

Piezometric Determination of Groundwater Flux and Phosphorus Loading of Torch Lake

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November 28, 2005**

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Abstract:

The Three Lakes Association and the Great Lakes Environmental Center are cooperating in the development of a predictive nutrient based water quality model for the Three Lakes System in order to quantitatively assess the impact of future developments on the Lake system's water quality. The first of the three lakes, Torch Lake, is being modeled based on Tributary input, Atmospheric input, Groundwater Flux, Torch Lake water body analysis and Torch Lake sediment analysis. This report focuses on the contribution of Groundwater flux, measured by piezometric wells distributed along the shoreline. The total measured groundwater flux is 84.2 cfs, the phosphorus nutrient loading from groundwater is 1509 kg/yr. These numbers are higher than estimated values for groundwater flux; however, the analysis will be improved by further evaluating the representative areas through which there is active appreciable groundwater flux.

Introduction:

Three Lakes Association (TLA)¹ and the Great Lakes Environmental Center (GLEC)² are cooperating in the development of a predictive nutrient based water quality model for the Three Lakes System (Torch Lake, Clam Lake, and Lake Bellaire) located in Antrim and Kalkaska Counties, in northern Michigan (Appendix Fig. 1). This project is being funded by a water quality monitoring grant from the Michigan Department of Environmental Quality (MDEQ)³. Because of the size and complexity of the Three Lakes System, the whole project will be carried out over the course of three years, the first year to focus on Torch Lake, the second year to focus on Clam Lake and Lake Bellaire, and the third part on the remainder of the Lake chain that eventually leads into Lake Michigan. This report concerns the overall nutrient based modeling of Torch Lake with a focus on the contribution of Groundwater Flux into that model.

Torch Lake is the largest of the three lakes and it is the longest and largest inland lake in Michigan by volume. There is no major industry surrounding Torch Lake, nor is there a central sewage treatment system. The shoreline is mostly private residential properties with individual septic systems. The lake is a highly oligotrophic lake with low algae concentration and very deep light penetration. The Secchi depth is 20-30 ft. Torch Lake is also very deep with a maximum depth of 310 ft, an average depth of 140 ft and a residence time of approximately 20 years. The bedrock of shale makes the water in Torch Lake very hard. Overall Torch Lake is a clean, deep, cold, hardwater, glacial lake

¹ Three Lakes Association, PO Box 689, Bellaire, MI 49615.

² Great Lakes Environmental Center, 739 Hastings St., Traverse City, MI 49686.

³ Michigan Department of Natural Resources, Geological Survey Division, Antrim County Bedrock, 1976.

renowned for its beauty which comes from its deep blue color and remarkable water clarity⁴.

The surround area of the Three Lakes System is a community that relies heavily on the summer tourism industry for their economic wellbeing. The tourism industry depends on the beautiful environment to draw in tourists and the Three Lakes System (and Torch Lake in particular) is an integral part of this aesthetically appealing environment. In this economic climate there is a great motivation to "exploit" these natural resources, i.e. build golf courses, lake side motels, trailer parks. These developments are necessary to draw money into the local economy; however, it is feared that an overdevelopment of the local areas could ruin the environment that forms the very foundation of the tourism industry. Hence, a quantitative tool is needed to predict what effect particular developments will have on the water quality of the lakes in the future. Since Torch Lake is a highly oligotrophic, the beauty and water quality of the lake is dependent on the low algal concentration which in turn is dependent on the low concentration of life limiting nutrients like phosphorus. Hence the predictive nutrient based water quality model required an overall balance of phosphorus in Torch Lake. The groundwater phosphorus flow is of considerable importance since any new development in the surrounding area will mostly affect the phosphorus loading of Torch Lake through groundwater flow.

It should be noted that another affect on the nutrient level in Torch Lake is being considered. Calcium Carbonate (CaCO_3) acting as an agent that precipitates the free phosphorus in the lake water and causes it to sink down and be trapped in the marl-like

⁴ Branson, Dean. Bretz, Norton. Endicott, Doug. Hannert, Tim. Roush, Paul. Project Plan; Characterization of Groundwater Phosphorus Input to Torch Lake. Ver. 5. May 16, 2005.

sediment thus preventing it from facilitating algal growth. The reaction is currently being analyzed. The CaCO_3 mechanism could buffer the adverse affects of additional phosphorus loading to a degree and will certainly affect the way that phosphorus affects the overall water quality of the lake. The exact mechanism and constraints of this precipitation reaction are still being researched.

Overview:

The overall nutrient based predictive water quality modeling of Torch Lake can be broken into five components: Tributary input, Atmospheric input, Groundwater Flux, Torch Lake water body analysis and Torch Lake sediment analysis⁵. The first three components contribute to the water balance of Torch Lake and data will be collected to determine their volumetric flow rates and the characteristics of the water they contribute. The body of water that makes up Torch Lake itself is also part of the water balance, but for the development of the model the lake's water level will be assumed to be at steady state. This is a valid assumption since Torch Lake's water level is controlled by a dam. The characteristics of the water in Torch Lake will obviously not be considered at steady state, since that is the whole point of the project. The sediment analysis does not contribute to the water balance but will be used to elucidate more about the reactions phosphorus undergoes once it enters Torch Lake.

The flow rate of atmospheric input into Torch Lake was collected through two simple rain meters positioned on the east and west ends of the Lake in addition to two MSU continuous rain sampling stations at the north and south ends of Torch. The volume of rain water collected per unit time and per area of the rain meter was then multiplied by the surface area of Torch Lake to get the overall water input through rain water. Evaporation was taken to be roughly equal to 85% of the rain inflow; however, the finished model will have a more precise measurement of this value based on temperature and humidity measurements from the MSU sampling stations. In terms of

⁵ Development of a Predictive Nutrient-Based Water Quality Model for the Three Lakes System Year 1: Torch Lake, T. Hannert, D. Branson, M. DeGraeve and D. Endicott, Three Lakes Association and Great Lakes Environmental Center, 04 MDEQ grant PO# 761P40021 (June, 2004).

the nutrient balance, evaporating rain water does not carry phosphorus, while falling rain water does deposit phosphorus from the atmosphere. To determine the concentration of phosphorus in the rain water, samples were taken to a GLEC laboratory⁶ to be analyzed. Measurements and sample were taken twice a month.

The flow rate of large tributaries was measured by using flow probes to build velocity profiles of a cross sectional area of the tributary. This was done by measuring velocity at different depths and at different distances from the shore. For smaller and shallower tributaries a marker was thrown into the tributary and the time it took to travel a given distance was used to ascertain the velocity. The cross sectional area was then measured to estimate the volumetric flow. Samples were also taken from the tributaries for measurement of phosphorus concentration at GLEC laboratories. Measurements and samples were taken 3 times a month and more often during storm events.

The measurement of the groundwater flux into Torch Lake was the most complicated process both in terms of data collection and analysis. Piezometric wells were installed at over 24 locations around the lake (Appendix Fig. 2). The locations were chosen to be approximately equidistant from one another with the constraint that the installation of the wells required approval from the owner of the residential property. It was assumed that groundwater flux into the lake was only appreciable around the shoreline and would decline exponentially as one moved away from the shoreline. The wells were used to measure the hydrostatic pressure and the flow resistance or hydraulic conductivity of shallow groundwater flow. These two measurements, in addition to the

⁶ GLEC SOP Number: CHM 2001: STANDARD OPERATING PROCEDURE FOR THE DETERMINATION OF TOTAL PHOSPHORUS IN SURFACE WATER SAMPLES

representative area of each well site, would be related to the volumetric groundwater flow rate through Darcy's equation, which will be discussed in greater detail in the following section. The wells were also pumped to obtain samples for analysis at the GLEC lab for phosphorus concentration. Lake water samples were taken from the lake water near the well in order to determine the background concentration of phosphorus in the lake water at the point where the groundwater is entering the lake. The characteristics of flow exhibited by the well were assumed to be characteristic of the flow through the entire area represented by the well. Also, the soil was assumed to be uniform in each area. Measurements and samples were taken once a month but it should be noted that groundwater data sampling was only done over the summer and does not indicate how the environment acts throughout the year.

Lastly, water composition data was taken for Torch Lake itself at both the north end and the south end. The samples were taken above and below the thermocline and analyzed for phosphorus concentration. The samples were also analyzed for hardness, alkalinity, levels of chlorophyll a and nitrate concentration. A probe was also lowered at the north and south basins to establish a vertical water profile of dissolved oxygen, pH, specific conductivity and temperature as a function of depth. Sediment core samples were taken at the north and south ends so that the amount of phosphorus trapped in the sediment could be analyzed at Central Michigan University in order to understand the conditions under which the phosphorus is dissolved or precipitated in the lake water. Sediment traps suspended by buoys were also used to estimate the rate of sedimentation. The data collected through the sediment core sampling and the sediment traps were used

to determine how phosphorus reacts when it enters the lake and to help determine how excess phosphorus loading will affect water quality.

Methodology:

To measure the groundwater flux into Torch Lake, 24 piezometric well sites were chosen along the shoreline. The wells were spread out in a manner to adequately cover the shoreline of the lake within both the economic constraints of the project and the fact that permission was required from the land owners before installation could commence. The wells were designed to measure the total shallow groundwater flow and allow groundwater sampling for phosphorus concentration.

The wells themselves consisted of a long segment of 1/4 inch diameter polyethylene tubing which was perforated at the end and wrapped with a fine mesh screen of pore diameter 0.1-0.3 mm. A steel point was then attached to the end of the tubing to allow the tubing to be hammered into the ground (Appendix Fig. 3). The well assembly was tested for phosphorus by running distilled water through the assembly and testing it for phosphorus concentration. During the installation, the well assembly was fed through a 3/4 inch diameter steel pipe so the steel point would be sticking out one end and the excess polyethylene tubing would be sticking out the other. The steel pipe was then hammered down 2-5 ft into the sand and gravel at bottom of the lake. Once the well was down, the steel pipe was drawn back and the steel point and polyethylene tubing were left down in the ground. An excess of polyethylene tubing was left sticking out of the ground and the tubing was plugged to prevent lake water contamination

Once the well was installed it was allowed to season for a period of one week in order to allow any silt that was stirred up during installation to settle. After the seasoning period the well was tested by drawing a small amount of ground water up from the well and taking the sample to be analyzed at the GLEC labs for phosphorus concentration. A

lake sample of the water around the well was also taken for analysis as a means of comparison to be able to see if the groundwater differed from the well water. The wells head height (dh), was also measured in order to obtain the hydrostatic pressure. Then the water level in the tubing was raised to a predetermined level (either 2 or 3 ft, H2) above the lake water line. The raised water level was then allowed to fall to a level 1ft above the water line (H1) and the rate of this drop was measured by timing (t) the distance it took to travel between the two points (H2-H1) (Appendix Fig. 5). In this way the hydraulic conductivity was measured⁷.

These data are related by Darcy's equation as follows:

$$Q = A(dh/dl)K_h.$$

Q is total groundwater flux of the well site
 A is the area of the well site
 dh/dl is the hydrostatic pressure
 Kh is the hydraulic conductivity
 dh is the length of the head on the well at equilibrium
 dl is the depth of the well below the ground

$$K_h = [D^2/8L(t)] * \ln(2L/D) * \ln(H_2/H_1) \text{ when } L/D > 4$$

D is the internal diameter of the polyethylene tubing
 L is the length of perforated polyethylene tubing through which the groundwater is absorbed
 t is the time for the water level to fall between H2 and H1
 H2 is the level that the water is initially raised to
 H1 is the lower level that the water is allowed to drop to

$$A = S * B$$

S = the shoreline represented by the nth well site, length between two points, (P2 and P1)
 P2 = the point equidistant from the nth and the (n+1)th well site
 P1 = the point equidistant from the nth and the (n-1)th well site
 B = the distance out towards the center of the lake from the shoreline through which the groundwater flow is appreciable

(See Appendix, Fig. 4 for shorelines, Fig. 5 for diagram of well measurements)

⁷ Branson, Dean. Bretz, Norton. Endicott, Doug. Hannert, Tim. Roush, Paul. Project Plan: Characterization of Groundwater Phosphorus Input to Torch Lake. Ver. 5. May 16, 2005.

During the installation and testing of these well points, it became problematic finding areas around the lake where the ground along the shoreline was not stratified with clay. It had been assumed that shoreline of Torch Lake was mostly made up of porous soil and the encountering of such large areas of clay was unexpected. In these areas the well point would go down and it would be impossible to draw up a sample of the water through the clay. In the areas where a clay-free well site could not be found at all, the area was assumed to contribute a negligible amount of groundwater flux. Out of the original 24 well sites, only 13 could be used for measurements. Measurements and samples of groundwater were taken once a month from June through September.

Results:

Of the 24 well sites distributed around Torch Lake (Appendix Fig. 2) 11 were in soil that was predominately clay and 13 were in more permeable soil that allowed groundwater flow. The length of perforated polyethylene tubing (L) was 3 inches and the internal diameter of the tubing (D) was .120 inches. The distance in the area calculation B was taken to be 100 ft for all wells (this assumption will be further discussed in the analysis section). Below is a table that shows how the other data varies for each well, (avg P means that the data was averaged over many measurements or was calculated from an average). The total groundwater flux into Torch Lake (Sum of all Q measurements) is **84.2 ft³/s**. Total phosphorus loading (Sum of all P measurements) is **1509 kg/yr**.

Well Num.	Avg. P (ppb)	Depth dl (ft)	Avg. Head dh (in)	Avg. Velocity (H2-H1/t) (in/s)	Avg. K*1000 (ft/s)	dh/dl (unitless)	Area S*B (ft ²)	Q (ft ³ /s)	P loading (kg/yr)
1	17.3	7.5	1.0	3.59	0.04	0.0113	980298	0.42	6.42
2	35.6	2	1.3	8.57	0.11	0.0521	978088	5.35	169.27
3	0.0	clay	clay	clay	clay	clay	790886	0.00	0.00
4	27.5	3.5	7.3	12.00	0.14	0.1746	651841	15.48	377.52
5	clay	clay	clay	clay	clay	clay	544042	0.00	0.00
6	clay	clay	clay	clay	clay	clay	394876	0.00	0.00
7	66.3	2	5.0	1.17	0.02	0.2083	816290	3.98	234.13
8	28.4	3	1.7	9.60	0.12	0.0463	1167091	6.32	159.25
9	4.8	3.5	7.8	12.00	0.14	0.1845	873441	21.92	93.42
10	8.0	2	3.5	8.42	0.08	0.1458	746591	8.74	62.10
11	27.3	2	1.3	6.00	0.07	0.0556	878802	3.31	80.41
12	20.4	2	0.9	9.00	0.11	0.0389	707513	3.11	56.43
13	2.2	3	1.2	12.00	0.14	0.0333	525080	2.38	4.65
14	clay	clay	clay	clay	clay	clay	870194	0.00	0.00
15	clay	clay	clay	clay	clay	clay	1050953	0.00	0.00
16	clay	clay	clay	clay	clay	clay	633925	0.00	0.00
17	clay	clay	clay	clay	clay	clay	1235538	0.00	0.00
18	clay	clay	clay	clay	clay	clay	1960603	0.00	0.00
19	clay	clay	clay	clay	clay	clay	1386386	0.00	0.00
20	21.7	6	2.5	6.00	0.07	0.0347	1165592	2.74	52.84
21	clay	clay	clay	clay	clay	clay	1095224	0.00	0.00
22	clay	clay	clay	clay	clay	clay	740825	0.00	0.00
23	5.9	4	2.5	10.00	0.11	0.0521	704450	3.96	20.77
24	33.5	2.5	3.2	6.00	0.07	0.1056	864250	6.46	192.22

Analysis:

Estimates of the groundwater flow into Torch lake have been made through two different methods, a water-difference method and a overall watershed-rainfall method. The difference method takes the water flow in from tributaries and through rain and subtracts the flow out from tributaries and evaporation (85% of rainfall). The resulting difference is the groundwater flux for Torch lake (48 cfs). The second method takes the area of the Torch Lake watershed and multiplies that by the average rainfall per area to find the total amount of water falling on the watershed and therefore entering the groundwater. Through this method, the estimate for groundwater flow into Torch lake is approximately 100 cfs. It is assumed in the watershed method that all the rainwater that falls onto the watershed is absorbed directly into the groundwater and is not taken up by plants and trees and transpired into the atmosphere, which it most certainly is. Hence this second estimate represents an highly idealized upper limit on the groundwater flow.

The value calculated through the piezometric wells is 84.2 cfs, significantly higher than the water balance estimate yet not so high that it falls outside the upper limit of the watershed rainfall estimate. Hence the value of 84.2 is too high of a value, but not so large so as to indicate that the entire methodology for sampling is incorrect, only some of the assumptions. It is important to note that the overall water balance estimate is not an acceptable replacement for the piezometric well method because it does not indicate how groundwater flow changes along the shoreline of Torch Lake. This assessment is necessary in order to determine if certain areas along the lake will carry excess phosphorus from developments into the lake at a higher rate.

After completing the data collection and looking at how the different numbers fit together to give an overall groundwater flux ($Q=A * dh/dl * Kh$) it has become apparent that the area (A) represented by each well site has a very large effect on the total flux result and yet is the measurement with the greatest assumptions. The area term consists of S, the shoreline represented by each well site, and B, the distance that the well represents from the shoreline towards the center of the lake.

First, there are problems in the original assumptions that led to the measurement of the representative shoreline sections (S) for each well. The original assumptions stated that the shoreline for each well would be of uniform soil characteristics, (Kh and dh/dl). Obviously the soil characteristics actually vary along the shoreline, but the variance should cancel out as long as the soil is at least similar to the soil represented by the well. The factor that most invalidates the assumption of uniform soil characteristics is the presence of patches of clay. These patches contribute zero groundwater flux and are discontinuities in the soil characteristics. Hence, efforts are being made to locate the patches of clay that are present in each section and remove them from the length of shoreline used in the area parameter for that well. This is being done by walking along each section of shoreline and probing the soil for clay, but the process is very time consuming. Through this process, the well measurements should more accurately represent the shoreline used in the calculation of area.

The second measurement (B) is also based on a very uncertain assumption. The parameter B, is supposed to be the distance out towards the center of the lake from the shoreline through which the groundwater flow is appreciable. This is assuming that the groundwater flow would decrease exponentially from the shoreline to the center of the

lake. This distance of appreciable flow has been roughly approximated as 100 ft. The actual distance is a complex function of the geography of the land both above and below the shoreline. Currently a set of wells is being placed at various distances out from the shoreline at one of the well sites on the lake to allow some sort of equation to be made that characterizes the decrease in groundwater flow as one moves away from the shoreline. This setup cannot be duplicated at the other well sites both because it is too expensive and because it would be a much larger obstruction to the residents of the property. Hopefully, as a result of the analysis, a more accurate value for B will be determined.

Lastly, the analysis of the amount of phosphorus loaded through the groundwater relative to the other sources shows that groundwater phosphorus loading contributes a similar amount to atmospheric and tributaries of phosphorus into Torch Lake. Tributary loading is estimated at 700 kg/yr with average tributary concentration at 8 ppb. Atmospheric loading is estimated at 900 kg/yr with average rain concentration at 6ppb. The phosphorus concentration in Torch Lake from the north and south basins is approximately 2.6 (average of all lake measurements) ppb. In comparison to all these sources of phosphorus, the groundwater phosphorus loading from the well piezometer methodology would be the largest contributor to the overall phosphorus loading into Torch Lake (1509 kg/yr with an average concentration of 21.3 ppb). However since this value has been shown to be too high, using the groundwater flow rate from water material balance estimate (48 cfs) and using the same average concentration (21.3 ppb) the phosphorus groundwater loading is 907 kg/yr. By either method the groundwater

phosphorus loading contributes as much or more than the tributary loading or atmospheric deposition.

Conclusion:

The overall groundwater flow into Torch Lake is higher than the water balance estimate but lower than the upper limit of the watershed estimate. The parameters K_h and dh/dl in Darcy's equation have been adequately measured but the assumptions that define the area term need to be re-evaluated. The shoreline term needs to be redefined to exclude the patches of clay shoreline of a section represented as having groundwater flow. The other term, B , needs to be quantified by getting data from the placement of wells at different distances from the shoreline in order to see where the appreciable flow ends. It was also shown that groundwater phosphorus loading is similar in magnitude to other sources of phosphorus loading (tributaries and rainwater). Once the groundwater phosphorus flux has been more accurately ascertained there remains even more work to be done. All the sources of phosphorus must be analyzed in order to find a way to determine the difference between natural phosphorus and the phosphorus from developments, (fertilizer and septic sources). Lastly, and perhaps most importantly, the mechanism of reactions that phosphorus undergoes once it enters the lake and the exact way that it affects the water quality must be understood.

Appendix:

Figure 1



(Torch Lake, Clam Lake, Lake Bellaire in relation to the Lower Peninsula of Michigan. The chain of lakes flows into Lake Michigan)

Figure 2

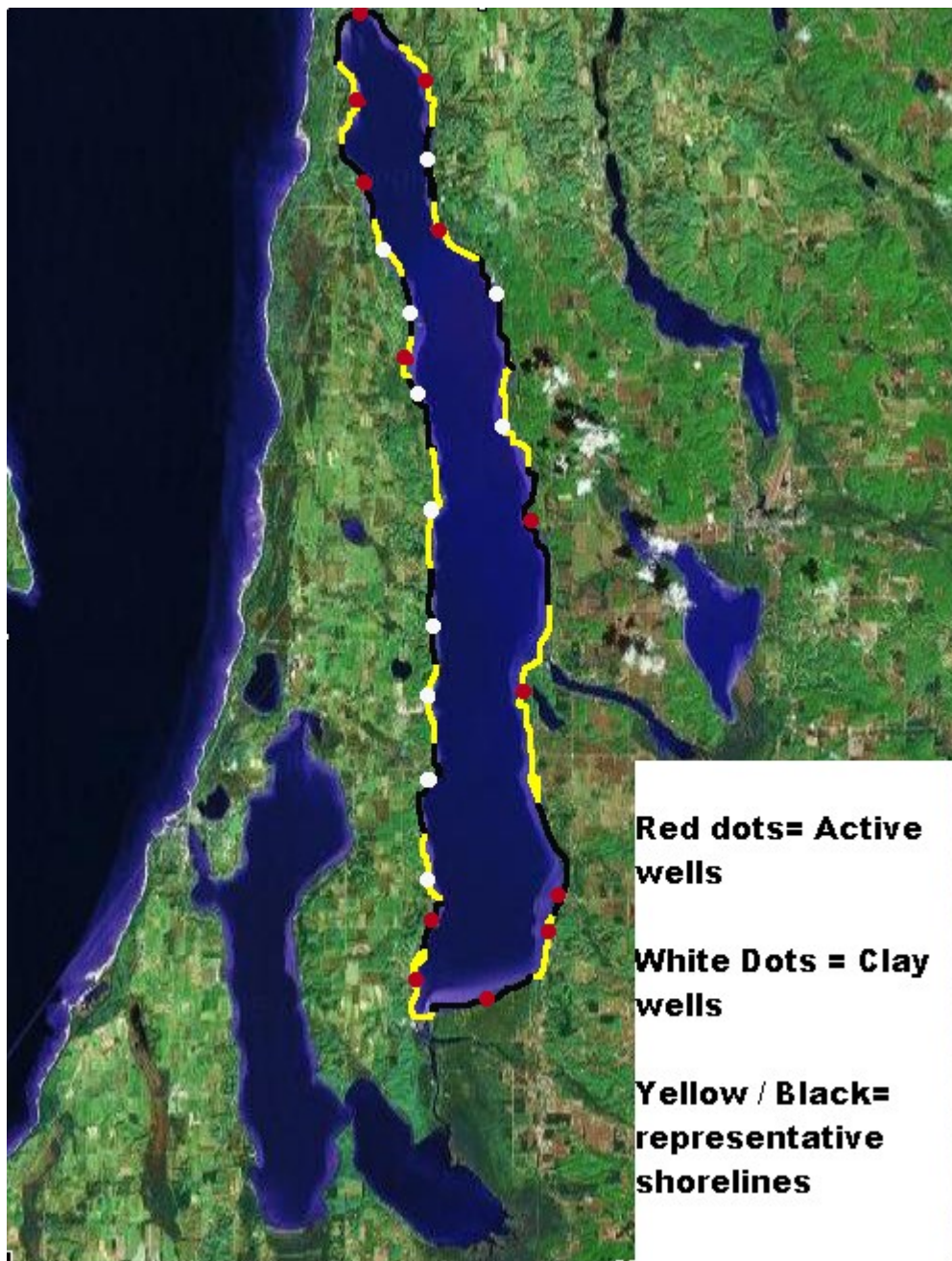


1
(Well locations along the shoreline of Torch Lake, White = clay, Red = Groundwater flow)

Figure 3

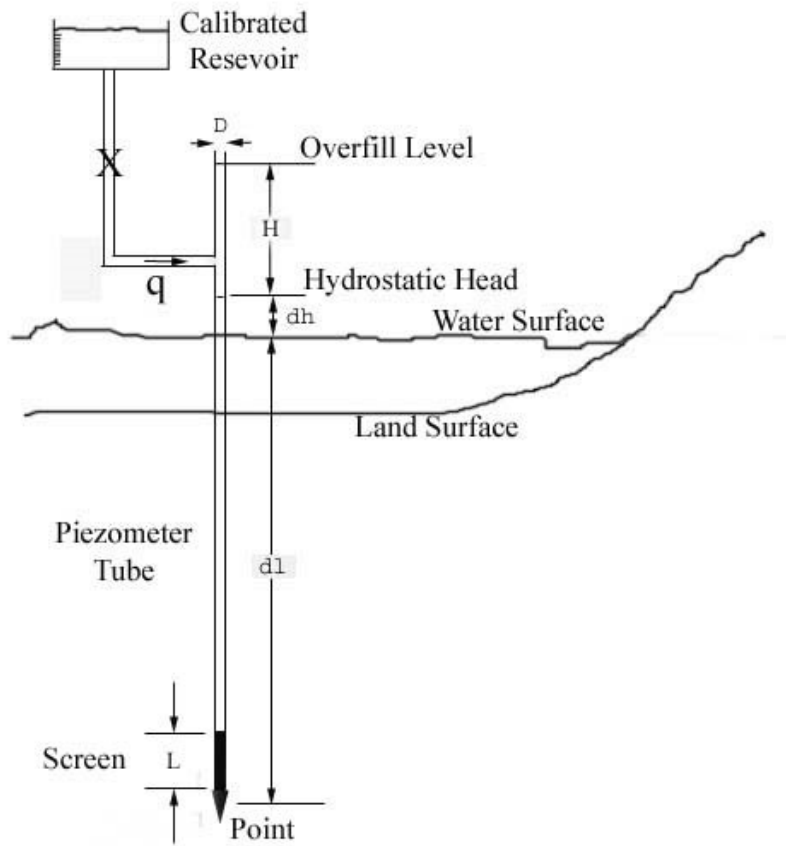


Figure 4



(Approximate representative shorelines (S) for each of Torch Lake's piezometric wells, well #1 is at the most northern well and subsequent wells are numbered clockwise)

Figure 5



(Diagram of well measurements. Instead of a Calibrated Reservoir, the timing of a falling water level, $H_2 - H_1/t$, was used to determine q .)

Acknowledgments:

Dean Branson, PhD in Chemistry and Principal Investigator for the Three Lakes Association, 2004 MDEQ Predictive Nutrient-Based Water Quality Model for the Three Lakes System, retired.

Norton Bretz, PhD in Physics, Treasurer and instrumentation specialist for the Three Lakes Association, retired.

Tim Hannert, MS Biology and Executive Director of Three Lakes Association, retired.

Development of a Predictive Nutrient-Based Water Quality Model for the Three Lakes System Year 1: Torch Lake, T. Hannert, D. Branson, M. DeGraeve and D. Endicott, Three Lakes Association and Great Lakes Environmental Center, 04 MDEQ grant PO# 761P40021 (June, 2004).

Project Plan; Characterization of Groundwater Phosphorus Input to Torch Lake.
Ver. 5. Branson, Dean. Bretz, Norton. Endicott, Doug. Hannert, Tim. Roush, Paul. May 16, 2005.