Little Traverse Lake Sampling, Database Development,
and Water Quality Data Analysis

Final Report for the Little Traverse Lake Property Owners Association

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Abstract

The objectives of this three-year project (2019 to 2021) are to collect new water quality data for Little Traverse Lake and merge these with historical data into a database. The combined data are used to ascertain the present-day status of the Lake, identify possible problems, and examine long-term trends and changes.

Algal nutrients (total phosphorus and nitrate), chlorophyll, Secchi Depth, dissolved oxygen, and other parameters were measured at several depths in the off-shore waters. Mixed species of periphyton and *Cladophora* were measured at nine near-shore sites.

The data from this sampling program and abundant historical data dating back as far as 1990 have been entered into a new EXCEL database. The database contains over 15,000 measurements of various water quality parameters.

Lake water transparency and other water quality parameters became significantly improved after a notable shift that occurred between the years 2001 and 2003. This transformation was caused by zebra mussel filtering. Over 600 measurements show that the total phosphorus concentration of the Lake has remained relatively constant over the past 31 years with an average value of 5.1 mg/m^3.

Much of these data can be summarized using the Carlson Trophic Status Index (*TSI*). This widely used and highly regarded indicator uses measurements of total phosphorus, Secchi Depth, and chlorophyll to calculate a number that characterizes various classifications of lake trophic status such as oligotrophic (30 to 40), mesotrophic (40 to 50), eutrophic (50 to 70), and hypereutrophic (greater than 70). Lakes with poor water quality have high *TSI* values, lakes with good water quality have low *TSI* values. A *TSI* value of 34.5 was calculated for Little Traverse Lake using 2021 data. This places the Lake comfortably within the oligotrophic category, an indication of excellent water quality. This conclusion is supported by several other measures of water quality as shown in Table 5.

It is important to recognize that some of the underlying cause-effect mechanisms associated with the Lake water quality remain conjectural and uncertain. Therefore, sustained vigilance is critical if the current status is to be preserved. This watchfulness

can be realized through a recommended sampling program that involves both off-shore and near-shore water quality measurements.

Summary

This project has three primary objectives: first, collect new water quality data for Little Traverse Lake and its tributaries; second, merge these new data with abundant historical data into a database application; and third, use the computational, graphing, and display capabilities of the database to facilitate analysis of the combined data to ascertain the current status of the Lake, identify possible problems, and examine long-term trends.

The project includes measurements of water quality parameters in the off-shore waters of the Lake, Shetland Creek, Shalda Creek, as well as at several near-shore Lake locations. These sites were sampled eight times in 2019, twelve times in 2020, and six times in 2021. This report analyzes new data collected in 2019, 2020, and 2021 as well as historical data dating back to 1990.

Algal nutrients (total phosphorus and nitrate) were measured in the Lake at three depths; surface, middle, and bottom. Five parameters were measured with submersible instrumentation (Hydrolab or YSI) at fourteen different depths to define vertical profiles of values. These parameters included dissolved oxygen, temperature, conductivity, pH, and oxidation reduction potential (*ORP*). Chlorophyll and Secchi Depth were measured at the Lake surface. Mixed species of periphyton and *Cladophora* were measured at nine near-shore sites. These near-shore sites are particularly important because they are expected to be more sensitive to changes in nutrient inputs (both present and future) compared to off-shore sites.

The resulting data from this sampling program as well as data from the Leelanau Conservancy dating back as far as 1990 have been entered into a new EXCEL database designed specifically for Little Traverse Lake. This database is maintained by the *LTLPOA* and has superlative capability to store, retrieve, and graphically display data in a convenient manner. The EXCEL application allows the user to compare and analyze a single water quality parameter for different years or two water quality parameters for the same year. It can also perform long-term trend analyses. All database tasks such as data input, data screening, maintenance, documentation, and distribution are controlled under the discretion and direction of the *LTLPOA*.

Water transparency data from this project and the Leelanau Conservancy measured as Secchi Depth and chlorophyll became significantly improved after a notable shift that occurred between the years 2001 and 2003. The observed clearing was the result of zebra mussel filtering as reported by Woller-Skar (2009). The Secchi Depth increased from an average value of 9.6 feet between 1990 and 2001 to 15.3 feet between 2003 and 2021. The chlorophyll concentration decreased from an average value of 2.6 mg/m^3 between 1990 and 2001 to 1.8 mg/m^3 between 2003 and 2021 (see Figures 4, 5 and 6). Notably, this pattern of improved clarity has persisted in recent years (see Table 5).

This dramatic clearing has been accompanied by a corresponding decrease in the severity of dissolved oxygen depletion in the bottom waters. Dissolved oxygen conditions can be characterized by counting the number of days when the bottom water concentrations are less than 2 mg/L. When this occurs, conditions become favorable for the release of dissolved phosphorus from the bottom sediments (Holmes, 2004). For example, in 1998 there were 90 days when the bottom water dissolved oxygen concentrations were less than 2 mg/L, compared to only 23 days in 2021. A similar decrease also occurred in other years as shown in Table 5. Another measure of dissolved oxygen condition is the hypolimnetic oxygen depletion rate (*HOD*). Measured *HOD* values during this project are typical for oligotrophic lakes and are consistent with the Walker (1979) model.

There were also significant improvements in *pH* and *ORP* conditions. The minimum summer bottom water *pH* was 6.7 in 1998 compared to a value of 7.3 in 2021. The minimum *ORP* in the bottom waters was -203 mV in 1998 compared to -99 mV in 2020. Higher *pH* and *ORP* values are indications of lower levels of decomposing organic material. Table 5 shows values for other years before and after the clearing.

Collectively, these results for Secchi Depth, chlorophyll, dissolved oxygen, *pH*, and *ORP* all support the presumption that the amount of organic material settling into the deep bottom waters has decreased as a consequence of zebra mussel predation on phytoplankton. This result is not unexpected because zebra mussel filtering shunts nutrients and organic material from the open water to the benthos through *pseudofecal* and fecal deposition.

Over 600 total phosphorus measurements have been taken since 1990. Total phosphorus concentrations have remained, on average, about the same over the 31-year sampling period. The average total phosphorus concentration is 5.1 mg/m^3. Phosphorus is the *limiting nutrient* that controls algal growth most of the year. At times during the summer, low nitrate concentrations may favor the growth of *nitrogen-fixing* undesirable blue-green algal species. Other water quality variables such as temperature and conductivity have also remained about the same with no obvious long-term trends. The sections below describe some of the seasonal dynamic features and ecological insights provided by the data.

The calculated Trophic Status Index (*TSI*) for various years based on annual average values of Secchi Depth, chlorophyll, and total phosphorus indicate that the Lake trophic status has improved from slightly mesotrophic before the clarity shift to solidly oligotrophic after the clarity shift (see Tables 4 and 5 for details).

The average measured flow of Shalda Creek (22.7 cfs) is 6.4 cfs higher than Shetland Creek (16.3 cfs). This difference is the net of the various water sources and losses. The average measured total phosphorus concentration of Shetland is 6.2 mg/m^3. Measured flow and total phosphorus concentrations of Shetland Creek have remained about the same with no obvious long-term trends.

In general, low densities of near-shore periphyton and *Cladophora* were observed with an annual average rating of less than one (see Table 5). This is equivalent to conditions between Light and Clear (see Figure 27). The most impacted sites were H9 and M2. Limited growth was also observed at sites G4b and F5 where no previous impacts have been recorded.

The above data and results portray a rational and convincing scenario of improvements in several indicators of the off-shore water quality that have occurred following the 2001 to 2003 clearing and these improvements have been sustained over the past 20 years. Apparently current zebra and quagga mussel populations have remained at levels sufficient to depress plankton concentrations despite recent reports that their numbers have declined in many lakes. Algal nutrient levels have remained about the same over this same period. These results suggest that possible detrimental impacts of increased watershed and lake shoreline development as well as aging septic systems are being offset by efforts to reduce nutrients entering the Lake.

However, it is important to recognize that some of the underlying cause-effect mechanisms associated with the present pristine water quality of the Lake remain conjectural and uncertain. Nutrient inputs from septic drain fields and the role of zebra and quagga mussels in nutrient recycling have not been quantified by direct measurement. Therefore, sustained vigilance is critical if the current status is to be preserved into the future. This watchfulness is realized through a recommended sampling program that involves both off-shore and near-shore water quality measurements. Emphasis is placed on Secchi Depth because it is good indicator of overall water quality despite its simplicity; total phosphorus because it is usually the limiting nutrient for algal growth and a few high values have been observed recently; and periphyton because they are very sensitive to small nutrient inputs. At a minimum, it is recommended that total phosphorus concentrations be measured in the spring and fall when the Lake is completely mixed vertically and that Secchi Depth and near-shore periphyton density measurements be taken twice monthly.

The data from the above efforts as well as from the ongoing Leelanau Conservancy monitoring program can be input into the EXCEL spreadsheet database application. These data and the database are the tools that provide the capability needed by the *LTLPOA* to detect possible future deterioration of water quality. For example, if the minimum Secchi Depth falls consistently below 5 feet, or the annual average total phosphorus concentration exceeds 8 mg/m^3, or obvious increases are observed in the periphyton density, then there is cause for concern and corrective measures may be warranted. The questions then become "what caused the problems and what are the best ways to correct them and to prevent further damage". These questions cannot be resolved in a judicious manner using monitoring data and trend analyses alone, rather it requires the development, calibration, and rigorous validation of cause-effect models as discussed in the **Recommendations** (Advanced) section below.

INTRODUCTION

The Good Harbor Bay Watershed Protection Plan (Brown, 2005) was developed to guide efforts to protect the water quality of lakes in the Good Harbor Bay watershed including Little Traverse Lake. This comprehensive report along with similar efforts by (Steinberg, 1994) described watershed characteristics such as population, land use, land cover, and soil type and slope. The report also defined pollution sources as well as critical issues and priorities. These efforts were based largely on analyses of water quality monitoring data available from the Leelanau Conservancy. These data and analyses are also summarized in reports by Canale and Nielsen (1997), Keilty (1997), and Keilty and Woller. (2002). Listed below are some of the water quality issues identified in these reports.

1. Lake levels
2. Pathogens
3. Swimmer's itch
4. Water clarity (Secchi Depth)
5. Nuisance algae (Chlorophyll, periphyton, phosphorus and nitrogen)
6. Species diversity/fishing (Dissolved oxygen, temperature, pH)
7. Invasive species

The focus of this project is water clarity, nuisance algae, and species diversity/fishing (Items 4, 5, and 6 above). The project has three primary components. First, collect water quality monitoring data from both the near-shore and off-shore lake waters as well as the main inlet and outlet streams. Second, develop an EXCEL database that can accommodate historical data as well as import and display current and future water quality data. Third, analyze all these data to determine the current status of the Lake and examine long-term trends. These analyses and the associated understanding of lake dynamics and processes can guide efforts to preserve and protect the water quality of Little Traverse Lake for future generations. The other issues in the above list are being addressed by other projects.

The following are questions that can be addressed using monitoring data alone.

1. Are current water quality conditions of Little Traverse Lake good or bad?
2. What is the trophic status of the Lake?
3. How does the water quality of Little Traverse Lake compare to other area lakes?
4. How do current water quality conditions compare to the past?
5. Are water quality conditions improving or deteriorating?

The following are advanced management questions that cannot be answered using monitoring data alone.

1. What are the causes of improvement or deterioration of water quality?
2. What is the most effective way halt future deterioration?
3. What is the best way to improve water quality if deterioration occurs?

These last questions require the development, validation, and application of a cause-effect model for the Lake water quality. Such a model for Little Traverse Lake requires estimates of septic tank and watershed land-use nutrient loading. Development of this capability is beyond scope of the current project, but some of the groundwork for future model development is included in the study.

LTLPOA **and LEELANAU CONSERVANCY SAMPLING PROGRAMS**

There are two water quality sampling programs concurrently active for Little Traverse Lake. One is associated with this project and the other is being conducted by the Leelanau Conservancy. These programs are described below.

LTLPOA Sampling Program

The *LTLPOA* program has collected data for three years at Lake and tributary sites. Eight samples were collected in 2019, twelve samples in 2020, and six samples in 2021. The sampling frequency was increased in 2020 define seasonal dynamics and enhance the reliability of calculations for the annual average total phosphorus concentration as suggested by Smith and Canale (2015). Figure 1 shows the single deep site used to characterize the off-shore waters, nine near-shore sites, and two tributary sampling locations. Water clarity is characterized by measuring Secchi Depth. Chlorophyll measurements are used to represent overall phytoplankton density rather than specific species enumeration. Algal nutrients considered in this project are total phosphorus and nitrate nitrogen. The health of the ecosystem is assessed using measurements of dissolved oxygen, temperature, pH, oxidation reduction potential, and conductivity.

This effort also includes expanding the water quality monitoring program by measuring near-shore *Cladophora* and mixed species periphyton density which has not been a component of previous studies. Nine shoreline sites have been established following an extensive preliminary survey of several optional near-shore sites. Two of the elected sites are baseline (G4b and F5 shown in Figure 1) that have shown little previous signs of periphyton growth and are monitored to identify any future contamination. The other seven sites have shown signs of periphyton growth or the presence of human enteric bacteria (Reimink, 2018). The density of the growth is described by measuring the filament length and by specifying a qualitative rating similar to Edwards (2018).

Leelanau Conservancy Sampling Program

The Leelanau Conservancy sampling program began in 1990 and may continue into the future. The program collects data from seven lake sites and fifty streams in Leelanau County. The lakes are sampled at multiple depths because the waters become stratified during the summer. The main parameters are Secchi Depth, chlorophyll, total phosphorus, and nitrate (usually 3 depths). Dissolved oxygen, temperature, pH, conductivity, and oxidation-reduction potential are measured at approximately ten depths.

No near-shore periphyton or *Cladophora* measurements are taken. Samples are also taken during various seasons because stratification and nutrient inputs are expected to vary with time. Normally the lakes are sampled about six times per year except for 1991, 1995, 1998, and 2005 when more intensive surveys were conducted. Stream sampling has been inconsistent and limited to a few samples per year and not all streams are sampled every year.

DESCRIPTION OF ACCESS and EXCEL DATABASES

There are two current databases that contain water quality data associated with Little Traverse Lake and Shetland and Shalda Creeks. A new EXCEL database was designed and constructed specifically for this project. An ACCESS database was constructed for the Leelanau Conservancy in 2005 and last updated in 2018. These databases are described in more detail below.

ACCESS Database

The Leelanau Conservancy supports an ACCESS database to accommodate lake and tributary water quality data (Leelanau Conservancy, 2005). This database is designed primarily to compare the water quality of various lakes in Leelanau County, and has adequately served the needs of the Conservancy for the last 15 years. The input of new data, software maintenance, and extraction of data are tasks usually performed by the developer. Such tasks are difficult to execute by others because the underlying software and application are complex and documentation is poor.

EXCEL Database

Because of the limitations of the ACCESS database, this project supported the development of an EXCEL database with a dashboard design and implementation (Canale 2020). The Main Menu for the EXCEL database is shown in Figure 2. The Main Menu shows a map of the sampling sites as well as six action buttons and an imbedded text document containing overall system documentation. The action buttons take the user to a new sheet that is devoted to storing and displaying data of various convenient categories as shown. The Miscellaneous button contains contact information of various parties, a list of scientific papers and reports dealing with the Lake, physical data, a residence time calculator, and a Carlson Trophic Status Index calculator.

This application is simpler, more transparent, and easier to maintain and distribute compared to the ACCESS database. Data input and extraction can be accomplished on a local level by *LTLPOA*. The EXCEL database also accommodates near-shore periphyton data whereas the ACCESS database does not have this component.

Figure 3 shows the general design and layout. This pattern is similar for the various categories in Figure 2. The first step is to enter data into the permanent white block area in the lower left of the sheet. Next the user selects the parameter and year for each (two) graphical displays. The underlying Visual Basic code then scans all the data in the lower left box and transfers the extracted data for the selected parameter and year into the gray box in the lower right section. The data in this section is displayed in the two charts. This design strategy allows the user to display two different parameters for the same year or the same parameter for different years. The upper right gray box is space reserved for dropdown lists and chart labels. Overall directions and documentation for each sheet are provided in an imbedded text document. Line by line documentation is also included as comment statements in the Visual Basic code.

Table 1 shows the number of lake and tributary samples for all parameters in the EXCEL database for the period 1990 to 2021. These data represent about 206 separate dates sampled over a 31-year period. Table 2 shows the number of samples taken from Little Traverse Lake for each year between 1990 and 2021. During years such as 1991, 1995, 1998, 2005, and 2020 more intensive sampling occurred facilitating definition of annual transients of the measured parameters. Note that algal nutrients are measured at three depths; surface, middle, and bottom. Parameters measured with the Hydrolab or YSI such as temperature and dissolved oxygen are measured at about ten different depths to define the vertical profile of values. The following sections describe some of the features of the data and insights regarding ecosystem dynamics.

DESCRIPTION OF LAKE CHEMISTRY and SECCHI DATA (1990 TO 2021)

Chlorophyll and Secchi Depth

Chlorophyll is a pigment that allows algae to use sunlight energy to convert carbon dioxide and other inorganic molecules into organic material via the process of photosynthesis. Chlorophyll concentrations are commonly used to estimate the plankton density in streams and lakes. The chlorophyll concentration in Little Traverse Lake depends on many factors, including water transparency, water temperature, predation by zooplankton, and the availability of nutrients, (especially phosphorus and nitrogen). As a result, the concentration is expected to have seasonal variations.

A Secchi disk is a circular disk (8 inches in diameter) that is lowered into the water as a measure of water clarity. The depth at which the Secchi disk can no longer be seen from the surface is the Secchi Depth. Secchi Depth has been used for many years as a limnological tool and is perhaps the most obvious indicator of water quality. The Secchi Depth is inversely related to the amount of phytoplankton biomass and other particulate matter such as calcium carbonate precipitate and silt.

Chlorophyll and Secchi Depth are expected to have significant correlation therefore these two parameters will be examined jointly. The general approach in this and the following sections is to start with viewing the long-trends and then looking at particular years for insights and correlations into annual cycles and dynamics.

Figure 4 shows the EXCEL database output screen for the long-term trend of Secchi Depth and Chlorophyll for the years 1990 to 2021. Note the distinct increase in the Secchi Depth and decline of Chlorophyll that occurs between 2001 and 2003. Figure 5 shows in more detail the trend of Secchi Depth between 1990 and 2001 compared to 2003 to 2020. Figure 6 shows in more detail the trend of Chlorophyll between 1990 and 2001 compared to 2003 to 2020. There is an obvious difference between these two time periods.

The increase in Secchi Depth occurred at a time when the zebra mussel population density was expanding in Little Traverse Lake. Woller-Skar (2009) reported that zebra mussels were first introduced in 1998 and were fully established by 2001 and attained an average density of 1,342 individuals per square meter in 2003. Abundant larval stage zebra mussels (*veliger*) have been reported recently by Froelich (2020). An individual zebra mussel is capable of filtering about 1 liter of water per day. At this rate, the entire volume of water in the Lake can be filtered in about 4 days. Similar increases in water clarity in other lakes have been directly linked to zebra mussel predation on plankton (Zhu, et al, 2006) and many others.

The link between Secchi Depth and Chlorophyll is also evident on a seasonal time scale as well as the long-term trend scale discussed above. Figures 7 and 8 show seasonal dynamics for 2005 and 2020. In each case Secchi Depth is high during spring and early summer and declines to a minimum at the end of summer. These dynamics are likely caused by improving growing conditions for phytoplankton due to increases in water temperature and nutrient availability (this will be discussed in more detail below).

Although, zebra mussel filtering has improved the water clarity of Little Traverse Lake, such activities may have a deleterious impact on the species composition of the plankton community. Woller and Keilty (20040, Woller-Skar (2009), and Gaskill and Woller-Skar (2018) reported significant replacement of relativity innocuous diatoms by the blue-green alga *Microcystis aeruginosa* and other cyanobacteria that produce Microcystin and other hepatotoxins. Furthermore, zebra mussel feeding activities enrich the benthos through *pseudofecal* and fecal deposition. As a consequence, there have been numerous reports of higher macroinvertebrates populations and nuisance benthic algal blooms in many lakes (see Stewart and Haynes, 1994; Stewart et. al., 1998; and Hecky et. al., 2004).

<u>*Total Phosphorus*</u>

Phosphorus is an essential nutrient for all aquatic growth and a healthy ecosystem. However, high concentrations in lakes can result in algal blooms and associated problems such as decreased water clarity and oxygen depletion. Figure 9a shows the long-term trend of total phosphorus in Little Traverse Lake between 1990 and 2021. The average total phosphorus concentration is 5.1 mg/m^3. Although there is an increasing trend between 2012 and 2021 (Figure 9b), the average concentration between 2012 and 2020 is about the same as the long-term average 1990 to 2020. Data collected in 2021 show a decline in total phosphorus as shown in Table 5. The increasing trend between 2012 and 2021 is partially a function of the unlikely low value of 2.2 mg/m^3 measured in 2012 where only three samples were taken. In addition, the higher average values in 2019 and 2020 are influenced by a few outlier measurements as shown in Figure 10. These high concentrations are likely outliers that are not representative of lake as a whole. This can occur when a sample is unknowingly taken in a Langmuir circulation debris field or when bottom sediments are disturbed. The argument that these few values are outliers is supported by the fact that there have not been corresponding declines in other measures of water quality. Thus, although these recent higher total phosphorus concentrations are of some concern, the data are inclusive, and no definitive conclusion can be made at this time. Obviously, future sampling should place emphasis on total phosphorus monitoring and continued vigilance is appropriate and recommended.

Now consider total phosphorus seasonal dynamics. Figure 11 compares total phosphorus concentrations in the surface, middle, and bottom waters for 1991 and 2005. The data for 1991 reflect conditions prior to reported zebra mussel activities while the data for 2005 characterize conditions shortly after zebra mussel infestation. Note that the Lake was sampled under the ice in mid-February of 1991. The high value measured in the bottom waters is likely the result of the accumulation of particulate phosphorus that settles from the surface under quiescent conditions under the ice and perhaps minor amounts from release from the sediment. During the spring of 1991 the total phosphorus concentrations were relatively low and uniform top to bottom. The late fall concentrations were also uniform with depth after fall turnover, but overall values increased by about 2 mg/m^3. This increase was the net result of spring runoff and loading from various sources. Note that bottom water concentrations are higher than the surface throughout most of the year. Bottom water concentrations increase with sediment release during periods of low oxygen concentrations and with the deposition of dead algae and other particulate from the surface waters. The 2005 concentrations have similar values and dynamics. Figure 10 shows 2019 and 2020 total phosphorus concentration seasonal dynamics. The overall patterns are similar (but less obvious) for these years and the average concentrations are about 1 mg/m^3 higher compared to the earlier years.

Note that quantitative relationships that relate the changes in these concentrations to sources and sinks of phosphorus loading have not been developed. Keilty and Woller (2002) performed simple linear regression of the total phosphorus data and other measurements as a function of time. In all cases the calculated regression coefficients were low indicating that conclusions regarding the trends were unreliable. Furthermore, their analyses did not account for changes in laboratory methodologies and the difference in the number of samples taken during various years. In addition, the phosphorus measurements themselves have inherent uncertainty because the low concentrations are near the detection limit and are subject to significant error (see Smith and Canale, 2015). The pitfalls of using simple regression to analyze fuzzy data are discussed in depth by Liu (1988) and Kelly (2007) and many others. Given these circumstances, more comprehensive statistical analyses are not recommended.

Trophic Status Index

The *trophic state* is an indicator of the total weight of biomass in a lake. The *Trophic State Index* (*TSI*) is a widely used and highly respected method to characterize the water quality in lakes. The three data correlation formulas for the *TSI* index are based on Secchi

Depth (*SD*), chlorophyll (*Chl*), and total phosphorus (*TP*). These relationships were developed by Carlson (1977), Carlson and Simpson (1996), and Carlson (2007).

$$TSI(SD) = 60 - 14.41 \cdot \ln(SD) \qquad (1)$$
$$TSI(CHL) = 9.81 \cdot \ln(Chl) + 30.6 \qquad (2)$$
$$TSI(TP) = 14.42 \cdot \ln(TP) + 4.15 \qquad (3)$$

The Carlson trophic state index is the average of the Secchi Depth, chlorophyll, and total phosphorus indices calculated using Equations 1, 2, and 3.

Lakes are commonly classified as being in one of four classes: *oligotrophic* (*TSI* = 30 to 40), *mesotrophic* (*TSI* = 40 to 50), *eutrophic* (*TSI* = 50 to 70), and hypereutrophic (*TSI* greater than 70). Table 3 demonstrates how *TSI* values correspond into various trophic classes (Carlson and Simpson, 1996) with *Chl* and *TP* having units of mg/m^3 and *SD* in meters.

Table 4 shows calculated *TSI* values for Secchi depth, chlorophyll, and total phosphorus before and after clarity shift that occurred between 2001 and 2003. The trophic state in 1995 was on the edge between *mesotrophic* and *oligotrophic* compared to current conditions that place Little Traverse Lake comfortably within the *oligotrophic* range. These results indicate an overall improvement in water quality of Little Traverse Lake. The *TSI* for Little Traverse Lake is mid-range compared to other lakes in Leelanau County.

<u>Nitrate</u>

Nitrogen is an essential nutrient for algal growth. Dissolved nitrogen in Little Traverse Lake occurs primarily in the form of nitrate ion with minimal amounts of nitrite and ammonia. The nitrate measurement includes minor concentrations of nitrite because typical laboratory procedures measure the sum of these two ions.

Figures 12 and 13 compares nitrate concentrations in the surface, middle, and bottom waters for 1998, 2005, 2019, and 2020. It is interesting to note that the data for these years (and others as well) are strikingly similar. These data show maximum nitrate concentrations of about 300 mg/m^3 in the early spring that decrease near the end of summer then increase into early fall. Note the steady decreases of the nitrate concentrations are similar to the dissolved oxygen concentrations declines during the summer (more on this topic in the next section). The decreases are associated with the activities of denitrifying bacteria that utilize nitrate as an oxygen source to decompose organic material and release nitrogen gas as a metabolic by-product. The surface nitrate concentrations generally fall to about 20 to 25 mg/m^3. The bottom concentrations are near the detection limit of about 5 mg/m^3. The limiting nutrient ramifications of these low levels are discussed in the next section below.

Limiting Nutrient

Management of water quality in lakes in many instances focuses on the control of the nutrient or factor governing the growth rate and maximum concentrations of algal biomass. The *limiting nutrient* is the substance that is in the least available amount relative to its needs for algal growth and reproduction. That is, algae will grow until one of the required nutrients for growth is not available in sufficient quantities. In most lake waters, including Little Traverse Lake, the liming nutrient is likely to be either nitrogen or phosphorus. Equation 4 is the classic molar balance formulation for photosynthesis where carbon dioxide and water are converted to organic matter and oxygen facilitated by light energy.

$$CO_2+H_2O \rightarrow CH_2O+O_2 \qquad (4)$$

This equation can be extended to include nitrogen and phosphorus (Redfield, et al, 1963).

$$106CO_2+122H_2O+16NO_3+HPO_4+18H \rightarrow C_{106}H_{263}O_{110}N_{16}P+138O_2 \qquad (5)$$

where $C_{106}H_{263}O_{110}N_{16}P$ is an approximation for the composition of a typical algal cell.

Thus carbon, nitrogen, and phosphorus are required by algae in the following ratios:

C:N:P = 106:16:1 on a molar basis or C:N:P 40:7:1 on a weight basis.

Thus, if in a closed system, the initial nitrogen concentration is larger than 7 times the phosphorus concentration, phosphorus is the limiting nutrient because the algae as they grow draw nitrogen and phosphorus out of the water at a ratio of approximately 7:1. In this case, the algae would deplete the phosphorus supply before nitrogen. If the initial ratio is smaller than 7 to 1, nitrogen is limiting nutrient. Most of the year nitrate concentrations are more than seven times larger than phosphorus concentrations in Little Traverse Lake, thus most of the time phosphorus is the limiting nutrient for algal growth. However, in some years the summer surface nitrate concentrations (where algae grow) may fall below 10 mg/m^3 while the total phosphorus concentration is about 5 mg/m^3. During these short time periods nitrogen is the limiting nutrient. Such conditions favor undesirable blue-green algal species that are able to utilize nitrogen in a dissolved gaseous form (*nitrogen-fixing algae*) such as *Anabaena cylindrica* and *Aphanizomenon flosaquae.*

DESCRIPION OF LAKE PROBE DATA (1990 TO 2021)

The data in this section are called Probe Data because these are data collected in the field using submersible electronic monitoring equipment such as the HydroLab or YSI. The equipment is employed by lowering it through the water column. Normally data are obtained at about ten depths to create a vertical profile. These data are recorded and retrieved directly from the instrument and do not require laboratory analyses.

Temperature

Figure 14 shows the long-term average, maximum, and minimum surface and bottom water temperatures for the period of 1990 to 2020. At first glance one can observe an almost 20 °F increase in the average surface waters between 1992 and 2010. Although a casual view of these measurements portrays this scenario, it is important to note that only one measurement was taken in the middle of the summer in 2010. In fact, samples taken between 2001 and 2013 were focused primarily on the summer months. Clearly, simple regression analyses would be inappropriate and the results would be alarmingly misleading. Figure 15 shows surface temperatures for the period 1990 to 2000 compared to 2014 to 2020 when data were taken over similar periods throughout the growing season. These data show that the average temperature was 1.5 °F lower during 2014 to 2020 compared to the earlier period. Overall, the data do not support definitive conclusions regarding increases or decreases in the long-term trends of the temperature of Little Traverse Lake.

Figure 16 compares the annual temperature dynamics for 1991 and 2020. The patterns are similar with temperatures uniform in depth in April and October. Note that the temperatures of the top and bottom layers are similar for both years, with an intermediate temperature at a middle depth. During maximum stratification the difference in temperature between the surface and bottom depths is about 20°F during mid-summer. Other years show similar dynamics with some differences due to variations in atmospheric temperature and wind conditions.

Note that air temperatures were cold enough in January 1991 to allow for one sample to be taken under the ice. The bottom water temperature (36.7°F) was warmer than surface temperatures (33.8°F) because the density of water is highest at around 39° F.

Dissolved Oxygen

Figure 17 shows bottom water dissolved oxygen concentrations for 1990 to 2000 compared to 2012 to 2020. Although the maximum and minimum concentrations are similar, the average bottom water concentrations are higher by 2.2 mg/L during the later period. This suggests that significantly less organic matter settles into the hypolimnion compared to earlier years. This observation is consistent with decreases in chlorophyll and increases in water clarity noted in previous sections of this report.

Figure 18 shows dissolved oxygen variations as a function of time in Little Traverse Lake at five different depths in 1991 and 2020. The dissolved oxygen concentration of the bottom water was 9.9 mg/L during the winter of 1991. The solubility of oxygen is 13.6 mg/L at a temperature of 36.7° F (see Figure 16). Therefore, a dissolved oxygen deficit occurs in the bottom water of about 3.7 mg/L due to sediment oxygen demand and the oxidation of dissolved organic material. Note that total phosphorus concentrations in the bottom waters also increased in 1991 (see Figure 11).

Figure 18 shows that dissolved oxygen concentrations in the bottom waters fall below 2 mg/L for several days during the summer months. The number of days the dissolved oxygen concentration less than 2 mg/L is a good indicator of the organic content of the water. The data in Figure 18 can be used to calculate the number of days the dissolved oxygen concentration is less than 2 mg/L. This done by interpolating the measurements to determine on what day the concentrations fall below 2 mg/L in the early summer and on what day the concentration increases above 2 mg/L in the early fall. In 1991 these thresholds were passed on July 6, 1991 and September 13, 1991. Thus, there were 69 days of low dissolved oxygen in the bottom water in 1991. Days below 2 mg/L for other years are displayed in Table 5. Note that 1998 appears to be the worst year, with conditions better in the early 1990s and improving in 2019, 2020, and 2021.

The periods of low oxygen concentrations favor the release of dissolved phosphorus from the sediments. The rate of this release has been measured in Platte Lake (Holmes, 2004). Phosphorus sediment release rates have not been measured in Little Traverse Lake. The release of soluble phosphorus from the bottom sediments during periods of low dissolved oxygen concentrations is an important factor that must be quantified to develop a phosphorus budget and a predictive mass balance model for the Lake. The amount of phosphorus released depends on the area of the affected bottom sediment, the phosphorus content of the sediments, chemical and physical characteristics of the sediment, and the duration of the low dissolved oxygen concentrations. The volume of the Little Traverse Lake must be known to determine the significance and impact of this release. Updated calculations for the volume and area are shown in Table A1.

Hypolimnion Oxygen Depletion Rate

Traditional methods use phosphorus, chlorophyll, and transparency to determine the trophic state of lakes (Carlson, 1977). Walker (1997) developed a method to expand on these traditional methods by utilizing measured hypolimnetic dissolved oxygen concentrations that are included in many lake water monitoring programs. In his paper, data from over 100 lakes were used to show that the trophic status index (*TSI*) is highly correlated with the areal hypolimnetic oxygen depletion rate. This empirical model is given by Equation 6.

$$\log_{10}(HOD) = -1.06 + 0.016 \cdot TSI \qquad (6)$$

where *HOD* is the hypolimnetic depletion rate in $gmO_2/m^2/day$. Figure 19 shows measured *HOD* values and *TSI* calculated for Little Traverse Lake for various years compared to Equations 6. In general, there is good agreement between the Walker model and the measured data for conditions both before and after the transparency transition period between 2001 and 2003.

Oxidation Reduction Potential (ORP)

The oxidation reduction potential (sometimes called the redox potential) characterizes the oxidizing or reducing power of water. *ORP* is determined by measuring the potential (mV) of a platinum electrode which is lowered into water using a HydroLab. High values (greater than 100 mV) indicate high concentrations of dissolved oxygen. Values below -100 mV are associated with hydrogen sulfide and methane production and the release of insoluble forms of phosphorus.

Figure 20 shows oxidation reduction potential (*ORP*) values in 1998 and 2020. Negative *ORP* values as well as low dissolved oxygen conditions are associated with the release of dissolved phosphorus from the sediments. Lower *ORP* in bottom waters in 1998 compared to 2020 suggests that there was more organic material in 1998. This is consistent with higher chlorophyll and more severe dissolved oxygen depletion in 1998 compared to 2020.

Hydrogen Ion (pH)

The *pH* of water is a measure of the hydrogen ion concentration. High *pH* values are associated with photosynthetic activities that deplete the concentration carbon dioxide. High *pH* tends to lower the solubility of many chemical constituents such as phosphorus, calcium carbonate, and heavy metals. Low *pH* values are associated with processes that generate carbon dioxide such as algal and bacterial respiration and the oxidation of organic materials.

Figure 21 shows *pH* seasonal dynamics during 1998 and 2020 for various depths. Lower *pH* in bottom waters in 1998 compared to 2020 suggests that there was more organic material produced in the Lake during the earlier period. This is supported by the higher chlorophyll and more severe dissolved oxygen depletion in 1991 compared to 2020. Higher *pH* in the surface waters compared to lower *pH* in the bottom waters occurs both years and is consistent with the photosynthesis and respiration processes above.

Conductivity

Conductivity is a measure of the ability of water to pass an electrical current. Conductivity in water is affected by the presence of negatively charged cations such as chloride, nitrate, and phosphate and positively charged anions such as sodium, magnesium, calcium, and iron. Conductivity is also affected by temperature with higher values resulting in higher conductivity. The instrumentation used in this project reports the value as Siemans/cm and adjusts measured values to 25 °C.

Figure 22 shows measured conductivity values for 1998 and 2019 for various depths. Overall conductivity values were higher in 1998 indicating higher concentrations of inorganic dissolved solids. Note that higher conductivity values were observed in the bottom waters compared to the bottom during both years as expected. The interactions among conductivity, *pH*, marl formation, and Secchi Depth involve very complex chemical and biological reactions and stoichiometry. A model for these processes was developed for nearby Torch Lake by Homa and Chapra (2011).

DESCRIPTION CREEK CHEMISTRY AND FLOW DATA (1990 TO 2021)

Figure 23 shows long-term trend in Shetland and Shalda Creeks flows from 1990 to 2021. The data (although quite sparse), show that the flow of Shalda Creek (20.2 cfs) is 5.0 cfs higher than Shetland Creek (15.2 cfs). This difference is the net of the various water sources and losses. The inputs are atmospheric in the form of rain and snowfall, tributary inflows, and inflows of groundwater. The losses are evaporation and tributary and groundwater outflows. The 5.0 cfs result is higher than the estimate of 3.3 cfs reported by Canale and Nielsen (1997) based on data from 1992 through 1995.

Figure 24 shows Shetland and Shalda Creeks flow dynamics for 2019 and 2020. The flows are high during the spring and early summer, decline during mid-summer, and then increase in the fall. This pattern is typical for many streams in the area.

Figure 25 shows long-term trend in Shetland and Shalda Creeks total phosphorus concentrations from 1990 to 2021. The average total phosphorus concentration of Shetland Creek is 6.2 mg/m^3. The average total phosphorus concentration of Shalda Creek is 6.1 mg/m^3.

The input of total phosphorus loading entering the Lake from Shetland Creek based on the above average flow and concentration is 194 lbs/yr. The output of total phosphorus loading leaving the Lake from Shetland Creek based on the above average flow and concentration is 233 lbs/yr. These results are quite unusual because normally 50 to 65% of the phosphorus loading entering a lake via tributaries is retained in the sediments resulting in a much lower outlet loading (for example Platte Lake, see Canale et al. 2010).

These results show that groundwater, septic tank drain field, and atmospheric sources of phosphorus are significant inputs that affect the water quality of Little Traverse Lake. These sources must be quantified to obtain a more in-depth understanding of water quality budgets and dynamics.

DESCRIPTION OF NEAR-SHORE DATA (2019 TO 2021)

Cladophora is a genus of green algae (family *Cladophoraceae*) that is usually found growing attached to rocks or timbers in the splash zones of lakes and streams. *Cladophora* is coarse in appearance and touch with regular branching filaments (see top row of Figure 26). *Spirogyra* is another common green alga usually found in shallow quiescent near-shore waters. This species is not branched and is very silky to the touch (see middle row of Figure 26). Periphyton is a complex mixture of algae, cyanobacteria, heterotrophic microbes, and detritus that is attached to submerged surfaces in most aquatic ecosystems (see bottom row of Figure 26). These three types of near-shore growth are found at various sites in Little Traverse Lake.

Several methods have been used to quantitatively characterize the biomass density and growth rate of *Cladophora* and periphyton in lakes and streams. Density may be determined by harvesting samples from natural or artificial substrates and measuring dry weight or chlorophyll concentrations. Growth rate may be estimated by measuring the rate of oxygen production or the uptake rate of C^{14}. The advantages, disadvantages, and application of various methods are discussed in more detail by Bott et al. (1997), Barry and Kilroy (2000), and Lambert and Cattaneo (2008).

The above methods have limitations, are more suited for research purposes, and are not practical for the current Little Traverse Lake applications. The use of qualitative visual assessments of periphyton coverage has long been used in streams and lakes. The US EPA uses a Rapid Bioassessment Protocol that includes a subjective ranking of observed algal growth in lakes and streams as described by Barbour et al. (1999). In current project, density is described following similar qualitative methods described by Edwards (2018). The algal density is characterized by measuring the length of selected filaments and by specifying a subjective rating from 0 to 5. Figure 27 shows example photographs from Little Traverse Lake sites that illustrate the rating scale.

Periphyton and *Cladophora* were measured at the nine previously selected near-shore sites on six dates in 2019, eleven dates in 2020, and six dates in 2021. Temperature and conductivity measurements were added in 2021. Periphyton measurements are good indicators of near-shore nutrient sources because many these organisms have the ability to rapidly absorb phosphorus and store it in excess of minimum growth requirements (Auer and Canale, 1980). This *luxury uptake* can increase the cell composition about five times the minimum requirements. The stored reserve can be used to support cell growth even when external nutrient sources may be absent. Thus, these organisms may be able proliferate even when nutrient inputs may have had a short-term duration due to varying wind conditions or intermittent changes in the magnitude of the nutrient sources. Thus, periphyton and *Cladophora* are widely considered to be sensitive precursors of changes in overall water quality conditions (Higgins et al, 2008). Comparatively, off-shore waters are not as sensitive to short-term near-shore transients unless these inputs persist and accumulate over time. Photographs were taken at each site during each sample date.

Figures 28 and 29 show the distribution of the periphyton rating during the survey when the density was maximum for both 2020 and 2021. These summer surveys coincided with the highest surface water temperatures of about temperature 77 °F and with phosphorus concentrations elevated above spring turnover lows. Sites H9 and M2 are clearly the most impacted near-shore sites and they also coincide with locations where enteric bacteria have been reported (Reimink, 2018). Figure 29 shows mid-summer periphyton and conductivity. Overall periphyton rating was lower in 2021 compared to other years. Relatively higher conductivity was observed at site L3, but there does not appear to be a relationship between periphyton rating and conductivity. Figure 30 shows the average rating for each site for 2019 and 2021. The M2 site had the highest average value equal to 1.85. The average rating for all sites and all dates was only 0.61 which corresponds to a rating between Light and Clear (see Figure 27 and Table 5). Growth was observed at sites G4b and F5 on some dates. This is of some concern because these sites have shown no previous signs of periphyton growth. It recommended that measurements be continued of the near-shore periphyton and *Cladophora* to determine if future impacts occur at G4b and F5 or if other sites show signs of increased nutrient availability.

It is interesting to note that *Cladophora* (as opposed to the general periphyton category) was mainly seen in the spring and fall under moderate water temperatures and was largely senescent during mid-summer when temperatures were higher (see Comments section of the Database for more details). This observation is consistent with results reported by Graham et al. (1982) who determined that the optimal temperature for *Cladophora* growth was about 59 °F. Other components of the mixed periphyton community may achieve optimal growth at higher temperatures but specific and detailed scientific literature on this topic is limited (Larned, 2010).

RECOMMENDATIONS (First Priorities)

First, it is recommended the *LTLPOA* purchase a Secchi disk (less than $100) and measure the Secchi Depth every two weeks and enter the data into the EXCEL database. These measurements convey much insight into the overall water quality despite their simplicity and somewhat qualitative nature.

Second, *LTLPOA* should measure near-shore periphyton and *Cladophora* at the nine established permanent sites two times per month starting in early May through the end of October and enter the data into the EXCEL database.

Third, the *LTLPOA* should measure the total phosphorus concentration (in triplicate) one meter below the surface at the deep-water lake site every year after spring and fall turnover (mid-May and October). The laboratory cost is approximately $250. The data should be entered into the EXCEL database every year.

Fourth, *LTLPOA* should request data for Shetland and Shalda Creek and Little Traverse Lake from the Leelanau Conservancy every year and enter this information into the EXCEL database. Note that all historical, current, and future data are stored and preserved in an easy-to-use EXCEL application file that is secured and maintained by *LTLPOA*.

Fifth, lake levels are important to *LTLPOA* property owners and high waters may introduce nutrients to the Lake by encroaching septic tank drain fields. Several years of Lake level data are available. The database should be expanded to accommodate the import and display of historical and future lake level data.

Sixth, *LTLPOA* should procure a copy of all historic, current, and future written memos, reports, and scientific papers related to the water quality of Little Traverse Lake. These documents should be stored in a digital format for easy retrieval.

Implementation of the above priority recommendations would place the *LTLPOA* in an excellent position to rationally detect possible deterioration of the off-shore or near-shore water quality of Little Traverse Lake. For example, a significant decline in water clarity would be noticed if the Secchi Depth falls consistently below 5 feet (see Figures 4 and 5). Similarly, worsening conditions would occur if the annual average total phosphorus concentration exceeds 8 mg/m^3 (Figures 9 and 10) or if obvious increases are observed in the periphyton density. These transformations would change the current oligotrophic status of the Lake to conspicuously mesotrophic (see Equations 1, 2, and 3). If these targets are eclipsed, the question then becomes "what caused the problems and what are the best ways to correct them and prevent further damage". These questions cannot be resolved in a judicious manner using monitoring data alone, rather it requires the development of cause-effect models as discussed below.

RECOMMENDATIONS (Advanced)

The following are recommendations to develop, calibrate, and validate a cause-effect model for off-shore Lake water quality. The first recommendation is to develop the model as an EXCEL application. The next five recommendations (listed in order of priority) strengthen the data associated with the model inputs and coefficients. These steps enhance credibility and increase the confidence in model results.

Lake Water Quality Model

A lake water quality model must be developed to address the above advanced type of cause-and-effect management issues. Such modeling technology has been employed in other lakes in the area, for example see reports by Canale and Auer (1982), Canale and Chapra (2002), Canale et al (2004), Canale et al (2010), DeGraeve and Endicott (2006), Homa and Chapra (2011), and hundreds more by several researchers for other lakes worldwide. Although the model equations and structure are well known, model credibility is a critical issue that relates to confidence in model conclusions and recommendations. Model trustworthiness depends strongly on the robustness of the data used to determine values for the input nutrient loads and model coefficients.

Septic Tank Drain Field Survey and Model

It is recommended that the *LTLPOA* conduct a survey to identify possible nutrient sources from septic tank drain fields. The data should be used to support the development of a model that can be used to estimate current and future nutrient loads to the Lake. Such a model should account for the system-wide number of septic tanks, the number of users for each tank, age of each installation, the distance and elevation between the tank and drain field from the shoreline, and the soil adsorptive capacity. The results from this model are a component of the nutrient loading mass balance needed by the water quality model described above.

Bottom Sediment Chemistry

It is recommended to conduct a survey to determine the spatial distribution and variation of grain size, organic content, and total phosphorus in the bottom sediments of the Lake. These data can be used to improve estimates of the sediment phosphorus release rate.

Atmospheric and Groundwater Nutrient Loading

It is recommended to expand the current monitoring program to collect data that can be used improve estimates of the concentration and loading of total phosphorus and nitrate from atmospheric and groundwater sources.

Periphyton Survey

The methodology employed in the current project to characterize shoreline conditions uses photographs and a qualitative visual scale to estimate periphyton and *Cladophora* density. This simple approach was favored to encourage and facilitate a long-term effort to monitor shoreline changes. It is recommended to expand this approach to measure density and distribution of shoreline algal populations and to link the observations to shoreline features such as substrate type, erosion, greenbelt length, greenbelt depth, shoreline alterations, groundwater and drain field inflows, and tributary inflows. Similar studies have been performed by the Tip of the Mitt Watershed Council for Burt Lake (Cronk, 2009) and by the Three Lakes Association for Torch Lake (Blanery, 2010).

Zebra Mussel Survey

As discussed above, the Leelanau Conservancy data shows appreciable changes in chlorophyll and Secchi Depth between 2001 and 2003 caused by zebra mussel colonization and filtering. Woller-Skar (2009) and Gaskill and Woller-Skar (2018) reported that the zebra mussel density was 1,342 individuals per square meter in 2003. Zebra mussel density has declined significantly and has been replaced by quagga mussels in many other lakes in the area in subsequent years. Therefore, it is not clear to what extent filtering mussels currently affect water quality dynamics in Little Traverse Lake although improved clarity conditions have persisted and abundant larval stage of zebra mussels (*veliger*) have been reported recently by Froelich (2020). More light on this scenario could be obtained by conducting a survey to determine the present-day distribution and density of zebra and quagga mussels in the Lake.

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Many have helped with the inspiration and final completion of this project. Lou Gurthet and Kristen Race got the project going, spearheaded fund-raising efforts, assisted with the project design, and coordinated with the *LTLPOA* Board. John Ransom from the Benzie County Conservation District performed the lake, stream, and shoreline sampling and survey work. Jeff Shutz performed significant research on the important task of calculating nutrient loads from septic tank drain fields and his pontoon boat was used to conduct the initial shoreline survey. Renae Gurthet has reviewed and tested the database

and has volunteered to enter future data. Julie Sutfin was involved with the shoreline study plan, participated in the initial shoreline survey, and coordinated the shoreline *qPCR* and enteric bacteria studies performed by Ron Reimink. Brian Price provided data from the Leelanau Conservancy sampling program. Tom Lauer provided helpful insights and suggestions regarding the role of zebra mussels in the increase in water clarity. Jerry Leanderson has collected lake level data for several years that may someday be entered into the database.

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Appendix A. Little Traverse Lake Volume, Area, and Depth

Steinberg et al (1994) provide values for depth, volume, and surface area of Little Traverse Lake and these results were subsequently quoted in the Good Harbor watershed plan report by Brown (2015). Unfortunately, the underlying data used to determine these values are not provided in these reports. Therefore, an independent effort was made during this project to verify and refine these estimates. The surface area between various depth contours was measured using a GPS nautical chart and a K&E 4238 polar planimeter. The volume of each segment was determined by multiplying the average of the top and bottom areas by the thickness. The total Lake volume was calculated by adding the volumes all the segments. This approach appears to be more accurate than previous published estimates. Values are displayed in Table A1.