Preliminary Nutrient Budget and Water Quality Modeling Assessment for Lake Roaming Rock

December 2020

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Understanding Internal Phosphorus Loading:

Internal phosphorus (P) loading can represent the major driving force behind harmful algal blooms (HABs) within many lake systems. Understanding when, where, and how much internal P loading is occurring in your lake is key to addressing water quality and HAB issues long-term. This information, paired with external P load estimates, provides the foundation for developing a P budget and water quality model that can be used to determine how restoration efforts will impact water quality.

The process of internal P re-cycling from lake sediments are complex and are influenced by many factors. These factors can include biological (e.g., bacterial activity, mineralization processes, and bioturbation), chemical (e.g., redox conditions, pH, iron, and nitrate availability), and physical factors such as resuspension and sediment mixing. Estimating the amount of internal P loading occurring per area under different factors can be done in a variety of ways. One way is to collect surficial sediments from the "active" P layer of sediment (typically the top 10 cm or 4 inches of sediment) and determine the amount of P bound to different forms in sediment. This can provide a direct estimate of P release under different conditions. For example, the amount of iron bound P can provide estimates of P release once oxygen has been depleted.

In this section, the sediment quality within Lake Roaming Rock was assessed to better understand internal P re-cycling and how to address it.

Methods:
Lake Roaming Rock sediment samples were collected from the locations indicated by the map below. An Eckman dredge was used to collect surficial sediments that represent the "active" sediment layer (top ~10 cm). The samples were sent the same day in a cooler to Vertex's analytical lab for analysis.

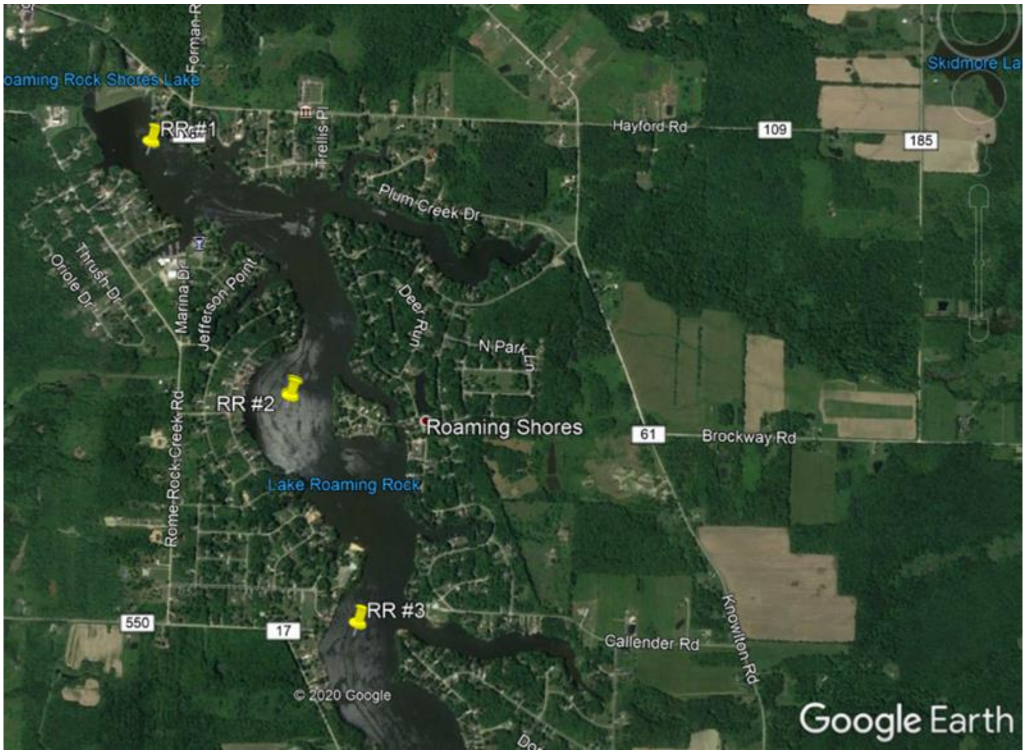


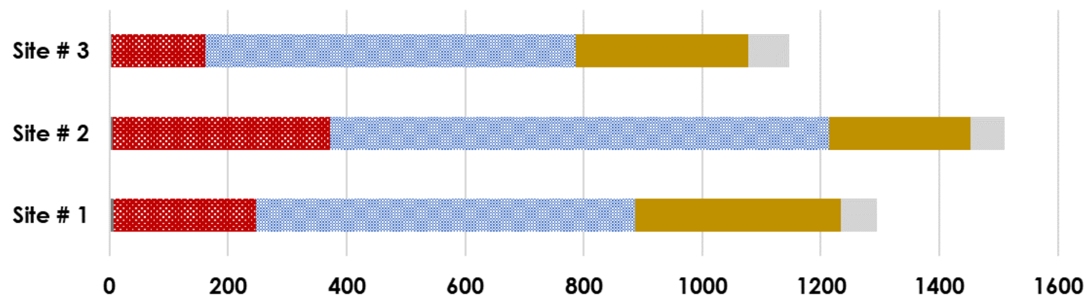
Figure 1. Sediment locations.

Sediment Quality Results

Solids content were consistent among sites, ranging from 26.7-28.8. This means that 73.3-71.2% of the sediment pulled from the lake was water. This is typical of lake sediments. Organic content of the sediment ranged from 11.0% to 13.1%, suggesting the lake has a low amount of organic material.

Total phosphorus ranged from 1548 mg/kg (Site 4) to 2042 mg/kg (Site 1). Values >500 mg/kg are considered high, but the availability of that phosphorus cannot be known from total phosphorus concentrations. Iron-bound and labile phosphorus, the dominant available fraction, is considered elevated when >100 mg/kg and is very high when >500 mg/kg. Values for Lake Roaming Rock are elevated averaging 255 mg/kg. There is a good amount of available phosphorus in the sediment that can be acted upon.

Organic and calcium bound phosphorus can represent a major source of internal phosphorus cycling in a lake. Organic bound phosphorus is released during bacterial decomposition, while calcium bound phosphorus is released during low pH events. Organic bound phosphorus is elevated with values over 100 mg/kg. Calcium bound phosphorus was not elevated and does not represent a significant amount of phosphorus that could be released.



	Site # 1	Site # 2	Site # 3
Labile-P	6.4	4.7	3
Fe-P	241	367	158
Al-P	640	842	626
Organic-P	346	238	290
Ca-P	60.9	57.7	69.5

mg P / kg

Figure 2. Sediment bound phosphorus (mg/kg) results. Labile or loosely bound phosphorus (Labile-P). Iron bound phosphorus (Fe-P). Aluminum bound P (Al-P). Organic bound phosphorus (Organic-P). Calcium bound phosphorus (Ca-P).

The total mass of available phosphorus that could be potentially acted upon can be calculated by taking the percent solids in the upper 10 cm (4 inches) of sediment times a specific gravity (typically 1.2), times the fraction of interest. The table below provides an example calculation using Iron-bound phosphorus concentrations; the fraction that will become available for uptake by algae under low oxygen conditions. The amount of phosphorus to be "treated" is significant ranging from 8.0 g/m2 (Site#1) to 11.7 g/m2 (Site #2). There are variety of ways to treat this fraction, but the two most common approaches are phosphorus inactivation and or oxygenation/circulation. Addressing this fraction of phosphorus would provide water quality improvement in Lake Roaming Rock. Further data collection and modeling would provide better estimates into how well the lake would respond and the longevity of treatment if this fraction of phosphorus loading is addressed.

Table 1. Mass of phosphorus to be treated.

	Organic	Solids	Total Phosphorus	Iron Bound Phosphorus	Mass of P to be Treated
Location	%	%	mg/kg dry weight	mg/kg dry weight	g/m2
Site # 1	11.7	27.5	2042.4	241	8.0
Site # 2	13.1	26.7	1598.3	367	11.7
Site # 3	11.0	28.8	1548.8	158	5.5
Average	11.9	27.7	1730	255	8.4

Nutrient Budget and Water Quality Modeling Assessment:

A nutrient budget can be a valuable tool for managing a lake's trophic status and for setting critical and permissible nutrient loading rates. Nutrient budgets can provide a means to identify and rank nutrient sources that contribute to a lake's trophic status. From this, a cost-benefit analysis can be conducted to rank management strategies designed to meet permissible nutrient loading rates. A nutrient budget for P and N was constructed for Lake Roaming Rock using the Lake Loading Response Model (LLRM). Literature and actual in-lake data values were inputted for external (i.e., watershed, atmospheric, waterfowl, groundwater, etc.) and internal loading, estimates for the total amount of phosphorus (P) and Nitrogen (N) loading to Lake Roaming Rock were estimated. Once the total nutrient load has been calculated and verified, the lake loading response model (LLRM) can then make water-quality predictions for total phosphorus (TP), total nitrogen (TN), chlorophyll *a* (chl. *a*), and Secchi (Z_{sd}), from which management goals can be established. The LRRM also provides scenario testing for internal and external management programs and can provide estimates regarding a lake's reference or background condition (before anthropogenic influences).

Estimated Nutrient Load:

Internal loading - was estimated using sediment phosphorus data (see appendix C) and literature values for nitrogen – with conversion to an areal load on an annual basis. The area of internal load was assumed to be below 15ft and comprises an area of ~214 acres. The data suggests a maximum release of 4493.4 kg P and 1265.8 kg N. However, the active internal load that supports algal blooms during summer cannot be determined from sediment data. In-lake data collected before and during bloom formation is needed to calibrate the active internal load and improve water quality model outputs.

External loading - is provided by the surrounding watershed. Lake Roaming Rock has a total watershed area of 40,740 acres, which is 52% forested, 42% agricultural, and 6% urban. Using literature nutrient loading rates based on land-use and experience in other systems, a total load of 7,456 kg/yr. P and 108,941 kg/yr. N is suggested by the LLRM. No adjustments have been made for distinguishing between active and non-active forms (i.e., particulate) of nutrients, and therefore water quality predictions may be under or over-estimated. External nutrient loads can be upwards of 50% or more particulate matter, which is not readily available for algal uptake and must be processed in the Lake, usually as part of the internal load. An adjustment to the model to account for active loads would improve water quality predictions.

Table 2. Nutrient and hydrology budget results.

TOTAL LOADS TO LAKE	P (KG/YR)	N (KG/YR)	WATER (CU.M/YR)
ATMOSPHERIC	38.4	959.5	19,15,162
INTERNAL	4,493.4	1,265.8	0
WATERFOWL	37.2	116.0	0
WATERSHED LOAD	7,456.5	108,941.6	76,318,850

Table 3. Lake Loading Response (LLRM) results.

SUMMARY TABLE FOR SCENARIO TESTING	Existing Conditions		Background Conditions	Feasible Watershed BMPs	Internal Load Restoration	External and Internal Load Restoration
	Un-calibrated Model Value	AVG. 2004-2005 Data	Model Value	Model Value	Model Value	Model Value
Phosphorus (ppb)	119.3	170.5	32.3	97.1	74.7	52.5
Nitrogen (ppb)	1027.4	n/a	600.9	757	1027.4	757
Mean Chlorophyll (ug/L)	74.5	24.25	13.8	56.9	40.5	25.7
Peak Chlorophyll (ug/L)	232.7	45	46.1	179.6	129.4	83.7
Mean Secchi (m)	0.59	0.55	1.61	0.69	0.85	1.11
Peak Secchi (m)	2.56	1.3	3.69	2.71	2.92	3.22
Bloom Probability						
Probability of Chl >10 ug/L	100.0%		65.3%	99.9%	99.5%	95.0%
Probability of Chl >15 ug/L	99.8%		33.8%	99.2%	95.9%	79.7%
Probability of Chl >20 ug/L	99.1%		16.0%	96.7%	87.8%	60.1%
Probability of Chl >30 ug/L	94.2%		3.6%	84.9%	63.8%	28.9%
Probability of Chl >40 ug/L	84.0%		0.9%	67.6%	41.2%	12.9%

Modeling Overview - water quality modeling allows us to compare predicted water quality conditions to actual in-lake conditions, thus providing inference into factors affecting water quality. For example, suppose model values predict a greater level of chlorophyll *a* than what is being observed in the Lake. In that case, there are factors (i.e., grazing, flushing, turbidity/color, algal type, climate, etc.) other than nutrients that are directly limiting algal growth that should be looked at and studied. Water quality models also support cost-benefit analysis of treatment options by 1) Identifying critical portions of a watershed or other major sources of pollutant loading and 2) evaluating the effects of different management practices on lake water quality.

Existing Conditions – provides model values using all available data as outlined in Appendix A and any actual data for comparison (model Vs. actual). The model values represent the predicted annual average water quality conditions for the study year. In this case, there was no defined study year; however, outputs reflect current sediment and land-use data and, therefore, should reflect more recent conditions. All actual data has been averaged for comparison. Actual data was taken from the 2004-2005 EnviroScience study, which allowed for some comparison between predicted and actual values.

Uncalibrated model values mean there was no defined study year. Uncalibrated model values provide less certainty in management scenario testing and limit the number of scenarios that can be tested. Calibrating the model can be done by defining a study year and collecting all necessary data that would impact water quality results in that study year. Such study elements are detailed under the monitoring needs section.

Background Conditions – scenario testing by which the watershed is converted to forested and the internal load is reduced by 95%. This scenario test provides an estimate of water quality before anthropogenic effects. It can be useful in setting realistic water quality goals as a lake can only be as good as it's reference condition.

Feasible Watershed BMPs – common BMPs rarely reduce phosphorus and nitrogen loads by < 50%; unless all runoff can be infiltrated, we are unable to make developed land behave like undeveloped land. In this scenario test, we applied a conservative 30% reduction to the total watershed load. Model values represent possible water quality conditions if such BMPs were implemented.

Internal load reductions – Assumes all internal phosphorus load is inactivated or removed. Model values represent possible water quality conditions if management actions are implemented.

Internal and external load reductions – Assumes feasible watershed BMPs and internal load strategies are implemented. Model values represent possible water quality conditions if management actions are implemented.

Major Findings:

- Lake Roaming Rock has a relatively large catchment per unit volume, which is associated with rapid lake flushing and higher nutrient and ion inputs.
- The watershed (40,740) to lake area (474 acres) ratio is approximately 86. What this means from a management perspective is that in-lake water quality problems can still arise even with limited watershed development.
- Lake Roaming Rock has a high flushing rate, which on average occurs approximately nine times per year. Algal biomass can be affected when the flushing rate exceeds the growth rate of at least some planktonic species. This seems to be the case for Lake Roaming Rock, with high nutrient concentrations and lower chlorophyll *a* levels. The timing of flushing is particularly important when predicting seasonal algal blooms. Drought periods during summer months are likely to cause more extreme water quality issues in Lake Roaming Rock.
- 86 defined sub-watersheds were identified in this study, each with varying land-uses and nutrient loads. See the attached excel sheet.
- External nutrient loading is the major contributing source to the Lake annually. However, it is not understood how external and internal nutrient loads affect water quality. For example, if a large fraction of the external load is particulate, then internal loading maybe governing seasonal water quality; conversely, if a large portion of the internal load stays in the hypolimnion, then external loads maybe governing seasonal water quality.

Management Recommendations:

A detailed management plan is outside the scope of this assessment. However, a shortlist of strategies that were modeled are provided.

Internal Load Reduction:

Oxygenation

Restoring deep water oxygen would greatly reduce internal nutrient loading, enhance the Lake's fishery, and likely shift the algal community to a more desirable one. The key process at work now is loss of oxygen that initiates chemical reactions that cause iron and phosphorus in surficial sediments to dissociate and move into solution over the sediment. The lack of oxygen in deep water for much of the year is ecologically undesirable, limiting habitat for fish and other aquatic life. Adding enough oxygen to counter the oxygen demand is, therefore, a valid approach to solving multiple problems.

There are two major categories of oxygenation, mixing (or destratifying circulation) and non-destratifying oxygenation (which can be accomplished with the input of air or pure oxygen). Mixing can be accomplished by pumping water up or down in the water column or by releasing air in deeper water to stimulate mixing. The complete mixing will raise the oxygen level in deeper water and should prevent at least severe oxygen loss. General design and cost estimates can be provided, but an oxygen demand study is recommended to accurately determine the lakes needs.

Phosphorus Inactivation

As the primary problem process is the dissociation of iron and phosphorus under low oxygen conditions, replacing the iron with a binder that is not subject to release in the absence of oxygen can inactivate the offending phosphorus. Several binders have been used, including aluminum, calcium, and lanthanum, the latter attached to clay particles in the commercially available Phoslock. Where the pH is near neutral, calcium does not work particularly well. Aluminum or lanthanum would be the preferred binders, and aluminum tends to be less expensive.

Treatment with aluminum depends on the area to be treated and the dose needed. We believe that the target area would be surficial sediment up to 10 cm deep in the area exposed to anoxia, which is all area under more than 15 feet of water in this case. The sediment tests allow us to calculate the mass of available phosphorus, which is 8.4 g/m^2. The maximum aluminum dose would be about 75 g/m^2. As additional treatment would be additive, it would be acceptable to apply aluminum at a lower rate, observe results, and treat again as needed. However, it would be most cost-effective to treat only once.

The treatment eventually wears off, with the average duration of benefits at close to 20 years for deeper lakes. Additional inputs from the watershed and upward diffusion of phosphorus through the inactivated zone are the main causes of an eventual return to excessive internal loading. Phosphorus inactivation will reduce the amount of algae produced and therefore lower the oxygen demand, but it will not eliminate the demand exerted by already accumulated organic sediment, and anoxia in the hypolimnion of Lake Roaming Rock would still be expected after an aluminum treatment.

External Load Reduction:

Watershed BMPs

More data are needed to evaluate cost-effective watershed management programs, but there are actions that can be recommended to minimize impact to the Lake by watershed properties. Property owners can reduce nutrient loading and pollution entering the Lake by minimizing fertilizer use, collecting and properly disposing of yard waste, not washing cars or other equipment in driveways. Minimizing impervious surface is highly desirable, and ensuring BMPs are being practiced in the expansive agricultural areas. Managing runoff for quality as well as rapid removal of quantity from athletic fields, parking areas, agricultural, and roadways is also recommended. Facilities that detain runoff or infiltrate it into the soil can reduce loading to area waterways.

Monitoring Needs:

This initial investigation has provided considerable insight, but some open questions remain. The table below summarizes monitoring needs moving forward.

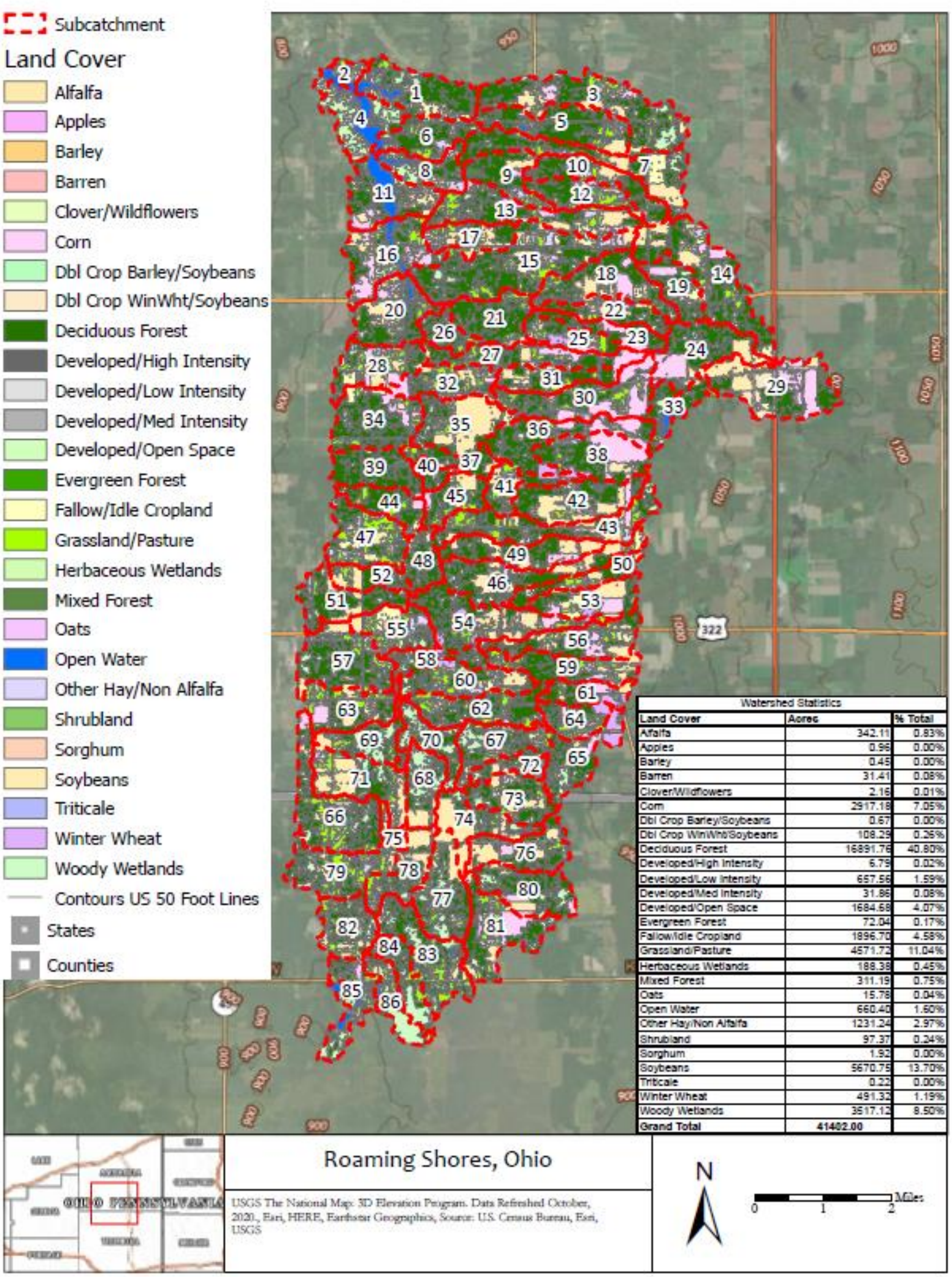
Table 4. Summary of monitoring needs.

Description	Purpose / Management Utility
2021 in-Lake water quality profiling for total and active nutrient forms; oxygen, temperature, and chlorophyll *a* profiling and Secchi. Algae and zooplankton identification and biomass.	Improves internal loading estimates and model outputs. Provides assessment on oxygen demand. Provides a framework to design an oxygenation/circulation system. Provides insight into factors (nutrients/food web dynamics) affecting algal bloom formation, intensity, and duration.
2021 wet and dry weather sampling for total and active nutrient loads at each major tributary. Minimum of 3 events for wet and dry.	Improves external load estimates and water quality model outputs. Provides insight into the external load's impact on algal bloom formation, intensity, and duration. Prioritizes tributary management. Provides the framework to design a tributary treatment system.
Advanced watershed modeling using a high mechanistic computer model (i.e., Storm Water Management Model (SWMM))	"Finer brush" modeling allows for improved outputs in water routing and attenuation. Can model monthly conditions and provide better insight into seasonal flushing rates as it relates to water quality. Overall, it improves the water quality model outputs by having a more accurate water budget. Prioritizes watershed BMPs and provides a design framework for implementation.
2021 late spring macrophyte identification and biovolume survey.	Provides insight into how plant biomass is affecting water quality. Refines water quality model outputs.
Electrofishing survey	Assessment and feasibility of a biomanipulation approach to improve water quality.

Appendix A: Types and sources of data used for LLRM set up

Feature	Purpose of Model	Sources for this Study
Lake bathymetry and volume	Determination of volume at any depth or water level	Used hydroacoustic data. Total lake volume: 8,697,958.23 m^3
Watershed and sub-watershed delineation	Define areas to which loading functions and water quality comparisons will be applied in the model	See GIS map appendix B
Sub-watershed land uses and corresponding areas	Determines range of possible loading to be used in the model	See GIS map appendix B
Precipitation	Used to calculate flows from land use and precipitation data	NOAA; long-term mean of 0.998 m (39.3 inches/yr.)
Flow Data	Used as a check on calculations from other data	Used literature values based off land-use.
Areal Water Yield	Used with watershed area as a check on flow values derived from the land use and precipitation	Literature values for the region; used the median value of 1.6 CFSM
Point source P and N monitoring data	Provides load from regulated sources	No permitted point source discharges to Lake or tributaries
On-site wastewater treatment (septic) system locations within direct drainage to the Lake	Allows estimation of septic inputs by calculation using data for distance from Lake, population served, and frequency of use	Sewer Line
Wildlife P and N inputs	Allows estimation of inputs from wildlife, mainly waterfowl	Estimates of waterfowl population very limited; assumed 20 birds per year for the model.
Atmospheric P and N loading	Provides estimate of loading from the atmosphere	Literature values for the region; used median values for urban areas.
Internal P and N loading	Provides estimate of loading from lake sediments	Used sediment fractioning data for P (appendix c) and literature derived values for N.
Stream P and N concentrations	Used to check model results	Very limited
In-lake water quality (P, N, chl. *a*, Z_{sd})	Used to check model results	Very limited

Appendix B: Sub-watershed and Land-Use



Watershed Statistics

Land Cover	Acres	% Total
Alfalfa	342.11	0.83%
Apples	0.96	0.00%
Barley	0.45	0.00%
Barren	31.41	0.08%
Clover/Wildflowers	2.16	0.01%
Corn	2917.18	7.05%
Dbl Crop Barley/Soybeans	0.67	0.00%
Dbl Crop WinWht/Soybeans	108.29	0.26%
Deciduous Forest	16891.76	40.80%
Developed/High Intensity	6.79	0.02%
Developed/Low Intensity	657.56	1.59%
Developed/Med Intensity	31.86	0.08%
Developed/Open Space	1684.68	4.07%
Evergreen Forest	72.04	0.17%
Fallow/Idle Cropland	1896.70	4.58%
Grassland/Pasture	4571.72	11.04%
Herbaceous Wetlands	188.38	0.45%
Mixed Forest	311.19	0.75%
Oats	15.78	0.04%
Open Water	660.40	1.60%
Other Hay/Non Alfalfa	1231.24	2.97%
Shrubland	97.37	0.24%
Sorghum	1.92	0.00%
Soybeans	5670.75	13.70%
Triticale	0.22	0.00%
Winter Wheat	491.32	1.19%
Woody Wetlands	3517.12	8.50%
Grand Total	41402.00	