. The explicit MOS was generated by setting a more restrictive in-lake water quality goal (38 µg/L) and calculating the phosphorus load necessary to meet this goal (Figure 4-3). The total external phosphorus load, less atmospheric loading, to meet 38 µg/L is 3,230 lbs/year. Therefore, the MOS is 7.2% of the TMDL, and 8.4% of the WLA. This is a sufficient MOS to account for uncertainties in the data and modeling.

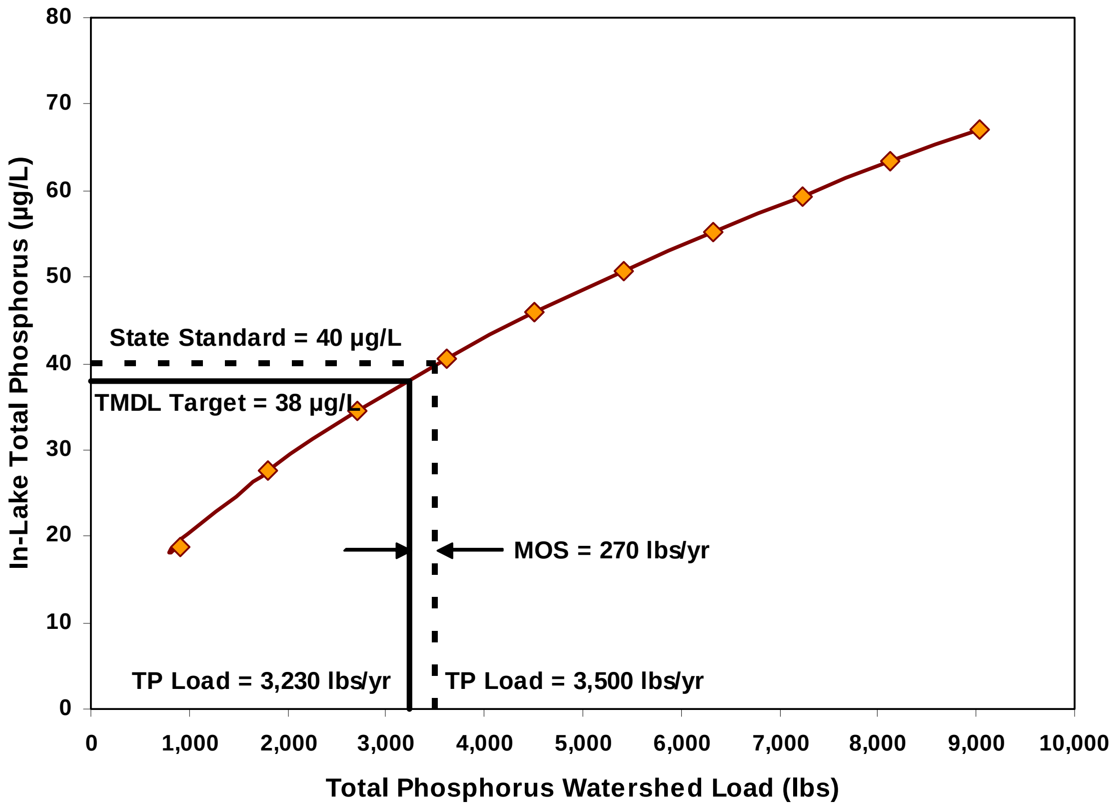


Figure 4-3. Determination of Explicit Margin of Safety.

4.5 RESERVE CAPACITY

The majority of the watershed area has already been developed. Future new development and re-development will be subject to anti-degradation provisions in the MS4 permit, which ensures no increase in loading from the current level. Therefore, the Reserve Capacity portion of the TMDL equation was set to 0 lbs/year TP.

A summary table of the TMDL and allocations is provided in Table 4-4 below.

Table 4-4. TMDL and Allocation Summary.

Point Sources	Permit #	Individual WLA (lbs/year TP)	Assimilation (%)	Gross WLA (lbs/year TP)
Categorical WLA				
City of Plymouth	MS400112	3,082	NA	3,082
City of Medicine Lake	MS400104			
City of Minnetonka	MS400035			
City of Golden Valley	MS400021			
City of New Hope	MS400039			
Construction Stormwater	Various			
Industrial Stormwater	Various			
Individual WLAs				
Hennepin County	MS400138	48	NA	48
Mn/DOT	MS400170	94	NA	94
Honeywell	MN0063266	27	78%	6
MinnTech	MN0063541	230	100%	0
Total WLA		3,481	7.2%	3,230
Load Allocation		253	NA	253
Margin of Safety (MOS)		270	NA	270
TOTAL		4,004	6.2%	3,753

4.6 SEASONAL VARIATION AND CRITICAL CONDITIONS

Water quality conditions in Medicine Lake vary significantly during the year. The TMDL target of 38 μg/L TP is for an average during the growing season, which includes June through September. Because the residence time in Medicine Lake is longer than a year, external TP loadings and in-lake response were considered on an annual basis to support the development of this TMDL.

The critical condition for lakes impacted by excess nutrients is the summer growing season, which in Minnesota is when phosphorus concentrations peak and clarity is typically at its worst. Lake goals focus on summer-mean total phosphorus, Secchi transparency and chlorophyll-a concentrations. Consequently, the lake response model (BATHTUB) focused on the summer growing season (June through September) as the critical condition. Because the hydraulic residence time of Medicine Lake is greater than one year, annual loading rates were assessed using the watershed model (P8) for the water year (October 1 – September 30). Climatic conditions for 2006 were determined to be typical and were used to set the TMDL. Therefore, the load reductions in this TMDL are designed so that Medicine Lake will meet the water quality standards over the course of a typical growing season.

4.7 REASONABLE ASSURANCE

Upon approval of this TMDL by USEPA, MS4 entities must review the adequacy of their Storm Water Pollution Prevention Program (SWPPP) to meet their respective WLA. If the SWPPP is not meeting the applicable requirements, schedules and objectives of this TMDL, MS4 entities must modify their SWPPP consistent with the requirements of their permit and this TMDL.

As noted in the Bassett Creek Watershed Management Commission (BCWMC) Watershed Management Plan (BCWMC, 2004) the City of Plymouth, Three Rivers Park District (TRPD), the City of Medicine Lake and the BCWMC have been partners working to improve the water quality of Medicine Lake for many years. Major components of the Implementation Plan are already planned, designed, and moving towards construction. This includes the West Medicine Lake Park Water Quality Ponds.

The comprehensive monitoring program, as discussed in Section 5, will provide valuable information to assess progress and adapt management activities, as needed.

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5. MONITORING

To ensure effectiveness and efficiency of TMDL implementation, ongoing monitoring will be conducted. The following monitoring plan is a very comprehensive plan to aid the communities in assessing whether progress toward the TMDL is being made. While this level of monitoring will provide valuable information to utilize in watershed and lake management efforts it is not required to determine if the allocations are being met. Monitoring will assess BMP implementation, in-lake condition, watershed loading and aquatic plant community composition.

BMP implementation tracking will be coordinated by the Bassett Creek Watershed Commission, as lead entity in the categorical TMDL. Each year, member communities will submit a summary of BMP projects and the anticipated phosphorus reductions to the Bassett Creek Commission in conjunction with Stormwater Pollution Prevention Plan (SWPPP) reporting. BMPs will be cataloged to track progress toward the individual wasteload reduction goals. Mn/DOT and Hennepin County should also track BMP implementation and document it in their MS4 annual reports.

In-lake monitoring will be conducted annually following completion of the TMDL (TRPD currently conducts this monitoring and will continue doing so). Samples will be collected biweekly (April thru October) following previously described protocols for eutrophic lake assessment (Heiskary 1994 and Heiskary 2007). Based on this sampling frequency, there is a 75% probability that a 30% change in lake condition will be detected after 3 years of monitoring (90% after 6 yrs; (MPCA 2007). Monitoring will be continued at this frequency for a ten year period and/or until implementation efforts have been completed.

A detailed watershed load monitoring study should be conducted to quantify the relative load reduction associated with various BMPs. Modeling using FLUX and P8 should be conducted concurrently to assess annual loading rates. Watershed monitoring will be conducted at the current TMDL monitoring sites following protocols described by Walker (1996). The scheduling of an initial monitoring effort should consider the timing of implementation activities and occur approximately five years after approval of the TMDL. Follow-up monitoring should be conducted for a one to two year period (depending on precipitation patterns), every five years until wasteload reduction goals have been achieved. Watershed load monitoring efforts should also include upstream-downstream assessments of individual BMPs to validate the predicted phosphorus removal and facilitate an adaptive approach to the design/implementation of future BMPs.

Sediment phosphorus levels should be assessed to better evaluate the applicability and potential cost-effectiveness of additional in-lake BMPs. Sediment phosphorus monitoring will be conducted following the protocol outlined by Pettersson et al. (1988).

Aquatic macrophyte monitoring will be conducted annually to assess: 1) the natural variability of the aquatic plant community; and 2) the efficacy of any future aquatic plant management programs (TRPD currently performs this sampling and plans to continue with this effort). Monitoring will be conducted at ~200 points throughout the littoral zone using a point intercept survey (e.g., Madsen 1999). Annual monitoring will be conducted until in-lake plant management activities have been completed.

6. PUBLIC PARTICIPATION

Completing a TMDL study and implementation plan requires substantial monitoring, data gathering, and modeling of internal (in the lake) and external (in the watershed) flows of nutrients. However, the science cannot determine the most important priorities for selecting among different implementation strategies that have distinct costs, operational timeframes, and ancillary benefits or risks. Nor can the science and modeling identify whether a selected wasteload allocation will be considered equitable. The Medicine Lake TMDL process therefore engaged stakeholders to provide the value-based feedback and prioritization to complement the modeling and scientific analysis, particularly in regard to making wasteload allocations and prioritizing best management practices.

6.1 INVOLVING STAKEHOLDERS IN THE DECISION MAKING

The overall stakeholder involvement goal was to develop Medicine Lake's TMDL in a "partnership process" that facilitated positive interactions and ownership of the results among the stakeholders. The foundation of the partnership process needed to be the commitment of participants to the process itself.

In particular, the Medicine Lake TMDL process needed to address stakeholder concerns for two distinct groups of stakeholder. First, water quality in Medicine Lake has been the subject of stakeholder discussion and programmatic initiatives for at least 30 years. This long history of initiative and measurement meant that looking backward into time the TMDL process had a ready-made set of stakeholders that extended beyond the typical involvement of MS4 permitees. This constituency for previous decisions on how to clean up the Lake might or might not be supportive of TMDL modeling and implementation recommendations that depart from previous efforts. The stakeholder involvement process needed to engage these stakeholders to ensure that the TMDL process reflected previous work and previous decisions, provided that doing so still allowed an implementation plan that put the Lake on track for meeting the TMDL.

Second, the stakeholders whose cooperation was required for future implementation efforts needed to buy into the TMDL and implementation plan. The future-looking stakeholders and the stakeholders from previous initiatives were not the same group of people, and may not have similar implementation priorities. The process needed to engage these stakeholders to ensure that the implementation plan was viable over the long-term.

6.2 STAKEHOLDER PARTICIPATION WORKPLAN

Task 3 of the TMDL workplan addresses involving stakeholders in the decision making process. The workplan describes the stakeholder participation task as an effort that:

> "facilitates positive interactions and ownership of the final TMDL recommendations and implementation efforts. The primary method of engaging stakeholders is through facilitated discussion in combined stakeholder/technical advisory committee meetings. The meetings will include identification of risks and opportunities, education on modeling and scientific data, and decision-making on preferred strategies and allocations. . . The eight meetings will be designed to permit state agency staff, the Citizen-Stakeholder-Technical Advisory Committee, and/or members of the public to comment on the work completed and to help shape the final recommendations."

Task 3 had five sub-tasks that directed the stakeholder engagement process:

1. ***Project initiation, management, and coordination*** with the MPCA, BCWMC, TRPD and the MPCA Master Contractor Project Team
2. ***Form the Citizen-Stakeholder-Technical Advisory Committee***, develop a meeting timeline, and refine the participation process.
3. ***Coordinate and facilitate*** Committee meetings and technical training sessions.
4. ***Provide additional facilitation*** outside of the scheduled meetings for conflict mediation.
5. ***Develop outreach media*** and prepare semi-annual and final summary report for the final TMDL report

In order to achieve broad buy-in for the TMDL implementation plan the process needs to engage a broad range of stakeholders. The Medicine Lake TMDL Steering Committee was structured to meet the goals of broad stakeholder representation and to incorporate previous decisions, efforts, and analyses conducted for Medicine Lake. As noted above, rather than simply look to the MS4 permitees as stakeholders, the Medicine Lake project created room at the Committee table for representatives from lake association, industry, homeowner associations, other (non-MPCA) State agencies, and environmental advocates. These representatives included people who had been involved in the long history of previous initiatives and studies, as well as some who were new to the process.

Table 6-1. Steering Committee.

Committee Member		Organization/Representing
Derek	Asche	City of Plymouth
Ginny	Black	City of Plymouth
Sheila	Chaffe	Wyndemere Farms Home Owners Assoc.
Karen	Chesebrough	Local Resident
Terrie	Christian	AMLAC
Kevin	Christian	AMLAC
Jack	Frost	Metropolitan Council Environmental Services
Lee	Gufstafson	City of Minnetonka
Kim	Hofstede	Carlson Companies
Ann	Holter	City of Medicine Lake
Guy	Johnson	City of New Hope
Len	Kremer	BCWMC - Barr Engineering
Barb	Loida	Mn/DOT
Linda	Loomis	City of Golden Valley
Fred	Moore	Local Resident
Beth	Neuendorf	Mn/DOT
John	Nieber	University of Minnesota
Jeff	Oliver	City of Golden Valley
John	Karwacki	City of Medicine Lake - MFRA
Nick	Proulx	DNR - Ecological Resources
Joel	Settles	Hennepin County Env. Services
Daniel	Stauner	City of New Hope
Liz	Stout	City of Minnetonka
Michael	Welch	BCWMC
Marcey	Westrick	BWSR
Kyle	Turner	Plymouth Environmental Quality Committee

The stakeholder engagement process engaged the Committee throughout the TMDL project, including seven Committee meetings and two public meetings. The meeting covered both month-to-month progress on the modeling and analysis, and facilitated decision-making on how to use the modeling information.

Project Meeting Schedule

October 8th, 2008 5-6:30	Public Meeting
November 18th, 2008 3:00-5:00	Steering Committee
January 8th, 2009 4:00-6:00	Steering Committee
March 12th, 2009 4:00-6:00	Steering Committee
April 9th, 2009 4:00-6:00	Steering Committee
May 14th, 2009 4:00-6:00	Steering Committee
August 29th, 2009 4:00-6:00	Steering Committee
October 22nd, 2009 4:00-6:00	Steering Committee
October 29th, 2009 6:00-7:30	Public Meeting

Each local government in the Medicine Lake subwatershed that has an MS4 permit or has funding or regulatory authority over stormwater was asked to have a one technical and one non-technical (elected or appointed official, citizen, or business owner) Committee representative. All meetings were held at the French Regional Park Visitor's Center near Medicine Lake except for the October 29th meeting.

6.3 OTHER STAKEHOLDER OUTREACH

Public meetings were held at the beginning of the process, to offer all stakeholders an introduction to the TMDL process, and the end of the process, to offer the general public an opportunity to ask questions and provide feedback prior to the completion of the final report to the EPA.

Finally, in addition to the Steering Committee and public meeting process, the project maintained a web site with all presentations, recommended background material, and summaries of all Steering Committee meetings. The process also included regular newsletter updates that were posted on the website. These outreach and participation tools were accessed by both Steering Committee members to provide to their constituencies, and by the general public.

6.4 STEERING COMMITTEE PROCESS

While the Committee's decision-making jurisdiction did not generally include technical issues, the Committee did review technical results, recommend changes in method or presentation. Early meetings in the TMDL process focused on ensuring that the Committee has foundation of understanding regarding the TMDL process, familiarizing them with the modeling process, and getting feedback from the Committee on initial modeling results.

One of the important elements addressed in the early meetings was how the previous monitoring, modeling, and implementation work was being incorporated into the TMDL process. Committee members knowledge of previous work in Medicine Lake was critical both to creating a level of comfort with the TMDL modeling results and integrating the new results into existing and proposed BMPs. The Committee involvement resolved a number of potential or perceived conflicts between previous modeling and implementation efforts and the TMDL implementation plan.

6.5 WASTELOAD ALLOCATION AND BMPS

The Steering Committee was given primary responsibility for two critical decisions in meeting the phosphorus reduction goal:

1) Allocating the wasteload among the various entities that manage land uses and stormwater systems in the Lake watershed; and

2) Identifying specific methods (Best Management Practices, or BMPs) that each entity will use to reduce phosphorus to its wasteload allocation level.

In order to make these decisions the Steering Committee identified a set of criteria for use by the consultant team and the Committee in making implementation plan recommendations. Setting criteria before actually considering options helped the Committee and consultant team by defining what the Committee finds important or valuable, then engaging in discussion within the framework of those definitions. The Committee set separate criteria for the two primary decisions.

Allocation Criteria	**Best Management Practice (BMP) Criteria**
Allocations must: 1. be equitable 2. consider limitations 3. be based on scientific data 4. consider historic actions (look forward and backward) 5. meet the minimum regulatory threshold	BMPs should be prioritized: 1. by cost effectiveness 2. by diversity of benefit 3. to emphasize shared implementation 4. to emphasize measureable results

For all the criteria, the Committee identified definitional qualifiers. Under the allocation criteria, for instance, the criterion “be equitable” was qualified by noting that an equitable allocation would consider:

- existing observed phosphorus load from each entity;
- the ability of the entity to meet the reduction goal; and
- all entities that were contributing to the problem.

6.6 INTEGRATION OF STEERING COMMITTEE DECISIONS

The project team integrated Steering Committee decisions into the final report at points. First, the feedback and discussion on the TMDL modeling process allowed successful integration of previous studies and recommendations into the TMDL.

Second, the decision criteria noted above were integrated into the final modeling and the creation of implementation scenarios.

7. IMPLEMENTATION STRATEGY

This section presents an Implementation Strategy to achieve and maintain the required load reductions for the Medicine Lake TMDL. This has been developed to make best use of the available information and include consideration of the challenges that will be faced in achieving the needed load reductions. The intent of this section is to provide a basis for taking the next step towards improving water quality in Medicine Lake. This Implementation Strategy focuses on reducing phosphorus loads from the surrounding watershed and maintaining background levels of internal loads. An Implementation Plan with additional information will be developed as a separate document.

The Implementation Strategy for the Medicine Lake TMDL includes:

- Continued maintenance of existing stormwater ponds and assessment and implementation of retrofits for improved performance;
- Continued curlyleaf pondweed control to maintain densities equal to or less than that experienced in 2006 (TRPD 2008);
- Construction of the West Medicine Lake Water Quality Ponds in the City of Plymouth;
- Continued educational efforts that promote stewardship;
- Continued streambank stabilization efforts;
- Continued shoreline restoration efforts;
- Assessment and implementation of BMPs that reduce runoff; and
- Continued monitoring, assessment and adaptive management.

A combination of these efforts can be expected to achieve the 28% reduction in watershed TP loads required to meet the TMDL and maintain or reduce existing internal loads. Attaining 1,287 lbs/yr TP reduction in the watershed load could cost between $2,500/lb and $5,000/lb, for a total cost between $3,217,500 and $6,435,000. This cost could be less considering BMPs implemented since 2007 have not been accounted for in the 1,287 lbs/yr TP reduction estimate. The continued combined efforts of the Bassett Creek Watershed Management Commission (BCWMC), the Three Rivers Park District (TRPD), the Association of Medicine Lake Area Citizens (AMLAC), the Minnesota Pollution Control Agency (MPCA), and the individual MS4 permit holders (primarily the City of Plymouth) will be critical to the success of the TMDL implementation efforts. The Implementation Plan will provide information to be used to guide implementation activities. The specific activities to be taken to achieve the required load reductions will be left to the discretion of the BCWMC and MS4 permit holders, including Mn/DOT and Hennepin County.

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APPENDIX A

Medicine Lake TMDL – P8 Model Development

Prepared By:

LimnoTech

September 1, 2010

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1. OVERVIEW

This document presents the results of the revised P8 watershed modeling conducted to support the Medicine Lake Excess Nutrient Total Maximum Daily Load (TMDL). A summary of model development, calibration and comparison of model results to available data is presented. These results demonstrate the model is sufficiently reliable to simulate conditions in the watershed in an effort to support TMDL decision-making.

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2. MODEL DEVELOPMENT

MPCA provided LimnoTech with the most recent P8 modeling files. Previous P8 modeling of the Medicine Lake watershed had been conducted by Barr Engineering (Medicine Lake Watershed and Lake Management Plan, March 2000). LimnoTech converted the existing P8 model input files to the most recent Windows-based version of P8 (Version 3.4). Previous modeling results presented in a memorandum dated June 12, 2009, were based on incomplete information in the model inputs files. The file conversion utility provided in P8 Version 3.4 did not translate the outlet information for ponds into the converted input files. Therefore, the outlet information, such as orifice diameter or weir length, had to be manually input into the Version 3.4 input files. Previously, LimnoTech had reviewed the inputs of the model, specifically characterization of subwatersheds and stormwater ponds, with the cities of New Hope, Golden Valley, Plymouth, and Minnetonka, as well as MnDOT. Model inputs were updated with the most recent information from the cities. These updates included minor changes in watershed boundaries and acreage in Golden Valley, and new stormwater ponds in East Medicine Lake Park and the South Basset Creek watershed. Model inputs were also reviewed to identify any inconsistencies in model parameterization throughout the watershed and minor revisions were made to improve consistency. These included minor adjustments to runoff coefficients in impervious areas and infiltration rates in stormwater ponds. Finally, new model input files were developed to directly correspond to the major subwatersheds as defined by the Three Rivers Park District (TRPD) and used in their BATHTUB modeling of Medicine Lake. Attachment 1 to this document includes a map of the major subwatershed and monitoring locations.

LimnoTech developed hourly precipitation and daily temperature files to represent the period from 2004 through 2008. Precipitation was based on the Golden Valley rain gauge, with substitutions from the Zachary rain gauge in Plymouth when hourly data was available, as well as substitutions from the Minneapolis-St. Paul International Airport and the Crystal Lake rain gauges when accurate data were not available otherwise. A summary of the annual precipitation based on water years is presented in Table 1 below.

Table 1. Summary of Precipitation Inputs to P8 Model.

Water Year	Period	Precipitation (inches)
2004	10/1/2003-9/30/2004	33.8
2005	10/1/2004-9/30/2005	27.9
2006	10/1/2005-9/30/2006	29.7
2007	10/1/2006-9/30/2007	27.3
2008	10/1/2007-9/30/2008	25.6

3. CALIBRATION

The model was calibrated to the monitoring period in 2006. TRPD provided assessments of the monitoring data for each sampling site within the Medicine Lake watershed using the FLUX program that develops pollutant loading rates from sample data and flow monitoring records. Attachment 1 provides a map showing the location of the sampling sites and their respective drainage areas. Adjustments of model parameters were made to achieve a reasonable match to the FLUX results. Consideration was first given to model-data comparisons for flow rates, then solids loads, and finally total phosphorus loads. The percent dissolved phosphorus predicted by the model was also evaluated in general terms to the observed data.

Calibration to flows, or volume of runoff, was generally acceptable with the existing inputs. Previous modeling efforts of the Plymouth Creek watershed had included some adjustments for time-of-travel. These were not adjusted further in this effort. Flows leaving Parkers Lake were adjusted by increasing infiltration rates in Parkers Lake to represent losses due to evaporation and attain an improved fit to downstream flow data. Adjustments were also made in infiltration rates at the downstream end of Southwest Plymouth Creek in the Fox Forest area above the 18th Avenue monitoring location. These adjustments were also made to improve simulation of monitored flows.

Final calibration results are presented in Figures 1 through 4. There were no pre-determined formal calibration targets. A “weight-of-evidence” approach was used to assess model calibration and validation. Best professional judgment was used in assessing comparisons to flow, suspended sediment (TSS), total phosphorus (TP), and dissolved phosphorus (DP) at multiple monitoring locations, with greater emphasis given to the larger watersheds. For comparison purposes, uncertainty bars on the FLUX results for TSS, TP, and DP were included representing two standard deviations as calculated by the FLUX program. Coefficient of variation (CV) values from FLUX were generally between 0.1 and 0.2. Confidence intervals for the P8 results are represented as ±25% on flow, ±45% on TSS, and ±35% on TP and DP. These confidence intervals for the P8 results are based on current best professional judgment for watershed modeling (http://www.epa.gov/waterscience/ftp/basins/training/w04lec17.zip). There was negligible mass balance error in the P8 model simulations.

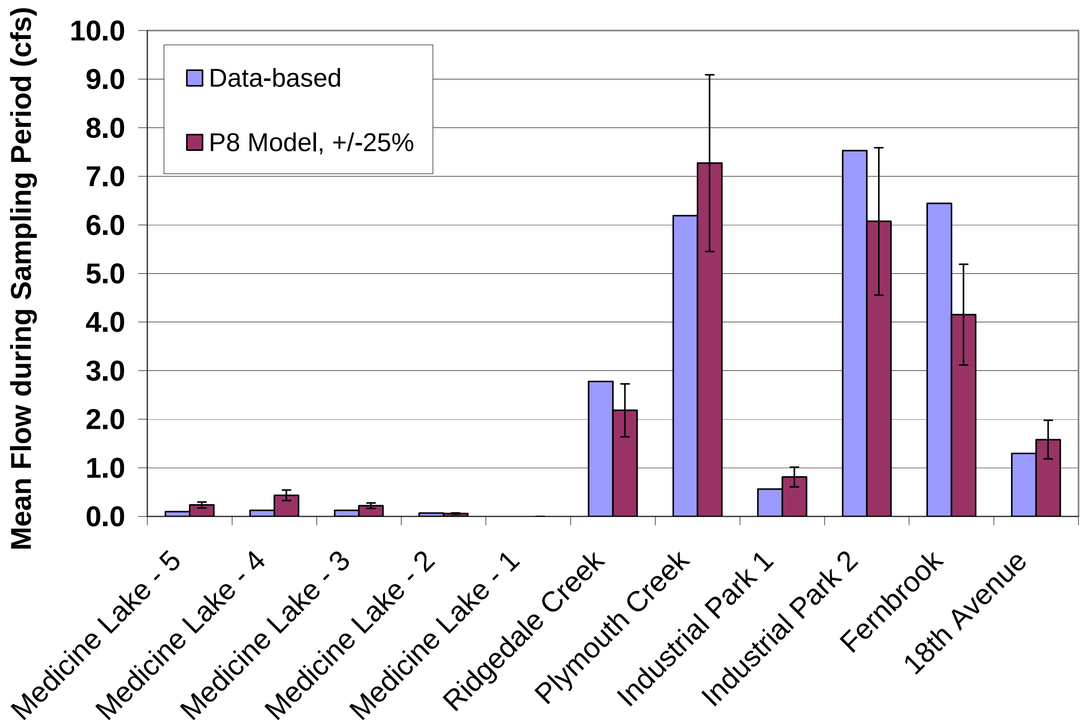

Figure 1. Model-Data Comparisons of Flow for Calibration Year 2006.

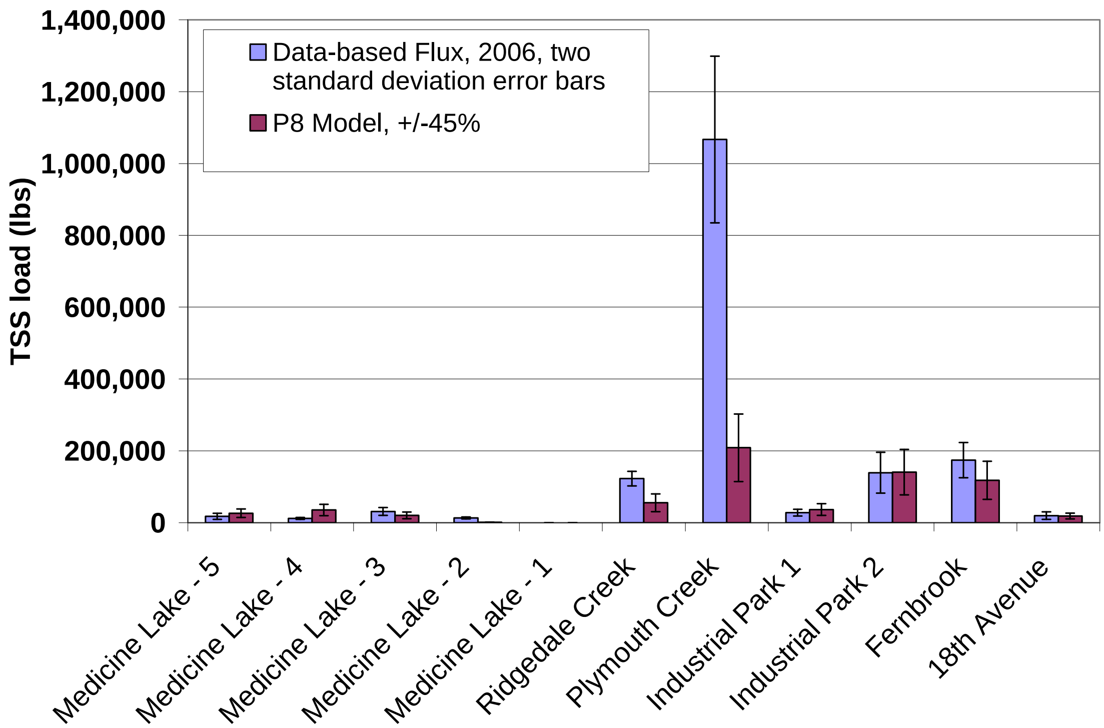

Figure 2. Model-Data Comparisons of TSS for Calibration Year 2006.

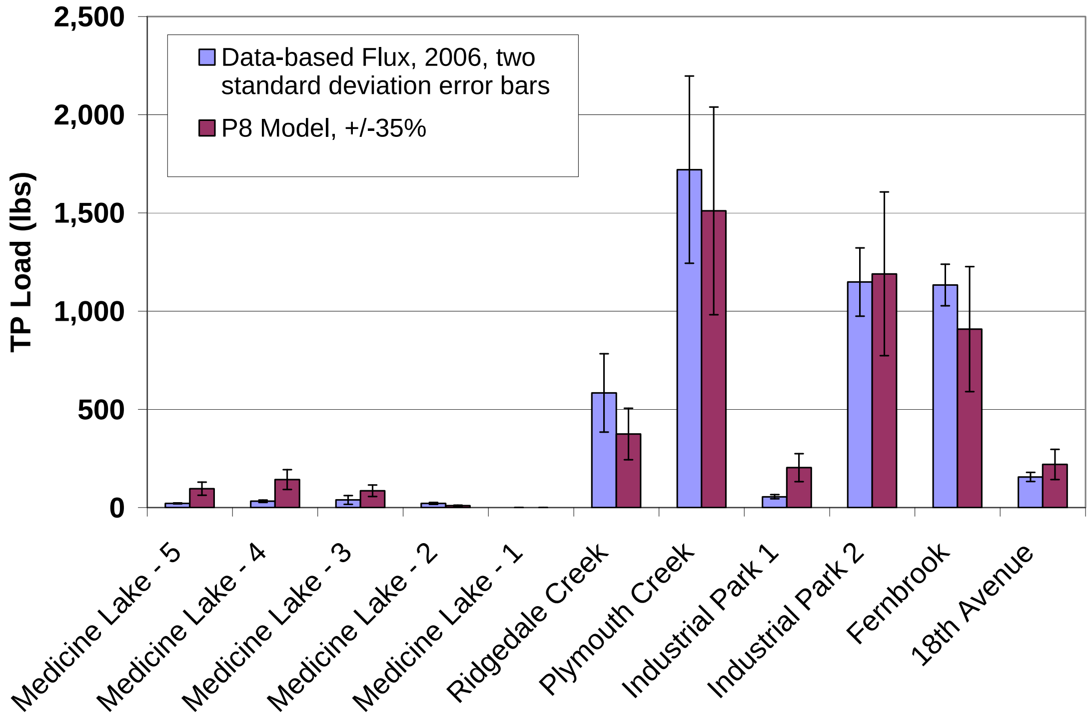

Figure 3. Model-Data Comparisons of TP for Calibration Year 2006.

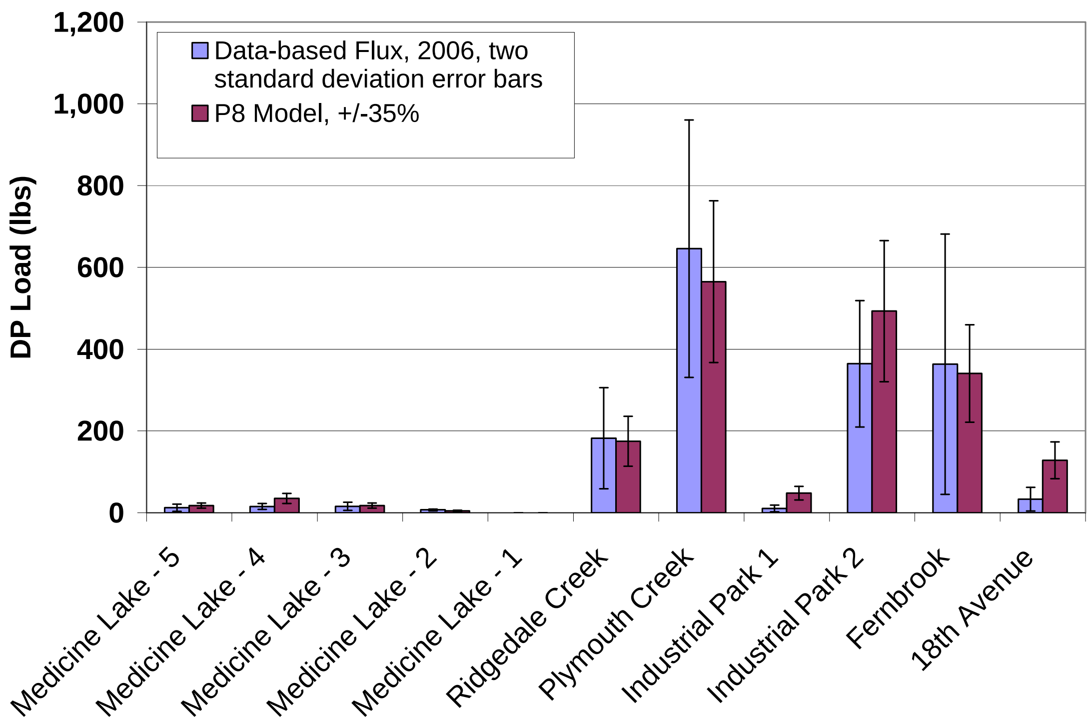

Figure 4. Model-Data Comparisons of DP for Calibration Year 2006.

For the Plymouth Creek watershed, the P8 model underpredicted the solids and phosphorus load at the downstream Plymouth Creek monitoring site. Adjustments were made in the particle removal scale factor for ponds along Plymouth Creek, specifically BC-P8C, BC-P8, BC-P11A, BC-P11B and BC-P11C. It was noted that even with an adjustment to prevent any settling of solids in these ponds, the model could not generate enough solids to match the load at the Plymouth Creek site estimated using the FLUX model. A couple possible explanations for this model-data discrepancy were assessed. These included:

- The data available for 2006 at the Plymouth Creek site may not be representative of actual loading rates for the entire monitoring period.
- Significant channel erosion occurred along Plymouth Creek which the P8 model is not capable of representing but is captured in the data.

To assess the representativeness of the 2006 data, plots of TSS versus flow rates were plotted for 2004-2007 monitoring periods. These comparisons are shown below in Figures 5 and 6.

Figure 5 shows that 2006 stands out as having a number of sampling events with substantially higher TSS values as compared to 2004 and 2005. 2007 also includes three data points at lower average daily flows with high TSS values. Figure 6 shows a similar comparison but this time using instantaneous flow measurements. Important to note in Figure 6 is that the instantaneous flows are much higher for the high TSS points in 2007, indicating a potential concern when using average daily flow values in the FLUX computations. These figures do indicate that FLUX results for solids loads in 2006 may be biased high. TRPD is conducting an assessment of the impact on FLUX results when multiple years of data are used to generate the TSS-flow relationship. Initial results indicate that solids loads for 2006 would be approximately 32% less when applying the lumped approach.

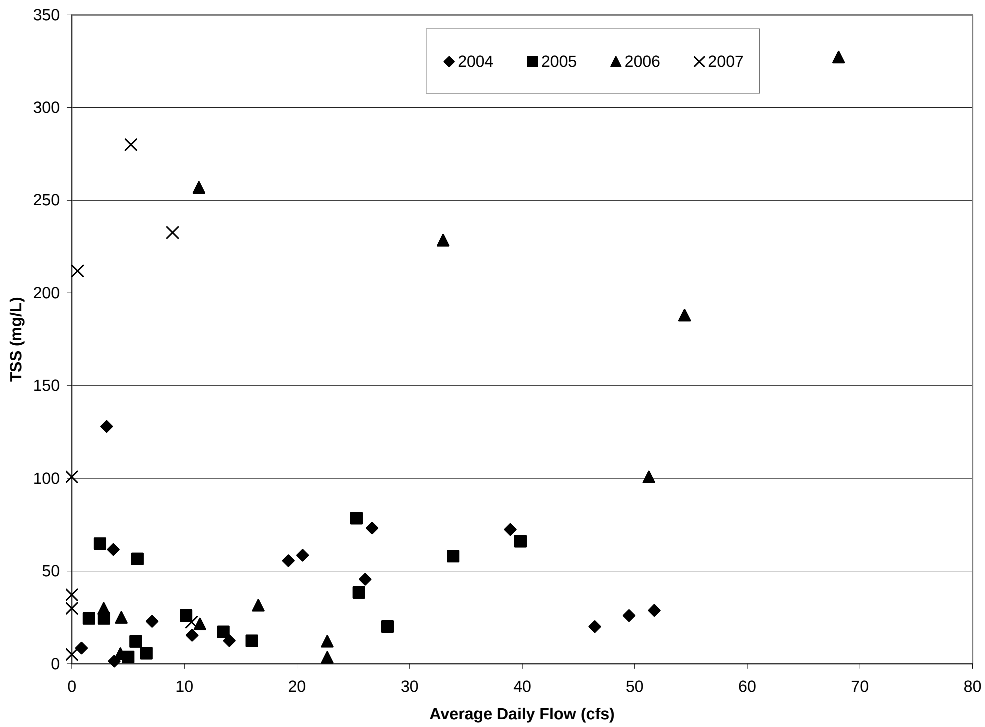

Figure 5. TSS Versus Average Daily Flow Comparison for 2004-2007 Data at Plymouth Creek Site.

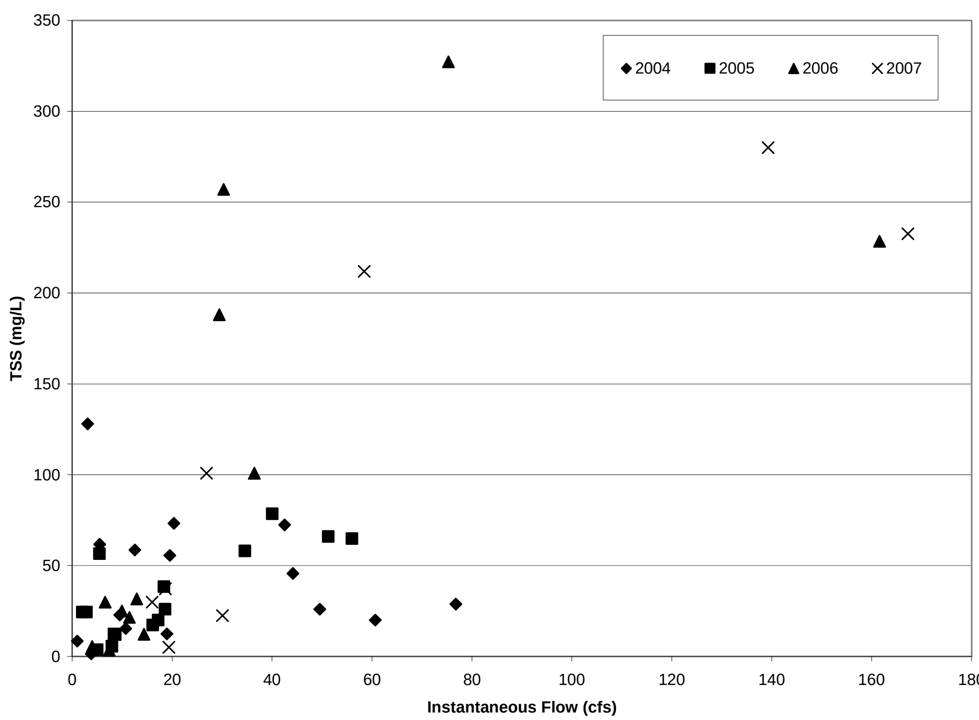

Figure 6. TSS Versus Instantaneous Flow Comparison for 2004-2007 Data at Plymouth Creek Site.

The potential impact of channel erosion in 2006 on the solids loading at the Plymouth Creek site was also assessed. The flow-duration curve for 2006 was compared to other monitored years to assess whether or not 2006 had a significantly higher frequency of occurrence of high flows. Figure 4 below indicates that 2006 flows were typical and excessive channel erosion would not be expected relative to other years. This does not indicate that no channel erosion occurred in 2006, but simply that excessive solids loads in 2006 due to channel erosion should not be expected based on the measured flows.

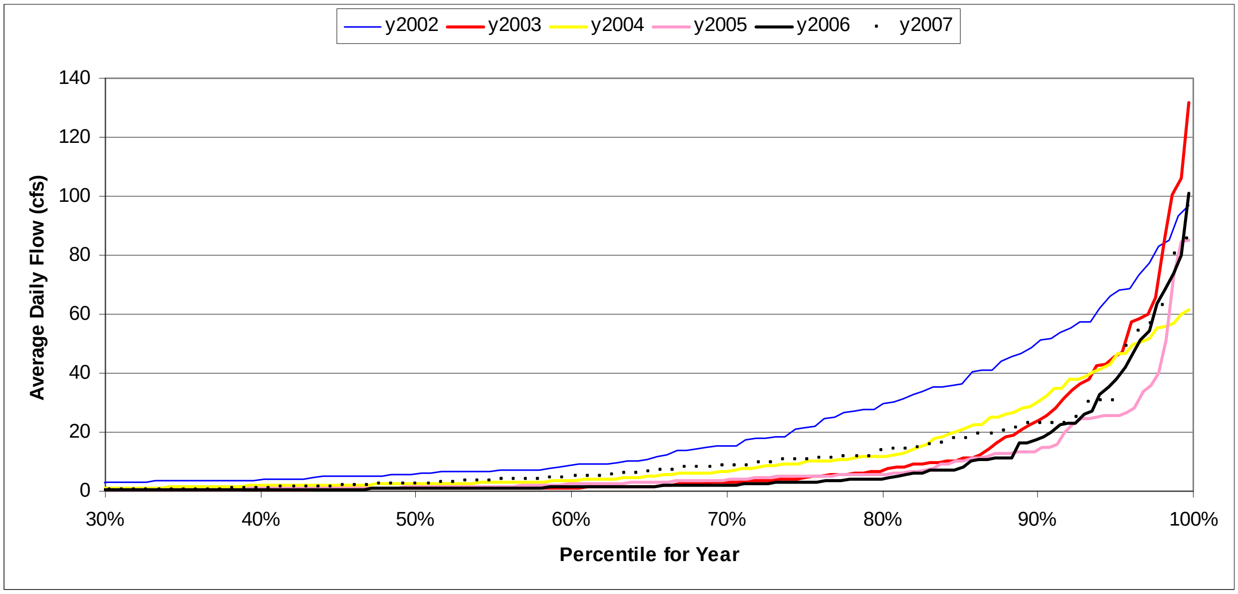

Figure 7. Comparion of Flow Duration Curves for Monitored Years at the Plymouth Creek Site.

The discrepancy between FLUX estimated solids loads and P8 predictions at the Plymouth Creek site for 2006 deserves additional consideration. However, P8 model validation to 2004, 2005, and 2007 monitoring periods, as presented later in this document, does not indicate a general bias in P8 to underpredict solids loads at this site.

Discrepancies in model-data comparisons were also observed at the 18th Avenue monitoring location. The model consistently predicted higher flows and phosphorus loads than what was represented in the data. A review of the modeling inputs indicated that the model representation of Parkers Lake, which is in the watershed upstream of the 18th Avenue monitoring location, simulated an excessive amount of discharge from the lake. Therefore, the representation of Parkers Lake was modified to reduce the amount of flow discharging from the lake. Also, the representation of the Fox Forest stormwater pond/wetland area, which is immediately upstream of the 18th Avenue monitoring location, was modified to represent additional removal of phosphorus in order to be reasonably consistent with the monitoring data. It is difficult to assess where exactly in this watershed the model significantly deviates from actual phosphorus loadings. Further monitoring in this watershed may be beneficial in developing this understanding.

The P8 modeling effort attempted to maintain a balance of multiple objectives within the available resources. The primary objective of the P8 model was to develop sufficiently accurate watershed loads to Medicine Lake. Accurate simulation of smaller scales is desirable, but small scale adjustments to match one data point without sound justification for making the adjustment in that area and not watershed-wide was not deemed acceptable. Application of the P8 model to assess smaller scale issues, such as a specific BMP opportunity, should consider the accuracy of the model at that scale and location. Additional data collection may be beneficial in those situations.

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4. VALIDATION

Following the calibration of the model to the 2006 monitoring data, the model was applied to simulate monitoring periods in 2004, 2005, and 2007 for validation purposes. Model-data comparisons for all years at all locations are presented in the Figures 7, 8, and 9 below.

Overall, the model-data comparisons demonstrate that the P8 model adequately simulates the temporal and spatial variation in phosphorus loads on a major subwatershed basis and does not show a strong bias in either over-predicting or under-predicting flows, solids loads, or phosphorus loads at any given site. One exception is solids loads at the Plymouth Creek site, where P8 underpredicts solids loads for all four years simulated. For solids at this site, further examination of the handling of solids and flow data is recommended, as noted previously.

The P8 model, given its general ability to simulate flows, solids, and phosphorus based on the model-data comparisons, is an acceptable tool to be applied to inform decisions related to achieving phosphorus reductions needed to meet a TMDL. However, during implementation of the TMDL, prior to making decisions on significant investments for specific BMPs, additional monitoring data and model refinement should be considered.

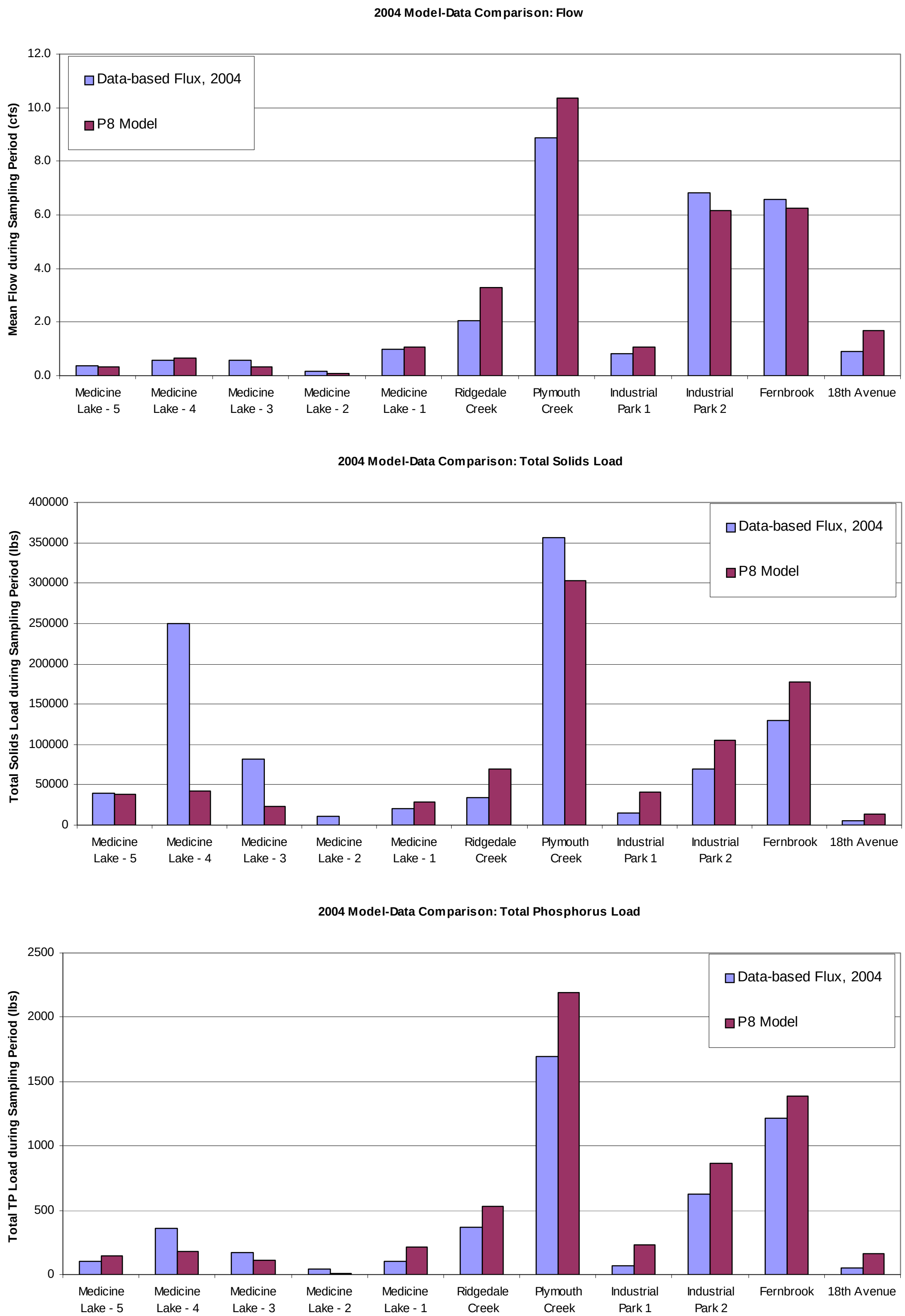
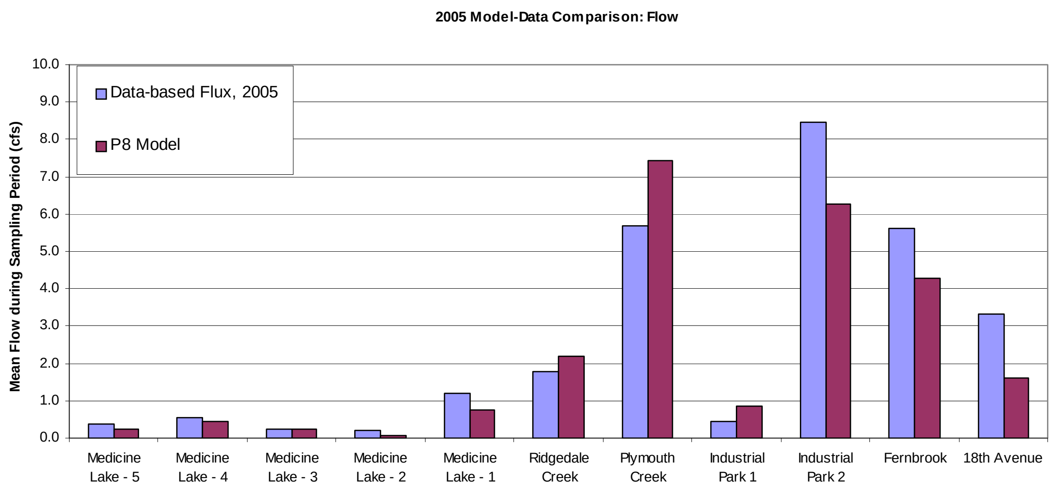
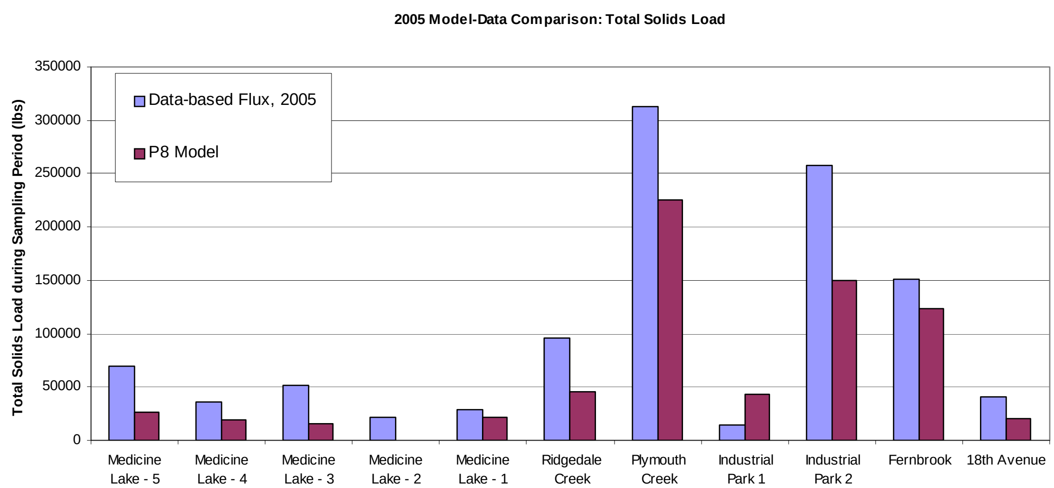


Figure 8. Model-Data Comparison for 2004.





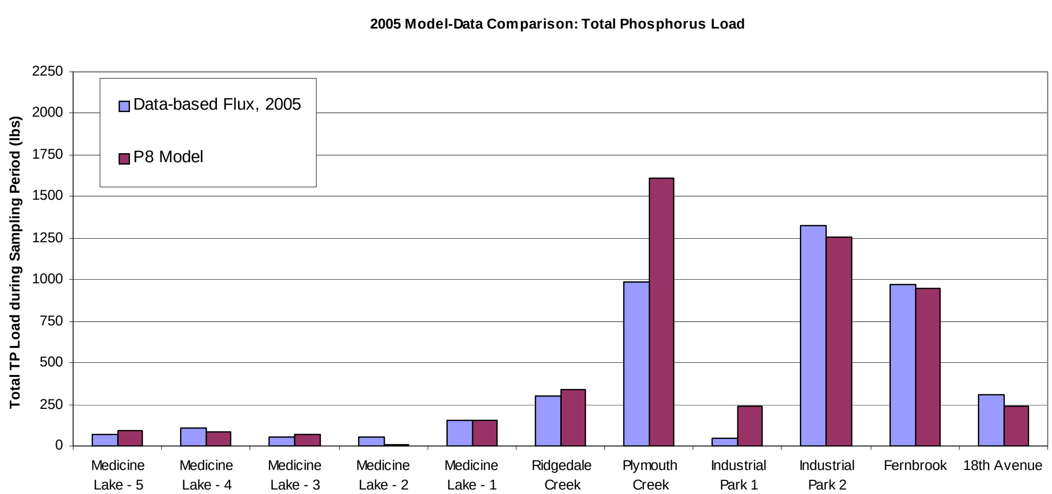


Figure 9. Model-Data Comparison for 2005.

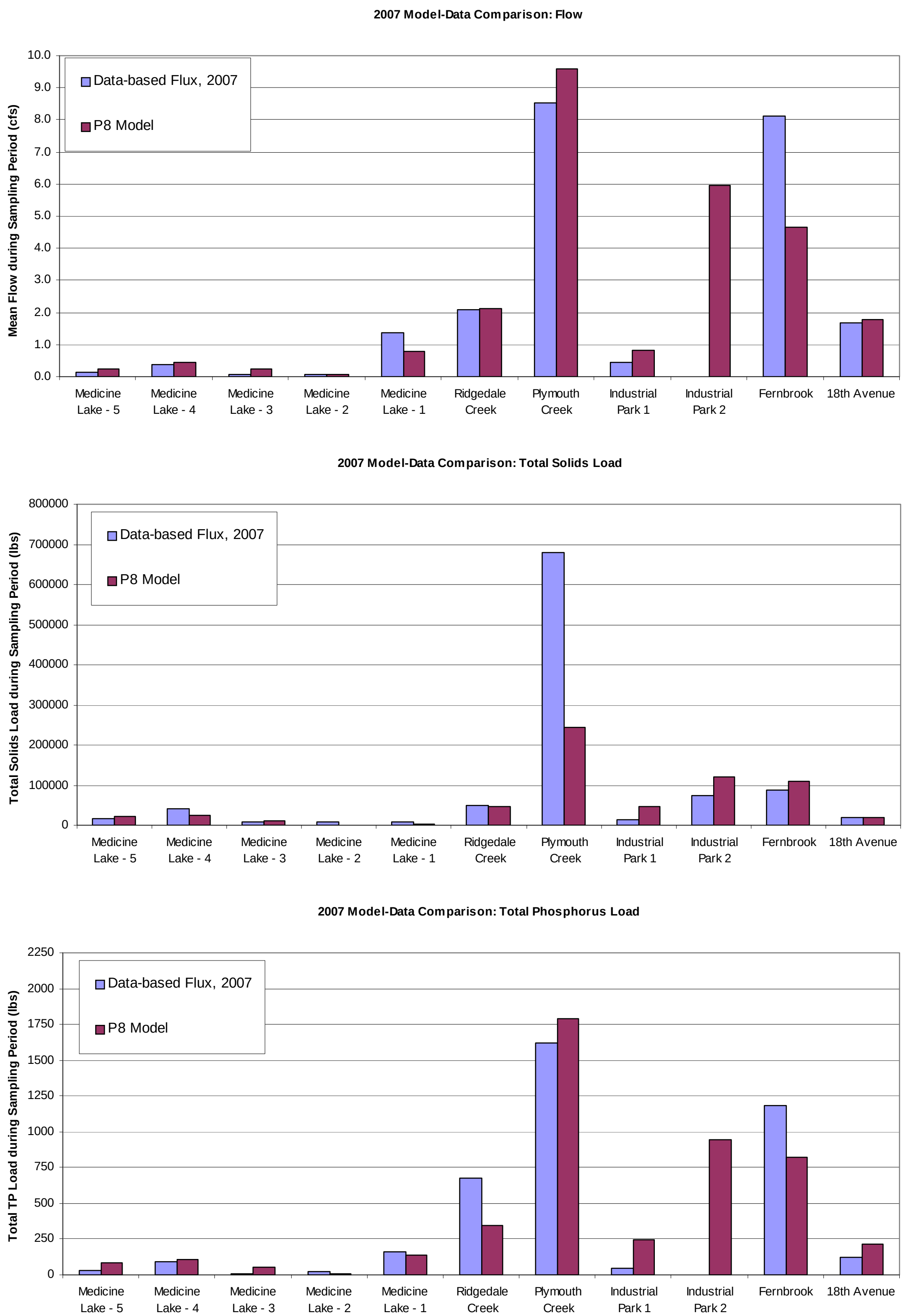
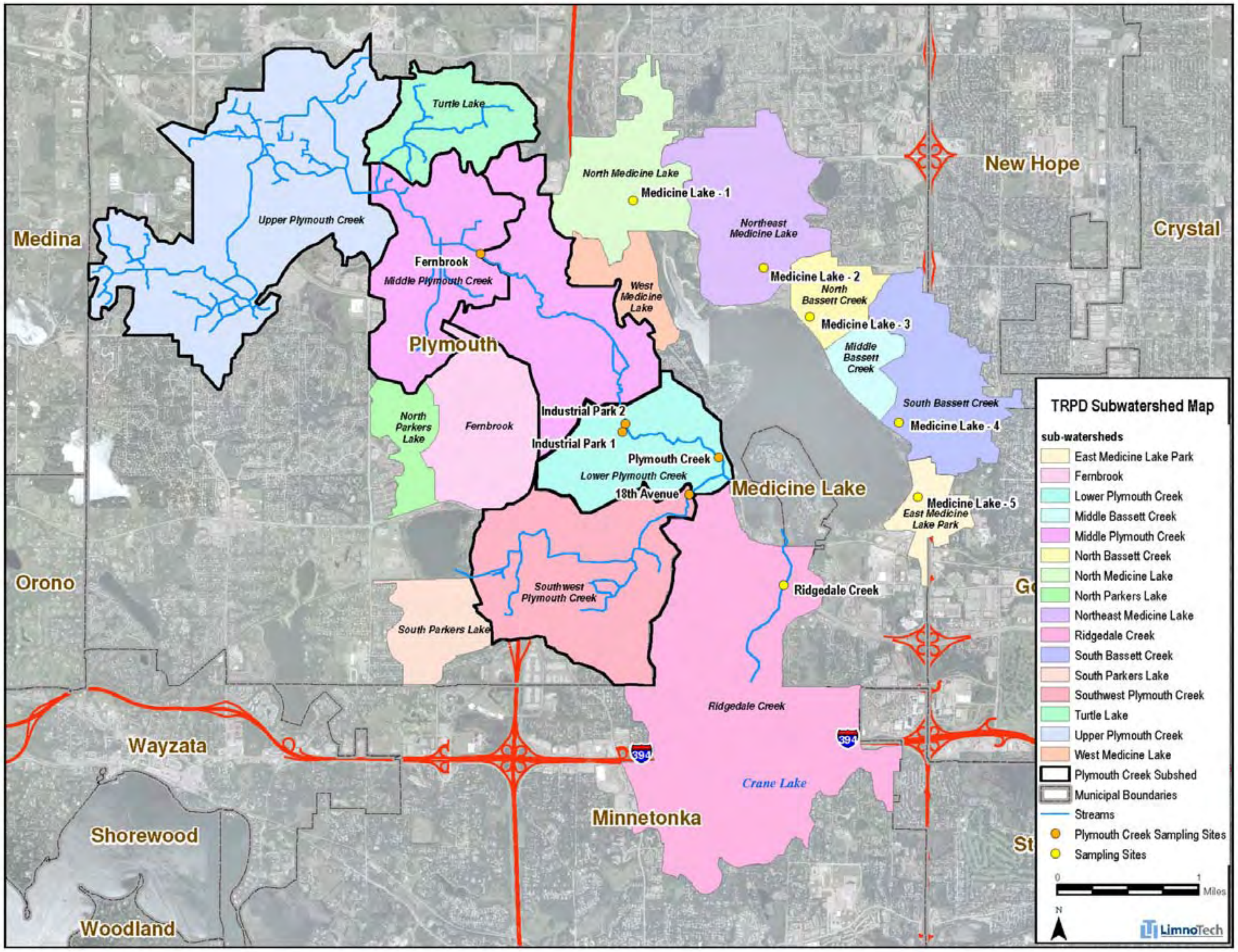


Figure 10. Model-Data Comparison for 2007.

Attachment 1 – Monitoring Site Location and Associated Drainage Areas



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APPENDIX B

Medicine Lake TMDL – BATHTUB Model Development

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September 1, 2010

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1. PROJECT OVERVIEW

This memorandum describes the BATHTUB modeling portion of the Medicine Lake Excess Nutrient Total Maximum Daily Load (TMDL). A BATHTUB model was developed to determine the assimilative capacity of phosphorus in Medicine Lake and estimate the phosphorus load reductions necessary to achieve in-lake water quality goals. A summary of the model development, calibration, validation, and in-lake load response is presented below.

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2. MODEL DEVELOPMENT

A BATHTUB model (Army Corps of Engineers Version 6.1) was developed to describe water quality conditions and estimate the assimilative capacity in Medicine Lake. BATHTUB is an empirical model that estimates lake and reservoir eutrophication using several different algorithms. The model estimates in-lake water quality conditions based on the lake morphological characteristics and a mass-balance of nutrient loading to the lake. Nutrient sources included in the model are atmospheric deposition, and both internal and watershed loading. The model was calibrated to observed water quality data from 2006, and validated against water quality data from three additional years (2004, 2005, and 2007). Following validation, an in-lake load-response simulation was performed to determine the assimilative capacity for Medicine Lake. The load response procedure was used to estimate the waste load allocations that would result in compliance with the water quality goals for Medicine Lake.

2.1 MODEL INPUTS

2.1.1 Morphological Characteristics

Medicine Lake is approximately 900 surface acres in size, with a maximum depth of 11 meters (Figure 1 and Table 1). The lake littoral area (< 15 ft in depth) comprises approximately 33% of the entire surface acreage. Medicine Lake has a large fetch (3-km) that is oriented from the northwest to the southeast. The lake typically stratifies during the summer at approximately 5 meters in depth. However, prolonged winds from the north and/or south often initiate complete or partial turnover events (in addition to the spring and fall turnover) that potentially exacerbate the internal loading of phosphorus (EPA 2000).

The in-lake water quality modeling for Medicine Lake is based on over ten years of data. Medicine Lake has been sampled bi-weekly for nutrients and water clarity from 1995 through 2007 (Figures 2 and 3; Vlach, B.R., et al. 2007). The BATHTUB model was developed to simulate the average, growing-season, water-quality conditions (May through September) from 2004 through 2007 (Table 2).

The morphometry and observed water quality conditions for Medicine Lake were represented within the BATHTUB model as a spatially-averaged single segment. Although Medicine Lake has two geographically distinct areas (Medicine Lake and Medicine Bay; Figure 1), it was modeled as a single segment because the results from comparative sampling efforts suggested that there was not a significant difference in water quality between the two bays (Table 3).

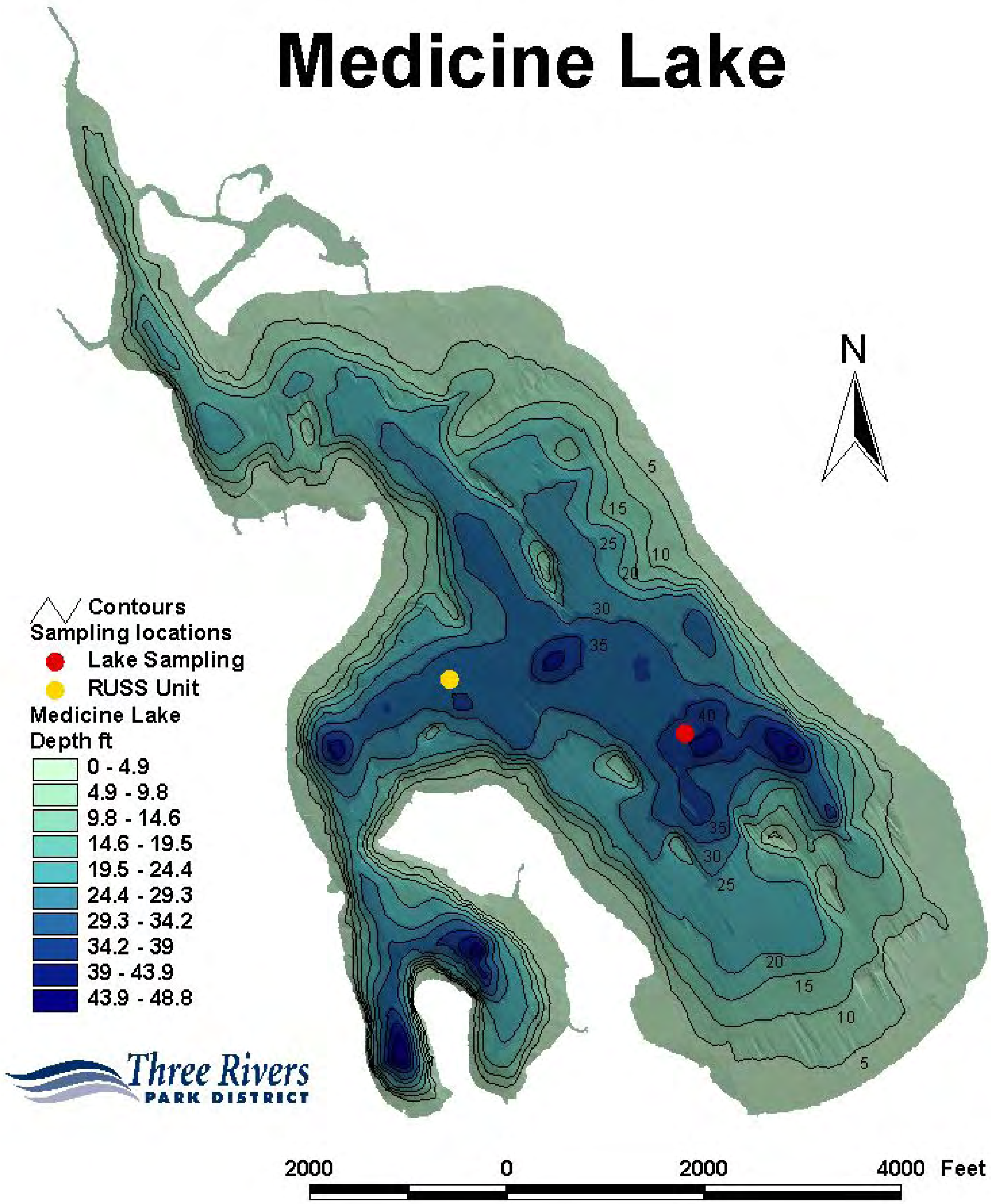

Figure 1. Bathymetric map of Medicine Lake. The primary sampling point is located in the main bay of the lake (Medicine Lake) and the southern arm of the lake (Medicine Bay) was sampled in 2006 for comparative purposes. All data from the RUSS unit was collected in 2002.

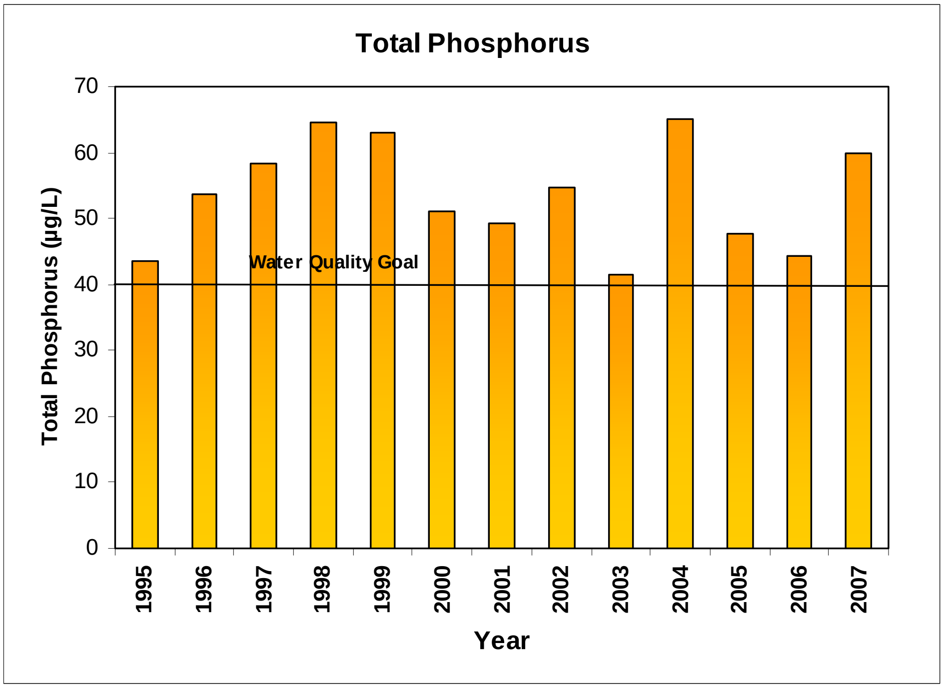

Figure 2. Annual growing season total phosphorus concentrations for Medicine Lake from 1995 through 2007. The Water Quality Goal line represents the 40 ug P/L state standard.

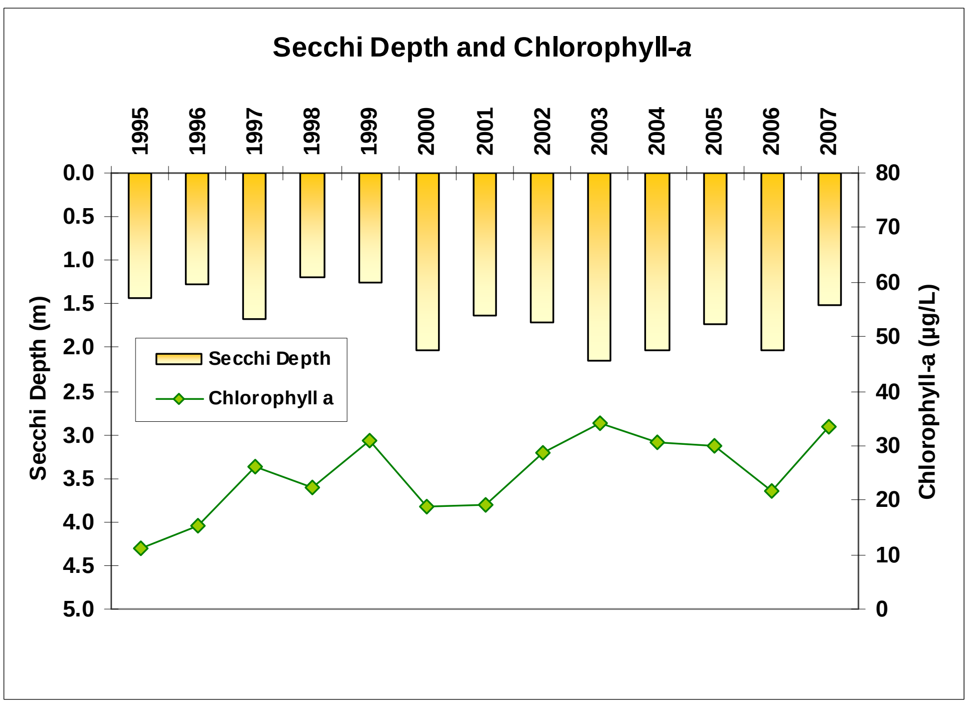

Figure 3. Annual growing season secchi depth and chlorophyll-a concentrations for Medicine Lake from 1995 through 2007.

Table 1. Medicine Lake Morphometry.

Morphometry Characteristics	
Surface Area	3.83 km^2
Mean Depth	5.3 m
Length	3 km
Mixed Layer Depth	5 m
Hypolimnetic Depth	7 m

Table 2. Average growing season water quality conditions for Medicine Lake from 2004 through 2007.

Average Water Quality Conditions			
Year	TP (µg/L)	Chl-a (µg/L)	Secchi (m)
2004	65.1	30.6	2.04
2005	47.6	30.0	1.70
2006	45.0	21.6	2.04
2007	60.0	33.3	1.52

Table 3. Comparison of water quality conditions between Medicine Lake and Medicine Bay sample sites in 2006.

2006							
					t-statistics		
Parameter	Lake	N	Mean	Standard Deviation	t-value	df	p-value
TP (µg/L)	Medicine	15	44.9	17.5	0.939	29	0.356
	Medicine Bay	15	51.2	20.0			
Chl-a (µg/L)	Medicine	15	22.7	16.4	0.125	29	0.902
	Medicine Bay	15	23.5	18.0			
Secchi (m)	Medicine	15	1.9	1.0	0.274	29	0.786
	Medicine Bay	15	2.0	1.0			

2.1.2 Watershed Loading

The Medicine Lake watershed (approximately 11,976 acres) drains land from six different municipalities (Plymouth, City of Medicine Lake, New Hope, Golden Valley, Minnetonka, and Medina) and two transportation agencies (Hennepin County and Minnesota Department of Transportation) that are served by Municipal Separate Storm Sewer Systems (MS4). To better quantify phosphorus loading from each MS4, the watershed was delineated into 11 primary subwatersheds.

The watershed load entered into the BATHTUB model was derived from a parallel P8 modeling effort (described in detail in the P8 Technical Memorandum; LimnnoTech 2009). Briefly, the P8 model was calibrated to monitoring data collected in 2006 from 11 different sampling sites distributed throughout the watershed and validated against monitoring data from years 2004, 2005 and 2007. Data from 2006 was selected as the calibration year because it represented a period that had average precipitation and phosphorus loading. In addition, internal phosphorus loading from curlyleaf pondweed die-off/senescence and multiple mixing events was minimal in 2006 (see Model Calibration for further discussion). P8 modeling estimates were used in the BATHTUB model (instead of direct monitoring data) to include load estimates from unmonitored subwatersheds. Annual watershed loads were input into BATHTUB as annual flow volumes and average phosphorus concentrations (Table 4) and were derived from the P8 model simulations using precipitation data corresponding to the water year time period (October through September).

Table 4. Annual Flow and Total Phosphorus Concentration for each Tributary.

	2004		2005		2006		2007	
Tributary	Flow (hm^3/yr)	TP (µg/L)	Flow (hm^3/yr)	TP (µg/L)	Flow (hm^3/yr)	TP (µg/L)	Flow (hm^3/yr)	TP (µg/L)
Plymouth Creek	5.83	202	5.26	211	5.83	184	5.38	210
18th Avenue	1.31	135	1.14	137	1.27	128	1.15	140
Ridgedale Creek	1.84	122	1.53	122	1.70	131	1.55	121
West Medicine Lake	0.16	206	0.13	216	0.15	258	0.26	202
North Medicine Lake	0.56	199	0.47	207	0.53	225	0.47	210
Northeast Medicine Lake	0.54	84	0.46	85	0.52	98	0.43	81
North Bassett Creek	0.20	298	0.17	312	0.19	340	0.17	314
Middle Bassett Creek	0.13	280	0.11	295	0.12	327	0.11	294
South Bassett Creek	0.62	157	0.47	161	0.59	185	0.52	156
East Medicine Lake Park	0.17	216	0.14	220	0.16	239	0.15	228
City of Medicine Lake	0.32	352	0.27	369	0.32	419	0.26	365

2.1.3 Internal Loading

There are two primary sources of internal loading in Medicine Lake – sediment release of phosphorus and curlyleaf pondweed die-off/senescence. Total internal loading was estimated to be an average 4232 lbs P/year using the BATHTUB model. Details of the internal load estimate using BATHTUB are described in Attachment A. The relative contribution of phosphorus from sediment release and curlyleaf pondweed die-off/senescence is described below.

2.1.3.a Sediment Release of Phosphorus

Sediment release of phosphorus is initiated by hypoxic/anoxic conditions in the hypolimnion during stratification (Figures 4 and 5). Phosphorus released from the sediment diffuses throughout the water column as stratification changes throughout the growing season. Typically, wind mixing and temperature changes are mechanisms that alter stratification patterns within the lake. Phosphorus release from the hypolimnion to the surface waters is at a maximum following complete de-stratification during fall turnover.

Internal diffusion of nutrients from the hypolimnion to epilimnion in Medicine Lake during the growing season is often accelerated by wind-initiated, partial mixing events. Medicine Lake has a fetch oriented from southeast to the northwest, and prolonged periods of prevailing winds from the south and/or north cause the water column to periodically mix throughout the growing season. Previous studies (e.g., EPA 2000) indicate that Medicine Lake experiences wind events that completely mix the water column several times throughout the year (Figure 6). Mixing events typically occur in July, August, and September and the amount of internal loading is likely variable, depending on the phosphorus concentration in the hypolimnion prior to mixing and/or migration of the thermocline.

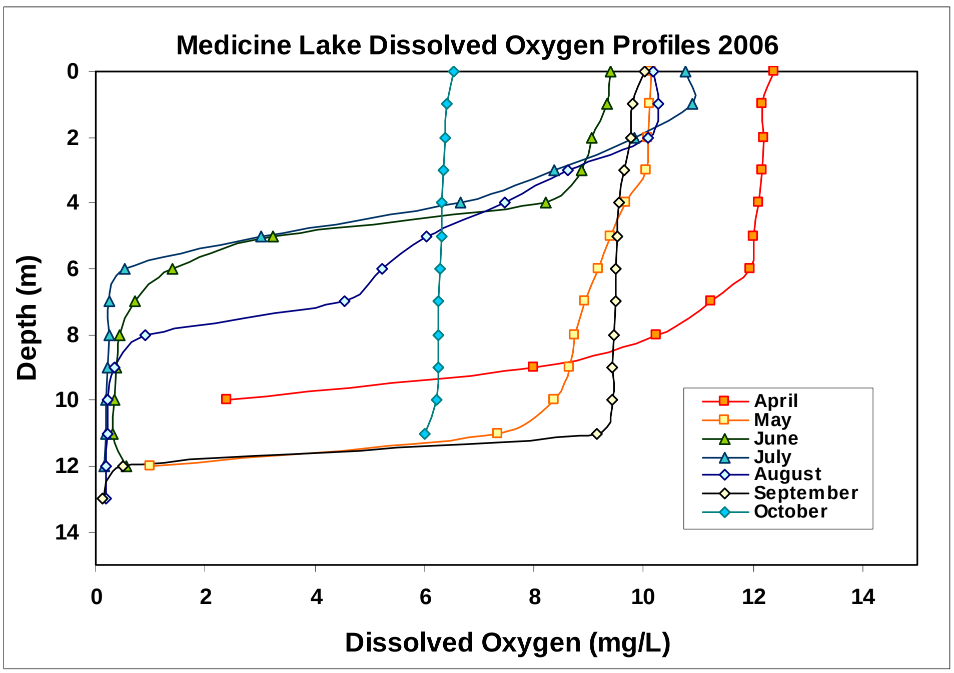

Figure 4. Medicine Lake dissolved oxygen profiles in 2006.

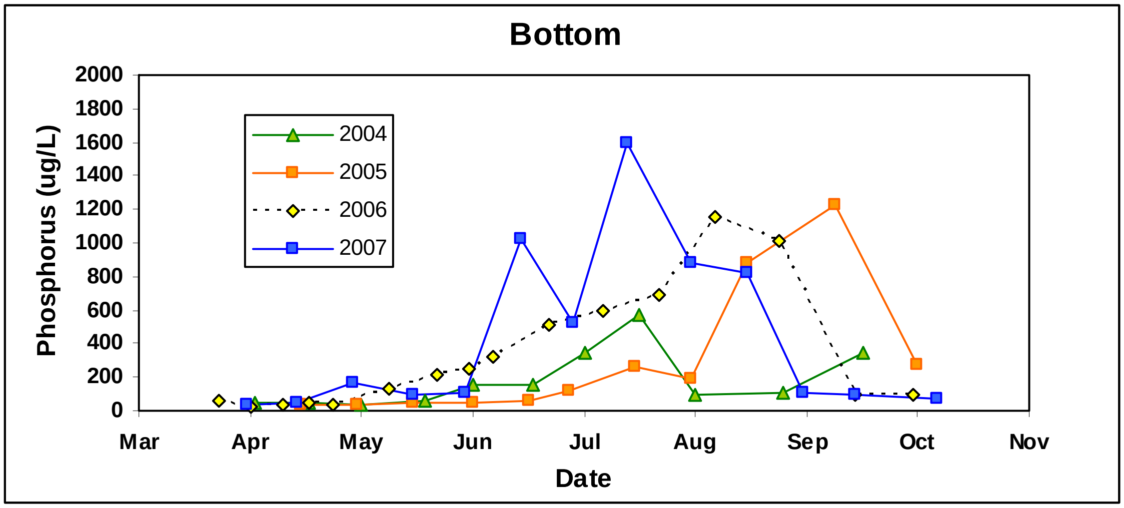

Figure 5. Medicine Lake total phosphorus concentrations in the hypolimnion.

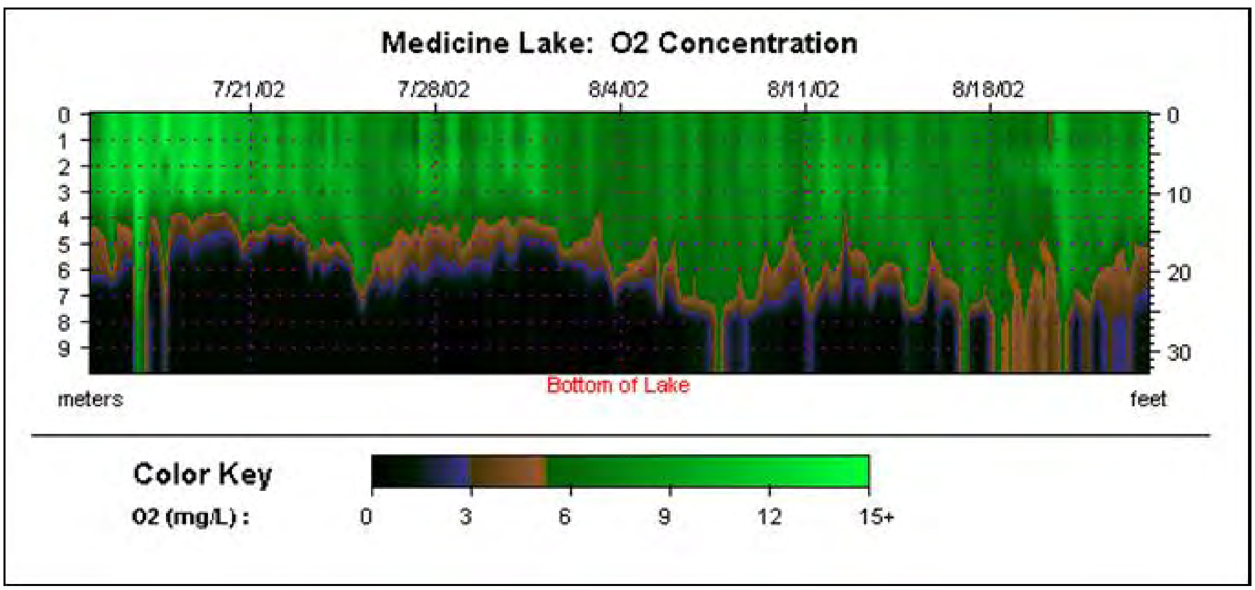

Figure 6. Continuous (15-minute intervals) dissolved oxygen measurements throughout the summer growing season on Medicine Lake. Time periods of uniform dissolved oxygen throughout the profile depict mixing events (likely resulting from prolonged wind and/or changes in temperature) during the summer in 2002.

Phosphorus from sediment release in the hypolimnion was estimated using an approach developed by Nürnberg et al. (1988 and 1995). The Nürnberg equation estimates phosphorus release by multiplying an internal loading rate by the hypolimnetic anoxia area (Equation 3). Internal loading rate is calculated by multiplying sediment release rates by an anoxic factor (Equation 1).

Equation 1:
Internal Loading Rate (mg/m^2-yr) = AF * RR
AF = Anoxic Factor (days/year)
RR = Sediment Release Rate (mg/m^2-day)

Equation 2:
Anoxic Factor (days/yr) = -36.2 + 50.1 log (TP) + 0.762 * Z / A^0.5
TP = Average summer in-lake TP Concentration (µg/L)
z = lake mean depth (m)
A = lake surface area (km2)

Equation 3:
Internal Load = Internal Loading Rate (EQ1) * Hypolimnetic Anoxia Area (m^2)

2.1.3.a.1 Sediment Release Rates

Sediment release rates for Medicine Lake were estimated to range from 4 to 9 mg/m2/day in 2006 (Figure 7). Sediment release rates were calculated using the Di Toro (2001) Sediment Digenesis module of the AQUATOX model (Release 3.0). Sediment release rates predicted by the AQUATOX model correspond to previous estimates (8 mg/m2/day) reported in the Medicine Lake Diagnostic Feasibility Study (Barr Engineering 1987).

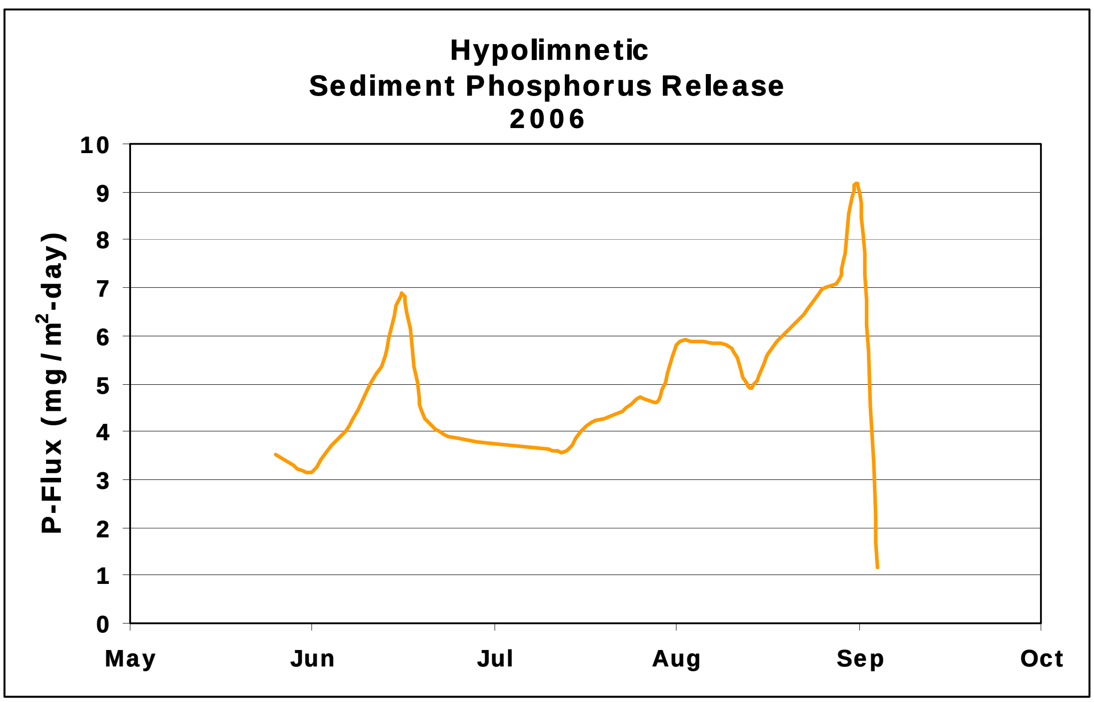

Figure 7. Medicine Lake Sediment Phosphorus Release Rates estimated using a sediment digenesis model with 2006 data.

2.1.3.a.2 Anoxic Factor

The anoxic factor represents the number of days that the sediment area, as estimated by the whole-lake surface area, is overlain by anoxic water (< 1 mg O2/L). Nürnberg (1987) developed a predictive relationship from a data set of lakes in central Ontario and eastern North America (Equation 2) to estimate the anoxic factor for individual lakes. Based on the Nürnberg equation, the anoxic factor for Medicine Lake was estimated at 49.2 days/yr in 2006.

Using the Nürnberg anoxic factor, the internal phosphorus load for Medicine Lake in 2006 was estimated to range between 814 lbs/yr (RR=4 mg/m2-day) and 1834 lbs/yr (RR=9 mg/m2-day). These estimates were compared to the hypolimnetic internal load derived from the AQUATOX model using daily sediment phosphorus release rates. Based on daily sediment phosphorus release rates, the AQUATOX model estimates 2048 lbs P/yr as the potential hypolimnetic internal P load. The maximum estimate derived from the Nürnberg equation was used to represent the potential hypolimnetic internal loading that could be transported to the surface waters during lake turn over.

2.1.3.b Internal Load due to Die-off/senescence of Curlyleaf Pondweed

Curlyleaf pondweed is a significant factor affecting water quality in Medicine Lake (Vlach and Barten 2007). Unlike most native aquatic plants, curlyleaf pondweed germinates in early fall, grows slowly during the winter months, and dies-off/senesces by the end of June or early July the following year. This unique life-history allows curlyleaf pondweed to out-compete many native plant species and occupy large areas of the littoral zone – Medicine Lake often has up to 30% surface area coverage of curlyleaf pondweed prior to die-off/senescence (Figure 8). Die-off/senescence of curlyleaf pondweed provides an internal source of nutrients within Medicine Lake. Die-off/senescence of curlyleaf pondweed and coincident increases in total phosphorus concentration often correspond with increased algal growth and reductions in water clarity (Figure 9). Internal loading of phosphorus resulting from curlyleaf pondweed die-off/senescence was estimated to be approximately 1,050 pounds of phosphorus in 2004 (Table 5; Vlach and Barten 2007). The amount of internal loading attributable to die-off/senescence likely depends upon the annual variation in curlyleaf pondweed densities. However, the data suggests that curlyleaf pondweed die-off/senescence may provide a significant source of internal phosphorus loading in many years.

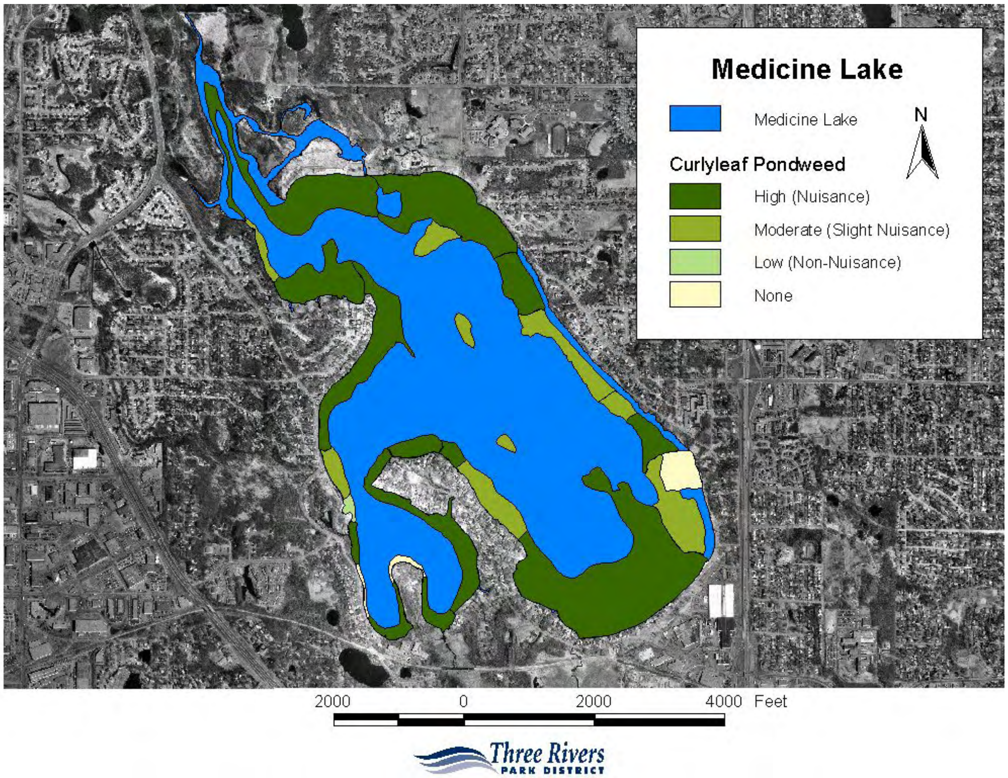

Figure 8. Curlyleaf pondweed densities throughout the littoral zone of Medicine Lake in 2004.

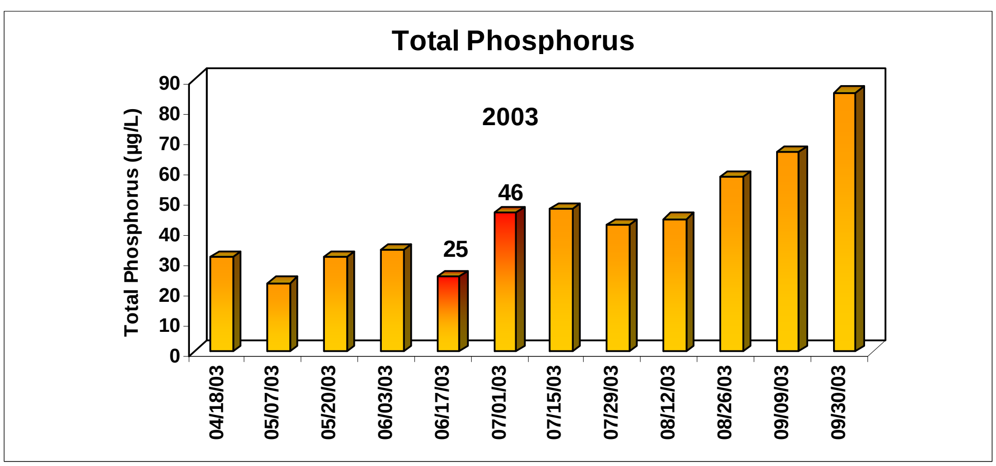

Figure 9. Seasonal changes in total phosphorus concentration in Medicine Lake in 2003. The large increase in total phosphorus concentration between June and July corresponds to curlyleaf pondweed die-off/senescence.

Table 5. Medicine Lake estimated total phosphorus loading from curlyleaf pondweed in 2004.

Site	Acreage	Average Biomass (g dry wt/m^2)	Average TP Conc. (mg/g dry wt)	Average (lbs TP/Acre)	TP Loading (pounds)
1	147.3	83.4	4.80	3.19	469.8
2	42.2	92.1	2.29	1.86	78.4
3	136.3	92.8	3.73	3.08	419.7
4	50.0	38.6	4.91	1.65	82.6
Total					1,050

2.1.3.c Representing Internal Load in BATHTUB

The average internal loading estimated using the BATHTUB model (above background levels) was 4,232 lbs P/year. However, the total phosphorus estimated from sediment release (Nürnberg; 1,834 lbs P/yr) and die-off/senescence of curlyleaf pondweed (1,050 lbs P/yr) was 2,884 lbs P/yr – approximately 32% lower than the internal load estimates used in the BATHTUB model. The difference between the respective internal loading estimates is likely attributed to the influence of several factors:

- The anoxic factor calculated using the Nürnberg equation may under represent the actual number of days of anoxia observed in Medicine Lake. Based on the Nürnberg equation, the anoxic factor was estimated as 49.2 days/yr in 2006. The actual number of days of hypolimnetic anoxia observed for Medicine Lake in 2006 was 102. The lower anoxic factor used in the Nürnberg equation may have underestimated the internal loading from the hypolimnion.

- Sediment release of phosphorus from littoral sediments and/or macrophyte decomposition (other than curlyleaf pondweed) also likely contributes to the total internal phosphorus load of the lake. Results from the supplemental AQUATOX modeling effort suggest that phosphorus release from the littoral zone account for a significant portion of the total internal phosphorus load. Phosphorus loading from the littoral zone is not represented in the Nürnberg equation.

- Sediment phosphorus release and internal loading from the hypolimnion to the epilimnion is a dynamic process that varies from year to year depending on the length, stability and depth of stratification (and the associated level of anoxia). Given that thermocline depth and stability vary within and among years (EPA 2000), sediment release of phosphorus estimated under static conditions in 2006 using the Nürnberg relationship is likely not applicable across all years – particularly years in which the thermocline is highly unstable.

- The amount of internal loading attributed to die-off/senescence of curlyleaf pondweed may be underrepresented in years with highly dense plant growth and/or increased littoral coverage. In the 2004 study referenced above, the phosphorus concentration of curlyleaf pondweed from four different locations in Medicine Lake ranged from 1.65 to 3.9 mg/g dry-wt. Additional studies have reported a phosphorus concentration of curlyleaf pondweed as high as 5 mg/g dry-wt (Unpublished; McComas 2006).

2.1.4 Atmospheric Deposition

Atmospheric depositional loading was estimated using the BATHTUB model. The default BATHTUB value for atmospheric deposition was 0.27 lbs/acres-year (30 mg/m2-yr). The BATHTUB default value was similar to other atmospheric TP loading rates reported in a technical memorandum to the Minnesota Pollution Control Agency that provided a detailed assessment of phosphorus loading sources to Minnesota Watersheds in 2007 (Barr Engineering 2007). The total surface area of Medicine Lake is approximately 946 acres. Consequently, total atmospheric deposition was estimated to be 253 lbs/year for Medicine Lake. The atmospheric depositional loading was included in the overall lake nutrient balance.

2.2 BATHTUB MODEL CALIBRATION

The BATHTUB model was calibrated to observed in-lake water quality conditions in 2006. The 2006 water quality data was selected for calibration because it represents a year in which internal loading was not significantly higher than the background levels implicitly represented by the BATHTUB model (see Attachment A). Internal load was low in 2006, likely because it was the third consecutive year of a curlyleaf pondweed control program (Vlach and Barten 2007) and multiple mixing events did not occur (based on biweekly dissolved oxygen profile sampling).

The Canfield and Bachmann General Lakes TP sedimentation equation (option 9) was used for the BATHTUB model simulations because it best predicted the observed water quality conditions in Medicine Lake (Table 6). The Canfield and Bachmann algorithm has been used successfully in previous lake nutrient TMDLs throughout the region. The BATHTUB model accurately predicted in-lake total phosphorus concentrations without adjusting the internal loading rates or calibration coefficients in 2006.

Table 6. BATHTUB Model Calibration to Existing Conditions in 2006.

Water Quality Parameters	Medicine Lake			
	Observed	BATHTUB Predicted	BATHTUB	
			Model Selection	Calibration Coefficients
TP (µg/L) Mean	46.0	45.9	9-Canfield Bachmann, Lakes	1
Chl-a (µg/L) Mean	21.5	21.6	5-P,Jones and Bachmann	1
SD (m) Mean	2.0	1.9	1-vs. Chl-a & Turbidity	1.2

Chlorophyll-*a* and secchi depth algorithms were selected based on the strength of the correlation between the predicted and observed in-lake conditions. The Jones and Bachmann chlorophyll-*a* model (option 5; based on a relationship between total phosphorus concentration and chlorophyll-*a*) was used to model chlorophyll-*a*. The BATHTUB model default algorithm (option 1; transparency vs. chlorophyll-*a* and turbidity) was used to predict secchi depth transparency. The secchi depth model calibration coefficient was adjusted incrementally (final value of 1.2) to improve the correlation between modeled and observed secchi depths (Table 6).

2.3 BATHTUB MODEL VALIDATION

The calibrated BATHTUB model was validated using in-lake water quality data from three additional years (2004, 2005, and 2007). The BATHTUB model was re-run for each year to estimate changes in water quality conditions that correspond to the respective P8 watershed loading estimates.

In the process of validating the BATHTUB model for years 2004, 2005 and 2007, two distinct patterns emerged for Medicine Lake. The BATHTUB model reliably predicted water quality conditions during periods (2005) when internal loading from curlyleaf pondweed and/or multiple mixing events was limited (Table 6; for further discussion see the Internal Loading section above). However, the BATHTUB model underpredicted in-lake water quality conditions for years where high curlyleaf pondweed densities and/or multiple mixing events were observed (2004 and 2007; Figure 10).

To account for the underprediction of total phosphorus concentration in years 2004 and 2007, the average internal loading rates within the BATHTUB model were increased to 1.55 mg P/m2-day in 2004 and 1.2 mg P/m2-day in 2007 (Attachment A). The adjustment of internal loading rates resulted in an addition of 4,770 pounds and 3,693 pounds of phosphorus to the overall respective mass balance of phosphorus in 2004 and 2007. The BATHTUB model accurately predicted in-lake total phosphorus concentrations in 2004 and 2007 after increasing internal loading rates (Table 7 and Figure 11).

Table 7. Results from the BATHTUB model validation runs for 2004, 2005, and 2007.

Year	TP (µg/L)		Chl-a (µg/L)		Secchi (m)	
	Observed	Predicted	Observed	Predicted	Observed	Predicted
2004	65.0	65.0	30.6	28.8	2.0	2.4
2005	47.0	45.4	30.0	21.3	1.7	2.0
2007	60.0	60.4	33.3	32.3	1.5	1.6

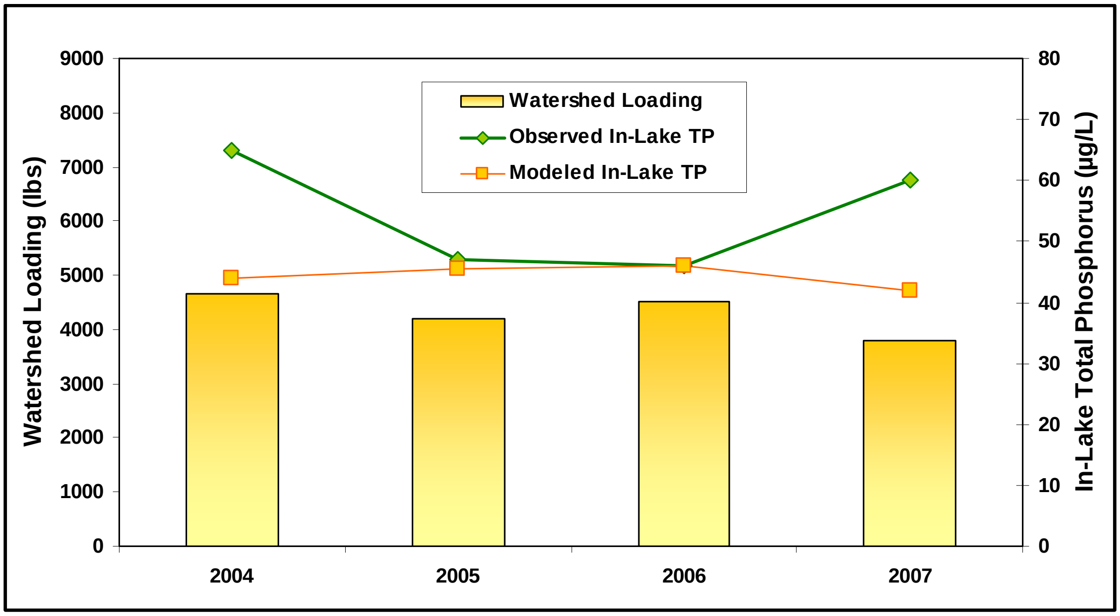

Figure 10. BATHTUB model simulations of in-lake TP concentrations from 2004-2007 using only the background implicit internal load represented in the model.

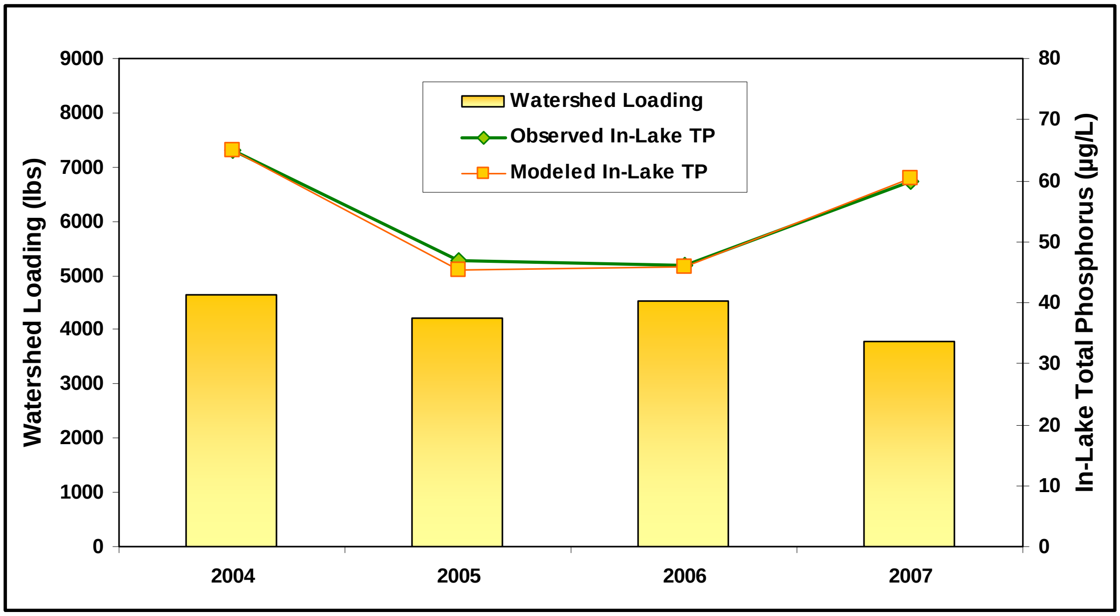

Figure 11. BATHTUB model simulations of in-lake TP concentrations from 2004-2007 with an additional internal loading rate represented in the BATHTUB model.

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3. ASSIMILATIVE CAPACITY

The TMDL represents the total mass of phosphorus that can be assimilated into Medicine Lake while continuing to meet the state water quality standards. For purposes of implementation, the TMDL equation is described as four different components: Waste Load Allocation (WLA); Load Allocation (LA); Margin of Safety (MOS); and Reserve Capacity (RC). The WLA represents phosphorus loading from point sources such as permitted stormwater discharge from the various MS4s. The LA represents phosphorus from nonpoint sources such as atmospheric deposition and internal loading. A portion of the TMDL is allocated to the MOS to account for uncertainty associated with modeling estimates and environmental variation. The RC represents the portion of the load that is set aside to account for future development.

$$\text{TMDL} = \sum \text{WLA} + \sum \text{LA} + \text{MOS} + \text{RC}$$

WLA = Waste Load Allocations
LA = Load Allocations
MOS = Margin of Safety
RC = Reserve Capacity

The BATHTUB model load-response function was used to evaluate the in-lake water quality response to varying phosphorus loads from the watershed. The load-response analysis was conducted for 2006 to describe the watershed load reductions necessary to meet in-lake goals independent of internal loading from curlyleaf pondweed die-off/senescence and multiple mixing events. The Minnesota state water quality standard for Medicine Lake is a growing-season average, in-lake total phosphorus concentration of 40 µg/L. Based on the load-response simulation, the total annual watershed phosphorus load must not exceed 3,500 lbs P/year to achieve the in-lake water quality goal (Figure 12). In addition, an explicit MOS of 270 pounds was added to ensure that water quality standards are achieved. The explicit MOS was generated by setting a more restrictive in-lake water quality goal (38 µg/L) and calculating the additional phosphorus reduction necessary to meet this goal (Table 8). Following the adjustment for the explicit MOS, the total annual watershed phosphorus load to the lake (or the WLA) must not exceed 3,230 pounds of phosphorus per year (Figure 12 & Table 8). To achieve the in-lake goals, the watershed load will need to be reduced by 28% (1,287 lbs P).

Table 8. Medicine Lake phosphorus sources and required reductions necessary to achieve in-lake water quality goal. The MOS of 270 is subtracted from the TMDL 3500 lb goal to arrive at the final 3,230 WLA value.

TP Source	TP Load (lbs/yr)			% Reduction
	Current	TMDL	Reduction	
Watershed (WLA)	4,517	3,230	1,287	28%
Atmospheric (LA)	253	253	0	0%
Internal (LA)	4,232	0	4,232	100% *
Margin of Safety (MOS)	-	270	-	-
Reserve Capacity (RC)	-	0	-	-
Total	9,002	3,753	5,519	61%

**The internal load reduction is 100% above the background levels implicitly accounted for in the BATHTUB (see the Internal Load section for further discussion).*

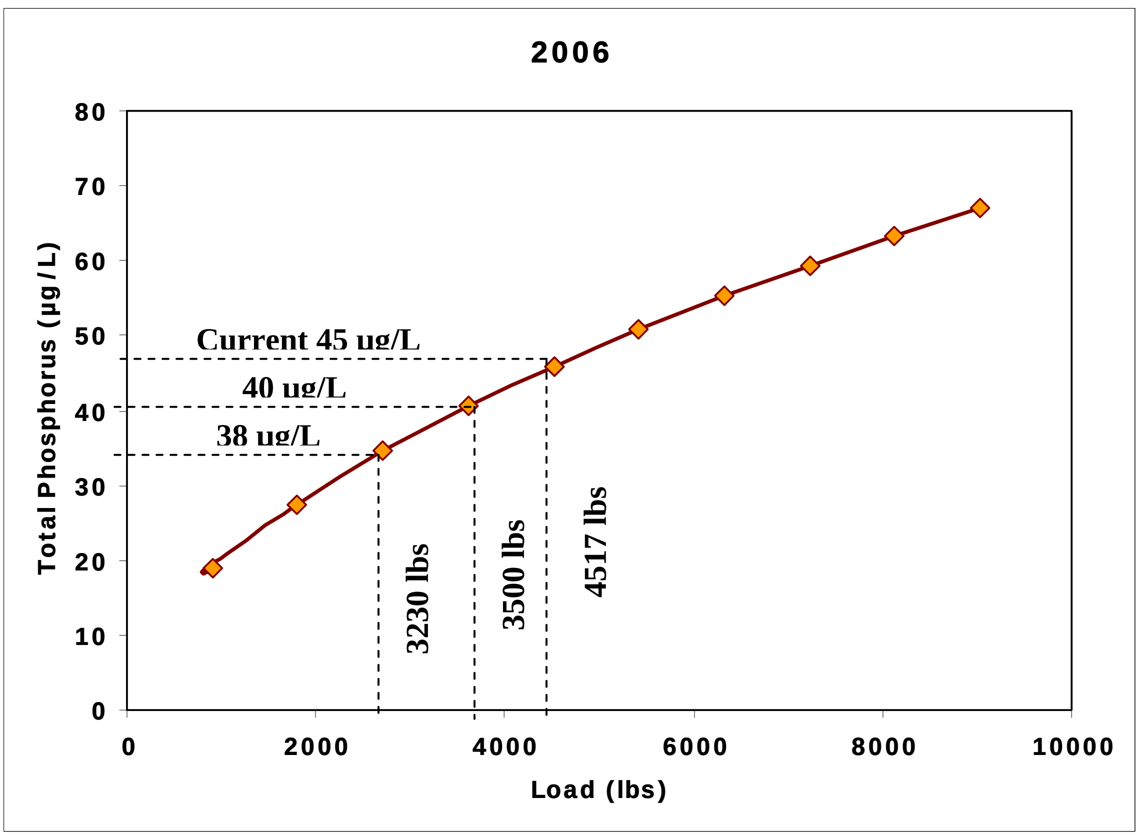

Figure 12. BATHTUB watershed load response to in-lake TP concentration for 2006.

Since the majority of the watershed area has already been developed and future development of currently undeveloped areas will be guided by a non-degradation plan (City of Plymouth, 2009), the Reserve Capacity portion of the TMDL equation was set to 0 lbs TP/year (Table 7). The Load Allocation represented in the BATHTUB model was 253 lbs TP/year (Table 7). The LA portion of the TMDL equation represents 253 lbs/yr from the atmosphere and 0 lbs/yr from internal loading. Setting the internal load value in the TMDL equation to 0 does not imply there is no internal load. Instead, the 0 value indicates that the internal load that will allow Medicine Lake to meet water quality goals can be no higher than the background levels of internal loading already represented in the BATHTUB model (additional sources of internal load are described in more detail in the Internal Load section above). To meet water quality goals in all years (particularly those with multiple mixing event and/or high densities of curlyleaf pondweed), internal load will also have to be reduced by an average of 4,232 lbs P/year.

Values for the WLA, LA, MOS, and RC were summed to arrive at the overall TMDL goal for Medicine Lake (Equation 4).

Equation 4

TMDL	**=**	**∑WLA**	**+**	**∑LA**	**+**	**MOS**	**+**	**RC**
3,753	**=**	**3,230**	**+**	**253**	**+**	**270**	**+**	**0**

The BATHTUB model was used to predict the change in chlorophyll-a concentration and secchi-depth transparency that will correspond to the TMDL loading scenario. With phosphorus loading at levels prescribed by the TMDL, secchi depth in Medicine Lake will increase to 2.4 m (Table 9) – meeting the state standard of 1.4 meters. However, the chlorophyll-a water quality standard will not be achieved with the load reductions prescribed by the TMDL (Table 9). The BATHTUB model predicts that chlorophyll-a concentration will decrease to 16.2 µg/L, which is above the chlorophyll-a water quality standard of 14 µg/L (Table 9). Assuming that the total phosphorus and secchi-depth transparency water quality standards are achieved, Medicine Lake will not be considered impaired due to excess nutrients.

Table 9. Predicted changes in water quality conditions in Medicine Lake for the TMDL modeled loading scenario.

Parameters	Loading Scenario: Existing Conditions	Loading Scenario: TMDL Modeled	Water Quality Standard
TP (µg/L)	46.0	38.0	40.0
Chl-a (µg/L)	21.5	16.2	14.0
Secchi (m)	2.0	2.4	1.4

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Attachment 1 – Modeling Internal Load

Background

Internal load is being estimated using results from the BATHTUB model(s) for years 2004-2007. The BATHTUB model estimates in-lake total phosphorus (TP) concentrations using an algorithm developed by Canfield and Bachmann, 1981. The Canfield-Bachmann algorithm was developed by establishing a relationship between in-lake TP concentrations, watershed load, atmospheric load, lake morphology and sedimentation rates using data from a wide range of lakes in North America. The ability of the Canfield-Bachmann algorithm to predict in-lake TP is depicted below (Figure 1). Because this model was developed empirically, and all lakes have some natural internal loading (i.e., sediment release of phosphorus), the Canfield-Bachmann algorithm implicitly accounts for some level of "background" internal loading. However, many lakes (e.g., Medicine Lake) often have rates of internal loading higher than background levels. To account for lakes that have internal loading that are higher than would be considered background (e.g., phosphorus from curlyleaf pondweed die-off/senescence and multiple mixing events), the BATHTUB model allows the user to input additional internal sources of phosphorus.

Replication of the Canfield-Bachmann Model Predictions

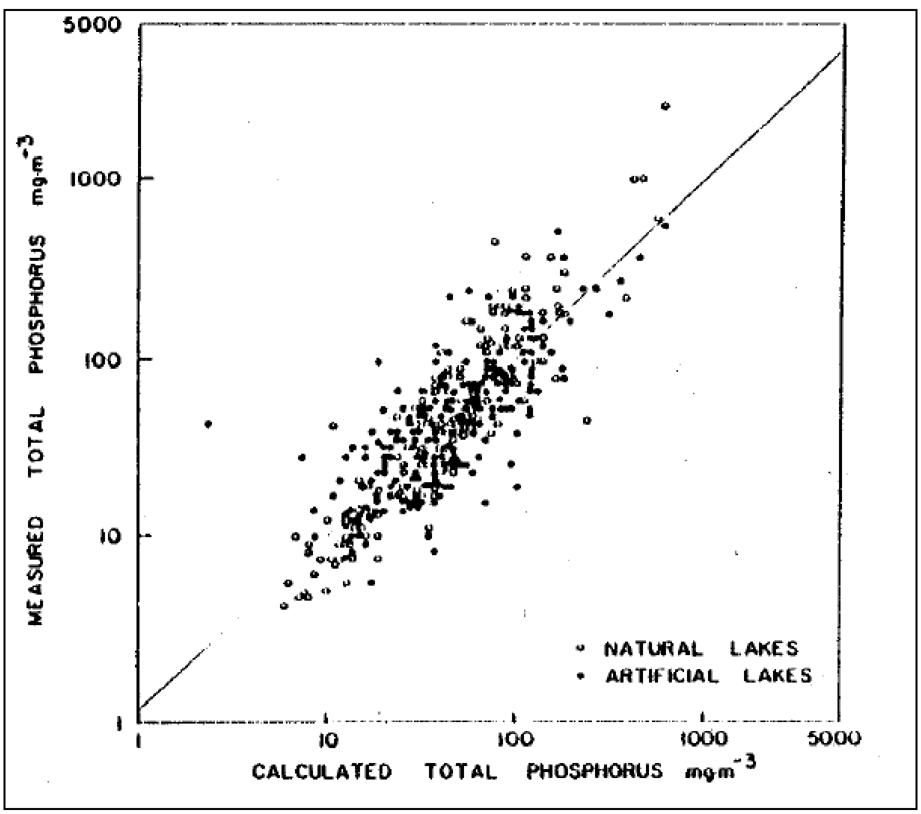


Figure 1-1. Is a scanned copy of Figure 2 from the original Canfield and Bachmann, 1981 paper (Can. J. Fish Aquat. Sci. 38:414-423) that compares the measured and

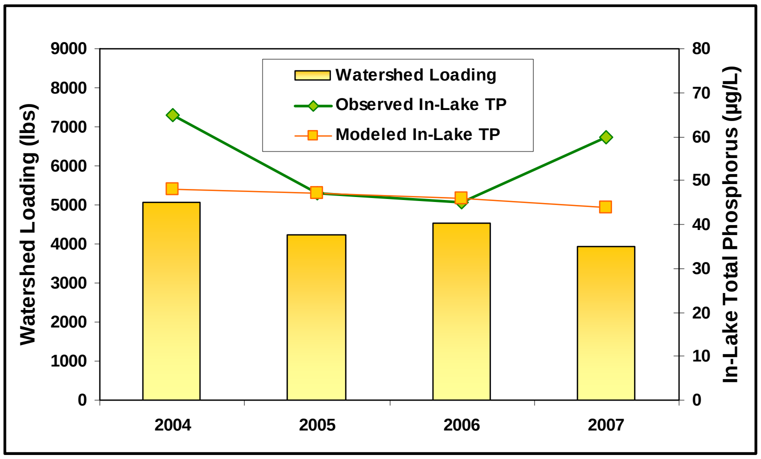
predicted TP concentrations from 1330 lakes (both natural and artificial). Presumably, some of the uncertainty associated with Canfield-Bachmann predictions can be attributed to variations in internal loading.

Accounting for Internal Load in BATHTUB

In the process of modeling Medicine Lake from years 2004-2007, two distinct patterns emerged. In 2005 and 2006 (years where there was little internal loading from either curlyleaf pondweed or multiple mixing events), the BATHTUB model reliably predicts in-lake TP concentrations. However, in 2004 and 2007 (years where curlyleaf was observed at high densities and/or multiple mixing events were noted), BATHTUB underpredicted in-lake TP concentrations – presumably from increased internal loading (Figure 2A).

To account for the under prediction in years 2004 and 2007, the BATHTUB model was modified by increasing average internal loading rates to 1.55 mg P/m^2-day in 2004 and 1.2 mg P/m^2-day in 2007. Following the modification to account for additional internal loading in 2004 and 2007, the model accurately predicts in-lake TP concentrations (Figure 2B). The 4,232 lbs P/year average value is being used to describe the internal load (above and beyond the background levels represented in BATHTUB) that will need to be addressed to meet water quality goals in all years.

BATHTUB Model Results with and without Additional Internal Loading



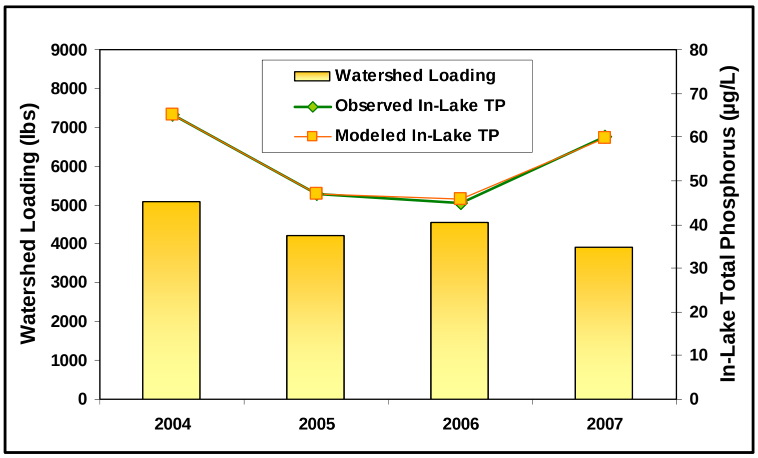


Figure 1-2. Graph A depicts results from the BATHTUB model simulations of in-lake TP concentrations from 2004-2007 using only the background internal load implicitly represented in the model. Graph B depicts results from the BATHTUB model simulations of in-lake TP concentrations from 2004-2007 with an additional average internal loading rate of 1.55 mg P/m2-day in 2004 and 1.2 mg P/m2-day in 2007. In both graphs, the solid bars represent total watershed loads, and correspond to the primary y-axis on the left. The lines represent observed and modeled TP concentrations, and correspond to the secondary y-axis on the right.