Database and Total Phosphorus Model for Big Platte Lake

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Executive Summary

There are over 100,000 measurements of various water quality parameters for the Platte Lake watershed. This data collection effort began in 1989 and measurements are available at several Platte Lake and tributary sites as shown in Figure 1.

The <u>first objective</u> of this project is to develop a database that can be used to conveniently store and retrieve historical as well as future data. This goal was attained by the development of a menu-driven dashboard design EXCEL spreadsheet application. Figure 1 shows sixteen active buttons that can be used to navigate to different components. These applications and other features of the database will be discussed in more detail below. This structure provides a template and consistent format for past and future measurements. EXCEL is ideally suited for this application. For all practical purposes, it can accommodate essentially unlimited amounts of pertinent water quality data. It is familiar to a wide audience of potential users and the resultant files are relatively small and easily shared among users via email.

The <u>second objective</u> is to provide users with the capability to detect trends in the data or identify possible new sources of nutrient loading with focus on total phosphorus (TP). The EXCEL database application developed for this project has extensive graphical and statistical capabilities that facilitate comparison of new data with the range of previous measurements. Nine custom spreadsheet tools were developed for this purpose. The right-hand window on Figure 1 shows the latest measurements for several parameters and highlights values that are outside the normal range.   This feature will be discussed further below. There are eight applications represented in the left-hand side column of buttons that are devoted to the task of inputting and displaying existing and future Lake and stream data. The top six buttons on the right-hand side are applications designed to allow the user to analyze trends and make more in-depth comparisons. The bottom two buttons on the right contain information that supports or documents calculations performed in other sections.

The <u>third objective</u> is to provide users with the ability to understand and gain insight into the comparative magnitude of various TP loading sources. This is accomplished by developing a watershed annual average mass balance for both flow and total phosphorus loading. The mass balance calculates stream loading for both baseline and event flow conditions. Non-point loads are determined for various sections of the Platte River. The mass balance is used to calculate the TP loss to the lake sediments. This loss is an important component of the predictive TP model.

The <u>fourth objective</u> is to provide users with a tool that can be used to predict the impact changes of in the magnitude of various watershed nutrient sources. A predictive long-term annual average total phosphorus model was developed that can be used to evaluate the adverse impact of watershed growth and the effectiveness of various abatement strategies. The user can perform predictive scenarios for changes in the rate of development in both the lower and upper watershed. The model can predict the beneficial impact of implementing BMP (Best Management Practices) that can lower the watershed UALs (Unit Area Loads). Finally, the model can predict the impact of new loads and improvements following implementing off-site treatment of household wastes.

These capabilities were designed to work together to harmoniously and seamlessly support efforts by the PLIA to protect and preserve the water quality of the Platte Lake despite threats from ongoing long-term watershed development and activities. Example results and recommendations are listed below.

Data Sources

Previous data for the Platte Lake watershed were scattered among various spreadsheets, databases, and reports. The data from all sources (including triplicate measurements taken in many cases) were copied and pasted into a single spreadsheet named Platte Database Appendix.

Total phosphorus (TP) has been measured at the single deep-water site on Big Platte Lake about 14,000 times between 1989 and 2021. On most dates, samples were taken at 8 depths and measured in triplicate. The other Platte Lake measurements include nitrate, chlorophyll, total dissolved phosphorus, and Secchi depth. This site also has over 25,000 measurements of temperature, dissolved oxygen, oxidation-reduction potential (ORP), pH, and conductivity taken at 8 depths (same as above). The data set also contains over 15,000 phytoplankton count measurements (Diatoms, Greens, Blue-Greens, and Golden) and almost 6,000 zooplankton measurements (Copepods, Cladocerans, and Rotifers). Finally, periphyton and *Cladophora* were measured at 7 near-shore sites in 2003.

Tributaries in the Platte Lake watershed have been sampled over 10,000 times at 19 sites since 1989. Most samples are TP measured in triplicate. Probe parameters (dissolved oxygen, temperature, oxidation-reduction potential, pH, and conductivity) have been measured at 8 sites since 2016. Also, data were collected at three sites during 25 separate storm events between 2003 and 2007. This effort resulted in over 500 measurements of total phosphorus and conductivity.

A sub-set of these data has been transferred to the active database. The current sampling program, that has been ongoing for the past several years, collects lake samples at only three depths; surface, middle, and bottom and only the average of the triplicates is recorded. **In order to facilitate trend analysis, the original historical data were consolidated into three depths, triplicate measurements were averaged, and obvious outlier data were removed.** The Surface sample in the database is the zero depth, the Middle sample is the average of the 7.5, 15, 30, 45, and 60 foot depths, and the Bottom sample is the average of the 75- and 90-foot measurements. This strategy follows the analysis of Smith and Canale (2015) where it was demonstrated that these three depths are adequate indicators of the volume average concentration when appropriate weighting factors are applied.

The consolidated TP, Secchi depth , nitrate, chlorophyll, and TDP as well as probe data and near-shore measurements are included in the database. The stream data are the USGS flow and TP and probe measurements. Other data for alkalinity, silica, and calcium are in the Platte Database Appendix spreadsheet but are not included in the interactive database to limit size and increase the ease of use of the database.

Design and Features of the Database

The overall design of the database is illustrated in Figure 2. In general, white background cells are locations where new data are entered or where selections are made regarding the parameter and time period to be displayed in a chart. Cells that have gray background color are locations where the VBA (Visual Basic for Applications) code inserts results of selections or calculations. The gray colored areas should not be modified. Cells that have light blue background color are neutral locations that are not being used in the current version. **The underlying computer code anticipates that data are located in fixed positions and does not accommodate changes in the location of data or the addition or deletion of rows or columns**. The contents of cells that contains a formula or a reference to another cell should not be altered. **Failure to adhere to these constraints could result in a considerable effort to restore the database functionality**.

Note that each sheet in the database has an embedded documentation that contains instructions and other useful information. This documentation can be expanded by the user at any time to provide additional working details. **The full features of the database require that the Visual Basic Editor is included to the EXCEL program and the Macros Enabled file type option must be activated.**

Main Menu. The Main Menu shows a site map that identifies the lake and tributary sampling locations. Sixteen buttons are provided that can be clicked to navigate through the other sheets in the database. The right-hand-side of the Main Menu shows the last measured values of several Lake and stream parameters along with yellow and red alarm values. The cell containing a measurement that exceeds the alarm values changes color in response. The alarm values are the one and two standards above the average measured value after 2015. Documentation can be viewed and modified by clicking the Open button.

Lake Chemistry. The Lake Chemistry Data sheet allows the user to compare the annual variation of any Lake chemistry parameter to the same parameter for different years or two different parameters for the same year. This sheet contains the average of triplicate measurements for Lake total phosphorus (TP), nitrate plus nitrite (NO3), chlorophyll (Chl), Secchi Depth, and total dissolved phosphorus (TDP). The data are reported for surface, middle, and bottom depths. Data for other chemical parameters and depths can be found Platte Database Appendix spreadsheet.

Cells C36 to E36 are volume fractions of the three depths that are used to calculate the volume-weighted total phosphorus concentration (see the Support sheet for more details). Note that the database calculates and displays the volume-weighted total phosphorus concentration and the percent compliance compared to the 8 mg/m^3 Standard that requires 95% compliance. TP values before the first measurements of the year are estimated using linear interpolation and the measured TP on the last date of the previous year. TP values after the last measurement of the year are estimated using linear interpolation and the measured TP on the first date of the following year. Sampling comments can be included in Column T. New data can be added to the database either manually or using the Import window in Columns U and V.

Lake Probe Data Sheet. The Lake Probe Data sheet can perform similar comparisons and plot temperature and oxygen vertical profiles for any date during the year. The probe data (temperature, dissolved oxygen, oxidation-reduction potential, conductivity, and pH) are entered in Columns B through H. New data must be sorted by date and depth prior to being appended at the end of the current data lists with no line skips. The database expects measurements for exactly 8 depths. **A missing measurement for any depth must be manually inserted using interpolation**. Charts can be updated for any year or parameter using Update Chart buttons. Note that the chart title, and the vertical scale and label change automatically in response to user selections (similar action occurs for other sheets).

When dissolved oxygen data are selected, the chart title also shows the annual pounds of total phosphorus released from the bottom sediments. Such release commences when the dissolved oxygen concentrations are low. Sediment release is calculated using the number of days when the concentration is lower than 2 mg/L, the bottom area, and measured sediment release rates. Sediment release results are necessary to calculate the annual phosphorus mass balance on another sheet. Consult the Support sheet for more details.

When temperature data are selected on Chart 1, an 8-layer volume weighted May through September temperature is calculated and displayed in column V. The volume weighting factors are located in Cells M40 through T40. These volume-weighted values are appended to the results for pervious years in column X and Y. These results can be displayed on the Long-Term Trend Analysis sheet.

Vertical profiles of dissolved oxygen and temperature can be displayed for any date during the year when temperature is selected for Chart 1 and dissolved oxygen is selected for Chart 2 for the same year.

Stream Chemistry Sheet. The Stream Chemistry Data sheet can be used to plot the TP for any three stream sites during one year, or plot any two sites for a user specified number of multiple years. This sheet contains TP data for 12 stream sites. Data for other chemical parameters and sites can be found in the Platte Database Appendix spreadsheet. New data should be sorted by date and appended at the end of the current data lists with no line skips. For convenience, use Ctrl down arrow to jump to the end of a column of data. The maximum and minimum years where data are available for each are shown in rows 38 and 39. Chart 1 is used to compare the annual variation of TP for any year at 3 different sites. Chart 2 is used to compare the TP of any 2 sites over a range specified by the user. New data can be added to the database either manually or using the Import window in Columns W and X.

Stream Probe Data Sheet. This sheet accepts and displays probe data for temperature, dissolved oxygen, conductivity, and pH for various sites. New data must be sorted by date and appended at the end of the current data lists with no line skips. The database assumes all measurements occur at the surface depth. Charts can be updated for any year or parameter.

Near Shore Data Sheet. Seven shoreline sites have been established for measurement of periphyton, *Cladophora*, temperature, and conductivity. These sites are the same as those sampled in 2003 by Woller and Heiman (2003). The GPS locations of these sites are shown on the Miscellaneous sheet. If data are missing for a given site enter the site number and leave blank Columns D through K blank. Data for the individual sample dates during the specified year are displayed by scrolling through the individual dates in column R. Note that this presentation provides both spatial differences and seasonal dynamics.

Wet Weather TP Data Sheet. The purpose of this section is to use data collected during high flow events to estimate an event TP concentration at 3 key stream locations; Stone, USGS, and Deadstream. This information is required to perform accurate mass balance calculations for the watershed because phosphorus loading depends on both the TP concentration and the magnitude of the flow. Higher flow rates result in higher TP concentrations as a consequence of erosion and resuspension of streambed particulate matter. Data for the individual sample dates during the specified year are displayed in Column T. The storm-event TP concentration is approximated as the average of all values over 25 mg/m^3.

Flow & Rain Data Sheet. The purpose of this sheet is to provide a convenient way to import daily USGS flow rates and area-wide precipitation data into the database. The “Get NOAA Rain Data” green button connects to the National Weather Service website where the Location, Product, Year Range, and Variable are selected. **The watershed precipitation is assumed to be the average of the Beulah, Frankfort, and Traverse City data**. Select the “Calendar Day Summary” for the appropriate year and copy data and paste as “text” into Cells B13, B49, and B85 for the various sites.

The “Get USGS Flow Data” green button connects to the USGS website where data for the Platte River at Honor, MI (04126740) can be retrieved. Select the Daily Data Time-Series, Discharge (Mean), the Begin and End dates, and Tab-Separated Table and then enter GO. Copy the data and paste into a single Cell at Q13 using the destination formatting option. Select the entire range from Q13 to Q370 and convert Text to Columns using the Data tab at the top ribbon of the spreadsheet.

Tributary Flow Data Correlation Sheet. The purpose of this sheet is to calculate the correlation between the flow at USGS and the flow at other stream locations in the watershed. Data for simultaneous measurements of flow at USGS and the flow at other sites can be entered in the white-background boxes . New values for the slope and intercept of the linear regression equation and the correlation coefficient (R^2) are calculated automatically when new data are entered. The regression equations are used to perform a watershed flow balance.

Flow & Rain & TP Comparison Sheet. The Flow & Rain & TP Comparison sheet can be used to compare the TP of any stream site with area-wide daily rainfall and USGS flow. This sheet also is used to calculate the number of wet weather high flow events that occur during any year. The number of storm-events can be specified by simple inspection of the daily rainfall and flow data. The estimated value is entered in O column. Alternatively, an Event Sensitivity Percent can be selected and entered in column N. The Find Events & Compare button is then used to launch a calculation of the number of events based on the instantaneous flow exceeding the 4-day moving average flow by the Event Sensitivity Percent. Ultimately, the final specification of the number of storm-events must based on the judgment of the user because of the limited TP measurement frequency.

Moving Average Analysis Sheet. The Moving Average Analysis sheet is used to compare any Lake or stream parameter with the monthly moving average for a user specified number of years. The Chart shows the average for each month in this range along with plus and minus 1, 2, or 3 standard deviations. The TP for any year is shown as the red line for comparison. These results allow the user to compare current measurements with the range historical data.

Long-Term Trends Sheet. The Long-Term Trend Analysis sheet has charts that display the long-term annual average of any parameter over a user-specified range. The user can select either the maximum and minimum, or 1, 2, or 3 standard deviations.

Watershed Mass Balance Sheet. The purpose of this sheet is to perform an annual average water and TP mass balance for the watershed. The mass balance provides insights into the relative magnitude and significance of various factors that affect the TP of the lake. An important result of the mass balance is the calculation of the Loss Rate of TP from the Lake. This is an important coefficient in the predictive TP model. Without these preliminary mass balance calculations, the Loss Rate would have to be estimated from literature values for other lakes. This would increase the uncertainty in model predictions and decrease credibility. The TP mass balance is also used to calculate the magnitude of non-point sources at various sections of the Platte River. Additional details are provided below.

Lake TP Model Sheet. This sheet has an annual volume-weighted average total phosphorus (TP) predictive model for the Lake. The model is designed to predict long-term changes in the Lake TP as a function of increases in the TP loading from various sources in the watershed or decreases in loads that result from remedial projects. Additional details are provided below.

Annual Averages Sheet. The purpose of this section is store annual average values for Lake and stream parameters that have been calculated in other sections. This avoids the need to re-calculate these values when calculating the watershed flow and TP balances. In addition, seven annual average values associated with Hatchery activities are input on this sheet. This information must be obtained from the Hatchery staff and must be inserted on this sheet.

__Support Sheet.__ This sheet provides detailed documentation of the fractions used to calculate the volume-weighted TP and temperature. It also contains all details associated with the calculation of the total annual sediment release load.

__Miscellaneous Sheet.__ This sheet has a residence time calculator, a Trophic Status calculator, and the latitude and longitude of various sample sites. Other information provided on the sheet include the relationship between the flow at USGS vs the Direct load and the TP of rainfall. The phosphorus concentration of the rain has been measured at the Hatchery weather station starting in 2003. The data were collected during or shortly after a rainfall event and therefore do not include the phosphorus associated with the fallout of particulate matter such as leaves and dust.

Description of Watershed Mass Balances

The purpose of the TP and water mass balances is to identify the magnitude and significance of various components of the overall loading and to calculate the Loss Rate in the Lake as shown in Figure 3.

__Flow Balance__

Annual average flows of the Platte River at the Stone Bridge, Veterans Park, Pioneer, and at the M22 outlet and tributary flows from Carter Creek, Collision Creek, and the North Branch are based correlations with the annual average flow of the Platte River at the USGS site (which is measured daily). These correlations were developed in 2002 and 2003 and located on the Tributary Flow Correlations sheet. Similar data are not available for the Haze Road site.

The flow in Brundage Creek at the Old Residence is also based on correlation with the USGS flow. However, this location is upstream of the Hatchery intake. The Brundage Creek flow below the Old Residence splits into 2 components. The flow to the Hatchery from Brundage Creek is measured daily, while the remainder empties into the Platte River upstream of the Hatchery discharge. Note that the flow leaving the Hatchery is greater than the intake flow from Brundage Creek because the outflow is the sum of inflows from Brundage Creek, Brundage Spring, Service wells, and the Hot Pond.

Note that the annual average flow at the M22 outlet is usually greater the sum of flows from USGS and the North Branch. The difference is the net of rainfall and direct flow minus evaporation.

__Total Phosphorus Balance__

The phosphorus mass balance for the Lake depends on the magnitude of the incoming flow and phosphorus concentration from various stream inflows. The phosphorus concentration is a function of the stream flow rate. Higher flow rates result in higher Total P concentrations as a consequence of erosion and resuspension of streambed particulate matter. The phosphorus annual loading is approximated by dividing the loading into two components. The base loading is calculated using a base flow and base concentration. The storm-event loading is calculated using a storm-event flow and a storm-event TP concentration.

Annual Load = base flow * base TP *(365-events) + event flow * event TP * events (1)

The number of events and the base and event flows at the USGS site are calculated on the Flow & Rain & TP Comparison sheet for various years. The base and event flows at other sites are calculated from the annual average flow at that site and the ratio of base to average flow and the event to average flow determined at the USGS site.

The Wet Weather TP sheet lists storm event total phosphorus concentrations at three sites: Stone Bridge, Brundage Creek at Old Residence, and USGS. It is assumed that the Carter and Collision event TP is the same as the Brundage Creek event TP, that the North Branch event TP is the same as Stone Bridge event TP, and that the Vet's and Pioneer event TP is the same as the USGS event TP.

The Hatchery and Brundage Creek TP and flow are measured daily and a load is subsequently calculated every day. The loads displayed in Cells U34 and W34 are the sum of these daily loads. Annual average values for flow and TP concentration are also displayed. Note that the annual average flow multiplied by the annual average concentration does not equal the sum of the daily loads because the displayed load is the sum of daily loads. Annual average values for flow and TP concentration and load for these sites are found on the Annual Averages sheet.

The Lost Fish load is the difference between the phosphorus contained in the fish passed at the lower weir and the phosphorus contained in the fish collected at the upper weir. This information provided by the Hatchery staff and is located on the Annual Averages sheet.

Direct loads enter the Lake from all sources downstream of the North Branch junction such as runoff from individual lakeside parcels and small streams that are not monitored. These values have not been measured directly but estimates were calculated by the BASINS loading model. These simulation results were approximated using linear correlation with the annual average flow at the USGS gage. The results are located on the Miscellaneous sheet.

The Sediment Release loading is based on the number of days the dissolved oxygen is less than 2 mg/L, the area of the affected region, and the sediment release rate (as measured by Holmes, 2004). The calculations are explained in more detail on the Support sheet.

The Atmospheric load is based on the amount of rain, the TP concentration of the rain water, and the surface area of the Lake. Values for various years are found on the Annual Averages sheet.

The Total Load In is the sum of the USGS, North Branch, Lost Fish, Direct, Sediment Release, and Atmospheric loads. This total is displayed in Cell F29. The TP Retained is the difference between the Total Load In and the outlet load at M22. The percent TP Retained in the Lake is the TP Retained divided by the Total Load In times 100. This value is shown in Cell F33.

The Loss Rate is calculated by dividing the TP loading retained by the area that accumulates settled material multiplied by the annual average total phosphorus concentration. It is assumed that the entire surface area of the Lake accepts settled materials. This value is shown in Cell F32.

$$Loss\ Rate = \frac{\sum Loads - TP \cdot Flow\ Out}{TP \cdot Area} \qquad (2)$$

The non-point loads are the difference between downstream and upstream loads measured at various Platte River sites. The non-point load between the Stone Bridge and the Vet's sites is shown in Cell W29. The non-point load between the Vet's and the Pioneer sites is shown in Cell R29. The non-point load between the Pioneer and the USGS sites is shown in Cell N29. The total lower watershed non-point load is displayed in Cell S21. These non-point loads can be used to identify loads into the River that are otherwise unknown and cannot be conveniently measured.

Note the that database flow and TP balance sheet is designed (Figure 3) to describe annual average conditions for any year based on measurements. It does not have the capability, as it stands, to perform "what if" calculations such as determining new Lake TP concentrations if the input loads change. This capability is described the TP Model section below.

Database Observations and Trend Analyses

The following section describes several example uses of the database.

Figure 4 shows TP measurements at 3 depths for 2020 and 2021 along with the volume-weighted average value (purple lines**). The concentrations before and after the last measurements are calculated using linear interpolation and the last measurement of the preceding year and the first measurement of the following year.** The imbedded Visual Basic Algorithm (VBA) counts the number of days the concentration is greater than 8 mg/m^3 and calculates and displays the percent attainment.

Figure 5 shows temperature and oxygen at 8 depths for 2021. The temperature measurements show that the thermocline forms at a depth of about 30 feet. Note that dissolved oxygen depletion occurs during the summer as well as under the ice. The imbedded Visual Basic Algorithm (VBA) counts the number of days the oxygen concentration is less than 2 mg/L at various depths and calculates the annual sediment phosphorus release. This value is used in the mass balance and predictive model calculations.

Figure 6 displays TP concentrations in the North Branch at Deadstream Road, Stone Bridge and USGS sites for 2021. As expected, concentrations generally increase throughout the spring, decline in late summer, and increase again in the late fall. The right-hand side of the chart shows all the Stone and USGS TP measurements between 2010 and 2022. Note the extraordinarily high TP high value for Stone in July 2016. This high value is also shown on Figure 7 and compared to the monthly average values for the period 2002 to 2020. It is observed that the July 2016 TP concentration exceeds the average plus 3 standard deviations. Two likely explanations for the high value are that it was due to riverbed scouring during a high flow event, or that the sample was contaminated during processing. Figure 8 shows rainfall and USGS flow for 2016. It is observed that steady flow conditions existed during July 2016, thus the high value is not associated with rainfall or flow event. Therefore, this high value does not reflect true conditions in the river and was deleted from the database and replaced by an interpolated value.

Figure 9 shows the long-term variations in TP and Secchi depth, and Figure 10 shows the long-term variation for chlorophyll for 2000 to 2021 along with minimum and maximum values for each year. The calculated Carlson Trophic Index using long-term average values is 36.8 (Miscellaneous sheet). This value places Platte Lake in the oligotrophic category.

Note that average Secchi depth and maximum summer values appear to be increasing above the long-term trend after 2016. Given the near-constant TP concentrations over this same time period, no obvious mechanisms are apparent and similar patterns were seen over 2000 to 2004 and 2006 through 2010. If this positive trend continues it may be related increasing zebra or quagga mussel populations or reductions in phosphorus bio-availability. However, these suggestions are highly speculative and would require significant research effort to verify them.

Figure 10 shows annual average values of four parameters. Note the nearly steady state TP trend despite significant variability in the flow at USGS and the total input load. The resistance to these changes occurs because the Loss Rate increases as input load and flow increase (Figure 10). Thus, increases in load and flow are offset by increases in the Loss Rate resulting in near steady state TP. There are no obvious mechanisms that can account for these correlations. Perhaps the fraction of particulate phosphorus increases when the flow and load increase, but data are not available to substantiate this speculation.

The right-hand side of Figure 11 shows the long-term variation in the May through September volume-weighted temperature of Platte Lake. This trend is based on almost 3,000 separate temperature measurements at 8 different depths. The Figure shows that the long-term temperature trend has remained about the same or decreased slightly over the past 22 years.

It is seen in Figure 6 that the TP concentration of the Platte River at the USGS site is usually greater the concentration at the Stone Bridge site. The flow data in the database can be used to calculate the total annual loading associated with this difference in concentration as shown in Figure 1 (see Miscellaneous Sheet). Note that the average difference in loads between 2005 and 2012 was 1,820 Lbs. In 2013 this steady difference increased rather dramatically to an average of 3,100 Lbs. It is interesting to note that this increase coincides with the introduction of agriculture waste applied on farmland less than one mile downstream of the Stone Bridge. The Lake model will be used below to calculate the impact of this increase in loading on the TP concentration of the Lake and compliance with the 8 mg/m^3 standard.

Description of Long-Term Annual Average Total Phosphorus Model

Development of Lake TP Model.

The goal is to develop a model that can predict changes in the long-term annual average total phosphorus concentration of the Lake as development of the watershed increases over time and determine the effectiveness of alternative abatement strategies. The model is based on the TP mass balance and can be calculated using Equation 3.

$$Vol \cdot \frac{dTP}{dt} = \Sigma Loads - FlowOut \cdot TP - Loss\ Rate \cdot Area \cdot TP \tag{3}$$

Equation 3 is a differential equation. The solution gives the TP as a function of time. However, the input loads and coefficients are available only on an annual average basis. Therefore, the solution of Equation 3 can be accurately determined using a yearly step-wise steady state approach as given by Equation 4.

$$TP = \frac{\sum Loads}{Flow\ Out + Area \cdot Loss\ Rate} \tag{4}$$

The model inputs are the TP loads, the Lake outflow rate, and Loss Rate as discussed below.

An unknown and potentially important component of the total load is the load that originates from lakeside septic tank drain fields. A model for this load must be developed before the Lake TP model can be completed. This model is described below.

Development of Model for Drain Field Loads.

Drain field TP loads result from septic tank overflows that are associated with numerous households surrounding the Lake. Many residences of the Platte Lake shoreline utilize septic tanks with discharge into a drain field for treatment of domestic and gray waste water. Such installations are referred to as Onsite Wastewater Systems (OWS). These loads are often overlooked in lake studies, however recently, Schellenger and Hellweger (2019) have shown that phosphorus from Onsite Wastewater Systems can be significant and should not be ignored in watershed planning despite the fact that phosphorus sorbs relatively strongly on soils. This conclusion is evident because phosphorus adsorption is reversible, and therefore loads that entered the system during earlier time periods will eventually reach the Lake. Previous mass balance and modeling efforts for Platte Lake have not included comprehensive analysis of potential loads from near-shore septic tank drain fields (Canale, et al 2004, 2010). The load that enters the Lake will likely vary from household to household based on differences in soil conditions, number of users, distance from the lake, and groundwater movement. The development of a model for each household surrounding the Lake is a daunting task and beyond the scope of this study. The goal here is to find a rough estimate of the magnitude and timing of the loads that enter the Lake from septic tank sources so that this loading compared to other sources.

Phosphorus removal from OWS occurs in two zones (see Figure 13). The vadose zone removes phosphorus in the immediate vicinity of the drain field under unsaturated flow conditions. Wastewater that escapes the vadose zone migrates toward Platte Lake via saturated groundwater flow conditions.

Phosphorus adsorbs to soil particles on its journey to the Lake. For low phosphorus concentrations, the amount of phosphorus that adsorbs onto soil particles can assumed to be a linear function of the groundwater concentration, that is

$$S = K_d \cdot c \tag{5}$$

where S is the amount adsorbed (mg P/kg soil), c is the groundwater TP concentration, and K_d is a constant (L/kg soil). K_d is called the linear sorption coefficient. For higher phosphorus concentrations the Langmuir or Freundlich isotherms may be preferred.

The phosphorus transport in the groundwater as it flows through the drain field to the Lake is described by the following partial differential equation.

$$R\frac{\partial c}{\partial t} = -\frac{u\partial c}{\partial x} + \frac{D\partial^2 c}{\partial x^2} \tag{6}$$

where t is time, u is the average pore water velocity or the seepage velocity divided by the porosity, x is distance from the effluent source, D is a constant longitudinal dispersion coefficient, and R is the retardation factor. This assumes that there are no transverse or vertical components of the average pore water velocity and dispersion.

The dimensionless retardation factor, R, is given by

$$R = 1 + \frac{K_d \cdot \rho_b}{n} \tag{7}$$

where ρ_b is the soil bulk density in the saturated aquifer and n is the effective porosity.

The solution of Equation 6 for the case of a continuous constant source is given by

$$w(x,t) = \frac{w_0}{2}\left\{erfc\left[\frac{(Rx-ut)}{2(DRt)^{\frac{1}{2}}}\right] + \exp\left(\frac{ux}{D}\right)\cdot erfc\left[\frac{(Rx+ut)}{2(DRt)^{\frac{1}{2}}}\right]\right\} \tag{8}$$

Where w(x,t) is the loading as a function of time and distance from the source. Superposition must be employed if the source loading is a function of time following the development and discussion by Schellenger(2018).

The example hypothetical calculations that follow start in 1940 and assume that there were 167 houses (Brown & Funk, 1940) around the Lake, that each person uses 80 gallons of water a day (Blount, 2021), that the septic tank TP effluent concentration is 10 mg/L (Stowe, 2014), and that a typical installation is located 25 meters from the Lake. The occupancy rate assumes that 25% of the houses are vacant or sparsely used, 25% of the houses accommodate 4 people for 100 days during the year, and that 50% of the houses have 2 people all year.

Removal efficiency in the vadose zone is a complex function of chemical and biological mechanisms that depends on pH and the concentrations of iron, aluminum, and calcium.

Although comprehensive models exist for these processes (Šimůnek and Bradford, 2008), it is assumed here that a constant fraction of 50% is removed in the vadose zone following approach used by Schellenger (2019). This results in a load of 250 pounds of TP per year entering the saturated zone in 1940. The following calculations assume that the source loading does not vary with time. This greatly simplifies the solution because it avoids the need to apply superposition.

Brennan et al (2015) measured a seepage velocity of 0.000003 ft/sec or 29 m/y for nearby Silver Lake that has soils similar to Platte Lake. The pore velocity is the seepage velocity divided by the porosity giving a pore velocity of 74 m/y for a porosity of 0.39. This value is used in Equation 6. It is assumed that the dispersivity is equal to 1 m based on Robertson et al 1991. The dispersion coefficient D is the pore velocity times the dispersivity or 74 m^2/yr. The soil density and porosity used in the model are typical values for sandy soils.

Insight into the behavior and significance of the septic tank loading can be attained by examining the progress of the TP plume as it moves toward the Lake. The simulations in Figure 14 start in 1940 using an estimate value of 171 for R and assume that the drain field is located 25 meters from the Lake.

Figure 14 shows the load as a function of distance downstream from the source for various years. Note that after 5 years the wave front has progressed only about 5 meters, after 10 years about 10 meters, and so on. Note that the load attains a value of about 32 pounds per year at 25 meters after 40 years. Figure 15 shows how the load varies with time at various fixed distances from the source. Again, note that the load attains a value of about 32 pounds per year after 40 years when the source is 25 meters from the Lake. These simulations roughly correspond to the 1980 Swanson measurements. However, there has been significant shoreline development that occurred after 1940. The gray curve on Figure 16 is the result of a simulation where it was assumed that there were 508 lakeside houses in 1940 (representing complete development). In this case the loading into the Lake is about 108 pounds in 1980 compared to 32 pounds for the case with no increase in the loading (green curve). The high development loading eventually increases to a maximum value of 785 pounds (compared to 250 pounds for the case of no increase in development).

The above preliminary simulations assumed that the loading at the source remained constant over time to facilitate understanding of the behavior of Equation 8. However, the historical loads from the septic tank drain field depend on the number of houses that surround the Lake. The number of lakeside houses is approximated using the sigmoid function

$$h(t) = \left\{\frac{1}{(1+\exp(-kt))^a}\right\} \cdot (H - h_0) + h_0 \qquad (9)$$

Where *h(t)* is the number of houses as a function of time, *k* and *a* are coefficients, h_0 is the starting number of houses in 1940, and *H* is the maximum number of houses.

Brown & Funk (1940) stated that there 167 cottages near the lakeshore in 1940. The Clean Lakes study (1983) reported that there were 370 lakeside houses in 1980 and Yarrow Brown (personal communication) counted 464 houses in 2020. These data were used to find values for *k* and *a* by trial and error.

Swanson (1981) performed a Septic Snooper study that measured a near-shore TP loading of 32.6 pounds in 1980 from active breakthrough plumes. This value and Equation 8 were used to estimate the value of the retardation factor by trial and error resulting in a value of 171. Note that the need to match the Swanson measurement places a strong constraint on the set of model parameters. For example, if the efficiency of the vadose zone was greater than 50% then the retardation factor would need to be re-calibrated by decreasing the R to match the measured Swanson loading.

Figure 17 shows the measured data and curve (blue color) representing the growth in the number of shoreline houses. The red curve in Figure 17 show calibration simulation results for the TP loading that reaches the Lake using the actual number of shoreline houses and the solution of Equation 6 using the superposition method. This loading is an input to the overall Lake TP model as discussed below.

The constant source form of the model was used to simulate the load to the Platte River from the Honor Waste Water Treatment Plant at full design capacity. Figure 18 shows the projected movement of phosphorus toward the Platte River. Results show that it takes the plume 500 years to propagate about 300 meters toward the Platte River. The discharge site from the Honor WWTP is about 1,000 meters from the Platte River. Thus, it is expected that the Honor WWTP discharge will not be a significant source of TP loading unless there is short-circuiting caused by a breakthrough from the soil surface.

Calibration of Lake TP Model

With the completion of the septic tank drain field model completed as described above, this section describes the other loads that impact the Lake.

LimnoTech (2007) used the BASINS model and data from 1990 to 2005 to determine phosphorus Unit Area Loads (UALs) for various land uses for low, average, and high Platte River flow conditions. The UALs have units of pounds per acre per year. These values were recalibrated as part of the current project using more recent data for the lower watershed from 2010 to 2020. These UAL values represent current conditions in the lower watershed. The nonpoint load for each land-use category is the product of the area and the corresponding UAL. The sum of all land-use loads is the total nonpoint load. The nonpoint loads change when land-use changes. For example, residential growth may occur at the expense of forested land-use. This increases the area associated with high UALs compared to lower forested UALs. Therefore, higher overall non-point loading occurs with subsequent changes the total phosphorus concentration of the Lake. The model also allows the user to change the UAL directly. High values used in the model are the average values plus one standard deviation. Low values in the model are average values minus one standard deviation.

The upper watershed non-point loading is represented by measured total phosphorus concentrations at the Stone bridge location on the Platte River. Average as well as plus and minus one standard deviation loading conditions were calculated using 2010 to 2020 measurements. The model allows the user to change and determine the impact of increases or decreases in the upper watershed non-point load.

Other phosphorus loads include non-point from atmospheric, sediment release, lost fish sources, and the septic tank drain field. The only point source in the lower watershed is the Platte River State Fish Hatchery. Model input values for these inputs are based on average as well as plus and minus one standard deviation using 2010 to 2020 measurements. The outflow rate is the flow at M22 calculated using the calibration with the flow at USGS.

Results of Lake TP Model

The Lake TP model was calibrated using the above inputs and adjusting the Loss Rate by trial and error to fit the measured volume-weighed TP data for 2008 to 2022. As new tributary and Lake measurements are made, the lower and upper non-point, internal, and Hatchery loads are automatically updated in the database. This may require small adjustments of the Loss Rates to maintain optimum agreement between the model and measurements.

Figure 19 shows the model output compared to measured volume-weighted TP data for each year (left side) and the percent compliance with the 8 mg/m^3 TP Standard (right side). The shaded area represents the range of uncertainty for plus and minus one standard deviation.

Measured data as well as the long-term model predictions show that the total phosphorus of Platte Lake is currently not meeting the Standard and is gradually getting worse. The TP concentration increased from 8.0 mg/m^3 in 2020 to 8.4 mg/m^3 in 2070 despite the very low net load from Hatchery that is in compliance with its discharge permit.

The slow deterioration of the Lake is caused by the increases in loading from septic tank drain field sources from 32.6 pounds in 1980 to about 400 pounds in 2020 . This loading is expected to increase to over 700 pounds by 2070 (see Figure 17). Compliance with the Standard drops from 45% in 2020 to about 36% by 2070.

Example Lake TP Model Cause-Effect Simulations

The model can be used to predict the impact of six different cause-effect scenarios on the TP of the Lake and compliance with the Standard. This capability allows the user to test the consequences of the following.

1. Changes in the rate of light residential development (LRD).
2. Changes in the rate of commercial growth.
3. Changes in the URL values.
4. Changes in the loading from the upper watershed.

5. Introduction of a new positive or negative load.
6. Decreases in the drain field loading.

The population of Benzie County increased from 17,505 in 2010 to 17,781 in 2022. This is equivalent to a growth rate of about 0.13 percent per year. This rate of growth was applied to the acreage of both LDR and Commercial land-use at the expense of forested land-use. The resultant increase in the TP of the Lake was negligible or about 0.1 mg/m^3. Compliance drops from 35 to 34 percent.

A growth rate of 1.0 percent per year increases the Lake TP concentration to about 9.1 mg/m^3 and further reduces compliance to 23 percent (Figure 20). Such rapid growth is not expected in the coming years, although its effects could be offset by decreasing the UAL values. For example, a one-time decrease in the UALs of 10 percent is required to negate the impact of 1.0 percent growth rate of residential development (Figures 21 and 22). Changes in the UAL values might be accomplished by implementing Best Management Practices (BMP) such as reducing stream bank erosion or implementing farming practices to reduce nutrient losses.

The impact of percent increases in the load from the upper watershed is less than similar percent increases in the lower watershed. This is the case because the upper watershed loads are less than half the lower watershed loads. A one-time increase of 5 percent of the upstream load increases the TP of the Lake by about only 0.1 mg/m^3.

The model can predict the impact of one-time increases or decreases in the total load. For example, the 1983 Clean Lakes Report stated that the annual Hatchery phosphorus load in 1978 was 3,305 pounds. The Report went on to recommend that the Hatchery loading be reduced to 1,745 pounds per year to maintain a transitional rate of eutrophication. The model results for a one-time continuous increase in the recommended loading results in an increase in the Lake TP to 10.5 mg/m^3 and compliance drops to about 5 percent (Figure 23). Clearly, the successful legal actions taken by the PLIA to challenge the proposed permit loading saved the Lake from serious deterioration. It is also encouraging to note that the model predicted TP concentration is consistent with historical measurements, thus providing validation of model credibility. Similarly, a one-time decrease in 1,745 pounds decreases the Lake TP to 6.6 mg/m^3 and increases compliance to over 80 percent (Figure 24).

Figure 12 (above) demonstrated that the non-point TP load between the Stone Bridge and USGS sites increased by about 1,280 Lbs/yr after 2013 following the application of agricultural waste on nearby farm fields. Figure 25 shows model simulation for the case where the non-point is reduced by 1,280 Lbs. This is equivalent to an assumption that the non-point load remained constant at 2012 levels . Note the Lake is close to compliance with the 8 mg/m^3 standard without the increase that occurred after 2012.

An off-site system for wastewater treatment would eliminate future loading from onsite wastewater systems (OWS). However, existing phosphorus that has accumulated in the aquifer needs to be flushed out before notable decreases in the loading are attained. If off-site treatment was started in the year 2000, the Lake TP concentration would be expected to be 7.9 mg/m^3 and compliance 53 percent in 2070 (Figures 26 and 27). New off-site capabilities that begin operation in 2030 will have little impact until about 2060. In other words, there is about a 30-year lag time between the start of off-site treatment before beneficial impacts will be observed.

Population growth in Benzie County has been about 0.13 % per year over the past several years. The predictive TP model simulations indicate that increases in TP loading that result from this low historical growth rate are not a major threat to the water quality of Platte Lake. Furthermore, potential increases in these nonpoint loads could be decreased if UAL values are lowered by enacting BMP. A 10% reduction in the UAL values can offset a 1% growth rate in the lower watershed loading.

Similarly, increases in the load from the upper watershed are expected to have little effect on the TP of Platte Lake. Furthermore, loads that originate in the upper watershed are buffered by losses in Bronson Lake, Lake Ann, and Long Lake. These lakes offer significant protection for Platte Lake from increases in upstream nonpoint loads.

Predictive model simulations indicate that the TP of Platte Lake will slowly increase over the next few years due to the accumulation and subsequent release of phosphorus stored in the aquafer from OSW systems. The loading from this source was estimated to be about 400 pounds in 2020 and this amount is expected to increase to about 800 pounds by 2080 and then remain constant at this level in future years. Diversion of future septic loads, while effective, will take about 30 years before the full benefits will be realized.

Model simulations show that phosphorus released into the groundwater from the Honor Wastewater Treatment Plant is not expected to be a problem in the future because the of the large distance between the facility and the Platte River. This conclusion would in incorrect if the TP plume should somehow reach the Platte River faster due to some short-circuiting mechanism.

Recommendations

Normal growth and activities in the watershed pose minimal threat to significantly decrease the water quality of Platte Lake. The largest risk is the introduction of phosphorus loading from some new and perhaps unexpected source. The current sampling program and database are ideally suited to detect this prospect. Therefore, it is recommended that the sampling program be continued and that the database to be actively updated and maintained.

Although the current sampling program is impressive, there are still gaps. For example, few data are available for the TP concentration of Collision Creek. Although the flow of this Creek is relatively small, it is recommended that the TP be measured twice per month for at least one year.

Flow correlations are available for the Platte River at Veterans Park and at Pioneer Road, but the relationship between the flow at USGS and the flow at Haze Road has not been determined. Thus, the nonpoint load between Vet's and Haze Rd. and Pioneer and Haze Rd. cannot be estimated. It is recommended that flow measurements be made at Haze Road and that correlations be made with corresponding USGS data.

The density and spatial distribution of near-shore periphyton and *Cladophora* are perhaps the most sensitive indicators of nutrient sources and changes in the TP concentration of the Lake. Essentially these populations act like “canaries in a coal mine”. Woller and Heiman (2003) identified seven critical locations that supported high populations. It is recommended that these sites be re-visited and six measurements per year be added to the current sampling program.

It is recommended that the PLIA retain its partnership with the Platte River State Fish Hatchery. Their laboratory does an outstanding job with the task of measuring low concentrations of total phosphorus. Also, the ability of the PLIA database to calculate an accurate TP mass balance for the watershed depends flow and loading inputs provided by the PRSFH.

Finally, it is recommended that the PLIA and watershed residents pursue all avenues to eliminate or reduce TP loads into the Lake. Such efforts include: encouraging the use of off-site or clustered systems for OSW, minimizing the use of fertilizers and cleaning products that contain phosphorus, preventing debris and dead plant material from entering the lake, and minimizing erosion from vulnerable sites.

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