LAKE WAUKEWAN AND LAKE WINONA
LAKE LOADING RESPONSE MODEL

TO: Angela LaBreque, Town of Meredith
FROM: Evan Ma, FB Environmental Associates
SUBJECT: **Lake Waukewan and Lake Winona Lake Loading Response Model**
DATE: April 22, 2026
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INTRODUCTION

The purpose of this report is to provide results from the Lake Loading Response Model (LLRM) developed for Lake Waukewan and Lake Winona as part of the Lake Waukewan and Lake Winona Watershed Restoration Plan (WRP) Update. This model is a full update of the LLRM developed for the original watershed restoration plan for the two lakes in 2016 (LWA & FBE, 2016). The LLRM is an Excel-based model that uses environmental data to develop a water and phosphorus loading budget for lakes and their tributaries[1]. Water and phosphorus loads (in the form of mass and concentration) are traced from various sources in the watershed through tributary basins and into the lake. The model incorporates data about watershed and sub-watershed boundaries, land cover, point sources (if applicable), septic systems, waterfowl, rainfall, volume and surface area, and internal phosphorus loading. These data are combined with coefficients, attenuation factors, and equations from scientific literature on lakes, rivers, and nutrient cycles. The following memorandum describes the process by which critical model inputs were determined using available resources and GIS modeling and presents annual average predictions[2] of total phosphorus, chlorophyll-*a*, Secchi disk transparency, and algal bloom probability. The model can be used to identify current and future pollutant sources, estimate pollutant limits and water quality goals, and guide watershed improvement projects.

[1] AECOM (2009). LLRM Lake Loading Response Model Users Guide and Quality Assurance Project Plan. AECOM, Willington, CT.
[2] The model cannot simulate short-term weather or loading events.

WATERSHED AND SUB-WATERSHED DELINEATIONS

Watershed and tributary drainage area (sub-watershed) boundaries are needed to determine both the amount of water flowing into a surface waterbody and the area of different land cover types contributing to nutrient loading. FB Environmental Associates (FBE) began by using the Lake Waukewan and Lake Winona watershed boundary from the original 2016 watershed restoration plan. FBE identified multiple differences between the watershed boundary file and the watershed boundary from the USGS National Watershed Boundary Dataset (WBD) (HUC12-010700020108) for the Lake Waukewan watershed, which also includes Lake Winona.

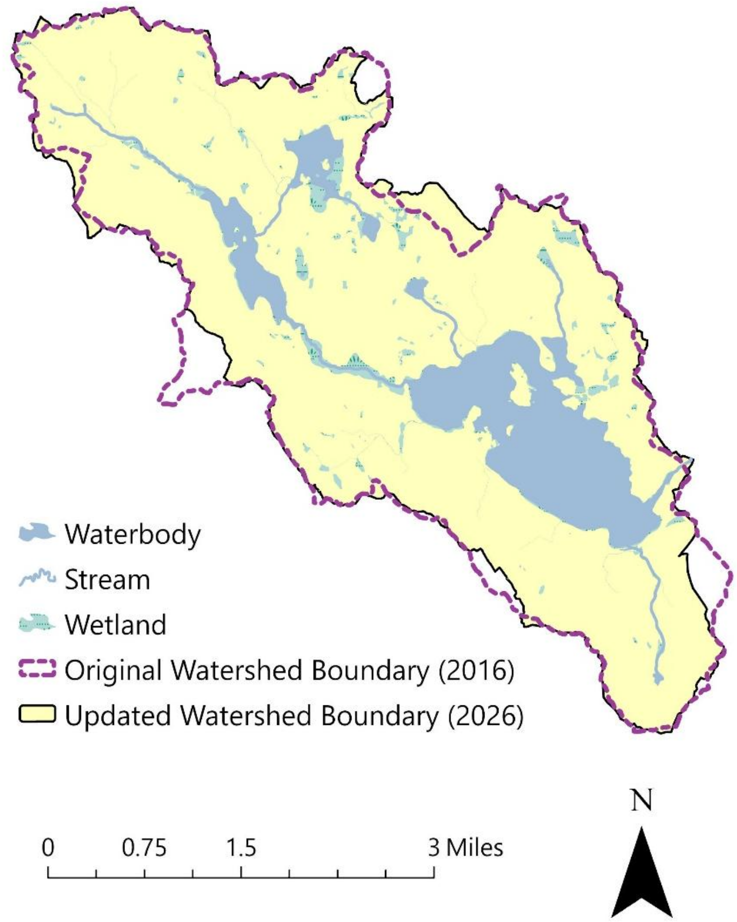

Figure 1. Differences between the watershed boundary for Lake Waukewan and Lake Winona watersheds between the original watershed management plan (maroon dotted line) and the updated watershed management plan (yellow with black outline).

FBE re-delineated the watershed and sub-watersheds for Lake Waukewan and Lake Winona after this inspection of the original sub-watershed boundaries from the 2016 watershed restoration plan (Figure 1). FBE's updated workflow consisted of desktop aerial watershed delineation using USGS 1/3 arc-second digital elevation models (DEMs) as an input to a spatial workflow using the ESRI ArcGIS Pro Spatial Analyst Hydrology toolbox. FBE then used Light Detection and Ranging (LiDAR) derived two-foot contours provided by New Hampshire's data clearinghouse, NH GRANIT, to rectify differences between the delineated watershed boundary and the HUC12 watershed boundary. The two-foot contours were not available during the development of the initial WMP and FBE did not have access to the spatial analyst hydrology geospatial toolbox. The LiDAR two-foot contours, aerial imagery, and Google Earth street-view imagery were used to confirm sub-watershed boundaries (Figure 2).

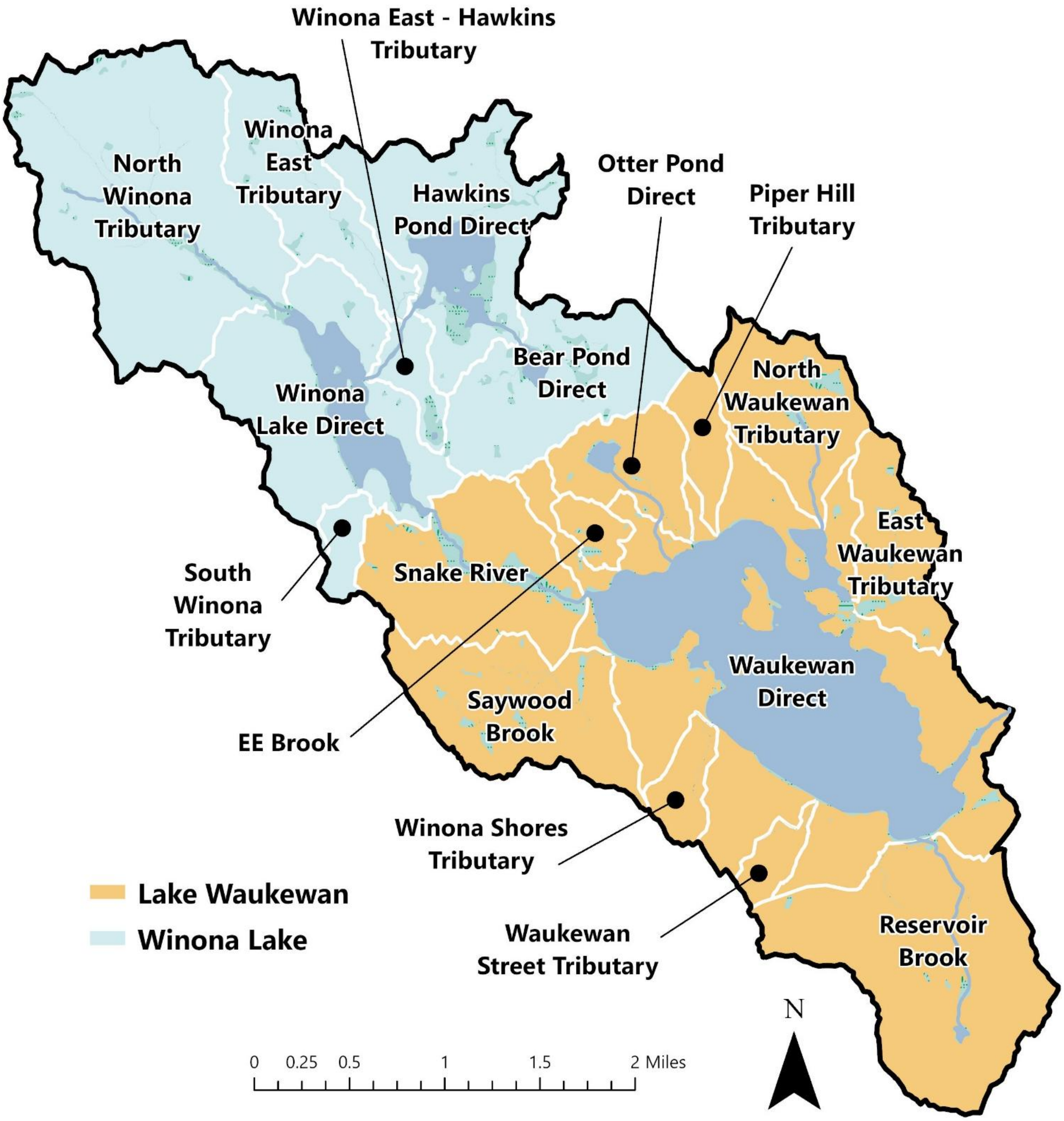

Figure 2. Final sub-watershed boundaries for the Lake Waukewan and Lake Winona watershed. A separate model was run for Lake Winona (light blue) for input to Lake Waukewan (orange). Refer to Figure 5 for how the sub-watersheds flow through each other, aka. routing.

LAND COVER FILE CREATION

Land cover determines the movement of water and phosphorus from the watershed to surface waterbodies via surface runoff and baseflow (groundwater). A significant amount of time went into reviewing and refining the land cover data by FBE. A shapefile of the watershed area was used as a baseline for establishing the area of interest. The entire area was assigned the “Forest 1: Upland” LLRM category as a default. Then, FBE overlayed wetlands from the National Wetlands Inventory (NWI), waterbodies from the National Hydrography Dataset (NHD), roads from the New Hampshire Department of Transportation (NHDOT), and building footprints from the publicly available Microsoft building footprints layer. All data was acquired from NH GRANIT. Streams from the NHD and roads from NHDOT were given 15-foot and 30-foot buffers, respectively. Next, rectangular grids (or quads) were created to break up the watershed into more manageable portions for review. ESRI World imagery dated 9/1/2023 and Google Earth imagery were reviewed for human-caused land cover changes, such as agriculture, residential or commercial development, cleared land, and additional roads. Changes were made using the Editor tools for editing polygon vertices and splitting polygons. Each new polygon was relabeled in the attribute table with the appropriate LLRM land cover category.

A few assumptions or actions were made during this process:

- Agricultural fields (whether row crops or hayfields) that were clearly not pasture were assigned to “Agric 2: Row Crop/Hayfield”; it was difficult to discern whether a field was used as a cover crop and so no cover crops were assigned in the watershed. FBE further refined land cover by distinguishing among hayfields (“Agric 2: Row Crop/Hayfield”), meadows that were non-wetland, scrub-shrub habitat (“Open 2: Meadow”), or extensive lawns or athletic fields or cemeteries (“Urban 5: Open Space”). Residential lawns were included in “Urban 1: Low Density Residential.” Recently logged areas (“Other 1: Logging”) were differentiated from upland forest areas (“Forest 1: Upland”), often evidenced by patchy forest cover and/or logging trails.
- Palustrine wetland areas from the National Wetlands Inventory (NWI) were added as “Forest 2: Wetlands.”
- Open water areas and streams from the National Hydrography Dataset (NHD) were added as “Open 1: Water.”
- Roads from the NHDOT roads layer were differentiated between “Urban 3: Roads” or “Other 1: Unpaved Roads.”
- Major bare soil areas that were not associated with new residential home construction were labeled as “Open 3: Excavation.”

Agricultural and developed lands were checked carefully since modeling coefficients (i.e., phosphorus export) are substantially higher for those land cover types. Aerial imagery was checked thoroughly for each major agricultural or developed area to distinguish between hayfields, grazing/pasture, lawns, and meadows. The resulting land cover file is a more accurate representation of current land cover within the Lake Waukewan and Lake Winona watershed compared to coarse-scale data such as the National Land Cover Dataset (NLCD) (refer to Figure 3 for a fine-scale comparison between the NLCD and FBE’s land cover file).

Within the LLRM, export coefficients are assigned to each land cover to represent typical concentrations of phosphorus in runoff and baseflow from those land cover types (Attachment 1: Land Cover). Unmanaged forested land, for example, tends to deliver very little phosphorus downstream when it rains, while low, medium, and high-density urban development exports significantly more phosphorus per unit area due to impervious surfaces, fertilizer use, soil erosion, car and factory exhaust, pet waste, and many other sources. Smaller amounts of phosphorus are also exported to lakes and streams via groundwater under baseflow conditions. This nutrient load is delivered with groundwater to the lake directly or to tributaries; however, much of the phosphorus is adsorbed onto soil particles as water infiltrates to the ground. Attachment 1: Land Cover presents the runoff and baseflow phosphorus export coefficients for each land cover type used in the model, along with the total land cover area by land cover type for each sub-watershed.

Figure 4 shows a basic breakdown of land cover by major category for the Lake Waukewan and Lake Winona watershed (not including surface areas of each lake), as well as total phosphorus load by major land cover category for the watershed. Developed areas cover 10% of the watershed and contribute 68% of the total phosphorus load to waterbodies in the combined Lake Waukewan and Lake Winona watershed.

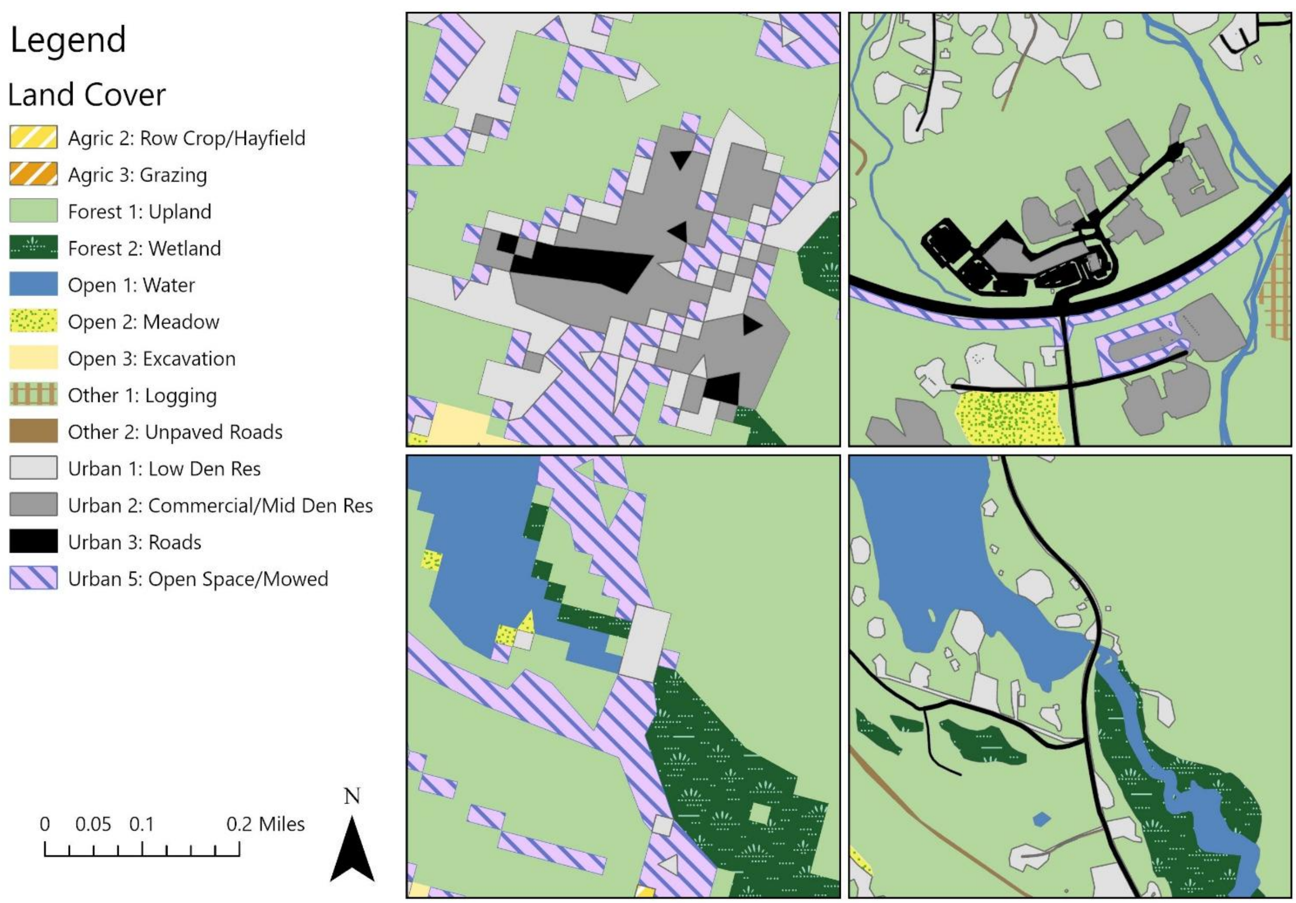

Figure 3. Two examples of land cover file comparisons between the 2024 National Land Cover Dataset (NLCD; left) and FBE's modified land cover file (right) for the Lake Waukewan and Lake Winona watershed.

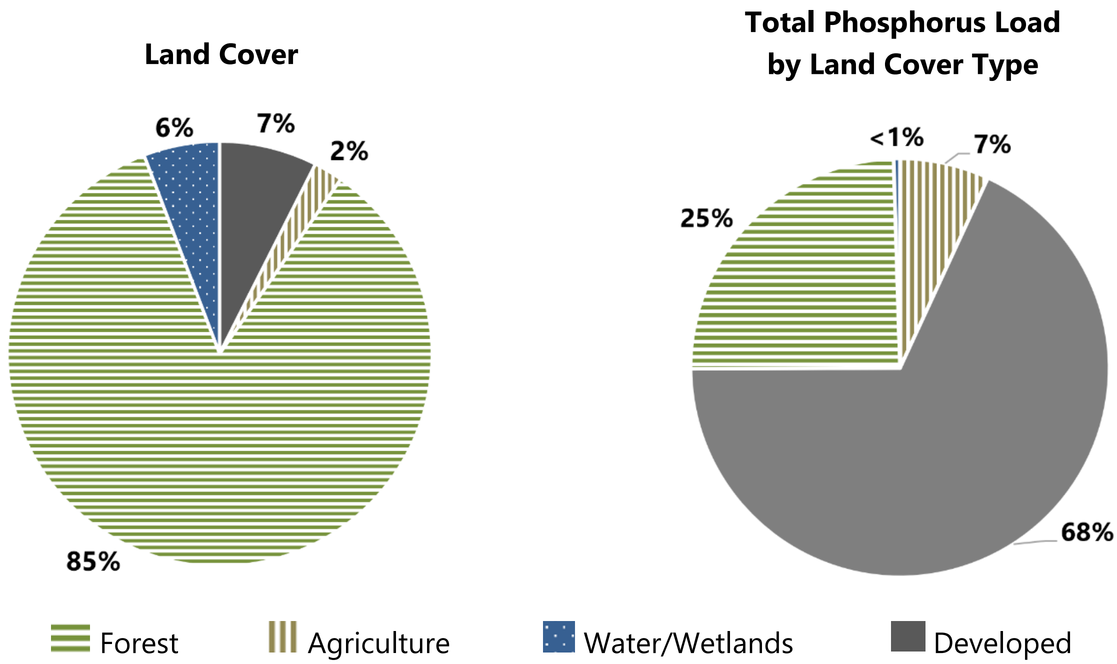

Figure 4. Lake Waukewan watershed (including Lake Winona) land cover area by general category (agriculture, developed, forest, and water/wetlands) and total phosphorus (TP) watershed load by general land cover type. Developed areas cover 10% of the watershed and contribute 68% of the TP watershed load to Lake Waukewan and Lake Winona). The water/wetlands category does not include the lake areas.

OTHER MAJOR LLRM INPUTS

The following presents a brief outline of other variable sources and assumptions input into the model. Refer to the Limitations to the Model section for further discussion.

- **Daily precipitation data** were obtained from the Daymet Single Pixel Extraction Tool for 1995-2024, using the centroid coordinates of the watershed. Additionally, monthly NOAA NCEI precipitation data for the LAKEPORT 2, NH US (Station ID: USC00274480) weather station were downloaded for 1995-2025. A linear regression model was created to predict the 2025 Daymet annual precipitation from the NCEI 2025 value. The average annual precipitation totals from 2016-2025 were input as 47 inches or 1.2 meters.
- **Lake volume and area estimates** were obtained from the NHDES via NH GRANIT's "Bathymetry Lakes Polygons" spatial file. These estimates were compared to the most recent NHDES Lake Trophic Survey Reports for each lake.
- **Point sources** were routed into the model. Lake Winona was modeled separately from Lake Waukewan. The output of water load from Lake Winona corrected for pan evaporation and predicted annual average in-lake phosphorus concentrations from this model was entered as a point source to the downstream Lake Waukewan model (Figure 5).

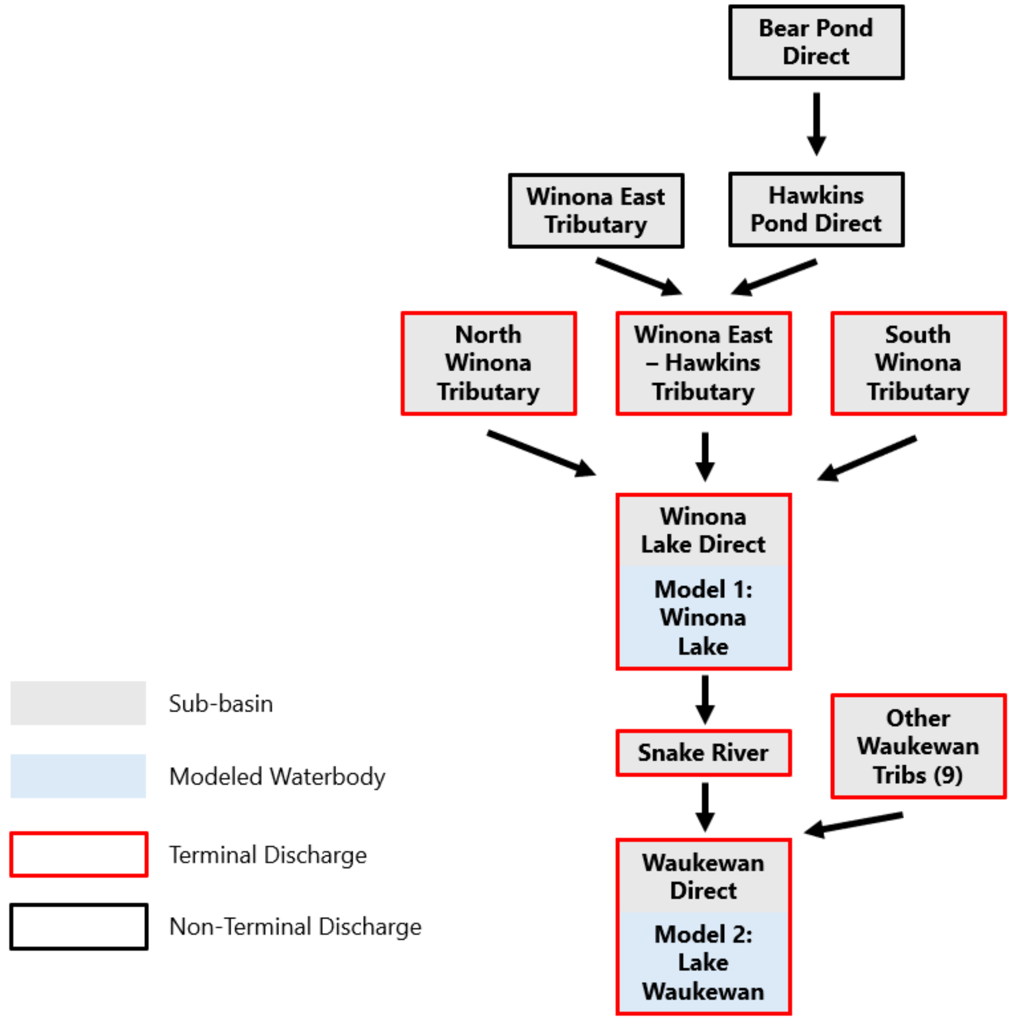

Figure 5. Conceptual diagram of point source and sub-watershed routing for the Lake Waukewan and Lake Winona models.

- **Septic system data** were estimated from property records. FBE identified and researched 253 parcels with buildings within 250 feet of Lake Waukewan (159 systems) and Lake Winona (94 systems) in the towns of Meredith, Center Harbor, and New Hampton. FBE searched property records for pertinent information such as date the house was built and seasonal or year-round use, if available (otherwise assumed year-round). From this information, the number of "old" (>25 years) and "young" (<25 years) shoreline septic systems used seasonally or year-round was determined and multiplied by the average number of bedrooms (as a proxy for household occupancy) for each category to determine the number of persons on septic systems around the lake. These data are used to estimate the water and total phosphorus load from septic systems near the lake.
- **Water quality data** were gathered from NHDES Environmental Monitoring Database (EMD). Data were screened for relevant site locations and water quality parameters (Secchi disk transparency, chlorophyll-*a*, total phosphorus, dissolved oxygen, and temperature). This includes data from FBE's 2025 *Lake Waukewan Source Water Assessment Report* (FBE, 2025). The model was calibrated using tributary and lake samples taken between 2016-2025. Sites were only included if they were

lake samples or a close match to the outlet of a sub-watershed used in the model. Data were summarized to obtain median and mean water quality summaries for total phosphorus, chlorophyll-*a*, and Secchi Disk Transparency and aggregated for multiple lake sites, if relevant.

- **Waterfowl counts** for Lake Waukewan and Lake Winona were based on a standard estimate of 0.3 birds per hectare of lake surface area. This default value is based on best professional experience with modeling other similar lakes in the area. Waterfowl can be a direct source of nutrients to lakes; however, if they are eating from the lake and their waste returns to the lake, the net change may be less than might otherwise be assumed. Even in this instance, the phosphorus excreted may be in a form that can be readily used by algae and plants.
- **Internal loading estimates** were derived from intensive sampling conducted in 2024, including grab samples at various depths in the hypolimnion from late August until early October. The internal load was assumed to be the difference between the mass of total phosphorus throughout the water column in the early season (5/13/2024) and late season when internal loading is at its peak (10/8/2024). This estimation method provides a partial-net estimate of the internal phosphorus load (between a gross estimate and a net estimate).

CALIBRATION

Calibration is the process by which model results are brought into agreement with observed data and is an essential part of environmental modeling. Usually, calibration focuses on the input data with the greatest uncertainty. Changes are made within a plausible range of values, and an effort is made to find a realistic explanation among environmental conditions for these changes. A moderate amount of tributary phosphorus concentration data were available for the modeling period (2016-2025) for both lakes, and thus measured values were used as guideposts. These data were mostly collected in the summer months. Improved tributary monitoring efforts that include stream discharge may be used to improve model calibration in the future. Observed in-lake phosphorus concentrations were given primacy during the calibration process, such that the ability of the model to accurately simulate annual average in-lake phosphorus concentration was used as a leading indicator of acceptable model performance. Continued water quality sampling in the watershed can be designed to reduce the uncertainty encountered in modeling and help assess assumptions made during calibration.

The following key calibration input parameter values and modeling assumptions were made:

- **Direct atmospheric deposition** phosphorus export coefficient was assumed to be 0.11 kg/ha/yr from Schloss et al. (2013) and represents a largely undeveloped watershed.
- Point source and sub-watershed **routing** for the Lake Waukewan and Lake Winona models is presented in Figure 5.
- Default **water and phosphorus attenuation factors** were first used before each sub-watershed's attenuation factors were adjusted to account for landscape features that would increase or decrease attenuation (Table 1). Water can be lost through evapotranspiration, groundwater, and wetlands, while phosphorus can be removed by infiltration or uptake processes. We generally expect at least a 5% loss (95% pass through, default) in water and a 10% loss (90% pass through, default) in phosphorus for each sub-watershed. Larger water losses (<95% pass through) can be

expected with lower gradient or wetland-dominated sub-watersheds. Additional infiltration, filtration, detention, and uptake of phosphorus will lower the phosphorus attenuation value, such as for sub-watersheds dominated by moderate/small ponds or wetlands (75%-85% pass through) or channel processes that favor uptake (85% pass through), depending on the gradient. Headwater systems are assumed to have a greater attenuation than higher order streams since the flow of water is lower, giving more opportunity for infiltration, adsorption, and uptake.

- The average of multiple **empirical formulas** for predicting annual in-lake phosphorus concentration was used according to the most appropriate formulas for each lake:
    - Lake Waukewan: Dillon & Kirchner (1975); Kirchner-Dillon (1975); Vollenweider (1975) + EPA; Vollenweider (1975; 1973); Larsen-Mercier (1976); and Jones & Bachmann (1976).
    - Lake Winona: Vollenweider (1975) + EPA; Vollenweider (1975; 1973); Larsen-Mercier (1976); Jones & Bachmann (1976); Reckhow General (1979); and Nürnberg (1998).

Table 1. Reasoning for water and phosphorus attenuation factors used by model and sub-watershed.

Waterbody	Sub-Watershed	Water Atten. Factor	Phos. Atten. Factor	Reasoning (water; phosphorus (P))
Lake Waukewan	East Waukewan Tributary	0.90	0.85	Attenuation by channel processes that favor uptake.
	EE Brook	0.95	0.90	Default water and P attenuation factor.
	North Waukewan Tributary	0.90	0.85	Attenuation by channel processes that favor uptake.
	Otter Pond Direct	0.90	0.85	Attenuation by channel processes and small pond.
	Piper Hill Tributary	0.95	0.90	Default water and P attenuation factor.
	Reservoir Brook	0.85	0.80	Attenuation by Monkey Pond.
	Sayward Brook	0.90	0.85	Attenuation by channel processes that favor uptake.
	Snake River	0.80	0.75	Attenuation by wetlands.
	Waukewan Direct	0.95	0.90	Default water and P attenuation factor.
	Waukewan Street Tributary	0.95	0.90	Default water and P attenuation factor.
	Winona Shores Tributary	0.95	0.90	Default water and P attenuation factor.
Lake Winona	Bear Pond Direct	1.00	1.00	Attenuation considered through downstream sub-watershed.
	Hawkins Pond Direct	1.00	1.00	Attenuation considered through downstream sub-watershed.
	North Winona Tributary	0.90	0.85	Attenuation by channel processes that favor uptake.
	South Winona Tributary	0.95	0.90	Default water and P attenuation factor.
	Winona East - Hawkins Tributary	0.75	0.70	Attenuation considered for upstream sub-watersheds; attenuation by ponds and wetlands.
	Winona East Tributary	1.00	1.00	Attenuation considered through downstream sub-watershed.
	Lake Winona Direct	0.95	0.90	Default water and P attenuation factor.

Limitations to the Model

There were several limitations to the model. Literature values and best professional judgement were used in place of measured data, wherever appropriate. Acknowledging and understanding model limitations is critical to interpreting model results and applying any derived conclusions to management decisions. The model should be viewed as one of many tools available for lake management. Because the LLRM incorporates specific waterbody information and is flexible in applying new data inputs, it is a powerful tool that predicts average annual in-lake total phosphorus concentrations with a good degree of confidence; however, model confidence can be increased with more data. The following lists limitations to the model:

- **The model represents a static snapshot in time based on the best information available at the time of model execution.** Factors that influence water quality are dynamic and constantly evolving; thus, the model should be regularly updated when significant changes occur within the watershed and as new water quality and physical data are collected. In this respect, the model should only be considered up-to-date on the date of its release. Model results represent annual averages and are best used for planning level purposes and should only be used with full recognition of the model limitations and assumptions.
- **Limited water quality data were available for calibration and internal loading estimates in Lake Winona and at tributaries throughout the watershed.** More data at the Lake Winona deep spot, lake outlets, and tributaries are needed to effectively calibrate the model to known observations and generate more accurate estimates of internal loading. We recommend that the model be re-evaluated after 10 years of consistent data collection. Data were limited for Snake River, Sayward Brook, Mayo Farm Brook, EE Brook, Lake Winona's North inlet and Heights Brook inlet, the Bear Pond outlet, and Lake Winona-Hawkins outlet, and were only used as guideposts during the calibration process. Other streams had a wealth of summer data, but lacked data during other months of the year and stream discharge data that can be helpful for model calibration. Due to limited data, it is uncertain the extent of possible anoxia and internal phosphorus loading in Lake Winona.
- **Septic system loading was estimated based on default literature values and regional statistics.** Default literature values for daily water usage, phosphorus concentration output per person, and system phosphorus attenuation factors were used and may not reflect local watershed conditions. Regional statistics on usage (duration and number of occupants) or best professional judgement were also used when information on septic systems was unavailable.
- **Sewered shoreline areas were considered to contribute no additional phosphorus to waterbodies.** Phosphorus loading from wastewater (septic systems and sewer) is inherent to the land use export coefficients for residential areas. Leaky sewer lines along shoreline properties (if any exist), similar to septic systems, are more likely to have a direct impact on the waterbody due to their proximity to the shore. Some properties on the southern shores of Lake Waukewan in Meredith are served by sewer lines. The total phosphorus load may be underestimated for Lake Waukewan if leaky sewer lines are common in the shoreland zone.

- **Waterfowl counts were based on default estimates and limited observation data.** In the future, a large bird (e.g., geese, ducks, etc.) census throughout the year would help improve the model loading estimates.
- **Land cover export coefficients were estimates.** Literature values and best professional judgement were used in evaluating and selecting appropriate land cover export coefficients for Lake Waukewan and Lake Winona. While these coefficients may be accurate on a larger scale, they may not represent site-by-site variation. Refer to documentation within the LLRM spreadsheet for specific citations.

RESULTS

CURRENT LOAD ESTIMATION

Overall, model predictions for Lake Waukewan and Lake Winona were in good agreement with observed data for total phosphorus (percent difference between model predictions and data for Lake Waukewan and Lake Winona, respectively: 0% and 1%), chlorophyll-*a* (10% and 21%), and Secchi disk transparency (30% and 21%) (Table 2). It is important to note that the LLRM does not explicitly account for all the biogeochemical processes occurring within a waterbody that contribute to overall water quality. As a result, the model is less accurate at predicting chlorophyll-*a* and Secchi disk transparency. For example, chlorophyll-*a* is estimated strictly from nutrient loading, but other factors strongly affect algae growth, including transport of phosphorus from the sediment-water interface to the water column by cyanobacteria, low light from suspended sediment, grazing by zooplankton, presence of heterotrophic algae, and flushing effects from high flows. There were insufficient data available to evaluate the influence of these other factors on observed chlorophyll-*a* concentrations and Secchi disk transparency readings.

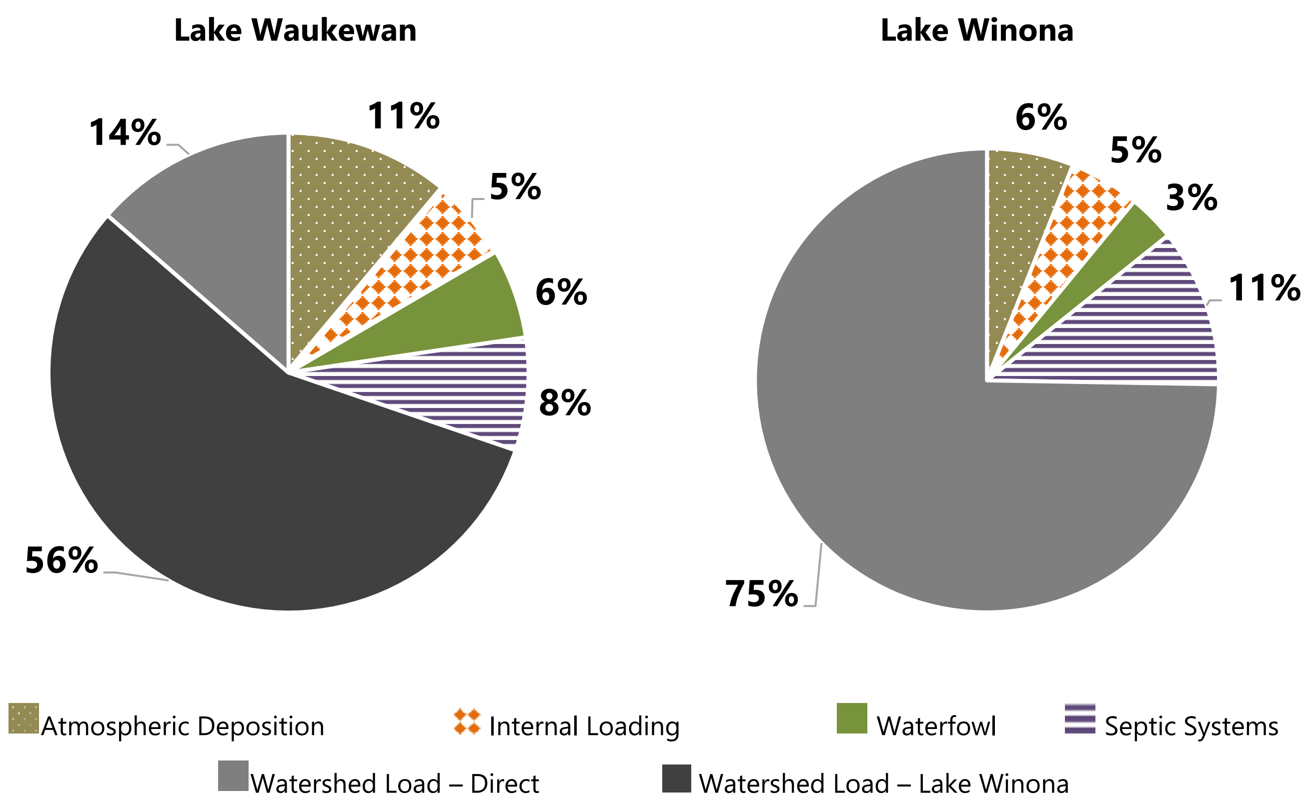

Figure 6. Summary of total phosphorus loading by major source for Lake Waukewan (left) and Lake Winona (right). Refer to Table 3 for a breakdown.

Watershed runoff combined with baseflow was the largest phosphorus loading contribution across all sources to Lake Waukewan. The watershed load accounts for 70% of the total phosphorus load in Lake Waukewan. This includes the watershed loads from both the direct Lake Winona (14%) and Lake

Waukewan (56%) watersheds (Table 3; Figure 6). Atmospheric deposition (11%), septic systems (8%), waterfowl (6%), and internal loading (5%), were smaller sources. Lake Winona had a similar breakdown, with the watershed load making up 75% of the total phosphorus load. Septic systems (11%) were the second largest source of phosphorus to Lake Winona. Development in the watershed is most concentrated along the shorelines of each lake and near the Lake Waukewan outlet which has dense single-family homes and commercial land uses. Phosphorus loading can occur with dense shoreline development in unsewered areas where septic systems or holding tanks are located within a short distance to the water, leaving little horizontal (and sometimes vertical) space for proper filtration of wastewater effluent. Improper maintenance or siting of these systems can cause failures, which leach untreated, nutrient-rich wastewater effluent to the lake. Part of Lake Waukewan's southern shoreline is serviced by the municipal sewer system, which also represents a potential vulnerability if the sewer systems are old or damaged and leaking wastewater into groundwater near the lake. Note that septic systems are a relatively small source of TP load to Lake Waukewan because 1) the estimate is only for those systems directly along the shoreline of Lake Waukewn and Winona Lake that are potentially short-circuiting minimally treated effluent to the lake, 2) part of the shoreline area is serviced by sewer which does not contribute any phosphorus loading in the model since the assumption is that the sewer lines are not leaking, and 3) shoreline septic systems for Lake Winona are included in that lake's watershed load (see Table 3 for a breakdown). The load from septic systems throughout the rest of the watershed is inherent to the coefficients used to generate the watershed load.

Internal loading is currently a relatively small source of phosphorus to Lake Waukewan and Lake Winona, though data from the 2025 *Lake Waukewan Source Water Assessment Report* (FBE, 2025) suggests that internal loading has been relatively stable over the past ten years, with the time around lake turnover being the only time of year when internal loading has worsened in the past ten years. The model predicts zero bloom days (Table 2) for Lake Waukewan and 19 bloom days per year for Lake Winona.

Normalizing for the size of a sub-watershed (i.e., accounting for the watershed annual discharge and direct drainage area) better highlights sub-watersheds with elevated pollutant export relative to their drainage area. The sub-watershed with the highest phosphorus mass exported per area was the Waukewan Street tributary with 0.26 kg/ha/yr. This sub-watershed and other sub-watersheds with moderate-to-high phosphorus mass exported by area in the range of 0.10 – 0.20 kg/ha/yr generally had more development (Table 4, Figure 7). These drainages make up most of the Lake Waukewan direct sub-watershed, which includes much of the more densely developed shoreline and commercial areas. Lake Winona sub-watersheds had lower phosphorus mass export per area, though the Winona East Tributary had a higher export compared to other sub-watersheds in the Lake Winona direct drainage area.

PRE-DEVELOPMENT LOAD ESTIMATION

Once the model is calibrated for current in-lake phosphorus concentration, we can then manipulate land cover and other factor loadings to estimate pre-development loading scenarios (e.g., what in-lake phosphorus concentration was prior to human development or the best possible water quality for the lake). Refer to Attachment 2: Estimating Pre-Development Phosphorus Load for details on methodology. Comparing the pre-development scenario to current conditions showed that total phosphorus loading to Lake Waukewan increased by 225%, from 118.2 kg/yr prior to European settlement to 384.6 kg/yr under current conditions (Table 3). For Lake Winona, total phosphorus loading increased from 42.2 kg/yr to

116.9 kg/yr (177%) across the two scenarios. These additional phosphorus sources under current conditions are coming from development in the watershed, septic systems, atmospheric dust, and internal loading (Table 3). Water quality prior to settlement was predicted to be excellent with extremely low phosphorus and chlorophyll-*a* concentrations and high water clarity (Table 2).

FUTURE LOAD ESTIMATION

We can also simulate land cover change and other factors to estimate future loading scenarios. This scenario estimates what the in-lake phosphorus concentration might be at full build-out under current zoning, representing the maximum possible development according to existing regulations. Refer to Attachment 3: Estimating Future Phosphorus Load at Full Build-Out and the 2026 *Lake Waukewan Watershed Build-out Analysis Report* (FBE, 2026) for details on methodology. Note that the future scenario did not assume the estimated 10% increase in precipitation over the next century (National Oceanic and Atmospheric Administration (NOAA), 2013). Climate change models for the region predict more intense and less frequent rain events. Higher precipitation can reduce the in-lake phosphorus concentration through dilution; however, high precipitation may also exacerbate erosion of phosphorus-laden sediment to surface waters and therefore could increase in-lake phosphorus concentration. This change cannot be incorporated into the future scenario estimation because the model does not consider the rate and distribution of the projected increase in precipitation.

Future loading estimation showed that total phosphorus loading to Lake Waukewan may increase by 82.4%, from 384.6 kg/yr under current conditions to 701.7 kg/yr at full build-out (2130) under current zoning (Table 3). For Lake Winona, phosphorus loading may increase from 116.9 kg/yr to 324.2 kg/yr (177%). Additional phosphorus will be generated from more development in the watershed, greater atmospheric dust, more septic systems, and enhanced internal loading (Table 3, Table 4). Some of the largest increases will come from sub-watersheds with the highest build-out potential, such as those in Center Harbor. These include the Hawkins Pond Direct, Bear Pond Direct, Winona East – Hawkins Tributary, EE Brook, Otter Pond Direct, Piper Hill Tributary, North Waukewan Tributary, and parts of the Lake Winona Direct, North Winona Tributary, Winona East Tributary, Snake River, East Waukewan Tributary, and Waukewan Direct sub-watersheds (Table 4, Table 5, Table 6, Table 7, Table 8). The Lake Waukewan model predicted higher (worse) phosphorus concentration of 12.9 μg/L, higher (worse) chlorophyll-*a* concentration of 4.4 μg/L, lower (worse) water clarity of 3.2 m, and an increase from 0 to 30 cyanobacteria bloom days compared to current conditions for the lake (Table 2). Predicted future water quality was similarly poor for Lake Winona with a total phosphorus concentration of 23.9 μg/L, a chlorophyll-*a* concentration of 10.6 μg/L and 226 days of cyanobacteria blooms during the year (Table 2).

Table 2. In-lake water quality predictions for Lake Waukewan and Lake Winona. TP = total phosphorus. Chl-*a* = chlorophyll-*a*. SDT = Secchi disk transparency. Bloom Days represent average annual probability of chlorophyll-*a* exceeding 8 μg/L.

Waterbody	Model Scenario	Observed Median TP *(μg/L)*	Predicted Median TP *(μg/L)*	Observed Mean Chl-*a* *(μg/L)*	Predicted Mean Chl-*a* *(μg/L)*	Observed Mean SDT *(m)*	Predicted Mean SDT *(m)*	Predicted Bloom Days
Lake Waukewan	Pre-Development	no data	2.2	no data	0.2	no data	12.7	0
	Current (2025)	7.1	7.1	2.2	2.0	6.9	5.1	0
	Future (2130)	no data	12.9	no data	4.4	no data	3.2	27
Lake Winona	Pre-Development	no data	3.1	no data	1.5	no data	9.7	0
	Current (2025)	8.5	8.6	5.0	4.0	5.5	4.4	19
	Future (2130)	no data	23.9	no data	10.6	no data	2.0	226

Table 3. Total phosphorus (TP) and water loading summary by model and source for modeled waterbodies in the Lake Waukewan watershed. *Includes watershed load from Lake Winona.

Waterbody	Development State	Measurement (Units)	Atmospheric	Internal	Waterfowl	Septic System	Watershed Load	Total Load To Lake
Lake Waukewan	Pre-Development	TP (kg/yr)	27.2	0	23.3	0	67.8*	**118.2**
		TP (%)	23	0	20	0	57*	**100**
		Water (m^3/yr)	4,636,557	0	0	0	16,538,001*	**21,174,558**
	Current (2025)	TP (kg/yr)	42.7	21.2	23.3	29.2	268.2*	**384.6**
		TP (%)	11	5	6	8	70*	**100**
		Water (m^3/yr)	4,636,557	0	0	24,517	16,454,361*	**21,115,434**
	Future (2130)	TP (kg/yr)	97.0	39.5	23.3	34.8	507.9*	**701.7**
		TP (%)	14	6	3	5	72*	**100**
		Water (m^3/yr)	4,636,557	0	0	31,502	16,334,197*	**21,002,256**
Lake Winona	Pre-Development	TP (kg/yr)	4.5	0	3.9	0	33.9	**42.2**
		TP (%)	11	0	9	0	80	**100**
		Water (m^3/yr)	781,096	0	0	0	7,665,837	**8,446,933**
	Current (2025)	TP (kg/yr)	7.1	5.7	3.9	12.9	87.3	**116.9**
		TP (%)	6	5	3	11	75	**100**
		Water (m^3/yr)	781,096	0	0	10,762	7,654,278	**8,446,136**
	Future (2130)	TP (kg/yr)	16.0	16.7	3.9	16.6	272.0	**324.2**
		TP (%)	5	5	1	5	84	**100**
		Water (m^3/yr)	781,096	0	0	15,361	7,597,146	**8,393,603**

Table 4. Summary of land area, water flow, and total phosphorus (TP) concentration and loading by model and sub-watershed (East Waukewan Tributary, EE Brook, North Waukewan Tributary, Otter Pond Direct) for Lake Waukewan. Land area does not include the area of the lake.

Development State	Measurement (Units)	East Waukewan Tributary *(99.6 ha)*	EE Brook *(25.7 ha)*	North Waukewan Tributary *(135.4 ha)*	Otter Pond Direct *(85.5 ha)*
Pre-Development Watershed Loads	Water Flow (m^3/year)	627,516	172,114	858,151	539,604
	Calc. P Conc. (mg/L)	0.005	0.005	0.005	0.005
	P mass (kg/year)	3.0	0.9	4.7	2.7
	P mass by area (kg/ha/year)	0.03	0.04	0.03	0.03
Current (2025) Watershed Loads	Water Flow (m^3/year)	624,476	171,945	849,311	538,855
	Calc. P Conc. (mg/L)	0.015	0.008	0.022	0.008
	P mass (kg/year)	9.7	1.4	18.8	4.3
	P mass by area (kg/ha/year)	0.10	0.06	0.14	0.05
Future (2130) Watershed Loads	Water Flow (m^3/year)	623,426	166,955	838,280	528,875
	Calc. P Conc. (mg/L)	0.019	0.065	0.047	0.044
	P mass (kg/year)	11.6	10.9	39.6	23.1
	P mass by area (kg/ha/year)	0.12	0.42	0.29	0.27

Table 5. Summary of land area, water flow, and total phosphorus (TP) concentration and loading by model and sub-watershed (Piper Hill Tributary, Reservoir Brook, Sayward Brook, Snake River) for Lake Waukewan. Land area does not include the area of the lake. The Snake River sub-watershed is adjusted to exclude Lake Winona, which is routed through the sub-watershed as a point source.

Development State	Measurement (Units)	Piper Hill Tributary *(42.3 ha)*	Reservoir Brook *(329.2 ha)*	Sayward Brook *(188.2 ha)*	Snake River *(201.1 ha)*
Pre-Development Watershed Loads	Water Flow (m^3/year)	287,226	1,995,255	1,201,343	1,119,995
	Calc. P Conc. (mg/L)	0.005	0.005	0.005	0.005
	P mass (kg/year)	1.5	9.8	5.9	5.8
	P mass by area (kg/ha/year)	0.03	0.03	0.03	0.03
Current (2025) Watershed Loads	Water Flow (m^3/year)	284,584	1,961,516	1,190,972	1,116,341
	Calc. P Conc. (mg/L)	0.019	0.029	0.020	0.015
	P mass (kg/year)	5.4	57.0	23.6	17.0
	P mass by area (kg/ha/year)	0.13	0.17	0.13	0.08
Future (2130) Watershed Loads	Water Flow (m^3/year)	279,483	1,954,174	1,180,151	1,107,283
	Calc. P Conc. (mg/L)	0.054	0.036	0.037	0.031
	P mass (kg/year)	15.1	70.8	44.1	34.0
	P mass by area (kg/ha/year)	0.36	0.22	0.23	0.12

Table 6. Summary of land area, water flow, and total phosphorus (TP) concentration and loading by model and sub-watershed (Waukewan Direct, Waukewan Street Tributary, Winona Shores Tributary) for Lake Waukewan. Land area does not include the area of the lake.

Development State	Measurement (Units)	Waukewan Direct *(412.7 ha)*	Waukewan Street Tributary *(26.7 ha)*	Winona Shores Tributary *(38.7 ha)*
Pre-Development Watershed Loads	Water Flow (m^3/year)	2,798,966	181,426	262,988
	Calc. P Conc. (mg/L)	0.005	0.004	0.004
	P mass (kg/year)	12.8	0.8	1.2
	P mass by area (kg/ha/year)	0.03	0.03	0.03
Current (2026) Watershed Loads	Water Flow (m^3/year)	2,783,275	177,657	262,649
	Calc. P Conc. (mg/L)	0.025	0.040	0.011
	P mass (kg/year)	68.7	7.0	3.0
	P mass by area (kg/ha/year)	0.17	0.26	0.08
Future (2130) Watershed Loads	Water Flow (m^3/year)	2,765,842	177,324	261,651
	Calc. P Conc. (mg/L)	0.037	0.043	0.019
	P mass (kg/year)	101.6	7.7	4.9
	P mass by area (kg/ha/year)	0.25	0.29	0.13

Table 7. Summary of land area, water flow, and total phosphorus (TP) concentration and loading by model and sub-watershed (Bear Pond Direct, Hawkins Pond Direct, North Winona Tributary, and South Winona Tributary) for Lake Winona. Land area does not include the area of the lake. * Does not include upstream sub-watersheds.

Development State	Measurement (Units)	Bear Pond Direct *(189.2 ha)*	Hawkins Pond Direct* *(233.7 ha)*	North Winona Tributary *(432.5 ha)*	South Winona Tributary *(27.4 ha)*
Pre-Development Watershed Loads	Water Flow (m^3/year)	1,345,169	1,203,025	2,818,074	190,270
	Calc. P Conc. (mg/L)	0.005	0.004	0.005	0.004
	P mass (kg/year)	6.1	4.8	13.1	0.8
	P mass by area (kg/ha/year)	0.03	0.02	0.03	0.03
Current (2026) Watershed Loads	Water Flow (m^3/year)	1,338,714	1,198,773	2,821,938	190,054
	Calc. P Conc. (mg/L)	0.012	0.014	0.008	0.009
	P mass (kg/year)	16.6	16.7	22.0	1.7
	P mass by area (kg/ha/year)	0.09	0.07	0.05	0.06
Future (2130) Watershed Loads	Water Flow (m^3/year)	1,324,100	1,184,405	2,812,873	189,679
	Calc. P Conc. (mg/L)	0.051	0.053	0.018	0.015
	P mass (kg/year)	66.9	62.9	51.5	2.9
	P mass by area (kg/ha/year)	0.35	0.27	0.12	0.11

Table 8. Summary of land area, water flow, and total phosphorus (TP) concentration and loading by model and sub-watershed (Winona East – Hawkins Tributary, Winona East Tributary, and Lake Winona Direct) for Lake Winona. Land area does not include the area of the lake. * Does not include upstream sub-watersheds.

Development State	Measurement (Units)	Winona East – Hawkins Tributary* *(37.9 ha)*	Winona East Tributary *(139.4 ha)*	Lake Winona Direct *(215.4 ha)*
Pre-Development Watershed Loads	Water Flow (m^3/year)	199,238	1,008,123	1,490,261
	Calc. P Conc. (mg/L)	0.004	0.005	0.004
	P mass (kg/year)	0.8	4.9	6.6
	P mass by area (kg/ha/year)	0.02	0.04	0.03
Current (2026) Watershed Loads	Water Flow (m^3/year)	197,768	1,005,613	1,487,499
	Calc. P Conc. (mg/L)	0.016	0.017	0.013
	P mass (kg/year)	3.3	17.2	20.0
	P mass by area (kg/ha/year)	0.09	0.12	0.09
Future (2130) Watershed Loads	Water Flow (m^3/year)	196,879	991,492	1,476,617
	Calc. P Conc. (mg/L)	0.031	0.066	0.038
	P mass (kg/year)	6.1	65.9	55.5
	P mass by area (kg/ha/year)	0.16	0.47	0.26

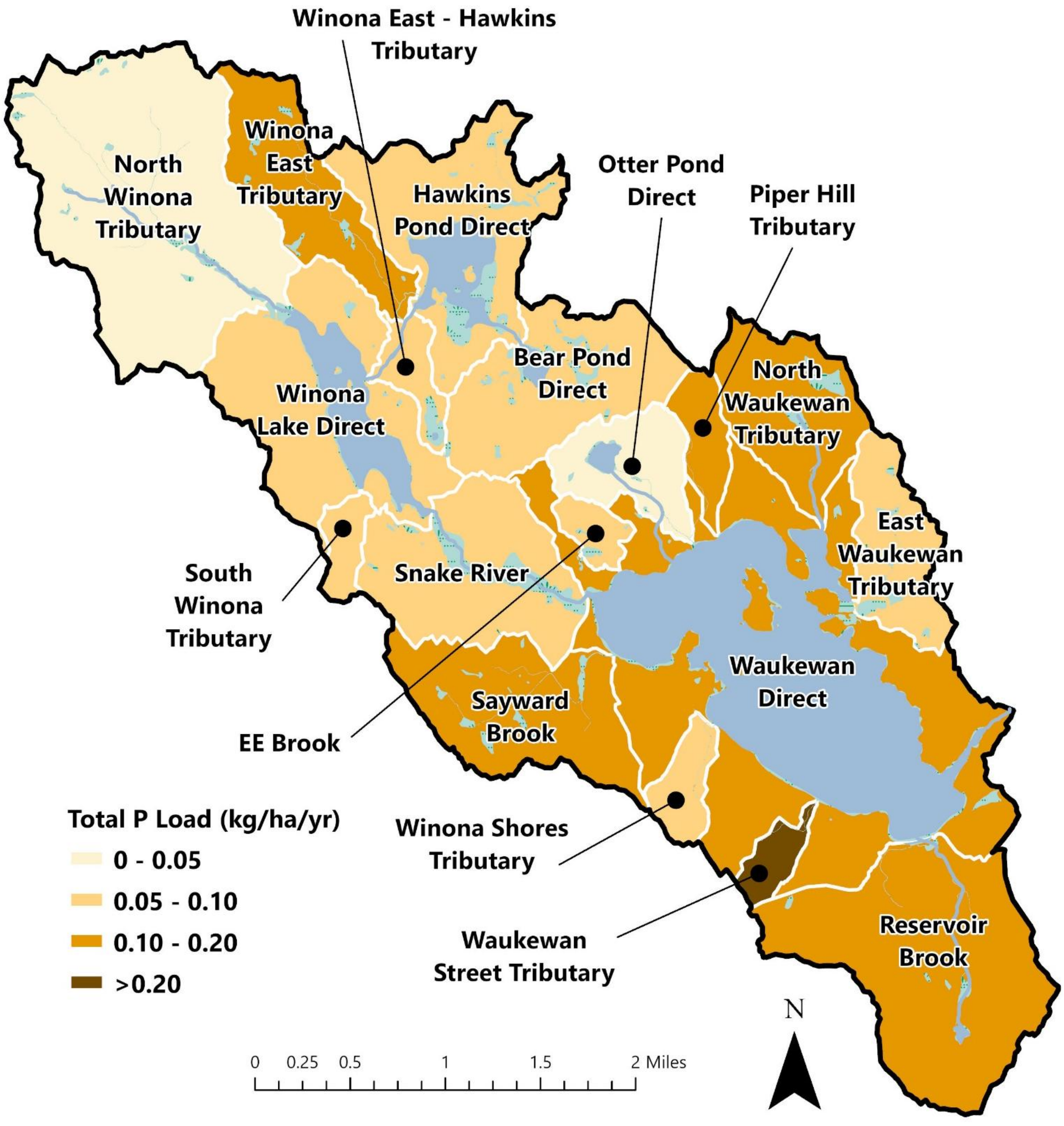

Figure 7. Map of current total phosphorus load per unit area (kg/ha/yr) for each sub-watershed in the Lake Waukewan and Lake Winona watershed. Higher phosphorus loads per unit area are concentrated in the more developed southern portion of the watershed.

CONCLUSION

The modeling showed that the water quality of Lake Waukewan and Lake Winona is threatened by current development activities in the watershed and would degrade further—severely in the case of Lake Winona—with continued unmitigated development in the future.

Both Lake Waukewan and Lake Winona are known to have historically excellent water quality, especially Lake Waukewan which is a public drinking water supply. However, both lakes have experienced cyanobacteria blooms in recent years. Despite water quality measurements and model predictions that suggest a low bloom risk (zero bloom days predicted for Lake Waukewan under current conditions), ephemeral water quality conditions may facilitate bloom formation especially in relation to anomalous weather patterns and record high temperatures observed in recent years. Blooms in Lake Waukewan have anecdotally been observed in the months approaching and following lake turnover, which often are not recorded as official NHDES cyanobacteria bloom warnings.

Modeled results for both waterbodies suggest that most of the phosphorus loading to the lakes comes from external sources (95% for each waterbody). Lake Winona and its watershed only account for 14% of the total phosphorus load to Lake Waukewan, likely due to 1) the large areas of intact forestland in the Lake Winona watershed and 2) nutrient attenuation through the Snake River. At full buildout, the total phosphorus load to Lake Winona is predicted to increase by 177%, indicative of the high buildout potential in this area. Watershed protection efforts may focus on high-loading sub-watersheds, including the direct shorelines of both Lake Winona and Lake Waukewan and the more intensely developed southern portion of the Lake Waukewan watershed.

For both modeled waterbodies, the LLRM predicts more prevalent blooms in the future. Any new increases in phosphorus to a lake can disrupt the ecological balance in favor of increased algal growth, resulting in degraded water clarity. The impact from new buildings and septic systems can be greatly reduced by implementing low impact development (LID) techniques and ensuring that all new septic systems are well separated from surface waters both horizontally and vertically (above seasonal high groundwater and in suitable soil). A substantial increase in phosphorus loading is predicted due to the development of currently undeveloped headwater areas, especially in the Lake Winona watershed and in the Town of Center Harbor (Hawkins Pond Direct, Bear Pond Direct, Winona East – Hawkins Tributary, EE Brook, Otter Pond Direct, Piper Hill Tributary, North Waukewan Tributary, and parts of the Lake Winona Direct, North Winona Tributary, Winona East Tributary, Snake River, East Waukewan Tributary, and Waukewan Direct sub-watersheds). Future loading may be prevented through land conservation efforts or land use planning that seeks to protect undisturbed natural areas while promoting lower impact development in areas with existing infrastructure to support the growing population. While the watershed management plan for Lake Waukewan and Lake Winona will provide a comprehensive action plan to improve and protect water quality in the watershed, the above modeling strongly indicates these initial suggestions: 1) maximize land conservation of intact forestland, 2) consider zoning ordinance amendments that protect natural resources or regulate lot sizes in the upper watershed, and 3) improve and maintain stormwater control practices throughout the watershed.

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ATTACHMENT 1: LAND COVER

Land cover water (precip) and phosphorus (P) export coefficients.

Land Cover	Runoff Export Coeff. **Precip** *(Fraction)*	Runoff Export Coeff. **P Export** *(kg/ha/yr)*	Baseflow Export Coeff. **Precip** *(Fraction)*	Baseflow Export Coeff. **P Export** *(kg/ha/yr)*
Urban 1 (Low Density Res.)	0.30	0.79	0.25	0.010
Urban 2 (Medium Density Res./Comm.)	0.50	0.82	0.05	0.010
Urban 3 (Roads)	0.50	1.16	0.05	0.010
Urban 4 (Industrial)	0.50	1.42	0.05	0.010
Urban 5 (Open Space/Mowed)	0.30	0.51	0.25	0.010
Agric 2 (Row Crop/Hayfield/Orchard)	0.30	0.37	0.30	0.010
Agric 3 (Grazing)	0.30	1.50	0.30	0.010
Forest 1 (Upland)	0.20	0.03	0.40	0.004
Forest 2 (Wetland)	0.05	0.003	0.40	0.004
Open 1 (Emergent Wetland/Lake)	0.05	0.01	0.40	0.004
Open 2 (Meadow)	0.30	0.20	0.30	0.004
Open 3 (Excavation)	0.80	0.80	0.10	0.010
Other 1: Logging	0.30	0.06	0.30	0.004
Other 2: Unpaved Road	0.60	0.83	0.05	0.010

Land cover areas for sub-watersheds in the Lake Waukewan watershed. Excludes the Lake Waukewan surface area. Land cover areas for the Lake Winona sub-watersheds are reported separately.

Lake Waukewan

Land Cover	East Waukewan Tributary *(ha)*	EE Brook *(ha)*	North Waukewan Tributary *(ha)*	Otter Direct *(ha)*	Piper Hill Tributary *(ha)*	Reservoir Brook *(ha)*	Sayward Brook *(ha)*
Urban 1 (Low Density Res.)	8.62	0.65	12.53	1.87	3.78	27.94	20.62
Urban 2 (Medium Density Res./Comm.)	*none*	*none*	1.07	*none*	*none*	20.60	*none*
Urban 3 (Roads)	0.54	0.01	1.98	0.05	1.14	11.98	2.03
Urban 4 (Industrial)	*none*	*none*	*none*	*none*	*none*	*none*	*none*
Urban 5 (Open Space/Mowed)	*none*	*none*	3.79	*none*	*none*	9.98	*none*
Agric 2 (Row Crop/Hayfield/Orchard)	0.00	0.00	4.61	0.82	0.46	4.93	6.01
Agric 3 (Grazing)	*none*	*none*	*none*	*none*	*none*	*none*	0.08
Forest 1 (Upland)	77.77	22.24	94.56	72.66	35.18	224.78	143.88
Forest 2 (Wetland)	9.17	1.64	8.09	1.17	0.28	2.13	7.07
Open 1 (Emergent Wetland/Lake)	0.21	0.00	1.57	6.39	0.17	5.02	1.08
Open 2 (Meadow)	2.58	1.07	6.62	2.45	1.21	6.84	4.21
Open 3 (Excavation)	*none*	*none*	*none*	*none*	*none*	*none*	*none*
Other 1: Logging	*none*	*none*	*none*	*none*	*none*	14.15	2.54
Other 2: Unpaved Road	0.70	0.07	0.59	0.10	0.05	0.81	0.67
Total Area	**99.58**	**25.68**	**135.39**	**85.51**	**42.28**	**329.16**	**188.20**

Lake Waukewan (cont.)

Land Cover	Snake River *(ha)*	Waukewan Direct *(ha)*	Waukewan Street Tributary *(ha)*	Winona Shores Tributary *(ha)*	Total Area *(ha)*
Urban 1 (Low Density Res.)	13.51	34.36	1.41	1.96	127.26
Urban 2 (Medium Density Res./Comm.)	*none*	21.58	4.74	*none*	47.98
Urban 3 (Roads)	2.12	8.10	1.66	0.24	29.84
Urban 4 (Industrial)	*none*	*none*	*none*	*none*	0.00
Urban 5 (Open Space/Mowed)	0.08	1.30	*none*	*none*	15.14
Agric 2 (Row Crop/Hayfield/Orchard)	2.57	7.74	0.00	0.00	27.13
Agric 3 (Grazing)	*none*	*none*	*none*	*none*	0.08
Forest 1 (Upland)	149.49	322.66	18.36	35.90	1197.48
Forest 2 (Wetland)	13.53	6.05	0.02	*none*	49.13
Open 1 (Emergent Wetland/Lake)	9.86	1.27	0.31	0.24	26.13
Open 2 (Meadow)	8.32	2.12	*none*	*none*	35.43
Open 3 (Excavation)	*none*	*none*	*none*	*none*	0.00
Other 1: Logging	*none*	*none*	*none*	*none*	16.69
Other 2: Unpaved Road	1.61	7.54	0.23	0.32	12.71
Total Area	**201.10**	**412.73**	**26.72**	**38.67**	**1585.01**

Lake Winona

Land Cover	Bear Pond Direct *(ha)*	Hawkins Pond Direct *(ha)*	North Winona Tributary *(ha)*	South Winona Tributary *(ha)*	Winona East – Hawkins Tributary *(ha)*	Winona East Tributary *(ha)*	Lake Winona Direct *(ha)*	Total Area *(ha)*
Urban 1 (Low Density Res.)	8.60	12.18	5.27	0.78	3.36	5.33	13.09	48.61
Urban 2 (Medium Density Res./Comm.)	*none*	*none*	1.18	*none*	*none*	*none*	*none*	1.18
Urban 3 (Roads)	1.45	1.87	1.14	0.18	0.67	0.34	1.74	7.40
Urban 4 (Industrial)	*none*	*none*	*none*	*none*	*none*	*none*	*none*	0.00
Urban 5 (Open Space/Mowed)	0.39	1.00	0.09	*none*	*none*	0.07	*none*	1.55
Agric 2 (Row Crop/Hayfield/Orchard)	0.53	7.52	0.77	0.00	0.15	0.84	0.88	10.69
Agric 3 (Grazing)	1.23	0.92	0.61	*none*	*none*	4.43	*none*	7.19
Forest 1 (Upland)	155.98	146.62	377.50	26.34	27.52	96.81	162.30	993.08
Forest 2 (Wetland)	13.87	17.05	10.20	*none*	4.27	3.72	2.23	51.33
Open 1 (Emergent Wetland/Lake)	5.95	39.02	4.22	*none*	1.75	1.42	0.09	52.45
Open 2 (Meadow)	1.16	0.90	6.27	*none*	*none*	1.82	0.35	10.50
Open 3 (Excavation)	*none*	*none*	*none*	*none*	*none*	*none*	*none*	0.00
Other 1: Logging	*none*	5.49	22.27	*none*	*none*	24.26	32.76	84.78
Other 2: Unpaved Road	0.01	1.15	2.95	0.12	0.16	0.32	2.01	6.72
Total Area	**189.18**	**233.72**	**432.47**	**27.43**	**37.89**	**139.36**	**215.44**	**1275.49**

ATTACHMENT 2: ESTIMATING PRE-DEVELOPMENT PHOSPHORUS LOAD

1. Converted all human land cover to forest (Forest 1).
2. Removed all septic inputs (set population to zero).
3. Removed internal loading, if applicable, assuming internal loading was the result of excess nutrient loading from human activities in the watershed that have accumulated in the lake sediments.
4. Reduced atmospheric loading coefficient to 0.07 kg/ha/yr.
5. Reduced point sources (other lakes) to reflect pre-development phosphorus loads from upstream lakes/ponds, if applicable, according to their LLRM outputs.
6. Roughly matched outflow TP to predicted in-lake TP.
7. Kept all else the same, assuming waterfowl counts and precipitation input did not change. See Future Load Estimation section for a discussion of future precipitation and why these changes cannot be incorporated into the model.

ATTACHMENT 3: ESTIMATING FUTURE PHOSPHORUS LOAD AT FULL BUILD-OUT

1. Estimated number of new buildings at full buildout by sub-watershed. CommunityViz software uses model inputs such as population growth rates, zoning, wetlands, conservation lands, and other constraints to construction, and generates a projected number of new buildings in the future. The new building count was generated for each sub-watershed at full buildout. Refer to the 2026 Lake Waukewan & Lake Winona Buildout Analysis Report (FBE, 2026).
2. Calculated developed land cover after full buildout projection. Each new building was assumed to generate new developed land uses, including buildings, roads, etc. Specifically, the existing areas of land cover categories Urban 1-5, Open 3, and Other 2 were divided by the number of existing buildings to determine how much of each land cover category is associated with each building, in the unit hectares per building. The number of new buildings per sub-watershed was multiplied by amount of hectares per building for each land cover category to calculate the change in land cover for each sub-watershed and land cover category.
3. Incorporated land use changes to LLRM for P loading predictions. Added the new developed land cover estimate in the LLRM. Within each sub-watershed, existing undeveloped land cover (Forest 1) were replaced with areas equal to added developed land.
4. Incorporated septic system loading to LLRM for P loading predictions. The number of new buildings within 250 ft of water was estimated from the CommunityViz output shapefile of projected new buildings. Projected buildings within 250 ft of lake shorelines were joined with the NHDES Water and Sewer Line parcel; projected buildings in the area served by sewer were removed.
5. Increased atmospheric loading coefficient to 0.25 kg/ha/yr.
6. Calculated potential increase in internal loading. Assumed a similar magnitude increase in future loading from internal loading sources as compared to the increase in all external sources for each model, including atmospheric deposition, waterfowl, septic systems, and the watershed load.
7. Roughly matched outflow TP to predicted in-lake TP.
8. Kept all else the same, assuming waterfowl counts and precipitation input did not change. See Future Load Estimation section for a discussion of future precipitation and why these changes cannot be incorporated into the model.