FRESHWATER
Scientific Services, LLC

www.fixmylake.com
18029 83rd Avenue North
Maple Grove, MN 55311
mail@freshwatersci.com
(651) 336-8696

Estimation of Internal Phosphorus Loading for Cedar Island Lake *(DOW# 27-0119)*

Prepared for the Cedar Island Lake Homeowners Association – December 2010
by James A. Johnson – Freshwater Scientific Services, LLC

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Introduction

Algae growth in Minnesota lakes is generally limited by the availability of the essential nutrient phosphorus. In turn, the amount of phosphorus in lakes depends in large part on (1) the amount of phosphorus that flows into the lake from external sources (e.g. stormwater runoff) and (2) the amount of phosphorus released from lake sediments. Knowing the relative contribution of phosphorus from these two sources (external and internal) is vital when developing management strategies to reduce phosphorus in lakes.

Internal phosphorus loading in deep lakes is highly dependent upon lake stratification (separation into a warm upper layer and a cool bottom layer). In such lakes, oxygen in the bottom layer (hypolimnion) is often used up by microbes, with low oxygen persisting in the bottom layer until the lake remixes in the fall. During this period of depleted oxygen, phosphorus that was bound to iron in the lake sediment is released. Over time, this results in a buildup of phosphorus in the bottom layer of the lake. During periods of strong stratification (summer), the top and bottom layers of deep lakes do not readily mix, so only a small portion of the built-up phosphorus from the bottom layer may be brought to the surface where it can fuel algae blooms. In general, deeper lakes undergo this process predictably every summer.

By contrast, phosphorus availability in shallow lakes is dramatically more dynamic, as the entire lake is mixed much more frequently. Consequently, the entire lake volume remains in direct contact with the sediment (as opposed to just the bottom layer in deep lakes), so nutrient recycling can occur more rapidly in shallow lakes. Furthermore, because shallow lakes generally remain well-mixed and oxygenated, the entire lake bottom can support animals (fish, insects, crayfish, etc.) that may stir up sediments or release high amounts of dissolved phosphorus in their wastes. This dynamic nature of internal loading in shallow lakes makes it difficult to predict annual loading, but it may be useful to bracket typical low and high internal phosphorus loading under different conditions. Such bracketing can be very useful when developing management strategies to reduce nutrients, particularly in deciding whether to focus on external or internal sources of nutrients and in setting realistic expectations for any management actions.

Study Context & Objectives

The CILHA is currently considering management options to improve the fishery and water quality of Cedar Island Lake. A better understanding of the relative importance of internal vs. external phosphorus loading would help the CILHA evaluate their management options and help them set realistic expectations for results.

Several methods are available for estimating internal loading. Mass-balance approaches require extensive monitoring and/or modeling of inflow, outflow, and in-lake changes in phosphorus. Consequently this approach was beyond the financial means of the CILHA. A second alternative, sediment core incubation, was also determined to be prohibitively expensive and of limited use, because it would only tell us the potential maximum rate of nutrient release under anoxic conditions. To use core incubation data, we would need additional monitoring to determine the duration of low oxygen and the total sediment area affected. Consequently, we decided to pursue a third, more “low tech” method that had worked well for estimating internal loading in nearby Rice Lake: *phosphorus increase during extended dry periods*. Although this method only produces a range of internal loading estimates, it provides a fuller picture of the frequency and magnitude of internal loading events, and is much less expensive than conducting sediment core incubations.

Over the past ten years there have been several extended dry periods when there was little to no inflow or outflow from the Cedar Island Lake. During such dry periods, any increase in phosphorus can be attributed to internal loading. Based upon the relative change of total phosphorus in Cedar Island Lake during these monitored dry periods, we were able to estimate net rates of internal phosphorus loading from sediments as well as net rates of phosphorus deposition back to sediments. In addition, we were able to identify possible underlying factors that affected loading rates during each period.

The specific objective of this study was to determine the range of internal phosphorus loading rates in Cedar Island Lake. As an additional benefit, this method required the development of a detailed bathymetric map (depth contours) for accurate estimation of lake volume. This map was provided to the CILHA for use in planning future management activities.

Study Lake

Cedar Island Lake (45°05’00”N, 93°26’30”W; DOW# 27-0119) is an 87-acre shallow (7 ft max depth), hypereutrophic (TSI=75), drainage lake in Hennepin County, MN (Figures 1 and 2). The lake’s hydrology is largely driven by stormwater runoff, which drains an area of approximately 700 acres (primarily residential land use with additional drainage from the nearby 494/94 interchange). Outflow from the lake is controlled by a pump, which empties overflow water into an underground pipe that eventually drains to Eagle Lake. Cedar Island Lake typically has low water clarity (1.3 ft average), high total phosphorus (200 μg/L), and high chlorophyll-a (100 μg/L) during the summer months, and is currently listed as an impaired water by the Minnesota Pollution Control Agency.

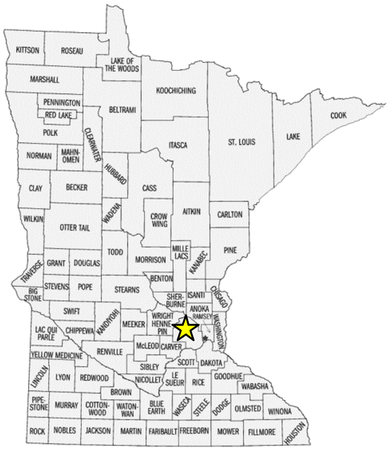


Figure 1. Location of Cedar Island Lake

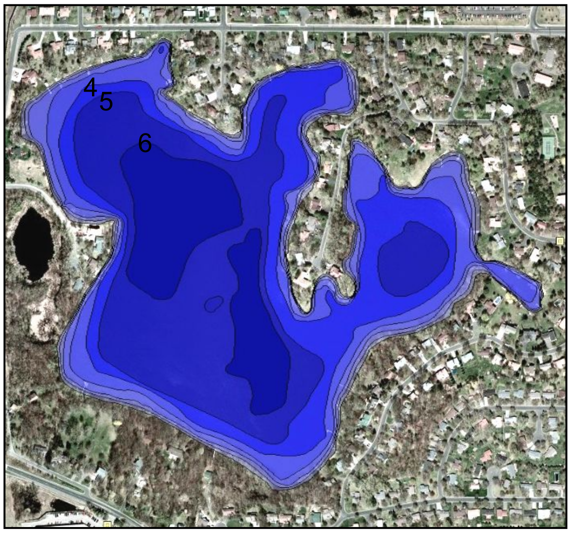


Figure 2. Depth-contour map of Cedar Island Lake produced by Freshwater Scientific Services, LLC; used to calculate accurate lake volumes for each assessed period. See Figure A-2 for larger map.

Methods

Data Sources

Water Quality (Total Phosphorus)

We combined water quality data sets collected by Blue Water Science (monthly from 2000–2009; McComas 2010) and by citizen lake volunteers as a part of the Minnesota Pollution Control Agency's *Citizen Lake Monitoring Program* (bi-weekly in 2001, 2003, 2006; MPCA 2010). This represents all of the available phosphorus measurements from the lake in the past 10 years.

Daily Precipitation and Weather Conditions

Daily precipitation data were downloaded from the Weather Underground website (www.wunderground.com) using data collected at a weather station 6 miles northeast of Cedar Island Lake (station KMNCHAMP1; Jefferson Hwy and Hwy 169). Daily wind data were compiled from daily climate summary reports produced by the Minnesota State Climatology Office (station MSP).

Lake Water Elevation

Lake water elevation data were downloaded from the Minnesota Department of Natural Resources, Lake Finder website (www.dnr.state.mn.us/lakefind/index.html).

Lake Volume

Lake volume was calculated using a detailed bathymetric map (Figures 2 and A-2) developed by Freshwater Scientific Services, LLC. This map was developed using over 11,000 depth/GPS position readings collected in Sept 2010 using a Lowrance LMS-520c sonar unit with an integrated GPS unit and logging capability. The recorded depth/GPS data were adjusted to reflect water depth relative to the ordinary high water (OHW) elevation of 902.4 ft and then translated into depth contours using desktop GIS software (ArcView 3.3). We then calculated the volume of each 1-ft stratum of the lake (e.g. 0-1 ft, 1-2 ft, etc.) using the surface area of the top and bottom of each stratum and the formula for partial cone volume (Equation 1). Total lake volume was calculated by summing all strata.

(Eq 1) $$V = [H \times (A_t + A_b + \mathrm{sqrt}(A_t + A_b))] \div 3$$

where…
V = Volume of stratum
H = height of stratum (1 ft for all but the bottom stratum)
A_t = area of the top (uppermost) of the stratum
A_b = area of the bottom of the stratum
sqrt = square root of

Based upon the calculated stratum volumes, we also developed hypsographic plots (Figure A-1) showing the area and volume below a given depth. Such plots are very useful for planning lake management activities that affect or are affected by lake volume (e.g. lake drawdown, herbicide application, rotenone application, aeration, etc.).

Internal Load Analysis & Calculations

We plotted daily rainfall, average daily wind speed, and in-lake total phosphorus (TP) for all years between 2001 and 2009 except for 2005 (insufficient data). We then identified any extended dry periods during which at least two TP samples had been collected (Figure 3). In all, we found 11 such periods, however, 6 of these periods occurred in one extended dry period in July and August of 2003. For each identified dry period, we noted the following: start date, end date, initial lake elevation, final lake elevation, initial TP and final TP. We then calculated net sediment phosphorus release (+) or deposition (-) within each period by first calculating the change in the mass of phosphorus in the lake (Equation 2) and then divided this change in P mass by the number of days and sediment area (Equation 3). These calculations yielded daily net phosphorus release (or deposition) per unit area of sediment (mg $P/m^2 \cdot d$; Table 1).

Period Net Internal Phosphorus Load

(Eq 2) $L_{internal} = (C_2 \times V_2) - (C_1 \times V_1)$

$L_{internal}$	*Total Period Internal Phosphorus Load*
C_1	*Observed in-lake TP at beginning of period*
C_2	*Observed in-lake TP at end of period*
V_1	*Lake Volume at beginning of period*
V_2	*Lake Volume at end of period*

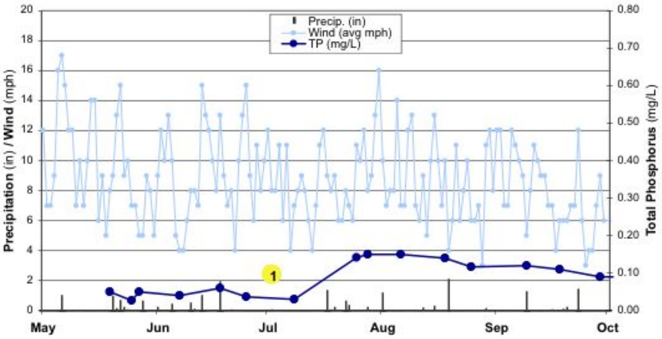
Net Internal Phosphorus Loading Rate

(Eq 3) $R_{internal} = L_{internal} (t \times A_{sed})^{-1}$ *($mg\ P/m^2 \cdot d$)*

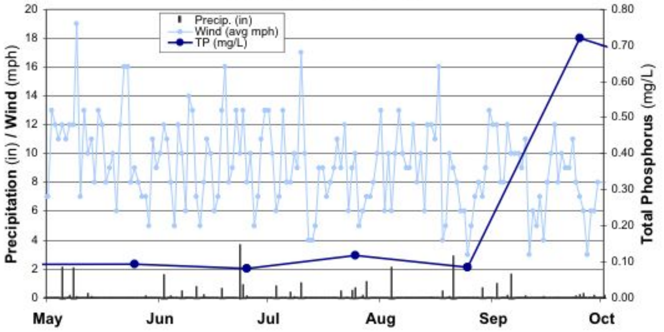
$R_{internal}$	*Internal Phosphorus Loading Rate*
$L_{internal}$	*Total Period Internal Phosphorus Load*
t	*Number of days in the observed time period*
A_{sed}	*Sediment surface area (assumed to be equal to lake surface area x 1.1)*

Figure 3. Growing season (May–Sept) total phosphorus (TP), daily precipitation, and daily average wind speed for Cedar Island Lake. Identified periods with minimal or no precipitation between TP samples are indicated by numbered yellow dots (11 total).

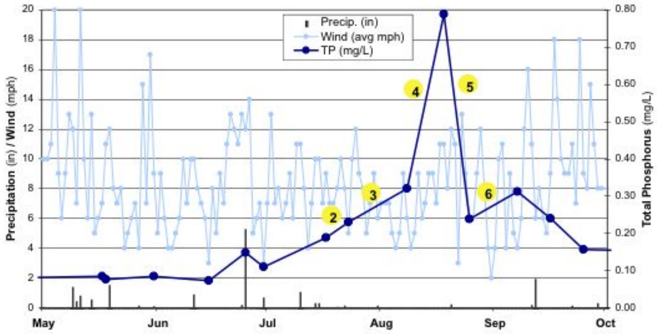
Cedar Island Lake: 2001



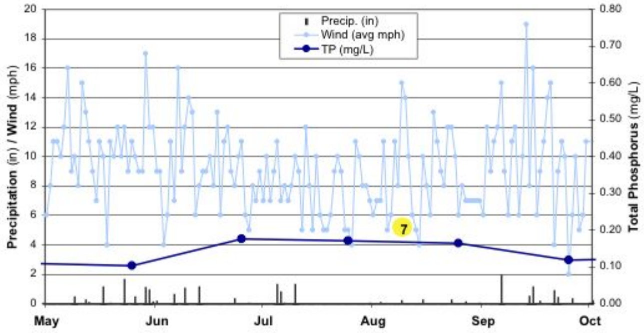
Cedar Island Lake: 2002



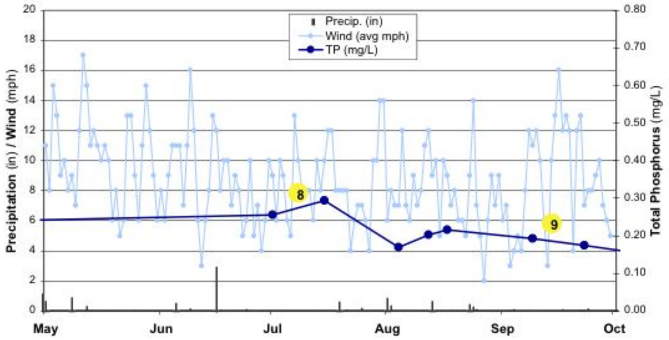
Cedar Island Lake: 2003



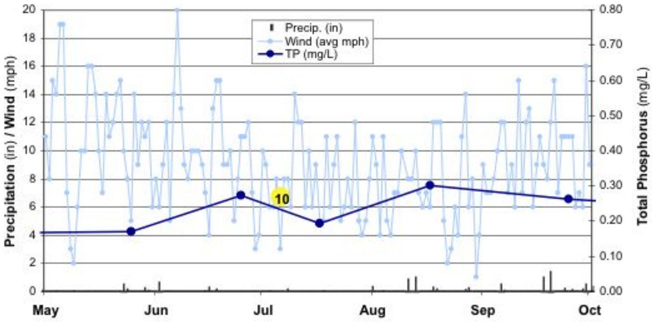
Cedar Island Lake: 2004



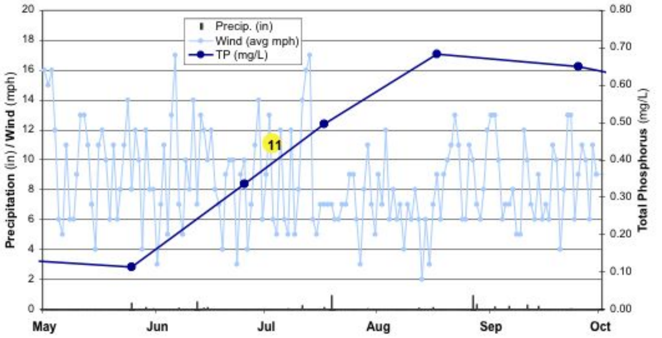
Cedar Island Lake: 2006



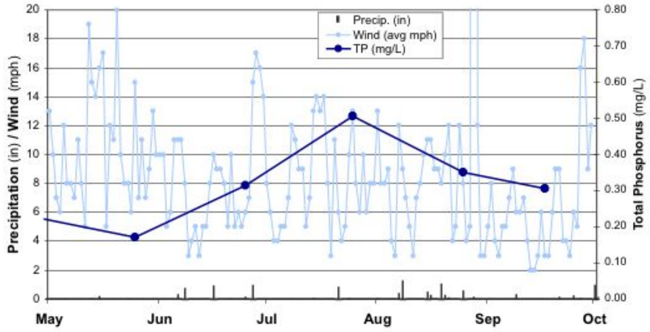
Cedar Island Lake: 2007



Cedar Island Lake: 2008



Cedar Island Lake: 2009



Results & Discussion

Summary of Internal Loading

During most of the evaluated years (2001–2009), TP in Cedar Island Lake averaged between 200 and 300 µg/L, but occasionally increased to much higher concentrations (>500 µg/L). For comparison, the Minnesota Pollution Control Agency "lists" shallow lakes that exceed 60 µg TP/L as impaired waters. Overall, TP in Cedar Island Lake was substantially higher than this threshold for impairment. However, TP varied from as low as 30 µg/l to nearly 800 µg/L, with the lowest concentrations (<100 µg/L) occurring in the spring (May and June) and the highest concentrations (>500 µg/L) occurring in the late summer (Aug and Sept). This seasonal pattern is typical of fertile shallow lakes (Scheffer 2004), but the upper end of the observed loading rates indicates that Cedar Island Lake is extremely fertile.

The observed wide range and sporadic fluctuations in phosphorus concentration indicated that the lake occasionally experienced intense pulses of phosphorus from internal sources (released from lake sediment). Furthermore, the large differences in TP between years (extremely high in some years) suggests that weather has a major influence on the lake's phosphorus concentration, with precipitation and wind being particularly important. Wet periods appeared to dilute and flush the lake (June–Aug 2002, June 2001), keeping TP below 200 (still very high), and drier periods appeared to promote much higher TP concentrations. Although stormwater inflow surely delivered some sediment and nutrients to the lake, a review of the plots in Figure 3 indicates that in-lake phosphorus concentrations were generally not increased by runoff (no strong examples of a spike immediately following a rain event except for the very large storm in June 2003). Conversely, the highest concentrations of TP in the lake generally occurred during drier periods when there was little flushing (Aug 2003, Aug 2008, July 2009). However, the TP concentration did not always increase during drier periods (Aug 2004), suggesting that precipitation was not the only factor involved; wind also appeared to impact internal loading to some degree. A few large spikes in TP were preceded by extended periods with low wind (few days with >10 mph average wind speed; July–Aug 2003, July–Aug 2008), suggesting that the lake may have experienced temporary areas of low oxygen near the lake sediment during extended calm periods. This would have resulted in a dramatic buildup of phosphorus in a thin layer of deoxygenated water near the bottom of the lake, with subsequent mixing of this phosphorus into the whole lake volume on the next windy day (Scheffer 2004, Sundby et al. 1986).

Collectively, these observation suggest that TP concentrations in Cedar Island Lake are largely driven by internal loading processes, but that the nature of this internal loading is somewhat sporadic and does not occur to the same degree in all years. In addition to the factors already discussed (precipitation and wind), other factors may enhance internal loading in the lake. In particular, large amounts of phosphorus may be released through resuspension of sediment by fish (carp and/or bullheads), strong winds (e.g. during severe thunderstorms) and intense motorboat activity (Yousef 1980, Asplund 1996) when the lake level is down. Previous studies have shown that high amounts of sediment resuspension can increase the release of phosphorus by 20-30 times compared to release from non-suspended sediments (Søndergaard et al. 2003). Additionally, super-abundant algae can promote additional release of phosphorus from lake sediments by depleting oxygen in the water during the night (respiration) and by driving pH up during the day (photosynthesis), both of which can trigger release of iron-bound P (Scheffer 2004).

Clearly, the process of internal loading in Cedar Island Lake is dynamic and complex, with multiple contributing factors. Given the amount of variability in these contributing factors, it is difficult to determine a specific internal loading rate for Cedar Island Lake. However, we were able to estimate the range of loading rates and gain additional understanding of the conditions that may affect loading rates in the lake. Table 1 summarizes our estimates of internal loading in Cedar Island Lake based upon data collected over the last ten years. The results presented are net loading rates, meaning that they reflect the sum of the simultaneous processes of phosphorus release (+) and phosphorus settling or deposition (–). These values provide a range of loading rates (2 to 50 mg P/m^2•d) during periods of phosphorus increase and a range of deposition rates (–1 to –85 mg P/m^2•d) during periods of phosphorus decrease. Overall, most of the release rates fall within the typical range of rates seen in other Minnesota lakes, however, we did observe one period (Period #4; Table 1) with a substantially higher loading rate (48.6 mg P/m^2•d). This high rate suggests that the lake experienced a rapid and intense pulse of phosphorus, likely from a substantial amount of sediment resuspension or sudden mixing up of phosphorus that had accumulated in pockets of low oxygen near the bottom of the lake during an extended calm period. Without additional data (oxygen measurements, documented sediment resuspension) we can not be sure of the cause of this large pulse of phosphorus, but such pulses appear to occur in roughly 1 out of every 2 years.

Table 1. Estimated phosphorus release (+) or deposition (–) of during each dry period; see Figure 3 for more information about each identified period. Negative values indicate a net loss of total phosphorus from the water due to settling of suspended sediment and organisms or precipitation of iron-bound phosphorus compounds (collectively "deposition").

Period #	*Start Date*	*End Date*	*Start TP (µg/L)*	*End TP (µg/L)*	*P Release/Deposition Rate (mg P/m^2•d)*
1	6/25/01	7/8/01	37	30	– 0.9 *
2	7/17/03	7/23/03	188	230	7.7
3	7/23/03	8/8/03	230	320	5.3
4	8/8/03	8/18/03	320	788	48.6
5	8/18/03	8/25/03	788	239	– 85.5 *
6	8/25/03	9/7/03	239	312	4.4
7	7/25/04	8/25/04	171	165	–1.0 *
8	7/1/06	7/15/06	255	294	1.6
9	9/9/06	9/23/06	192	174	– 2.0 *
10	6/25/07	7/17/07	273	193	– 5.4 *
11	6/25/08	7/17/08	335	496	8.0

Final Remarks

Based upon the observed range of internal phosphorus loading rates and frequency of intense pulses of phosphorus in Cedar Island Lake, the CILHA should consider purchasing a dissolved oxygen meter to monitor oxygen levels in the lake. Such measurements would help to determine whether the lake periodically loses oxygen near the sediment, resulting in high internal loading. In addition, it would be useful to conduct a small study on the effects of intense motorboat activity on sediment resuspension and phosphorus levels in the lake. Furthermore, if the CILHA conducts a successful removal of bullheads from the lake, more intensive water quality monitoring (additional water samples, daily dissolved oxygen measurements) should be included in the project plan to estimate the impact of fish removal on internal loading. This additional monitoring would help guide future management planning and help evaluate the success of implemented management activities.

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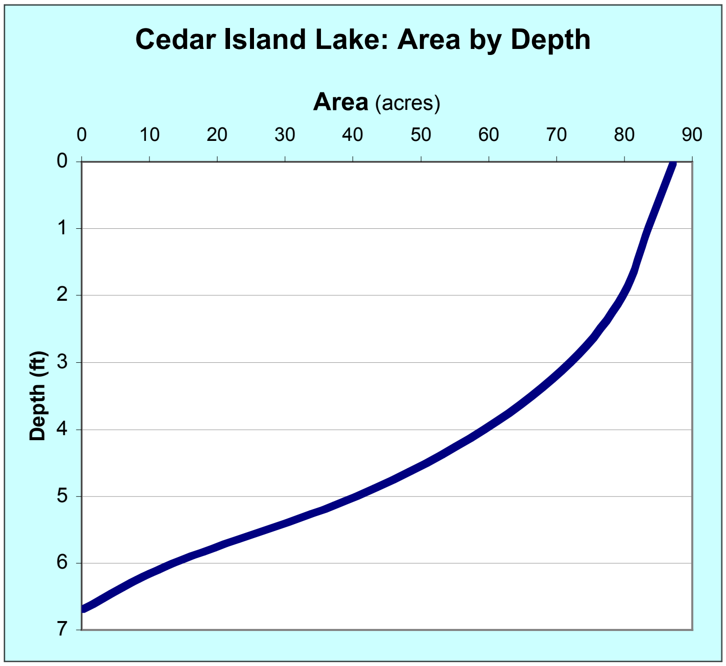
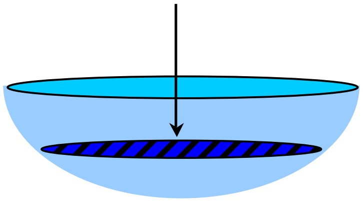
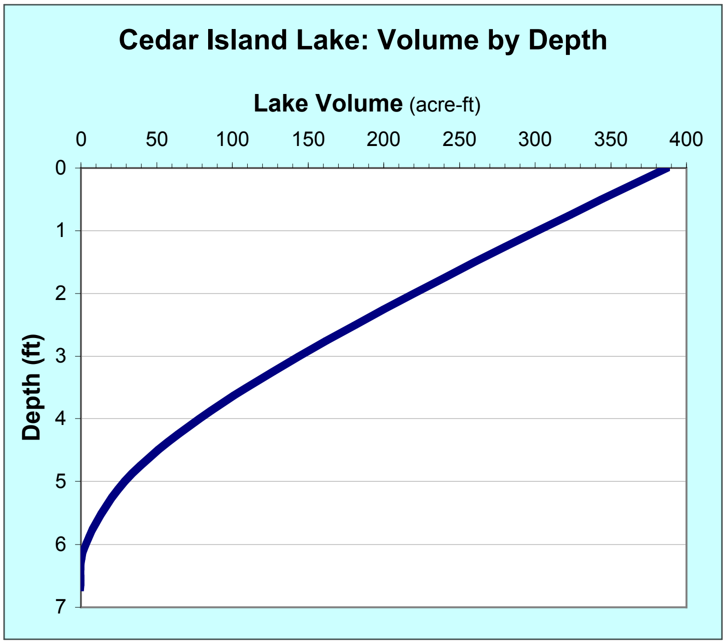
Appendix A

Figure A-1. Hypsographic curves for Cedar Island Lake; area by depth (top), and volume by depth (bottom); Curves developed using the detailed bathymetric map created by Freshwater Scientific Services, LLC




Used to determine area of plane at a given depth



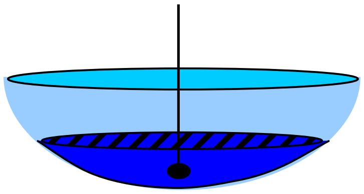

Used to determine volume of water below a given depth

Figure A-2. Bathymetric map of Cedar Island Lake created by Freshwater Scientific Services, LLC; Sept 2010. Map also provided to CILHA electronically for use in Google Earth.