NE Lakeshore TMDL: Lake Model Setup and Results

December 14, 2021 DRAFT

Prepared by Wisconsin Department of Natural Resources, Bureau of Water Quality

Introduction

This report summarizes the modeling setup and results for 26 lakes in Fond Du Lac, Kewaunee, Manitowoc, and Sheboygan Counties. These lakes are part of the larger North East Lakeshore Total Maximum Daily Load for total phosphorus (TP) and total suspended solids (TSS). These lakes are either on Wisconsin's Impaired Waters List for eutrophication-related impairments, are considered potentially impaired based on available data, or were lakes over 100 acres with public access. These lakes were selected to be evaluated for phosphorus Total Maximum Daily Loads (TMDL) development to address issues of nutrient enrichment.

The 26 lakes are composed of three two-story fishery lakes with an applicable TP criterion of 15 μg/L, 13 deep seepage lakes with a TP criterion of 20 μg/L, nine deep drainage lakes with a TP criterion of 30 μg/L, and one shallow lake with a TP criterion of 40 μg/L. Monitoring data indicates that not all the lakes are exceeding their applicable TP criterion; however, all show the potential for eutrophication related impairments such has habitat impairments and low dissolved oxygen.

Model Setup and Development

Steady-state modeling was conducted in MS Excel using several empirical lake phosphorus response models presented in the documentation for Wisconsin Lake Modeling Suite (WiLMS), Version 3.318.1, WDNR 2001.

WiLMS is a lake water quality modeling tool developed by the Wisconsin Department of Natural Resources (WDNR). Key conceptual features and assumptions of WiLMS are described in the WiLMS user manual (WDNR 2003) and summarized below:

- Lake TP concentrations are be predicted using one of several empirical equations. The empirical equations were derived from statistical analysis of field data from multiple lakes across the United States.
- A lake is represented as a zero-dimensional, completely mixed body of water with no horizontal or vertical variability in water quality.
- Water and nutrient loads are applied on an annual time step. Lake TP concentrations predicted by the selected models are growing season averages.

Early versions of WiLMS were released as a Microsoft Excel workbook pre-programmed with the models for predicting lake water quality. WiLMS has since been released as standalone software program with a graphical user interface for entering inputs and viewing outputs. Because the current effort involved setting up many models, the graphical interface was not used but rather an Excel version was used. The empirical formulas in the Excel version were updated to ensure that outputs were consistent with the most recent version of WiLMS available at the time of this report (version 3.3).

The models (empirical equations) evaluated for each lake include:

- Canfield-Bachmann 1981 Natural Lakes
- Canfield-Bachmann 1981 Artificial Lakes
- Walker 1987 Reservoirs
- Reckow 1979 Natural Lakes
- Reckow 1977 Anoxic Lakes
- Reckow 1977 Oxic Lakes (qs < 50 m/yr.)

Lake Morphology and Nutrient Criteria

Lake surface area and volume were based on values reported in DNR's Register of Waterbodies (ROW). ROW is the official WDNR surface water inventory database. It contains waterbody name, waterbody ID code (WBIC) and various physical characteristic data including area and volume. In a limited number of cases, lake volumes were not available in ROW and were estimated from lake maps using Geographic Information System (GIS) software.

Table 1: Lake morphology information.

Lake	County	WBIC	Surface Area (acres)	Mean Depth (ft)
Becker Lake	Calumet	77300	35	14.6
Big Gerber Lake	Sheboygan	56600	15	NA
Boot Lake	Calumet	77600	11	7.8
Bullhead Lake	Manitowoc	68300	70	12.5
Carstens Lake	Manitowoc	66800	22	11.3
Cedar Lake	Manitowoc	45100	137	9.5
Crystal Lake	Sheboygan	45200	129	23.0
Elkhart Lake	Sheboygan	59300	292	44.8
English Lake	Manitowoc	68100	48	32.0
Gass Lake	Manitowoc	67100	6	12.3
Harpt Lake	Manitowoc	84600	32	19.5
Hartlaub Lake	Manitowoc	67200	37	18.5
Horseshoe Lake	Manitowoc	64200	21	26.2
Jetzers Lake	Sheboygan	62700	16	16.8
Little Elkhart Lake	Sheboygan	46000	52	8.6
Little Gerber Lake	Sheboygan	56700	8	NA
Long Lake	Manitowoc	77500	127	10.8
Pigeon Lake	Manitowoc	64000	80	20.0
Round Lake	Calumet	68600	11	22
Shea Lake	Kewaunee	85400	32	10.9
Shoe Lake	Manitowoc	46700	10	19.5
Silver Lake	Manitowoc	67400	73	13.0
Tuma Lake	Manitowoc	87900	14	10.6
West Alaska Lake	Kewaunee	94300	27	11.0

Lake	County	WBIC	Surface Area (acres)	Mean Depth (ft)
Weyers Lake	Manitowoc	49400	6	15.2
Wilke Lake	Manitowoc	58000	93	8.7
Wolf Lake	Fond Du Lac	60800	75	19.1

Surficial total phosphorus monitoring data for the modeled lakes were acquired from the department's comprehensive Surface Water Integrated Monitoring System (SWIMS). The period of record for each lake was defined as years with TP samples collected in at least two growing season months (1 June - 15 September). Data were summarized in accordance with the mathematical procedures outlined in Wisconsin's Consolidated Assessment And Listing Methodology (WDNR 2021) and compared to the corresponding lake's water quality criteria per s. NR 102.06 Wis. Admin. Code.

Table 2. Summary of lake monitoring data used in model development and lake water quality criteria.

Lake	Start Year	End Year	Mean (µg/L)	LCL (µg/L)	UCL (µg/L)	Criteria (µg/L)	Meeting Criteria?
Beckers	2012	2020	160.0	146.3	174.9	30	No
Big & Little Gerber[1]	1990	1993	17.5	15.1	20.2	30	Yes
Boot	2013	2017	199.5	179.1	222.2	20	No
Bullhead	2008	2020	51.4	46.4	56.9	20	No
Carstens	2011	2020	92.8	81.4	105.8	30	No
Cedar	2008	2019	15.8	15.0	16.7	40	Yes
Crystal	2008	2018	11.7	11.1	12.3	15	Yes
Elkhart	2008	2020	11.1	10.5	11.8	15	Yes
English	2010	2020	23.9	21.7	26.3	20	No
Gass	2012	2020	84.0	72.6	97.1	30	No
Harpt	2009	2020	30.4	26.6	34.7	20	No
Hartlaub	2012	2020	30.2	26.6	34.3	30	No
Horseshoe	2012	2019	18.6	16.4	21.0	15	No
Jetzers	2002	2002	38.9	14.2	106.8	20	No
Little Elkhart	2003	2020	20.1	18.1	22.3	20	No
Long	2008	2020	89.5	84.4	94.8	30	No
Pigeon	2008	2019	16.7	15.4	18.1	20	Yes
Round	2012	2017	92.0	82.6	102.6	20	No
Shea	2017	2018	48.4	38.9	60.2	30	No
Shoe	2012	2020	21.3	17.9	25.4	20	No
Silver	2008	2019	39.4	35.1	44.2	30	No
Tuma	2012	2018	20.4	19.1	21.8	20	No
West Alaska	2016	2017	18.5	16.8	20.3	20	Yes
Weyers	2012	2020	40.4	34.8	46.9	20	No
Wilke	2012	2020	19.7	18.4	21.1	20	Yes
Wolf	2015	2019	34.5	28.1	42.3	30	No

LCL = Lower Control Limit   UCL = Upper Control Limit

[1] Area-weighted mean of Big and Little Gerber Lakes.

Long term annual average water and nutrient loads to each lake were estimated using the Soil and Water Assessment Tool (SWAT) model developed for the North East Lakeshore TMDL (Cadmus 2021). Please refer to the "Northeast Lakeshore TMDL: SWAT Model Setup, Calibration, and Validation" prepared by Cadmus Group LLC dated March 15, 2021.

In several instances SWAT derived flows into the lakes were higher than those predicted using the lake modeling. This can occur because of the relatively coarse nature of the digital evaluation model (30x30 meter grid) used to develop the SWAT model. Most watersheds in the TMDL are fairly large and used the widely available digital elevation models referenced above; however, in smaller watersheds or watersheds with less topographic relief the more detailed data derived from finer scale LiDAR data sets (0.6x0.6 meter grid) were used to adjust the watershed areas. This approach allows for a better estimation of the amount of water captured in internally drained areas or water that otherwise does not drain to the lakes within these watersheds. This is reflected in Figures 1 and 2 below which show the drainage area delineations using the 30X30 meter grid and the LiDAR respectively. Note the smaller drainage area, shown in purple, in Figure 2.

Figure 1. Watershed area derived with 30X30 meter digital elevation model.

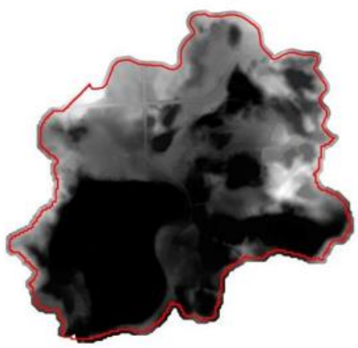
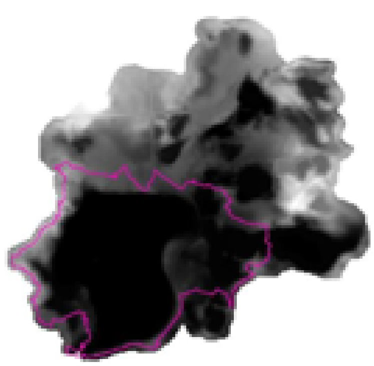


Figure 2. Watershed area derived with LiDAR.



SWAT derived nutrient and hydraulic loading estimates were adjusted proportionately based on the adjusted watershed areas. Point source phosphorus loadings were based on long term average loading reported on discharge monitoring reports from 2008-2019.

Table 3. Watershed adjustments, long term average SWAT derived hydraulic and phosphorus loads, and point source phosphorus loads.

Lake	SWAT Watershed #	SWAT Watershed (acres)	Adjusted Watershed (acres)	% Diff	Adjusted Flow (cfs)	Adjusted S SWAT Load (lbs/yr)	Point Source Load (lbs/yr)
Becker	187	982	1,223	25%	1.13	542.1	
Big & Little Gerber	215	1,896	1,896	0%	2.81	1422.3	
Boot	18	116	105	-9%	0.13	34.6	
Bullhead	178	1,673	234	-86%	0.28	105.6	
Carstens	178	864	603	-30%	1.02	593.3	
Cedar	185	469	469	0%	0.94	60.2	
Crystal	186	254	254	0%	0.63	21.9	
Elkhart	183	1,417	1,417	0%	2.60	207.3	
English	177	129	137	6%	0.21	60.1	
Gass	175	341	576	69%	0.34	94.3	
Harpt	181	722	677	-6%	0.80	165.9	
Hartlaub	174	603	271	-55%	0.65	139.2	
Horseshoe	204	1,510	905	-40%	2.10	336.0	
Jetzers	213	80	80	0%	0.12	23.3	
Little Elkhart	198	591	591	0%	0.94	43.2	
Long	182	447	620	39%	0.62	193.1	
Pigeon	190	382	58	-85%	0.11	32.6	
Round	179	24	33	38%	0.06	2.2	
Shea	195	1,245	933	-25%	0.68	132.1	
Shoe	230	131	84	-36%	0.14	4.2	
Silver	60	425	433	2%	0.54	117.3	20
Tuma	217	55	43	-22%	0.07	2.3	
West Alaska	203	315	163	-48%	0.15	31.3	
Weyers	173	115	119	3%	0.15	8.1	
Wilke	189	604	537	-11%	0.81	156.8	
Wolf	192	2,788	2,788	0%	3.74	629.5	

Phosphorus loading from nearshore septic systems was included as an additional source of phosphorus in each lake model. WiLMS includes the following equation for calculating phosphorus loading from septic systems:

$$L = E * P * (1 - R)$$

L = Annual phosphorus load from septic systems (kilograms/year)
E = Septic tank phosphorus export rate (kilograms/person/year)
P = Population using septic systems (persons)
R = Phosphorus retention coefficient (dimensionless)

For all systems, the phosphorus export rate from septic systems was to the default WiLMS value of 0.5 kilograms/person/year, and the phosphorus retention coefficient was set to the default WiLMS value of 0.9.

The population using septic systems (P) was estimated for each lake using a count of homes that are within 500 feet of the lake shore and outside of municipal sanitary sewer service areas. Initial counts of homes with septic systems were derived using GIS map layers of land parcel boundaries, sanitary sewer system boundaries, and aerial photos. Initial counts were refined using input from county land planning department staff. Seasonal residences were determined by comparing the postal address to the site address as reported in the parcel table. If the addresses were different the residence was considered seasonal. Counts of permanent residences with septic systems were multiplied by the county average number of persons per household from the 2010 US Census to convert to the number of persons using septic systems. Seasonal residences were treated in a similarly but were further multiplied by 0.25 to account for less frequent occupation. No adjustments were made to account for whether systems were up or down gradient of the lake (i.e., all septic drain fields assumed to discharge toward lake).

Finally, annual atmospheric TP loading directly to the to the lake surface was based on the default loading rates from WiLMS (0.3 kg/ha/yr.). Direct net precipitation (precipitation-evaporation) on the lake surface was based on county wide averages provided in WiLMS.

Table 4. Net precipitation, septic and atmospheric loading information.

Lake	Net Precipitation (in)	Atmospheric Load (lbs/yr)	Capita Years	Septic Load (lbs/yr)
Beckers	3.5	9.4	5.6	0.6
Big & Little Gerber	3.3	5.9	0	0
Boot	3.5	2.8	15.1	1.7
Bullhead	3.2	18.6	49.2	5.4
Carstens	3.2	6.0	15.3	1.7
Cedar	3.2	36.7	144.0	15.9
Crystal	3.3	34.5	0	0
Elkhart	3.3	78.2	128.1	14.1
English	3.2	12.8	83.1	9.2
Gass	3.2	1.6	9.0	1.0
Harpt	3.2	8.6	12.1	1.3
Hartlaub	3.2	10.0	23.7	2.6
Horseshoe	3.2	5.5	22.0	2.4
Jetzers	3.3	4.3	5.0	0.6
Little Elkhart	3.3	13.9	0	0
Long	3.2	34.1	105.1	11.6
Pigeon	3.2	21.3	126.0	13.9
Round	3.5	3.0	5.6	0.6
Shea	3.4	8.4	10.3	1.1
Shoe	3.2	2.5	0.6	0.1
Silver	3.2	19.4	26.0	2.9
Tuma	3.2	3.8	4.5	0.5
West Alaska	3.4	7.1	16.9	1.9
Weyers	3.2	1.5	0	0
Wilke	3.2	24.8	113.0	12.5
Wolf Lake	3.1	20.1	123.7	13.6

Modeling Approach and Loading Capacity Determination

All lakes were evaluated using six different empirical models which predict the in-lake total phosphorus based on hydraulic and phosphorus loading and lake morphometry. Not all models were applicable to all lakes as each model as each of the phosphorus prediction regressions was derived from a data set containing specific lakes and their corresponding characteristics. For the application of a model regression to be valid, the site-specific characteristics must fall within the range of the model's regression. The empirical model variables, formulae and constraints are described below:

Model Variables:

- P = Predicted mixed layer total phosphorus concentration (ug/L)
- L = Areal total phosphorus load (mg/m^2-yr)
- z = Mean depth (m)
- T_w = Hydraulic residence time (yr)
- ρ = Flushing rate (yr^{-1})
- q_s = Surface overflow rate (m/yr)
- P_{in} = Average inflow total phosphorus concentration (µg/L)

Models:

Canfield-Bachmann 1981 Natural Lakes Model

$$P = \frac{L}{z\left(0.162\left(\frac{L}{z}\right)^{0.458} + \rho\right)}$$

Constraints:

- $4 < P < 2600$ µg/L
- $30 < L < 7600$ mg/m^2-yr
- $0.2 < z < 307$ m
- $0.001 < \rho < 183$ yr^{-1}

Canfield-Bachmann 1981 Artificial Lakes Model

$$P = \frac{L}{z\left(0.114\left(\frac{L}{z}\right)^{0.589} + \rho\right)}$$

Constraints:

- $6 < P < 1500$ µg/L
- $40 < L < 820{,}000$ mg/m2-yr
- $0.6 < z < 59$ m
- $0.019 < \rho < 1800$ yr^{-1}

Walker 1987 Reservoir Model

$$P = P_{in}(1 - R)$$

$$R = 1 + \frac{1 - \sqrt{1 + 4K_2P_{in}T_w}}{2K_2P_{in}T_w}$$

$$K_2 = \frac{0.17q_s}{q_s + 13.3}$$

Constraints:

$1.5 < z < 58$ m
$0.13 < T_w < 1.91$ yr
$14 < P_{in} < 1047$ μg/L

Reckow 1979 Natural Lake Model

$$P = \frac{1000L}{11.6 + 1.2q_s}$$

Constraints:

$4 < P < 135$ μg/L
$70 < L < 31{,}400$ mg/m^2-yr
$0.75 < q_s < 187$ m/yr

Reckow 1977 Anoxic Lake Model

$$P = \frac{L}{0.17z + 1.13\frac{z}{T_w}}$$

Constraints:

$17 < P < 610$ μg/L
$24 < P_{in} < 621$ μg/L

Reckow 1977 Oxic Lake Model ($q_s < 50$ m/yr)

$$P = \frac{L}{\frac{18z}{10+z} + 1.05\frac{z}{T_w}e^{0.012z/T_w}}$$

Constraints:

$P < 60$ μg/L
$P_{in} < 298$ μg/L

For each lake, the various model results were compared against the monitoring results provided in Table 5 to determine an appropriate modeling approach to determine the loading capacity of each lake. Five different modeling approaches were employed (A, B, C, D, and E) and are detailed below.

Table 5. Empirical lake response model results and loading capacity modeling approach. All values are summer mean concentrations (μg/L).

Lake	Obs.	C-B Natural	C-B Artificial	R Natural	R Anoxic	R Oxic	W Reservoir	Modeling Approach
Beckers	96	74	NA	199	NA	69	96	B
Big & Little Gerber	138	102	160	221	151	85	138	E
Boot	59	49	NA	115	NA	58	59	D
Bullhead	43	38	16	120	35	NA	43	B
Carstens	134	98	127	249	NA	91	134	B
Cedar	24	23	7	NA	16	29	24	A
Crystal	12	14	NA	NA	6	NA	12	A
Elkhart	15	16	8	NA	9	NA	15	A

Lake	Obs.	C-B Natural	C-B Artificial	R Natural	R Anoxic	R Oxic	W Reservoir	Modeling Approach
English	26	26	15	67	19	NA	26	B
Gass	79	63	68	121	NA	59	79	B
Harpt	45	39	33	84	47	37	45	B
Hartlaub	43	37	28	85	42	38	43	B
Horseshoe	49	42	47	69	48	35	49	E
Jetzers	32	30	14	69	25	NA	32	B
Little Elkhart	19	18	7	24	15	20.0	19	B
Long	44	39	16	113	NA	NA	44	B
Pigeon	24	25	NA	NA	13	NA	24	A
Round	14	15	NA	23	NA	NA	14	D
Shea	49	42	29	83	51	44	49	B
Shoe	12	12	5	16.7	8	13	12	D
Silver	41	36	18	94	35	NA	41	B
Tuma	17	18	NA	29	9	NA	17	B
West Alaska	37	33	13	83	29	NA	37	A
Weyers	18	18	10	25	15	18	18	D
Wilke	44	38	17	86	39	48	44	A
Wolf	47	41	40	73	50	36	47	C

Modeling Approach A (Table 6): These lakes are currently meeting their water quality criteria and the modeled results were in the range of the observed results (i.e., at least one model over predicted the in-lake phosphorus concentration and at least one model under predicted the in-lake phosphorus concentration). This model fit indicates that the total phosphorus loading estimates derived from the SWAT model and estimates from other sources are reasonably accurate and can be used to derive a protection TMDLs for these waters. In these cases, the loading capacity for the lakes is set equal to the current estimated loading.

Table 6. Calculated loading capacities for protection TMDLs.

Lake	Loading Capacity (lbs/yr)
Cedar	112.8
Crystal	56.4
Elkhart	299.6
Pigeon	67.8
West Alaska	40.3
Wilke	194.0

Modeling Approach B (Table 7): These lakes are not currently meeting their water quality criteria and the modeled results were in the range of the observed results. As with the lakes under Modeling Approach A, this model fit indicates that the total phosphorus loading estimates derived from the SWAT model and estimates from other sources are reasonably accurate and can be used to derive TMDLs for these waters.

Because no model precisely predicted the observed in-lake phosphorus concentration, the two models that bracketed the observed values were used to predict the loading capacity, This was done by weighting the models based on their performance under current conditions:

$$w_{over} = \frac{1}{abs(obs - Pred_{over})}$$

$$w_{under} = \frac{1}{abs(obs - Pred_{under})}$$

Where:

w_{over} = weight assigned to model which most closely overpredicted in-lake TP
$Pred_{over}$ = Predicted in-lake TP from model which most closely overpredicted in-lake TP
w_{over} = weight assigned to model which most closely overpredicted in-lake TP
$Pred_{under}$ = Predicted in-lake TP from model which most closely underpredicted in-lake TP
Obs = observed in-lake TP

To determine the loading capacity, total external loading was decreased until the weighted average of the two selected model results was equal to the lake's water quality criteria -

$$Pred_{final} = \frac{Pred_{over} * w_{over} + Pred_{under} * w_{under}}{w_{over} + w_{under}}$$

Table 7. Selected empirical lake response models, calculated model weight, and calculated lake loading capacities.

Lake	Overpredict Model	W_{over}	Underpredict Model	W_{under}	Loading Capacity (lbs/yr)
Beckers	R Anoxic	0.026	C-B Natural	0.016	92.8
Bullhead	R Anoxic	0.015	C-B Natural	0.12	35.6
Carstens	C-B Artificial	0.20	W Reservoir	0.65	105.7
English	C-B Artificial	0.45	R Oxic	0.21	61.8
Gass	C-B Artificial	0.095	R Natural	1.5	30.7
Harpt	W Reservoir	0.15	R Natural	0.32	93.0
Hartlaub	C-B Artificial	0.14	R Natural	0.44	149.9
Jetzers	R Anoxic	0.033	C-B Natural	0.15	12.0
Little Elkhart	R Anoxic	0.23	W Reservoir	13	56.8
Long	R Anoxic	0.042	C-B Natural	0.022	74.2
Shea	C-B Natural	1.6	W Reservoir	0.21	75.6
Silver	C-B Natural	0.58	C-B Artificial	0.34	104.8
Tuma	R Anoxic	0.12	C-B Artificial	0.35	6.4

Modeling Approach C (Table 8): This lake is not currently meeting its water quality criteria and at least one model provided results greater than the mean of the observed data, but less than the upper confidence interval and all other models overpredicted in-lake TP. This may indicate that the loading estimates for these lakes are somewhat overestimated. For these lakes the model that most closely matched the observed data was used to determine the loading capacity. Because the models are overpredicting the in-lake concentration, the selected models were not adjusted to match the current condition as to provide a somewhat conservative estimate of loading capacity.

Table 8. Selected empirical lake response models and calculated lake loading capacities.

Lake	Selected Model	Loading Capacity (lbs/yr)
Wolf	W Reservoir	493.1

Modeling Approach D (Tables 9 and 10): These lakes are not currently meeting their water quality criteria and all models underpredicted in-lake TP based on the expected external loading. This leads to two alternative hypotheses, either the watershed loads were underestimated due to local characteristics, or more likely there these lakes have a substantial internal loading component. All empirical lake response models include some level of implicit internal loading as all lakes used to develop the models carried some level of internal loading. However, lakes with high levels of internal loading will deviate from more typical conditions predicted by the models. In these instances, both the current condition loading and the TMDL loading capacity was based on the geometric mean of the back calculated loads from the applicable empirical lake response models.

While internal loading appears likely, higher than expected watershed loading cannot be fully ruled out without further study. From an implementation standpoint, a more detailed evaluation of local land use practices and other external sources should be conducted in concert with any evaluation of internal loading control as part of future lake management planning.

In some case, historic loadings or land management maybe significantly impacting current water quality and would not be accounted for by the current SWAT model. For example, a 1938 aerial photo of Round Lake (Figure 3) shows a barnyard as a potentially significant source of manure and nutrients located immediately adjacent to the lake. The greyish color of the lake in the photo is also indicative of an algae bloom.

Figure 3. 1938 Arial photo of Round Lake

Table 9. Back calculated loads from applicable empirical lake response models based on current in-lake phosphorus levels.

Lake	C-B Natural (lbs/yr)	C-B Artificial (lbs/yr)	R Natural (lbs/yr)	R Anoxic (lbs/yr)	R Oxic (lbs/yr)	W Reservoir (lbs)	Loading Estimate (lbs/yr)
Boot	231.3	564.7	NA	67.8	NA	NA	206.9
Round	116.7	216.7	122.2	23.4	NA	NA	92.2
Shoe	14.3	15.1	28.2	8.7	19.1	14.2	15.6
Weyers	26.1	31.9	38.4	15.7	26.1	34.2	27.7

Table 10. Back calculated loads from applicable empirical lake response models and calculated lake phosphorus loading capacities.

Lake	C-B Natural (lbs/yr)	C-B Artificial (lbs/yr)	R Natural (lbs/yr)	R Anoxic (lbs/yr)	R Oxic (lbs/yr)	W Reservoir (lbs)	Loading Capacity (lbs/yr)
Boot Lake	9.4	10.1	NA	6.8	NA	8.1	8.5
Round	9.9	9.6	26.6	5.1	NA	NA	10.6
Shoe	13.1	13.7	26.5	8.2	17.9	12.9	14.4
Weyers	10.6	11.4	19.0	7.8	12.9	11.5	11.8

Modeling Approach E (Tables 11 and 12): For Horseshoe Lake and Big and Little Gerber Lakes, all models overpredicted in-lake TP based on the SWAT model's predicted external loading. In the case of Horseshoe Lake, there has been extensive modification of the upstream hydrology and there are multiple on-network ponds and wetlands as part of a mitigation bank which may be allowing for additional phosphorus sedimentation upstream of Horseshoe Lake. Horseshoe Lake is currently listed as impaired, for purposes of the TMDL, both the current condition loading and the TMDL loading capacity was based on the geometric mean of the back calculated loads from the applicable empirical lake response models.

Table 11. Back calculated loads from applicable empirical lake response models and calculated lake phosphorus loading capacities for Horseshoe Lake.

Scenario	C-B Natural (lbs/yr)	C-B Artificial (lbs/yr)	R Natural (lbs/yr)	R Anoxic (lbs/yr)	R Oxic (lbs/yr)	W Reservoir (lbs)	Loading Capacity (lbs/yr)
Current Conditions	109.3	117.7	134.9	NA	132.9	131.0	124.8
TMDL Conditions	85.6	90.4	109.1	NA	NA	103.6	96.7

In the case of Big and Little Gerber Lakes, the reasons for the underprediction are unclear. Big and Little Gerber Lakes are in located in the Otter Creek drainage system which has had numerous BMPs installed as part of an earlier priority watershed project, so it may be that agricultural practices in this watershed may be different than those used for the SWAT model. Neither Big and Little Gerber Lakes are currently listed as impaired, and for purposes of the TMDL, the current condition loading was based on the geometric mean of the back calculated loads from the applicable empirical lake response models. As neither lake is listed as impaired, no reductions are required for the TMDL (protection TMDL).

From an implementation standpoint, a more detailed evaluation of local land use practices and other external phosphorus sources should be considered as part of future lake management planning.

Table 12. Back calculated loads from applicable empirical lake response models and calculated lake phosphorus loading capacities for Horseshoe Lake.

Scenario	C-B Natural (lbs/yr)	C-B Artificial (lbs/yr)	R Natural (lbs/yr)	R Anoxic (lbs/yr)	R Oxic (lbs/yr)	W Reservoir (lbs)	Loading Capacity (lbs/yr)
Current/ TMDL Conditions	124.5	133.5	156.1	NA	165.5	136.7	142.5

Summary of Model Results

By in large the SWAT model loading estimates provided reasonable nutrient and hydraulic load estimates to the lakes examined. Once adjustments were made to account for internally drained areas, the estimated external loads were able to accurately predict in-lake TP in 20 of the 26 lakes examined.

For four lakes, the estimated SWAT loads underpredicted in-lake TP. It appears likely that for these lakes, higher than expected internal loading may be responsible for this difference, although higher than expected watershed loading cannot be fully ruled out without further study.

For two lakes the SWAT loads overpredicted in-lake TP. For Horseshoe Lake this overprediction may be due to phosphorus sedimentation in upstream ponds, for Big and Little Gerber Lakes the reasons for the overprediction are less clear and requires further evaluation of the drainage network and the potential impact of the springs that provide year round groundwater baseflow to the lakes.

References

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