Michigan Department of Environmental Quality
Water Bureau
August 2008

Total Maximum Daily Load for Phosphorus for
Bear Lake
Muskegon County

INTRODUCTION

Section 303(d) of the Federal Clean Water Act and the United States Environmental Protection Agency's (USEPA's) Water Quality Planning and Management Regulations (Title 40 of the Code of Federal Regulations, Part 130) require states to develop Total Maximum Daily Loads (TMDLs) for water bodies that are not meeting water quality standards (WQS). The TMDL process establishes the allowable loadings of pollutants for a water body based on the relationship between pollution sources and in-stream water quality conditions. TMDLs provide states with a basis for determining the pollutant reductions necessary from both point and nonpoint sources (NPS) to restore and maintain the quality of their water resources.

The purpose of this TMDL is to identify the sources of phosphorus to Bear Lake and determine the maximum allowable phosphorus load that can be assimilated by the lake and meet applicable WQS.

PROBLEM STATEMENT

The 2008 Section 303(d) listed reach for Bear Lake totals approximately 415 acres in Muskegon County in west Michigan (Figure 1). The TMDL reach for Bear Lake appears on the Section 303(d) list as:

Water body name: Bear Lake
AUID: 040601021003-01
Impaired designated use: Other indigenous aquatic life and wildlife
County: Muskegon
Cause: Excess Algal Growth and Total phosphorus
Size: 415A
Location Description: Tributary to Muskegon Lake located north of Muskegon Lake, Laketon Twp.

Bear Lake was included on the 2008 Section 303(d) list due to excess algal growths and elevated total phosphorus (TP) (LeSage and Smith, 2008). Bear Lake is considered to be hypereutrophic as evidenced by elevated levels of TP, shallow secchi depth measurements, elevated chlorophyll *a* levels and heavy summer blooms of cyanobacteria (Cadmus and AWRI, 2007). The frequency of algal blooms has prompted the use of various treatments since 2003 using aquatic herbicides in an attempt to reduce nuisance growths of algae in Bear Lake (ANC, 2008 - personal communication).

External and internal sources of phosphorus are responsible for the elevated phosphorus levels in Bear Lake and the resulting nuisance algal blooms. Phosphorus is an essential nutrient for primary productivity in lakes and is considered the limiting nutrient (the nutrient in shortest supply) in the majority of Michigan lakes, including Bear Lake. Typically, impairments of designated uses in freshwater lakes in Michigan are a result of excess primary productivity caused by anthropogenic sources of phosphorus to the system.

Sampling of the lake by the Michigan Department of Environmental Quality (MDEQ) for nutrients and other parameters (e.g., secchi depth, chlorophyll *a*, dissolved oxygen, temperature, pH, and conductivity) was conducted monthly from April through November 2006 to determine existing water quality in Bear Lake (Table 1). Samples were collected from three stations (Figure 2). The lake was also sampled in July and August 2006 and in April 2007, by the Grand Valley State University, Annis Water Resources Institute (AWRI) (Cadmus and AWRI, 2007).

NUMERIC TARGET

The overall objective of the TMDL is to reduce total phosphorus loads to Bear Lake to levels that are expected to result in the attainment of WQS; specifically, to reduce excessive algal growth and increase water transparency. All references to phosphorus in the document are assumed to mean “total phosphorus” unless otherwise specified.

Figure 1. Bear Lake Watershed in Muskegon County, Michigan (Cadmus and AWRI, 2007).

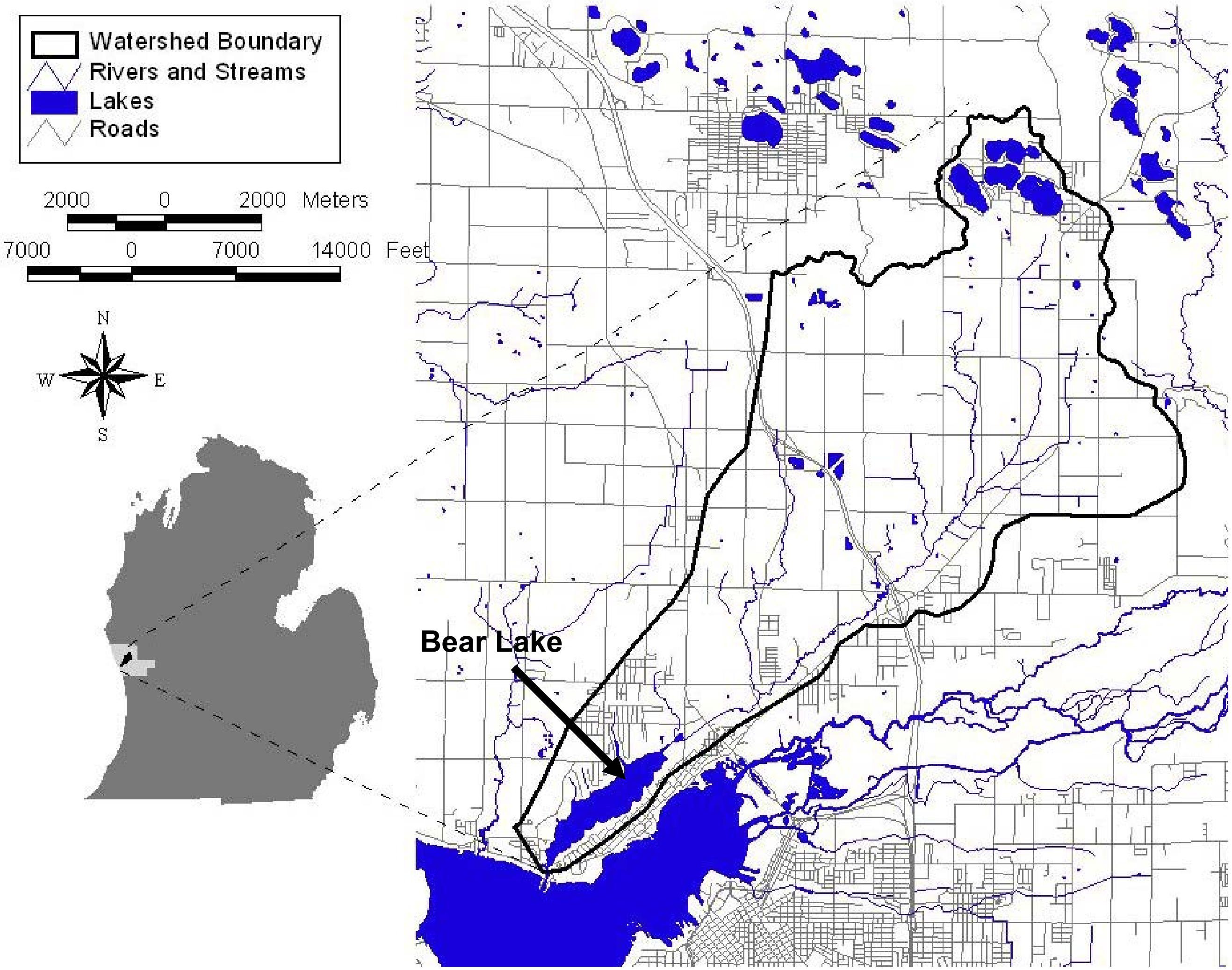

Table 1. Monthly average water quality data for the three stations in Bear Lake in Muskegon County, Michigan, 2006 and 2007. (Cadmus and AWRI, 2007; MDEQ, unpublished data).

Date	Secchi Disk (m)	SRP-P (mg/L)	TP-P (mg/L)	Chl *a* (mg/L)
April 2006	1.0	<0.005	0.034	0.021
May 2006	0.83	<0.005	0.053	0.017
June 2006	0.9	<0.005	0.037	0.018
July 2006	0.6	<0.005	0.070	0.035
August 2006	0.6	<0.005	0.047	0.032
September 2006	0.7	<0.005	0.036	0.022
October 2006	0.9	<0.005	0.039	0.020
November 2006	1.0	<0.005	0.027	0.009
April 2007	0.85	<0.005	0.034	0.009
Annual Average	0.82	<0.005	0.042	0.020

SRP-P = Soluble Reactive Phosphorus as Phosphorus
TP-P = Total Phosphorus as Phosphorus
Chl *a* = Chlorophyll *a*

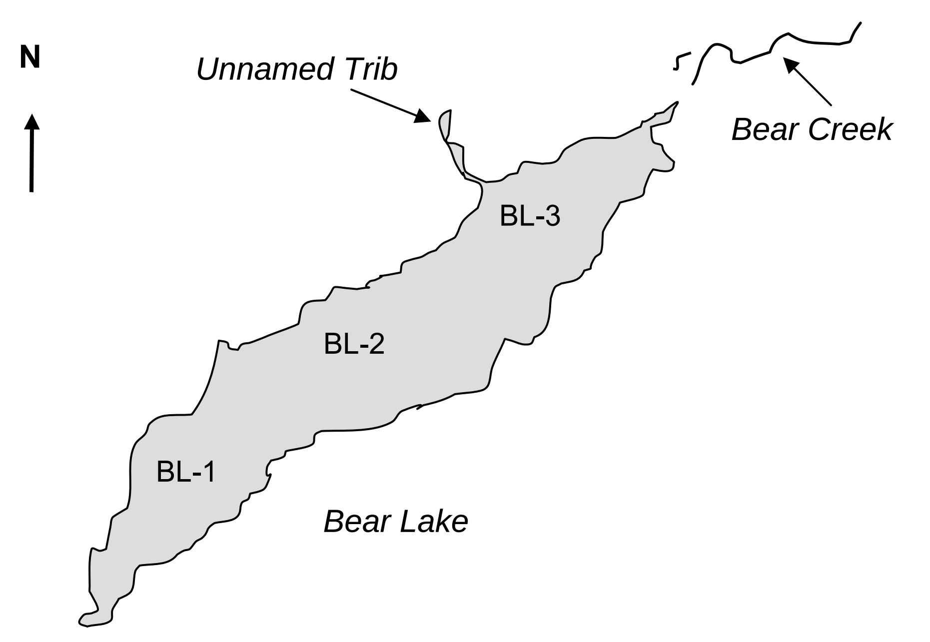

Figure 2. Sampling locations in Bear Lake, Muskegon County, Michigan.

Rule 100 (R 323.1100) (Designated Uses) of the Part 4 rules, WQS, promulgated under Part 31, Water Resources Protection, of the Natural Resources and Environmental Protection Act, 1994 PA 451, as amended, requires that Bear Lake be protected for warmwater fish, other indigenous aquatic life and wildlife, agriculture, navigation, industrial water supply, public water supply at the point of intake, partial body contact recreation, total body contact recreation from May 1 to October 31, and fish consumption. The impaired designated use for Bear Lake addressed by this TMDL is the *other indigenous aquatic life and wildlife* use (R 323.1100(1)(e)), due to nuisance blooms of cyanobacteria. Excess phosphorus can stimulate nuisance growths of cyanobacteria that indirectly reduce oxygen concentrations to levels that cannot support a balanced fish or aquatic macroinvertebrate community (e.g., extreme day/night time fluctuations in oxygen); and can shade out beneficial phytoplankton (algal) and aquatic macrophyte (vascular plant) communities that are important food sources and habitat areas for fish and wildlife.

R 323.1060(2) (Plant Nutrients) was developed to provide the authority to limit the addition of nutrients that are injurious to the designated uses listed above. Michigan does not have ambient numeric nutrient criteria for phosphorus within its WQS; however, the heavy blooms of cyanobacteria are a violation of the narrative standard in subrule (2) of R 323.1060. Michigan's plant nutrient rule is as follows:

R 323.1060 Plant Nutrients.

Rule 60. (1) Consistent with Great Lakes protection, phosphorus which is or may readily become available as a plant nutrient shall be controlled from point source discharges to achieve 1 milligram per liter of TP as a maximum monthly average effluent concentration unless other limits, either higher or lower, are deemed necessary and appropriate by the department.

(2) In addition to the protection provided under subrule (1) of this rule, nutrients shall be limited to the extent necessary to prevent stimulation of growths of aquatic rooted, attached, suspended, and floating plants, fungi or bacteria which are or may become injurious to the designated uses of the surface waters of the state.

The numeric load and concentration targets for phosphorus reductions in Bear Lake were developed based on a weight-of-evidence approach that uses biological threshold information obtained from the literature and empirical modeling. These steps are: (1) determine a concentration target using a biological threshold and modeling framework; and (2) determine an allowable loading to meet the concentration target. The derivation and justification of the numeric targets for Bear Lake are described below.

Biological Thresholds and Modeling Framework

Numeric targets for nutrients can be developed for lakes by evaluating changes in biological responses (thresholds) along a nutrient gradient. These thresholds are levels above which major changes in lake biology occur due to a causal variable; in this case, phosphorus. Significant biological thresholds (e.g., secchi depth, chlorophyll *a* levels, phytoplankton/zooplankton biomass, and fish community structure) have been found in lakes at phosphorus concentrations ranging from 0.008 to 0.06 milligrams per liter (mg/L) (Soranno et al., 2008; Heiskary and Wilson, 2005). Thresholds from 0.008 to 0.021 mg/L can occur for water clarity and phytoplankton and zooplankton biomass. Thresholds from 0.03 to 0.06 mg/L can occur for severe algal blooms, and the shift in a fishery to a rough fish dominated system (Downing et al., 2001; Heiskary and Wilson, 2005). These changes in specific biological responses can be used as surrogates for how biological integrity may change along a nutrient gradient (Soranno et al., 2008).

A biological thresholds and predictive modeling (BTPM) framework, developed by researchers from Michigan State University in consultation with the MDEQ, using input variables from a set of 374 Michigan lakes, was used by the MDEQ to develop numeric targets for Bear Lake using the following steps:

1. Predict an expected natural phosphorus concentration for the lake.
2. Compare the expected natural phosphorus concentration to the biological thresholds and select an appropriate biological threshold.
3. Compare the selected biological threshold to current lake phosphorus concentrations. If current phosphorus concentrations exceed the threshold, establish the threshold as the concentration target.

The expected natural phosphorus concentration is determined using hydrogeomorphic-land use features. For natural lakes (versus impoundments), mean depth (in meters), the proportion of geologic outwash, agriculture, and urban land use, as well as true color are used in the model to predict the expected condition.

The equation to determine the expected natural phosphorus concentration is:

$$TP_N = [e^{(1.867 - 0.257(\ln a) - 0.202(b) + 0.344(\ln c))}] * (1.39)$$

Where:

TP_N = expected TP concentration for natural lakes in micrograms per liter
a = arithmetic mean lake depth in meters
b = proportion of surficial geology-outwash within a 500 meter buffer around the lake
c = true color of lake in platinum - cobalt units measured as absorbance during the period July through September
ln = natural log
1.39 = level of allowance

The level of allowance represents model uncertainty in the prediction of the expected condition, and allows for some low or minimal level of human disturbance to the lake given present day land use patterns (Soranno et al., 2008).

The hydrogeomorphic-land use features used for Bear Lake were as follows: mean depth (2.07 meters), proportion of geological outwash (0.0), and true color (40 platinum cobalt units). Based on these site-specific features, the expected natural phosphorus condition of Bear Lake is 0.027 mg/L.

The next step in the BTPM approach is to compare the expected natural phosphorus condition to biological thresholds and choose a threshold value. A threshold value is determined by choosing the first threshold along a phosphorus gradient that is greater than the expected natural phosphorus concentration (Soranno et al., 2008).

Given that the expected natural phosphorus concentration of the lake was estimated to be 0.027 mg/L, the threshold of importance to Bear Lake is 0.03 mg/L, since this is the first threshold greater than the expected natural phosphorus concentration (Figure 3). A concentration of 0.03 mg/L is a level above which severe summer blooms of cyanobacteria tend to occur. Choosing the next lowest threshold (0.018 mg/L) would not be appropriate since the natural expected condition for Bear Lake (0.027 mg/L) is greater, and the lake would never naturally be in this lower threshold range. Choosing a threshold value of 0.04 mg/L would allow the phosphorus concentration in the lake to increase to levels that might result in severe algal blooms during the summer. Nuisance blooms of algae currently occur in Bear Lake at average phosphorus concentrations ranging from 0.047 to 0.070 mg/L during July and August, respectively (Cadmus and AWRI, 2007; MDEQ, unpublished data).

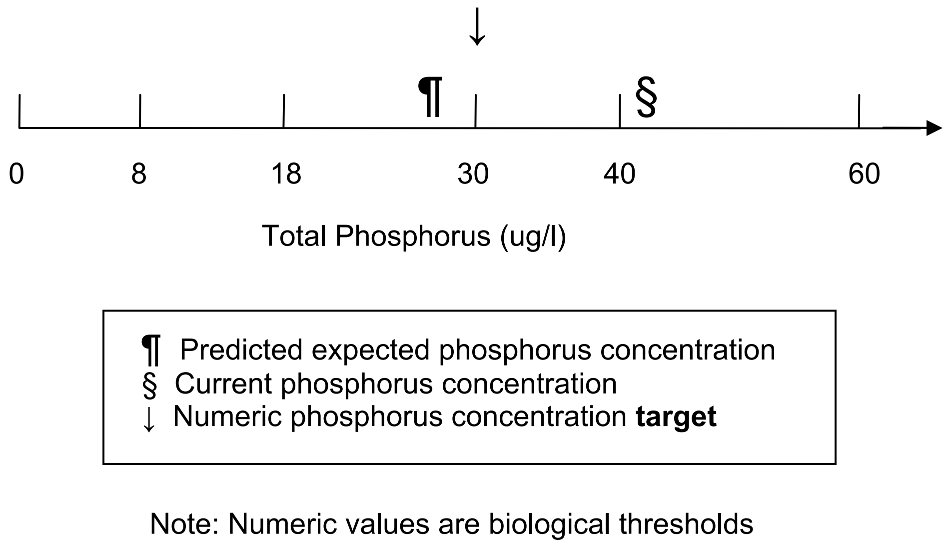

Figure 3. Determination of a phosphorus goal (arrow) for Bear Lake.

The final step in the BTPM approach is to compare the selected threshold with current lake phosphorus concentrations to select an appropriate target for the lake. Because the current concentrations are above the threshold, the threshold is the target. The MDEQ used the thresholds in Figure 3 to determine a target phosphorus level for Bear Lake. Current concentrations of phosphorus in Bear Lake, using the data from the 2006 and 2007 sampling events, average 0.042 mg/L on an annual basis. The growing season (April through September) average phosphorus concentration in the lake is 0.044 mg/L. The annual average and growing season phosphorus concentrations were calculated by averaging each concentration at all depths and sites to obtain a monthly average, then averaging the monthly values (Table 1). Since the existing phosphorus condition in Bear Lake as an annual average of 0.042 mg/L is greater than the threshold value of 0.03 mg/L, it was determined that existing phosphorus concentrations in the lake should be reduced to meet the numeric target level of 0.03 mg/L based on the BTPM approach. This value will ensure a restored biological integrity in Bear Lake.

This value is considered to be a level between a high-eutrophic (highly nutrient enriched) lake and a low-eutrophic (moderately nutrient enriched) lake (Wetzel, 1988). Therefore, this numeric target is appropriate for restoring a balanced algal community to Bear Lake. The target of 0.03 mg/L will apply as a monthly average during the growing season from April through September. Current phosphorus concentrations in October and November average 0.033 mg/L and will likely decrease to below the target value of 0.03 mg/L once phosphorus reductions have begun. Therefore, the critical time period for making phosphorus reductions in Bear Lake is during the growing season.

Allowable Loading Development

Empirical modeling was used to determine the allowable loading rate of phosphorus to Bear Lake given a target of 0.03 mg/L (Reckhow, 1978; Walker, 1977).

The following steps outline how the model was used to develop the relationship between annual phosphorus loading and in-lake phosphorus concentrations, and how the target loading rate of phosphorus to Bear Lake was developed:

Step 1: Choosing the Model

Numerous lake models exist that describe the relationship between phosphorus loads and phosphorus concentrations. The user must be aware of the advantages, disadvantages, and limitations of each when choosing a model. The MDEQ reviewed several lake models before choosing one to characterize the conditions in Bear Lake (Table 2).

The Walker model and Jones and Bachman model both predicted an in-lake phosphorus concentration of 0.041 mg/l for Bear Lake. The Walker model was chosen as the most appropriate model for predicting the phosphorus load necessary to meet the numeric target, since Bear Lake fits the model constraints and the model predicted a lake phosphorus concentration similar to current Bear Lake concentrations given an estimated loading (Walker, 1977). The Jones and Bachman model was not used since this model may have a tendancy to overestimate in-lake phosphorus concentrations in shallow lakes, and standard error and parameter statistics were not provided in order that error and uncertainty surrounding the model could be explicitly evaluated (Reckhow 1978).

The Walker model is based on an evaluation of 105 northern temperate lakes and has the following known constraints: the lake must be oxic (i.e., water column remains oxygenated), the average in-lake phosphorus concentration must be less than 0.9 mg/L, the average influent phosphorus concentration must be less than 1.0 mg/L, and the ratio of mean depth (meters) to hydraulic detention time (years) must be less than 50 meters/year (Walker, 1977). Bear Lake meets the constraints of the Walker model. The average in-lake concentration of phosphorus in Bear Lake is 0.042 mg/L, the average influent phosphorus concentration is 0.036 mg/L, the ratio of mean depth to hydraulic detention time is 17.25 meters/year, and the lake remains oxic throughout the year during the daytime period. It is unknown whether or not the lake goes anoxic during the nighttime period. Additional studies measuring diel oxygen profiles would be needed to verify if this is the case. A comparison of the loading rate using each model evaluated can be found in Appendix B. The hydraulic detention time of 0.12 years (44 days) for Bear Lake was calculated using the annual mean outlet flow for Bear Lake channel of 32 cubic feet per second (cfs) and a surface volume of 2,822 acre-feet. A comparison of hydraulic detention times using each mean monthly flow throughout the year, and the change of in-lake phosphorus concentrations with varying hydraulic detention time, was completed and can be found in Appendix B. The hydraulic detention time for Bear Lake ranges from 0.068 years (25 days) to 0.30 years (110 days).

The model predicted an in-lake phosphorus concentration of 0.041 mg/L using a current annual loading rate (including both internal and external sources) of 3,387 pounds per year (0.914 grams per square meter per year [g/m^2/yr]) (see *Source Assessment, Calculation of Phosphorus Loadings* for description of annual loading rate). This predicted concentration is very similar to the current average in-lake phosphorus concentration of 0.042 mg/L measured in 2006 and 2007 (Table 1). Therefore, the Walker model was determined to be a good predictive tool for calculating the load of phosphorus necessary to attain the target phosphorus concentration of 0.03 mg/L.

Step 2: Calculating Target Loading

The following equation represents the Walker model followed by site-specific variables of mean lake depth (meters) and hydraulic detention time (years):

$$P = \frac{P_a\,DT}{D_m}\left[\frac{1}{1 + .824DT^{.454}}\right]$$

Where:

P = target in-lake phosphorus concentration (mg/L) = 0.03 mg/L
P_a = annual phosphorus loading (g/m^2/year)
DT = hydraulic detention time (years) = 0.120 years
D_m = mean lake depth (meters) = 2.07 meters

Rearranging the model allows one to predict the annual phosphorus load at a given in-lake phosphorus concentration. The annual load is the mass critical to attaining WQS, since for many lakes, the long-term inputs of phosphorus, rather than short-term inputs, are what contribute to overall lake productivity. The following equation represents the Walker model followed by site-specific variables used to predict the target annual load at an in-lake numeric target concentration of 0.03 mg/L.

$$P_a = (D_m/DT)[1/(1 + .824 \times DT^{.454})](P)$$

Where:

P = in-lake phosphorus concentration (mg/L) = 0.03 mg/L
P_a = annual phosphorus loading (g/m^2/year)
DT = hydraulic detention time (years) = 0.120 years
D_m = mean lake depth (meters) = 2.07 meters

$$\begin{aligned} P_a &= (2.07/0.12)[1/(1 + .824 \times 0.12^{.454})](0.03) \\ &= (17.25)[1/(1 + (.824 \times 0.3819)](0.03) \\ &= (17.25)[0.7606](0.03) \\ &= 0.3936 \end{aligned}$$

The model predicts the goal of 0.03 mg/L can be obtained with a maximum annual phosphorus load of 0.3936 g/m^2/year. Converting this load to pounds per year equates to an annual target load of 1,458 pounds per year. This is the load that is necessary to attain an in-lake phosphorus concentration of 0.03 mg/L during the growing season (April through September) in Bear Lake and attain designated uses.

Table 2. Emperical models considered by the MDEQ (Table modified from New Jersey Department of Environmental Protection, 2004). Equation terms are defined on the previous page.

Reference	**Equation**	**Application**
Jones and Bachmann (1976)	$P = \dfrac{0.84P_a}{D_m\,(0.65 + 1/DT)}$	Database of 51 natural lakes in the north temperate region. Model may overestimate P in shallow lakes with high D_m/DT
Reckhow (1977)	$P = \dfrac{P_a}{\dfrac{18\,D_m}{10 + D_m} + 1.05\,D_m/DT\;e^{0.012\,Dm/DT}}$	Oxic lakes with D_m/DT < 50 m/yr; P<0.06 mg/L
Reckhow (1978)	$P = \dfrac{P_a}{11.6 + 1.2D_m/DT}$	General north temperate lakes, wide range of loading concentration, areal loading, and water load. Lakes are assumed to be completely mixed and P concentration is an average value.
Walker (1977)	$P = \dfrac{P_a\,DT}{D_m}\left[\dfrac{1}{1 + .824DT^{.454}}\right]$	Oxic lakes with D_m/DT<50 m/yr; P<0.9 mg/L
Vollenweider (1975)	$P = \dfrac{P_a}{D_m/DT}\left[\dfrac{1}{1 + \sqrt{\dfrac{D_m}{D_m/DT}}}\right]$	Overestimates P in lakes with high D_m/DT and under estimates P in highly enriched lakes.

SOURCE ASSESSMENT

The Bear Lake watershed drains approximately 29 square miles (19,058 acres), originates in Dalton Township, is entirely in Muskegon County, and is comprised of 16 sub-basins, including the Twin Lake area not shown in Figure 4. Bear Lake is a shallow 415 acre drowned river mouth lake that discharges to Muskegon Lake, and ultimately Lake Michigan. It has a mean depth of 6.8 feet (2.07 meters) and a maximum depth of 11.8 feet (3.6 meters) (Wilson et al., 2005). Bear Creek is the major tributary that flows directly into Bear Lake with a smaller tributary, Fenner Ditch, entering the lake from the north east end (Figure 2). Fenner Ditch is smaller in size and contributes less phosphorus than Bear Creek (Table 3). There are two additional smaller tributaries that directly discharge to Bear Lake, but these are typically dry year-round and are assumed to contribute little phosphorus load to the lake. Little Bear Creek discharges into Bear Creek upstream of Bear Lake. Discharge from the lake is through the Bear Lake outlet (Ruddiman Road) at the confluence with Muskegon Lake. Phosphorus loadings exported from Bear Lake through the outlet are difficult to quantify due to a "wedging" effect caused by wind-induced backflow from Muskegon Lake. A detailed description of the watershed can be found in the *Bear Creek and Bear Lake Water Management Plan* (Jarvis et al., 2004).

Land Use/Land Cover

The majority of soils in the watershed are sandy having high infiltration and low runoff potential. However, some riparian zones along Little Bear Creek and Bear Creek are classified as having clay soils with low infiltration rates and high runoff potential (Cadmus and AWRI, 2007). The largest land use category in the watershed is natural cover including forested lands, grass/pasture lands, and water/wetlands (Table 4). Urban areas including commercial, industrial, and residential land uses constitute the second largest land use, with agricultural land comprising the third highest land use category.

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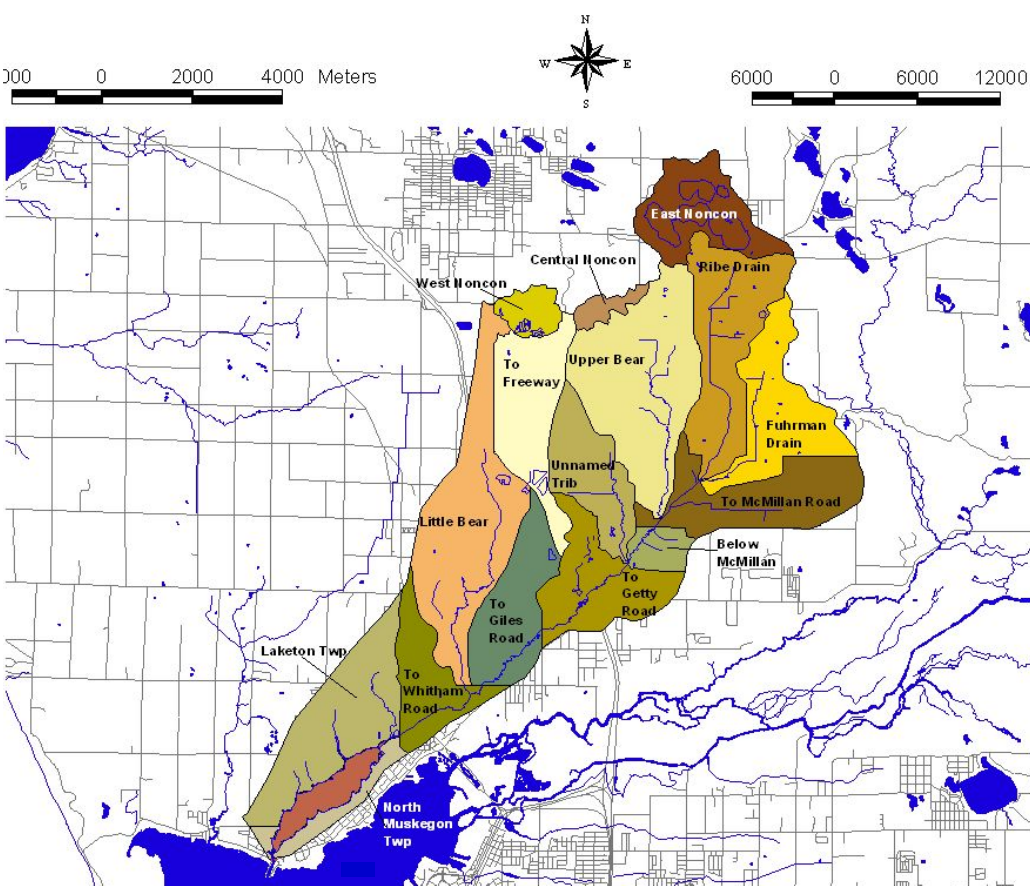

Figure 4. Bear Lake Watershed and Sub-basins (Cadmus and AWRI, 2007).

Table 3. Mean monthly flows for the major tributaries in the Bear Lake Watershed (MDEQ, 2007).

Mean Monthly Flow Estimations (cfs)				
Month	Little Bear Creek at Giles Road	Bear Creek at Witham Road	Fenner Ditch at Dykstra Road	Bear Lake Outlet
Jan	11	30	1.7	35
Feb	12	34	1.8	39
Mar	13	50	2.1	57
Apr	13	45	2	52
May	11	30	1.7	34
Jun	9.2	19	1.4	22
Jul	7.5	11	1.1	13
Aug	8	13	1.2	15
Sept	8.2	14	1.3	16
Oct	9.7	22	1.5	25
Nov	11	30	1.7	34
Dec	11	33	1.8	38
Average	**10**	**27**	**1.6**	**32**

Table 4. Bear Lake Watershed Land Use Categories as Percentages (Cadmus and AWRI, 2007).

Land Use Category	Percent Land Use Category	Acres
Natural Cover	**61.3**	**11,678**
Forest	40.0	7624
Grass/Pasture	15.7	2984
Water/Wetlands	5.6	1070
Urban	**32.9**	**6269**
Commercial	3.0	571
Industrial	5.3	1011
Residential	24.6	4686
Agriculture	**5.8**	**1111**
Total	**100.0**	**19,058**

All sources of phosphorus entering the lake were characterized on an annual scale (pounds of TP per year). Loadings were determined on the basis of internal and external loadings.

<u>External Loadings</u>

The external loading of TP to Bear Lake was estimated using the following sources of information:

- The calculated acreage of each major land use category based on the 1998 Michigan State University Land Use (i.e., the economic use of the land) and Land Cover (i.e., the vegetation, structures, or other features) data with ESRI TM ArcView GIS 3.3, and the National Agricultural Imagery Program's (NAIP's) 2005 digital orthophotograph (Cadmus and AWRI, 2007).

- The average annual runoff volumes and NPS losses of TP using the Long-Term Hydrologic Impact Analysis (L-THIA) model (Purdue University and USEPA, 2001).

- Hydrological and flow information developed by the MDEQ, Land and Water Management Division, Hydrological Studies Unit.

- Flow information and water chemistry data collected by AWRI and MDEQ in 2006 and 2007 (Cadmus and AWRI, 2007; MDEQ, unpublished data).

The Bear Lake watershed encompasses 19,058 acres. The area draining Bear Creek is 18,261 acres and contributes 87 percent of the phosphorus load to Bear Lake. The remaining 797 acres of the lake watershed area contributes 9 percent of the phosphorus load, and is comprised of the Fenner Ditch watershed draining 257 acres, and the area immediately surrounding the lake that drains 540 acres. The remaining 4 percent is contributed by septic tanks and precipitation.

The external loading determination was broken into the following categories:

a. Bear Creek (including Little Bear Creek)watershed (18,261 acres).
b. Fenner Ditch to Bear Lake watershed (257 acres).
c. Immediate drainage of Bear Lake watershed (e.g., total watershed minus Bear Creek and Fenner Ditch) (540 acres).
d. Septic tanks in immediate vicinity of Bear Lake.
e. Precipitation.

The external loads were developed assuming that 100 percent of the phosphorus entering the lake from Bear Creek, Little Bear Creek, Fenner Ditch, precipitation, septic tank drainage, and the immediate area of the lake would reach Bear Lake and be available for algal uptake. The majority of the external loading was estimated to originate from point sources covered under statewide and countywide National Pollutant Discharge Elimination System (NPDES) MS4 permits, and includes commercial, industrial, residential, and agricultural sources of phosphorus.

The MDEQ, Water Bureau, NPDES Management System (NMS) was used to identify permitted discharges in the Bear Lake watershed. There are three MS4 general NPDES permitted point sources (Muskegon County Drain Commission (CDC), Muskegon County Road Commission (CRC), City of North Muskegon), and one general noncontact cooling water NPDES point source (Bayer CropScience, USA) (Table 5). The Michigan Department of Transportation (MDOT) has a statewide MS4 permit covering storm water (MI0057364). Effluent discharge data for phosphorus was not available for calculating loading attributable to these point sources. Therefore, the phosphorus point source loading estimates by land use type were calculated using L-THIA to estimate the loss of phosphorus from commercial, industrial, residential, and agricultural areas covered under the MS4 permits (Tables 6a-6c).

L-THIA uses the event mean concentration and curve number procedures to calculate annual pollutant loads based on land use, soil type, and meteorological data.

Table 5. NPDES Permitted Point Source Discharges to the Bear Lake TMDL Watershed. (MDEQ 2008). *Exact outfall locations for MS4 permitted facilities are unknown.

Facility	**Permit No.**	**County**	**Receiving Water**	**Latitude**	**Longitude**
Individual Permit					
MDOT Statewide MS4	MI0057364	Statewide	-----	*	*
MIG250000 General Permit	**Non-Contact Cooling Water**				
Bayer CropScience USA	**MIG250370**	Muskegon	Little Bear Creek	43.288055	-86.248055
MIG610000 General Permit	**Watershed - Municipal Separate Storm Sewer System**				
Muskegon CDC MS4	MIG610151	Muskegon	Countywide	*	*
Muskegon CRC MS4	MIG610150	Muskegon	Countywide	*	*
MIS040000 General Permit	**Jurisdictional – Municipal Separate Storm Sewer System**				
City of North Muskegon	MIS040006	Muskegon	Bear Lake	*	*

Calculation of Phosphorus Loadings

Bear Creek and Fenner Ditch Watersheds, and Immediate Drainage Area of Bear Lake

The L-THIA model was used with estimates of land use type acreage to determine an estimated phosphorus load from the various land use types based on annual average runoff volumes from the Bear Creek (including Little Bear Creek and the Twin Lakes area) and Fenner Ditch watersheds, and the immediate drainage area of Bear Lake (Tables 6a, 6b, and 6c). The acreage of land use types was calculated using the 1998 Michigan State University Land Use/Cover data with ESRI TM ArcView GIS 3.3, and the NAIP's 2005 digital orthophotograph (Cadmus and AWRI, 2007). A percent load contribution for each land use type was calculated by dividing the L-THIA phosphorus load estimate per land use by the total load for all land use types estimated by using the model. For example, by dividing the L-THIA load estimate for commercial land use in the Bear Lake watershed (59 pounds) by the total load estimated by L-THIA for all land use types (1,338 pounds) the commercial land use type was estimated to contribute 4.4 percent of the phosphorus load to Bear Lake from the Bear Creek watershed (Table 6a).

Table 6a. L-THIA estimates of phosphorus loads and percent load contribution from the various land use types in the Bear Creek watershed.

Land Use Category	Acres	L-THIA Load Estimates (lbs/yr)	L-THIA Load Estimates (lbs/acre)	Percent Load Contribution
Commercial	105.3	59	0.56	4.4%
Industrial	13.3	3	0.23	0.2%
Residential	2,387.6	625	0.26	46.7%
Agricultural	756.4	621	0.82	46.4%
Forest	10,111.4	17.24	0.0017	1.32%
Grass/Pasture	4,329	13.15	0.003	0.98%
Water/Wetlands	557.6	0	0	0%
Total	**18,261**	1338		100%

Table 6b. L-THIA estimates of phosphorus loads and percent load contribution from the various land use types in the Fenner Ditch watershed.

Land Use Category	Acres	L-THIA Load Estimates (lbs/yr)	L-THIA Load Estimates (lbs/acre)	Percent Load Contribution
Commercial	0	0	0.56	0%
Industrial	0	0	0.23	0%
Residential	183.3	45	0.26	99.8%
Agricultural	0	0	0.82	0%
Forest	50.3	0.074	0.0017	0.0016%
Grass/Pasture	16.7	0.044	0.003	0.001%
Water/Wetlands	7	0	0	0%
Total	**257**	45.1		100%

Table 6c. L-THIA estimates of phosphorus loads and percent load contribution from the various land use types in the immediate drainage area of Bear Lake watershed.

Land Use Category	Acres(1)	L-THIA Load Estimates (lbs/yr)	L-THIA Load Estimates (lbs/acre)	Percent Load Contribution
Commercial	143	67	0.47	64%
Industrial	143	27	0.19	26.4%
Residential	143	10	0.07	9.5%
Agricultural	0	0	0	0%
Forest	89	0.006	0.0001	0.0001%
Grass/Pasture	20	0.004	0.0002	0.00003%
Water/Wetlands	0	0	0	0%
Total	**540**	104		100%

(1) Acreage is estimated using L-THIA and the difference between Bear Creek and the unnamed tributary watershed acreage estimates.

Actual phosphorus loads from the Bear Creek (included Little Bear Creek) and Fenner Ditch watersheds (versus the estimated loads determined by L-THIA) were calculated using mean monthly flows, measured flows, and phosphorus concentrations when available (Appendix A). The sum of the monthly loads of phosphorus into Bear Lake from these two tributaries was estimated to be 1,627 pounds per year (Table 7).

Table 7. Phosphorus loading data for Bear Creek at Witham Road, and Fenner Ditch at Dykstra Road, Muskegon County, Michigan, 2007.

Tributary	Average P Load (pounds/day)	Annual P Load (pounds/year)	Average P Conc. (mg/L)
Bear Creek *	4.19	1,529	0.036
Fenner Ditch	0.27	98	0.031
Total		1,627	

* The Bear Creek phosphorus loading data included contributions from Little Bear Creek.

The load contribution of phosphorus specific to each land use type was determined by multiplying the percent contribution of each land use by the total external phosphorus load entering the lake from Bear Creek (including Little Bear Creek) and Fenner Ditch (Table 8). For example, the commercial land use type in the Bear Creek watershed contributes 4.4 percent of the load to the lake. Multiplying 4.4 percent by the external load of 1,529 pounds/year entering from Bear Creek results in a phosphorus load contribution by commercial land use type of 67 pounds per year.

It was assumed that 100 percent of the Fenner Ditch watershed is comprised of residential land use, since L-THIA estimated that 99.8 percent of the phosphorus load in this watershed was contributed by the residential land use type (Table 6b). Less than 0.01 pounds of phosphorus per year is contributed by other land use types in this watershed (e.g., water, grass/pasture, and forest). Therefore, the 98 pounds of phosphorus load entering Bear Lake from Fenner Ditch is assumed to be from residential areas, and was assumed to be covered under the MS4 permits.

The export of phosphorus from the immediate drainage area (540 acres) surrounding Bear Lake was estimated by determining the acres of forest (89 acres) and grass/pasture (20 acres) in the area using estimates from L-THIA, and then allocating the remaining acreage equally between commercial, industrial, and residential land use types, since these estimates were difficult to determine using the same L-THIA modeling approach (Table 6c). The immediate drainage area surrounding Bear Lake was estimated to contribute 104 pounds of phosphorus per year from the various land use types in this area (Table 8).

The percent difference in load when using the L-THIA versus measured flow and phosphorus concentrations to calculate the load estimates was used to develop a Margin of Safety (MOS) to account for the uncertainty in developing the external loads of phosphorus to Bear Lake. More discussion on this topic can be found in the MOS section.

Septic Tanks in Immediate Vicinity of Bear Lake and Precipitation

Additional sources of phosphorus to the lake include the contribution from direct inputs from septic systems and precipitation (Table 8). For the septic tank load estimates, all septic systems were assumed to be properly functioning with a load of 0.25 pounds/capita/year, 2 capita/households, and 87 households with septic systems within 300 feet of the lake shoreline (USEPA, 1974; Westshore Consulting, 2004; Google Earth (http://earth.google.com/)). The direct inputs from septic systems are difficult to quantify, but were estimated to contribute 44 pounds per year of phosphorus to the lake on an annual basis. The direct inputs from precipitation are difficult to quantify, but were estimated to contribute 64 pounds of phosphorus directly to the lake on an annual basis. The TP load from precipitation falling directly to the surface of the 415-acre lake was estimated using a loading rate of 0.156 pounds/acre/year (USEPA, 1974).

Table 8. External loads to Bear Lake from the watershed.

Land Use Types	Annual P Load (pounds/year)	Percent Load Contribution	P Load Based on Percent Contribution
Bear Creek	1,529 *		
Commercial		4.4	67
Industrial		0.2	3
Residential		46.7	714
Agriculture		46.4	710
Forest		1.32	20
Grass/Pasture		0.98	15
Water/Wetlands		0	0
Fenner Ditch	98 *		
Residential		100	98
Septic	44		
Precipitation	64		
Immediate Drainage	104 +		
Commercial		64	67
Industrial		26	27
Residential		9.6	10
Forest		0.0001	0.006
Grass Pasture		0.00003	0.004
Total	1,839		

* Actual measured loads
\+ Estimated loads by subtraction

<u>Internal Loadings</u>

The following three approaches were used to estimate the internal loading potential of phosphorus from the sediments in Bear Lake (Cadmus and AWRI, 2007): (1) a comparison of Bear Lake sediment phosphorus concentrations with three other west Michigan drowned river mouth lakes; (2) a determination of the iron (Fe) to TP ratio in surface sediments of Bear Lake; and (3) the application of Nurnberg's regression for dry sediments using Bear Lake sediment TP concentrations. More accurate estimates of internal loading could be obtained by conducting internal loading analysis on sediment cores incubated under both aerobic and anaerobic conditions, and comparing these results to estimated rates using Nurnberg's Regression equation.

Comparison of Lake Sediments

Sediment phosphorus concentrations in Bear Lake are similar to concentrations found in other west Michigan drowned river mouth lakes (e.g., White Lake, Mona Lake, and Spring Lake) (Cadmus and AWRI, 2007). Sediment phosphorus concentrations in Bear Lake range from 59 to 1172 milligrams per kilogram (mg/kg) (dry weight) with a mean concentration of 903 mg/kg (dry weight).

Fe:TP Sediment Ratios

The release of soluable reactive phosphorus from aerobic sediments, like those found in Bear Lake, is low in lakes with Fe:TP ratios greater than 15 (Jensen, 1992). The Fe:TP ratios in Bear Lake from sediments collected at 15 sites ranged from 16.9 to 53.2. The relatively high ratios found in Bear Lake suggest that there is sufficient Fe in Bear Lake sediments to deter the release of phosphorus from the sediments. Results of the analysis did suggest that sites in the eastern part of the lake may be more vulnerable than other areas within the lake to internal loading if phosphorus from external sources continues to enter Bear Lake (Cadmus and AWRI, 2007).

Nurnberg's Regression Equation

The estimated phosphorus release rates from Bear Lake sediments were based on a regression equation that uses sediment phosphorus concentrations (Nurnberg, 1988). A release rate of 0.0034 g/m^2/day was estimated for Bear Lake using the equation.

Based on an evaluation of the three approaches, the internal loads were developed using Nurnberg's Regression Equation. It was assumed that internal loading occurred from May through August at the rate of 0.0034 g/m^2/day, since this 123-day time period would likely have the greatest potential for sediment phosphorus release due to increased use of Bear Lake (i.e., increased motor traffic). The Bear Lake sediment/water interface appears to remain oxic throughout the summer based on limited sampling conducted during daylight hours. To accurately confirm this observation, a diel dissolved oxygen study of Bear Lake would need to be completed. The sediments are susceptible to resuspension to the overlying water column due to shallow lake depths and high use of Bear Lake for recreational activities. Wind-induced mixing may also play a role in sediment resuspension of phosphorus to the water column. The estimated export of phosphorus from the sediments at a release rate of 0.0034 g/m^2/day, totaled 1,548 pounds per year (0.4182 g/m^2/yr) over the 123-day period.

<u>External and Internal Loading Summary</u>

The current annual TP load to the lake is estimated to be 3,387 pounds per year (0.914 g/m^2/year). This includes an external load of 1,839 pounds per year (0.496 g/m^2/year), from point and NPS, and an internal load of 1,548 pounds per year (0.4182 g/m^2/year) estimated from sediment release rates for the period May through August (Cadmus and AWRI, 2007). The internal loading of phosphorus accounts for approximately 46 percent of the current total annual load to Bear Lake.

LINKAGE ANALYSIS

Bear Lake has been documented as having heavy cyanobacteria blooms during the summer, which has resulted in nonattainment of the narrative nutrient standard. The blooms can be attributed to several factors related to the physical and chemical characteristics of Bear Lake. Bear Lake has a short hydraulic detention time (0.12 years) and is relatively shallow (2.07 meters). Emperical models, such as the Walker model, which was used to develop the numeric phosphorus target loads for Bear Lake, allow determination of in-lake phosphorus concentrations in relation to hydraulic detention time (years) and depth (meters).

Bear Lake does not stratify during the summer and appears to be well mixed throughout the year (polymictic) due to shallow depths and having a greater potential for wind mixing. The mixing of sediments with the lake water releases phosphorus that can be used by algae for growth. Phosphorus is necessary for primary productivity, but can also become injurious at concentrations that exceed a lake's assimilative capacity. These exceedances of a lake's capacity to assimilate excess phosphorus can result in a change of phytoplanktonic assemblage within the lake to a community dominated by cyanobacteria. The presence of heavy cyanobacteria blooms throughout the summer months has been well documented in Bear Lake (Cadmus and AWRI, 2007). The heavy blooms are a result of external and internal phosphorus loadings that cause an increase in chlorophyll *a* levels, a decrease in sechhi depth measurements, and lowered water clarity (Table 1). The dominant cyanobacteria in Bear Lake is *Microcystis aeruginosa*. Moderate levels of release of TP from the sediments of Bear Lake and the shallow depths are ideal conditions for the stimulation of summer *Microcystis aeruginosa* blooms. Published literature has reported that the dominance of cyanobacteria in a lake tend to increase at phosphorus concentrations greater than 0.03 mg/L (Downing et al., 2001). Chlorophyll *a* concentrations are typically greater than 0.010 mg/L at phosphorus concentrations above 0.03 mg/L. These levels often lead to a reduction in water transparency to less than one meter (Canfield and Bachmann, 1981). This appears to hold true for Bear Lake. The average concentrations of phosphorus and chlorophyll *a* in the lake are 0.044 mg/L and 0.022 mg/L, respectively, during the growing season (April through September), and the average sechhi depth is 0.8 meters.

A phytoplankton community dominated by cyanobacteria species changes the lake's trophic structure as well as its ecological integrity. Ecological responses to blooms of cyanobacteria include reduced transparency of the water column that can limit light penetration needed for a balanced plant community, altered competitive interactions among phytoplankton, effects of toxin production on aquatic and terrestrial wildlife, and possible fish kills due to reduced dissolved oxygen levels after subsequent bloom collapse (Havens, 2006).

The molar ratio of total nitrogen (TN):TP can be used to estimate the potential of nutrients to limit productivity during the summer period. Epilimnetic TN:TP ratios greater than 37:1 are suggestive of lake systems that have phytoplankton communities limited by phosphorus. The TN:TP ratios in Bear Lake in the summer were determined to be 50:1, implying that the phytoplankton community is likely limited by phosphorus during the summer (Cadmus and AWRI, 2007).

Other relationships, such as Carlson's Trophic Status Index has been used to describe the relationship between chlorophyll *a*, secchi depth, and varying levels of TP to characterize algal biomass (Carlson, 1977). The summer median Trophic Status Index values for chlorophyll *a*, secchi depth, and TP in Bear Lake were reported to be 65, 59, and 64, respectively (Cadmus and AWRI, 2007). The above index values for Bear Lake indicate that the system is hypereutrophic and dominated by cyanobacteria, which has been well documented during the summer months.

LOADING CAPACITY (LC) DEVELOPMENT

Concurrent with the selection of numeric targets, development of the LC requires identification of the critical conditions. The "critical condition" is the set of environmental conditions (e.g., flow) used in developing the TMDL that result in attaining WQS and has acceptable low frequency of occurrence. The target goal of 0.03 mg/L phosphorus in this TMDL is a seasonal average and will apply during the months of April through September. The higher water temperatures and increased light intensity during the growing season typically result in nuisance algal growth if concentrations of phosphorus exceed the target goal. The cooler water temperatures and reduced light intensity in the non-growing season months tend to limit the frequency and intensity of nuisance conditions. Therefore, if the 0.03 mg/L target goal for Bear Lake is met during the growing season (April through September), WQS are expected to be attained during the remainder of the year.

LOADING CAPACITY

The LC is the sum of individual waste load allocations (WLAs) for point sources and load allocations (LAs) for NPS and natural background levels. In addition, the LC must include a MOS, either implicitly within the WLA or LA, or explicitly, that accounts for uncertainty in the relation between pollutant loads and the quality of the receiving water body. Conceptually, this definition is denoted by the equation:

$$LC = \Sigma WLAs + \Sigma LAs + MOS$$

The LC represents the maximum loading that can be assimilated by the receiving water while still achieving WQS. The overall LC is subsequently allocated into WLAs for point sources, LAs for NPS, and the MOS. As described in the Numeric Target Section, the LC for this TMDL is 1,458 pounds per year, a 1,929 pound per year reduction from the current (3,387 pounds per year) loading.

WLAs

Queries of the MDEQ, NMS database, yielded three MS4 countywide general NPDES permitted point sources, one individual groundwater state issued permitted point source, one general noncontact cooling water NPDES point source, and one MDOT statewide MS4 permit. There are no individual industrial storm water permits or construction site Notice of Coverage permits in the Bear Lake watershed. In addition, there are no Concentrated Animal Feeding Operation permits.

Runoff from residential, commercial, industrial, and agricultural areas are covered under the general CDC, CRC, and city of North Muskegon MS4 permits, and statewide MDOT MS4 permit. The MDOT owns and operates approximately 413 acres or 2 percent of the Right-of-Way in the Bear Creek watershed. Phosphorus load from this source will be assumed to be two percent (0.5 pounds) of the 30 pounds of phosphorus from the industrial land use type in the Bear Lake watershed, since transportation is considered under this land use type when estimating phosphorus load using L-THIA. In accordance with USEPA guidelines regarding NPDES land use runoff, phosphorus from these sources have been considered in the WLA portion of this TMDL. Based on estimates from the L-THIA modeling, development of loadings from measured and estimated flows, measured phosphorus concentrations, and percent phosphorus contribution of land use types, a current annual total load estimate of approximately 1,701 pounds per year is attributable to these sources.

To achieve the TP goal of 0.03 mg/L in Bear Lake as a seasonal average (April through September), a reduction of 848 pounds per year of phosphorus from all WLA sources is necessary (Table 9). This includes storm water associated with residential, commercial, industrial, and agricultural land use areas covered under the countywide CRC, CDC, and city of North Muskegon general MS4 permits. The Muskegon CRC has no jurisdiction of roads or storm water discharges within the city of North Muskegon. The reductions of phosphorus in pounds per day are listed in Table 9 for each WLA source.

LAs

The LA component of the TMDL defines the fraction of the LC for TP from NPS including the following: forested, grass/pasture, water/wetlands, precipitation, septic drainage, and internal loading. An estimated annual load of 99 pounds per year is attributed to runoff from forested, grass/pasture, water/wetlands, and precipitation. No reductions from the forest, grass/pasture and water/wetland land uses and precipitation are proposed because the expected concentrations of TP are less than the 0.03 mg/L numeric phosphorus target for the lake. An estimated 44 pounds per year of phosphorus is attributed to septic tank drainage. The reduction of phosphorus necessary from LA sources is listed in Table 9. Any future growth in the Bear Lake watershed that affects nonpoint sources of phosphorus will need to take the TMDL load allocation into consideration.

Internal Loading

The internal loading of phosphorus is considered to be a NPS and will be considered under the LA. It is assumed that the rate of phosphorus released from the sediments will be reduced once reductions of the external point and NPS are completed. However, since this rate is not easily quantified, and at this point in time, is unknown, a load of 322 pounds per year is allocated to this source. This value is the remainder of the load after the LA is allocated to background sources, the WLA is allocated to point sources, and MOS loads are allocated. A reduction of 1,226 pounds per year (6.8 pounds per day) from sediment phosphorus release is needed to meet the target goal of 0.03 mg/L. It is assumed that this reduction in sediment release will occur over time once external sources of phosphorus are reduced to meet the LC. The MDEQ acknowledges that it will be some time before phosphorus in the sediments of Bear Lake is depleted. However, any reductions in phosphorus to Bear Lake that can be made will be beneficial in restoring the designated uses to the lake.

MOS

The MOS in a TMDL is used, in part, to account for variability in source inputs to the system, or lack of knowledge concerning the relationship between pollutant loading and water quality. The MOS can be either implicit (i.e., incorporated into the TMDL analysis through conservative assumptions) or explicit (i.e., expressed in the TMDL as a portion of the loadings). In this TMDL an explicit MOS was used in developing the target loads for attaining WQS. An explicit MOS of ten percent was included to account for the uncertainty in developing the external loads of phosphorus to Bear Lake. This was the percent difference in load when using L-THIA versus measured flow and phosphorus concentrations to calculate the load estimates. The MOS was calculated as follows:

MOS = 0.10 x (1,458 pounds per year) = 145 pounds per year

Table 9. TMDL phosphorus allocations on an annual basis for Bear Lake, Muskegon, Michigan.

Source	Current Load	Loading Capacity			
			Reduction		
	lbs P/yr	lbs P/yr	lbs P/yr	%	Lbs P/d(6)
Total	3387	1458		56	
WLA(1)					
Commercial(2)	134	67	67	50	0.4
Industrial(3)	29.5	14.5	15	50	0.08
MDOT Statewide MS4	0.5	0.5	0	0	0
Bayer CropScience, USA	0	0	0	0	0
Agricultural(4)	710	355	355	50	1.9
Residential(5)	822	411	411	50	2.2
Subtotal	1696	848	848		
LA					
Forest	20	20	0	0	0
Grass/Pasture	15	15	0	0	0
Water/Wetlands	0	0	0	0	0
Precipitation	64	64	0	0	0
Septic Tank Drainage	44	44	0	0	0
Internal Loading	1548	322	1226	79	6.8
Subtotal	1691	465			
Margin of Safety	n/a	145			

(1) The WLA portion includes target loads contributed under the MDOT MS4 and Muskegon CDC, CRC, and city of North Muskegon MS4 permits. The Bayer CropScience, USA is assumed to contribute no phosphorus to surface waters and no reductions in phosphorus loading are proposed.
(2) Includes storm water associated with commercial land use in the Bear Creek and immediate drainage area of the Bear Lake watershed.
(3) Includes storm water associated with industrial land use in the Bear Creek and immediate drainage area of the Bear Lake watershed.
(4) Includes storm water associated with agricultural land use in the Bear Creek and immediate drainage area of the Bear Lake watershed.
(5) Includes storm water associated with residential land use in the Bear Creek and unnamed tributary watersheds, and immediate drainage area of the Bear Lake watershed.
(6) The daily phosphorus loads were computed by dividing the pounds per year for each source by the number of days (180) in which the target for Bear Lake is applied (April through September).

SEASONALITY

The development of current phosphorus loads to Bear Lake was determined using base flow conditions for the water bodies discharging to Bear Lake, and associated TP concentrations, internal phosphorus loading from the sediments, and storm event data collected in 2006 and 2007. Flow and phosphorus data from four separate storm events (0.5 to 1.0 inch range) were collected in order to determine if storm events played a role in the amount of loadings being exported to the lake from the surrounding watershed. It was determined that Bear Creek contributed approximately 90 percent of the storm load to the lake while Little Bear Creek contributed approximately 10 percent (Cadmus and AWRI, 2007). Loadings of phosphorus during the four rain events exceeded phosphorus loadings during base flow measurements by an order of magnitude. The numeric target concentration for phosphorus of 0.03 mg/L accounts for critical conditions such as storm event loadings and should be met as a growing season (April through September) average concentration.

MONITORING

This TMDL's approach requires that future monitoring be conducted to assess whether activities implemented under the TMDL will result in water quality improvements. This monitoring will be conducted as resources allow. At a minimum, Bear Lake should be sampled monthly from April through September every other year to assess whether or not the target of 0.03 mg/L TP is being attained once measures to reduce phosphorus loadings have been implemented.

REASONABLE ASSURANCE ACTIVITIES

The CDC and CRC MS4 permits identified in Table 5 require that a watershed management plan be developed and that the plan identify actions specific to storm water controls to achieve the goals of the TMDL. A "Bear Creek Watershed Hydrologic Study" was completed in 2002 and reported that there were significant increases in runoff volume from peak flow rates during 24-hour storm events (MDEQ, 2003). Effective storm water management controls will help to mitigate the erosional effects and increased nutrient loading caused by increased flows.

A Watershed Management Planning Grant for the Bear Creek and Bear Lake Watershed was given by the USEPA and the MDEQ in 2002 and was used to develop a Bear Creek and Bear Lake Watershed Management Plan (Jarvis et al., 2004). The plan was published in 2004 and outlines the future need for effective land use planning that will aid in improving and maintaining water quality in the Bear Lake watershed, and reducing nutrient pollutant loads contributed from various sources.

A county-wide ordinance to ban phosphorus in fertilizer went into effect in December 2006. The ordinance will help to reduce the amount of excess phosphorus entering Bear Lake and the upstream watershed that is contributed by fertilizers containing phosphorus, that become part of storm water generated by runoff from land, pavements, building rooftops, and other surfaces. Since storm water runoff accumulates pollutants such as oil and grease, chemicals, nutrients, metals, and bacteria as it travels across land, managing stormwater runoff in an urban environment is crucial to protecting surface water resources (USEPA, 2008).

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Appendix A

Base Flow Measurements, Bear Creek at Witham Road, Muskegon, Michigan												
Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
cfs[4]	30	34	50	45	19.03[3]	19	11	12.57[3]	14	22	19.21[3]	33
mgd	19.38	21.96	32.3	29.07	12.29	12.27	7.11	8.12	9.04	14.21	12.41	21.32
TP	0.026[1]	0.026[1]	0.026[1]	0.027[2]	0.025[2]	0.033[2]	0.053[2]	0.024[2]	0.031[2]	0.055[2]	0.018[2]	0.026[1]
			0.026[3]					0.026[2]			0.026[3]	
											0.020[3]	
Avg TP	0.026	0.026	0.026	0.027	0.025	0.033	0.053	0.025	0.031	0.055	0.021	0.026
Lbs/day	4.2	4.76	7.0	6.5	2.6	3.4	3.1	1.7	2.3	6.5	2.17	4.6
No./days	31	28	31	30	29	29	31	28	30	31	30	31
Lbs/month	130.3	133.3	217.1	196.4	75.4	98.6	97.4	47.6	69	201.5	65.1	142.6
Storm Event Measurements, Bear Creek at Witham Road, Muskegon, Michigan[5]												
					23.2	6.2		1.8				
					2.7			17.5				
								3.0				
Total Lbs/month	130.3	133.3	217.1	196.4	101.3	104.8	97.4	69.9	69	201.5	65.1	142.6
Σ	1,529											

Base Flow Measurements, Unnamed Tributary at Dykstra Road, Muskegon, Michigan												
Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
cfs[4]	1.7	1.8	2.1	2	1.7	1.4	1.1	1.2	1.3	1.5	1.7	1.8
mgd	1.1	1.16	1.36	1.3	1.1	0.9	0.71	0.78	0.84	0.97	1.1	1.8
TP[6]	0.031	0.031	0.031	0.031	0.031	0.031	0.031	0.031	0.031	0.031	0.031	0.031
Lbs/day	0.28	0.30	0.35	0.34	0.28	0.23	0.18	0.20	0.22	0.25	0.28	0.31
No./days	31	28	31	30	29	29	31	28	30	31	30	31
Lbs/month	8.82	8.40	10.9	10.08	8.82	6.98	5.69	6.25	6.52	7.77	8.53	9.62
Σ	98.38											

(1) Estimated from November 2006 samples.
(2) MDEQ data collected in 2006 (measured).
(3) Cadmus data collected in 2006; 2007 (measured).
(4) Calculated mean monthly flows (Land and Water Management Division, MDEQ).
(5) Loads calculated from storm event measurements.[3] These were added to the base flow measurements depending on the storm duration to obtain a total monthly phosphorus load.
(6) Average concentration of four samples.[3]

Base Flow Measurements, Little Bear Creek at Giles Road, Muskegon, Michigan												
Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
cfs[3]	11	12	13	13	11	9.2	7.5	8	8.2	9.7	10	11
mgd	7.11	7.75	8.40	8.40	7.11	5.94	4.84	5.17	5.30	6.27	6.46	7.11
TP[2]	0.018[1]	0.018[1]	0.016	0.016	0.030	0.029	0.030	0.025	0.032	0.033	0.018	0.018[1]
Lbs/day	1.067	1.16	1.12	1.12	1.78	1.44	1.21	1.08	1.41	1.73	0.97	1.07
No./days	31	28	31	30	29	29	31	28	30	31	30	31
Lbs/month	33.08	32.48	34.72	33.6	51.62	41.76	37.51	30.24	42.3	53.63	29.1	33.17
Σ	453.21											

[1] Estimated from November 2006 samples.
[2] MDEQ data collected in 2006 (measured).
[3] Calculated mean monthly flows (Land and Water Management Division, MDEQ).

Appendix B

Lake Model Calculations:

(1) Reckhow (1978)

$$P = \frac{Pa}{(11.6 + 1.2\,(D_m/DT))} = \frac{0.914\ g/m2/yr}{(11.6 + 1.2\,(17.25))} = \frac{0.914}{32.3} = 0.028\ mg/l$$

(2) Walker Model (1977)

$$P = \frac{P_a \times DT/D_m}{1 + 0.824 \times DT^{0.454}} = \frac{.914 \times (.120)/2.07}{1 + 0.824 \times .120^{0.454}} = \frac{0.053}{1.31} = 0.041\ mg/l$$

(3) Jones and Bachmann (1976)

$$P = \frac{0.84 \times Pa}{D_m \times (0.65 + DT^{-1}))} = \frac{0.84 \times 0.914}{(2.07 \times (0.65 + 0.12^{-1}))} = \frac{0.768}{18.59} = 0.041\ mg/l$$

(4) Vollenweider (1975)

$$P = \frac{Pa}{D_m/DT}\left[\frac{1}{1 + \sqrt{\frac{D_m}{D_m/DT}}}\right] = \frac{0.914}{2.07/.12}\left[\frac{1}{1 + \sqrt{\frac{2.07}{2.07/.12}}}\right] = 0.053\ (0.7427) = 0.039\ mg/l$$

(5) Reckhow Oxic Model (1977)

$$P = \frac{Pa}{\frac{18D_m}{10+Dm} + 1.05\,(D_m/DT)\,e^{0.012(Dm/DT)}} = \frac{0.914}{\frac{(18)(2.07)}{10 + 2.07} + 1.05\,(17.25)\,(1.23)} = \frac{0.914}{25.37} = 0.036\ mg/l$$

Where: Pa = 0.914 (current annual P load to Bear Lake)
Dm = Average lake depth (m) = 2.07 m
DT = Detention time (yr) = 0.12 yr

Hydraulic Detention Times

Month	Outflow (cubic ft/second)	Volume/yr (acre-ft/yr)	Hydraulic Detention Time (years)	Hydraulic Detention Time (days)
January	35	25,339	0.111	40.15
February	39	28,235	0.10	36.5
March	57	41,266	0.068	24.8
April	52	37,646	0.075	27.4
May	34	24,615	0.115	42.0
June	22	15,927	0.177	64.6
July	13	9412	0.30	109.5
August	15	10,860	0.26	95
September	16	11,583	0.244	89.1
October	25	18,099	0.156	56.9
November	34	24,615	0.115	42.0
December	38	27,511	0.103	37.6
Average	32	23,167	0.121	44.2

Model Phosphorus Loadings with Varying Hydraulic Detention Time

Month	Hydraulic Detention Time (yrs)	Phosphorus Concentration (ug/l)				
		Reckhow (1978)	Walker (1977)	Jones and Bachman (1976)	Vollenweider (1975)	Reckhow Oxic (1977)
January	0.111	27	37	29	49	33
February	0.10	3425	34	35	46	31
March	0.068	19	24	24	30	19
April	0.075	20	27	27	33	21
May	0.115	28	40	40	51	34
June	0.177	36	57	60	78	53
July	0.30	46	90	93	132	83
August	0.26	43	78	82	118	74
September	0.244	42	77	78	111	71
October	0.156	33	50	53	69	47
November	0.115	28	39	40	51	34
December	0.103	26	35	36	45	31
Average	0.121	28	40	40	39	36