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# Technical Memorandum

Prepared for: Town of Stow, MA

Project Title: Lake Boon Evaluation

Project No.: 156423

**Technical Memorandum No. 2**

Subject: Lake Boon Health Assessment

Date: Revised: February 15, 2022

To: Kathy Sferra, Conservation Director

From: Andrew Goldberg, Project Manager

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*Limitations:*

*This document was prepared solely for the Town of Stow, MA in accordance with professional standards at the time the services were performed and in accordance with the contract between the Town of Stow, MA and Brown and Caldwell dated February 19, 2021. This document is governed by the specific scope of work authorized by the Town of Stow, MA; it is not intended to be relied upon by any other party except for regulatory authorities contemplated by the scope of work. We have relied on information or instructions provided by the Town of Stow, MA and other parties and, unless otherwise expressly indicated, have made no independent investigation as to the validity, completeness, or accuracy of such information.*

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# Introduction

This Technical Memorandum describes the current water quality conditions in Lake Boon based on data collected in the 2021 monitoring program and based on preliminary modeling conducted by Brown and Caldwell. The intent of providing this memorandum in draft form is to share a progress update with the Steering Committee, solicit input from the Steering Committee, and to use the preliminary findings to guide the development of alternatives that will result in improved lake health. BC looks forward to discussing this memorandum with the Steering Committee and refining the findings over the coming months as we prepare a project report.

This technical memorandum is organized into sections that describe the monitoring program and a 3-step process to model the health of Lake Boon (the lake). Figure 1 depicts these modeling steps. In step 1, BC developed and calibrated a hydrology model for the Lake. In step 2, BC performed a preliminary evaluation of the lake's trophic status using water quality monitoring data and the Vollenweider method. In step 3, BC developed a phosphorus loading and water quality model for Lake Boon and validated the model for 2021 conditions. In future phases, BC will apply the modeling framework to identify, develop, and test the effectiveness of a wide range of strategies to improve overall water quality. This memorandum does not include management scenario modeling nor an evaluation on the impacts of climate scenarios on the lake's health, but these analyses will be included in a project report.

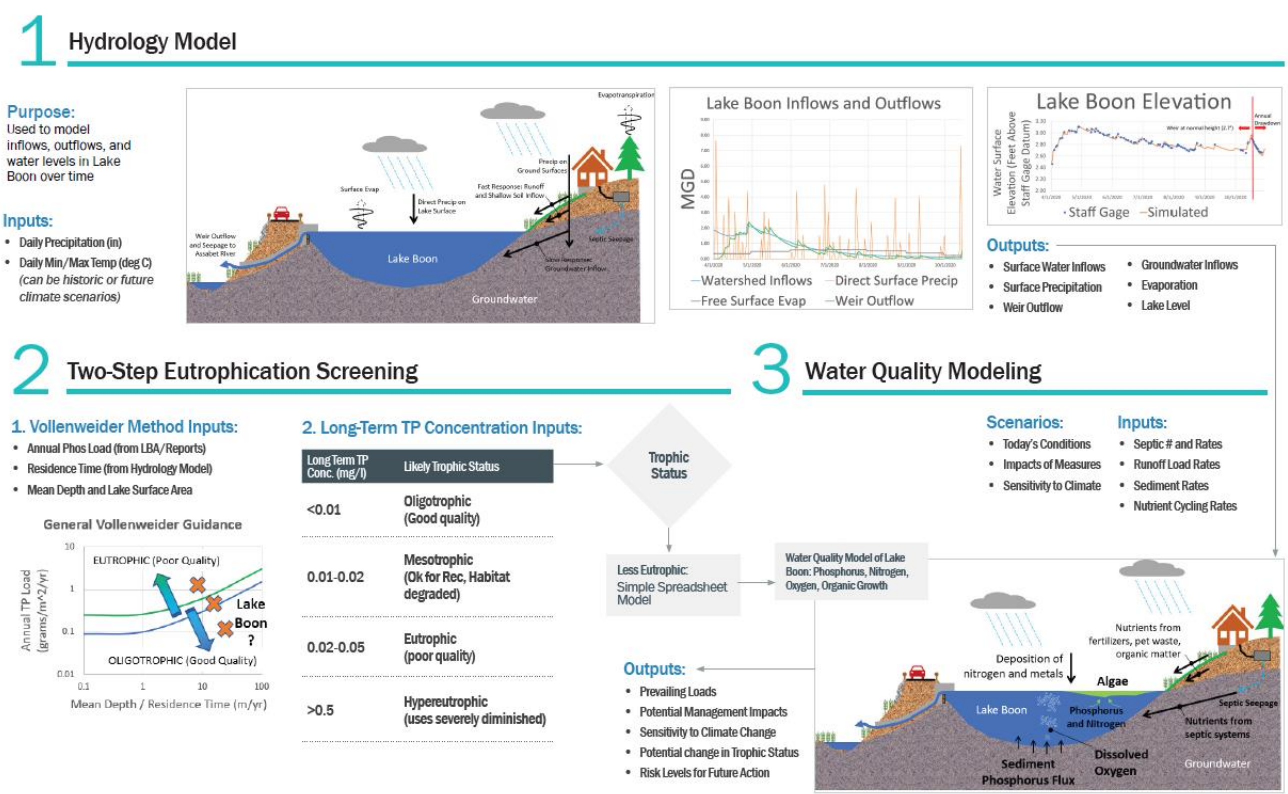


**Figure 1 3-Step Modeling Process**

We recognize that monitoring is on-going and will continue during and after 2022. These analyses were based on data received through November 2021 and a technical memorandum on phosphorus flux in the Lake's sediments received on February 3, 2022, from the University of Massachusetts Dartmouth School for

Marine Science and Technology. Similarly, because this modeling effort is on-going, the findings presented herein are preliminary and subject to change as analyses are refined and additional work is completed.

# Section 1: Monitoring Program

In April 2021, Brown and Caldwell prepared a monitoring plan for the 2021 season, which was then implemented from April through October. The monitoring plan provided trained volunteers with instructions on how to collect data in support of the health assessment. The monitoring program included procedures for the collection of water quality samples for a variety of parameters including phosphorus, nitrogen, and solids; collection of field measurements such as conductivity, temperature, dissolved oxygen, and streamflow; and quality control procedures. Data was collected from each of the four lake basins and at culverts where flow was observed, as shown in Figure 2.

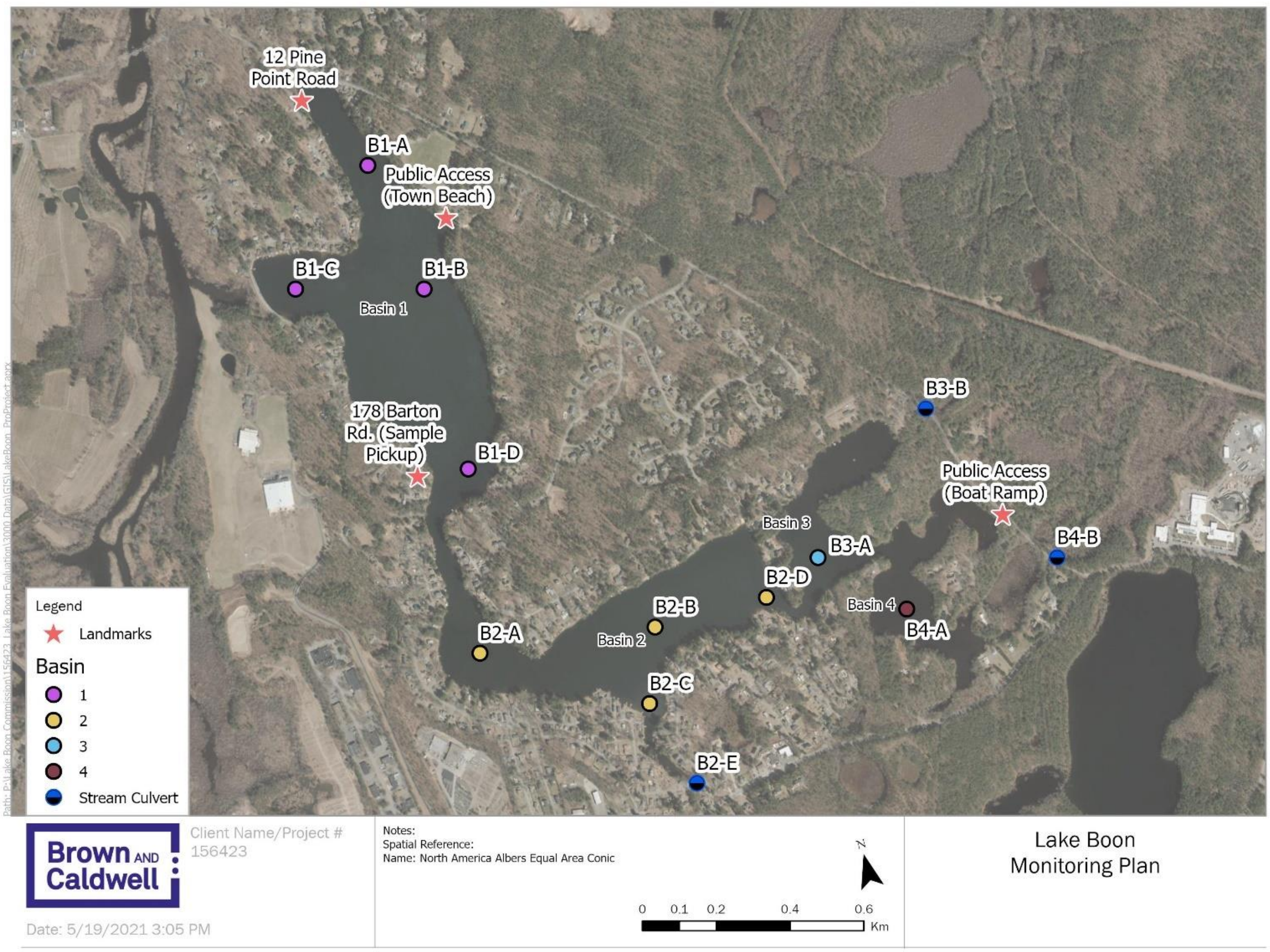


**Figure 2 Monitoring Locations**

Trained volunteers collected water quality samples and measurements from monitoring locations monthly during the monitoring period (4/18, 5/16, 6/16, 7/25, 8/15, 9/12, and 10/10). Data collected on these dates was augmented with targeted data collection on additional dates, primarily to collect data from before and after major rainfall events, and to identify potential pollution "hotspots" via: (1) conductivity surveys conducted on 8/30 and 12/10; and (2) investigations in the Monahan's Cove sub-watershed throughout the spring and summer months. Data from the monitoring program were consolidated into a structured spreadsheet format and incorporated into a data dashboard using Microsoft's Power BI software. Many of the figures shown in section 1 of this memo were created from this dashboard. On May 25, 2021, Brown and Caldwell provided the Steering Committee for the Healthy Lake Boon initiative with access to the dashboard (refer to Technical Memorandum 1 for details). In a future phase of this project, the dashboard will be transferred to the Lake Boon Commission and embedded on a public-facing website. Key findings from the monitoring program are described in the sections below. Subsequent sections also provide context about how the data were used in modeling activities completed to-date.

### 1.1.1 Selected Monitoring Program Observations

**Precipitation**

- Daily precipitation data were collected from the rain gauge on Pine Point Road (Figure 3). Weather data were also retrieved from a nearby NOAA Weather Station in in Acton, MA. There was a strong correlation between locally observed rainfall and observations from Acton, MA.
- Approximately 45 inches of precipitation were measured in 2021, which was slightly more than an average year, but nearly double the cumulative precipitation measured in 2020, which was about 25 inches.
- Precipitation amounts during summer months were higher than average, and July 2021 was the rainiest July on record for MA.
- The 2021 hurricane season was the third-most active year in recorded history, and the lake was impacted by Hurricanes Elsa, Henri, and Ida (Chappell, 2021).

Figure 3

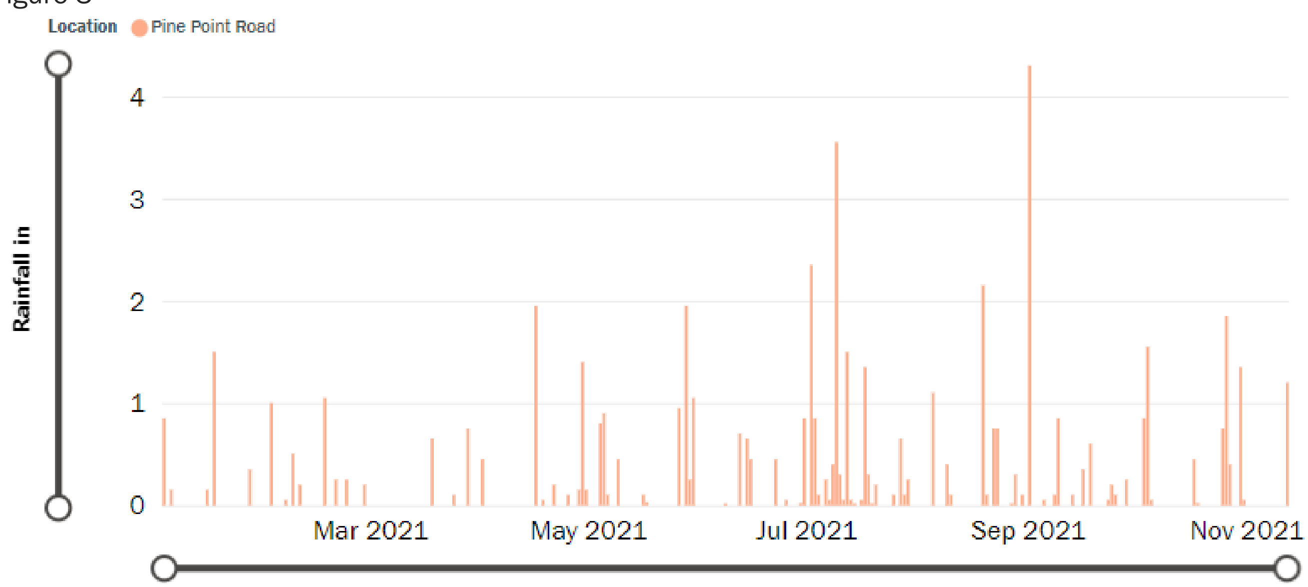


**Figure 3 Observed Rainfall during the 2021 monitoring program**

**Water levels**

- Water levels were measured daily at the staff gauge near the dam outlet (Figure 4).



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- Water levels in the lake are managed by adding and removing flashboards at the dam outlet structure. Generally, boards are removed in the fall to lower the water level and boards are replaced in the spring. This management practice is intended to manage weeds and manage water quality.
- Water levels ranged from approximately 2 feet above the staff gage in early 2021 through May to just over 3 feet from May through October. Values peaked following major storm events, and at times were lowered before storm events by removing boards in the dam. Water levels began steadily declining in September 2021, corresponding with the start of drawdown.

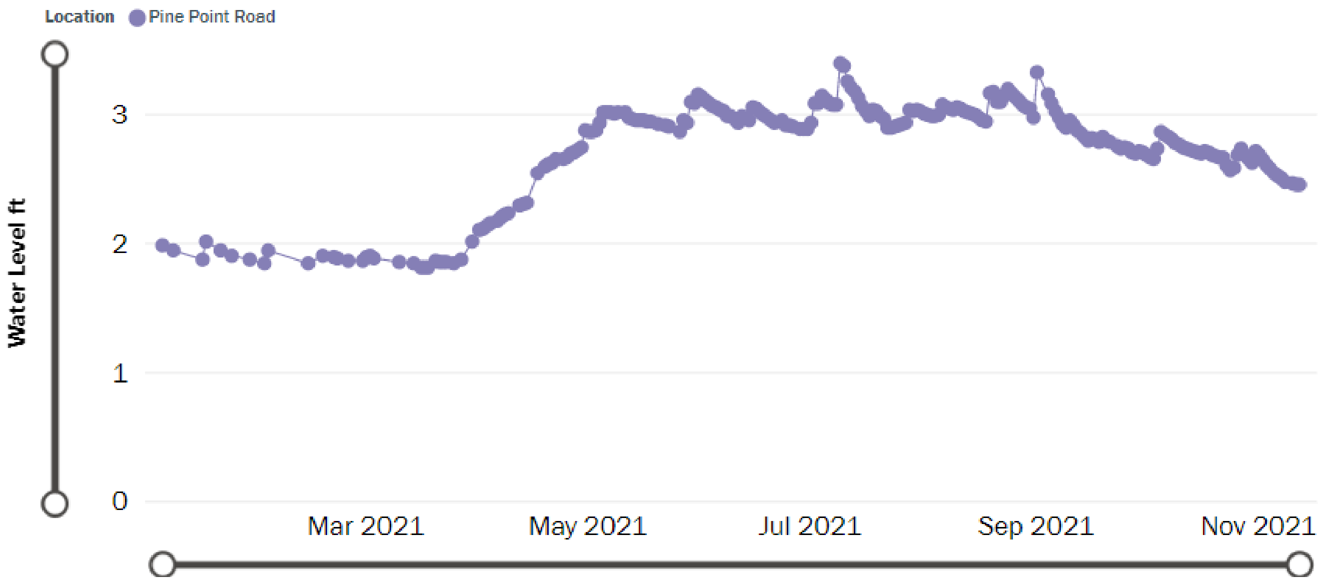


**Figure 4 Observed Water Level during the 2021 monitoring program**

### Streamflow

- Streamflow was measured at culverts that discharge surface water into the Lake (Figure 5). Most of the measurements were recorded at location B2-E. Values peaked following major storm events, as described in subsequent sections.

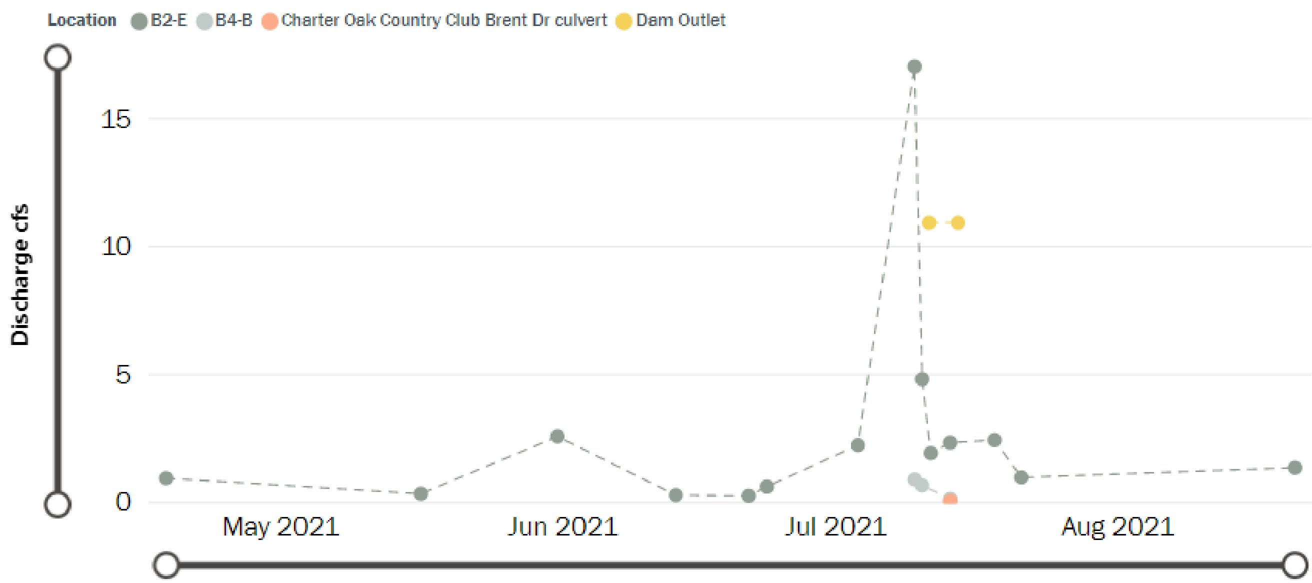


**Figure 5 Streamflow Measurements during the 2021 monitoring program**

### Temperature Profiles

- The temperature-depth profile significantly changed throughout the monitoring program.
- In April, the temperature profile for each basin indicated that stratification was minimal, as visualized by the relatively steeply sloped line connecting each point along the temperature-depth profiles, as shown in Figure 6. In May, there was a significantly larger temperature gradient between the surface and the bottom of the lake, in basins 1 and 2, which was indicative of the formation of stratified layers. Stratification was more pronounced in basins 1 and 2, which are deeper than basins 3 and 4.
- Similarly, the temperature gradient between the surface and bottom decreased starting in September and October, which was indicative of fall turnover.
- The change in temperature at various depths for April-October June 2021 is shown below for B1-B, B2-B, and B3-A, respectively.

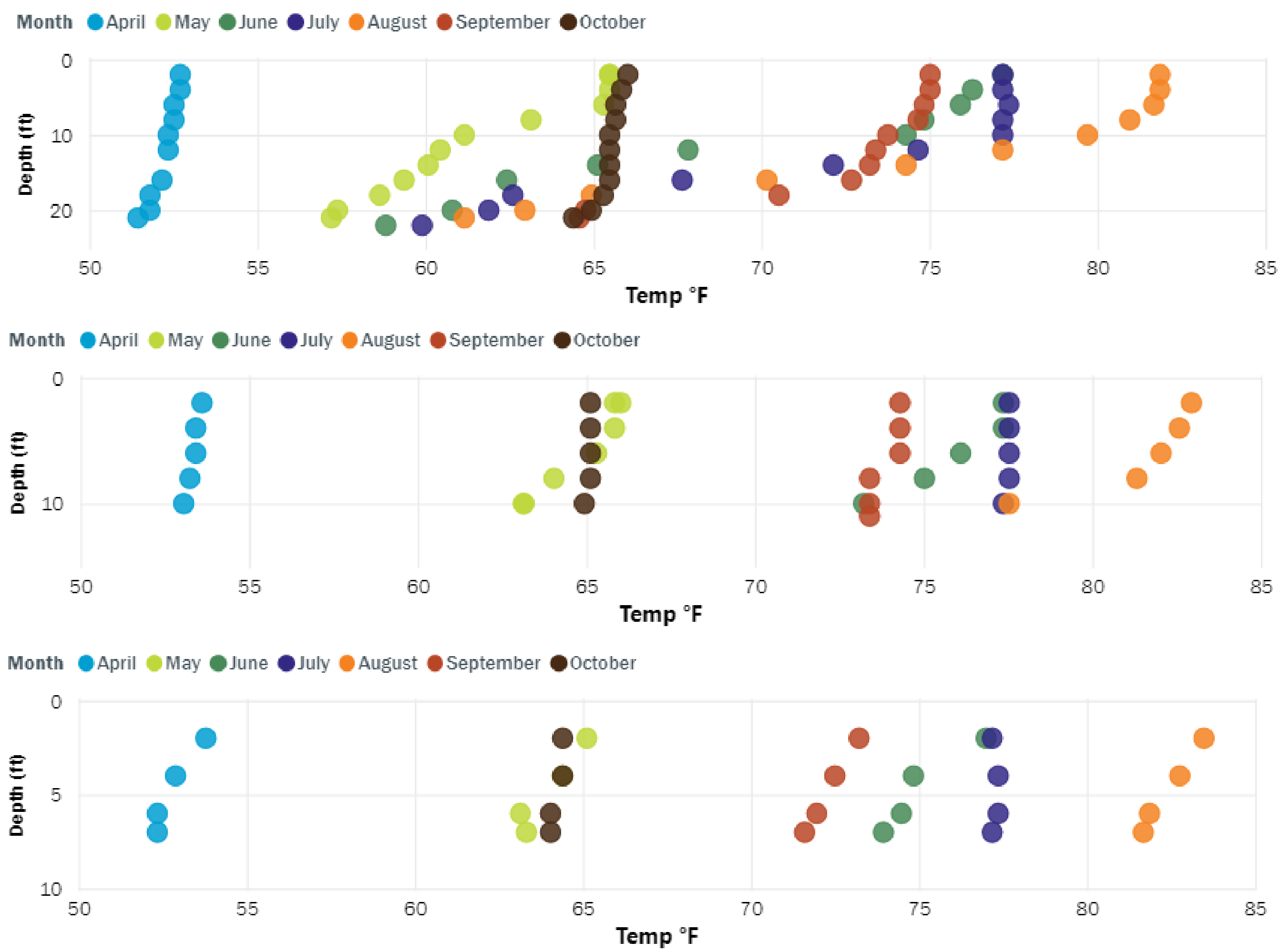


**Figure 6 Temperature profiles at B1-B, B2-B, and B3-A (top to bottom) during the 2021 monitoring program**

### Dissolved Oxygen Profiles

- The effects of stratification on dissolved oxygen (DO) are more apparent in deeper areas of the lake, as at B1-B, where hypoxic conditions were measured throughout the spring and summer 2021. Starting in June 2021, measurements of DO concentration were observed as low as <1 mg/L at a depth of 20 feet, near anoxic conditions, a state that accelerates the release of phosphorus from sediments. The SMAST Technical Memorandum relates aerobic conditions at the lake's bottom to the flux of phosphorus between sediment and the water column. This relationship is discussed further in section 2.3.4.
- Conversely, in shallow areas of the lake, like at B3-A, dissolved oxygen was not observed below Massachusetts Surface Water Quality Standards for Class B waterways in warm water fisheries, 6.0 mg/L.
- Dissolved oxygen concentrations at the deepest parts of B1-B (20 feet) and B3-A (7 feet) are shown in Figure 7.

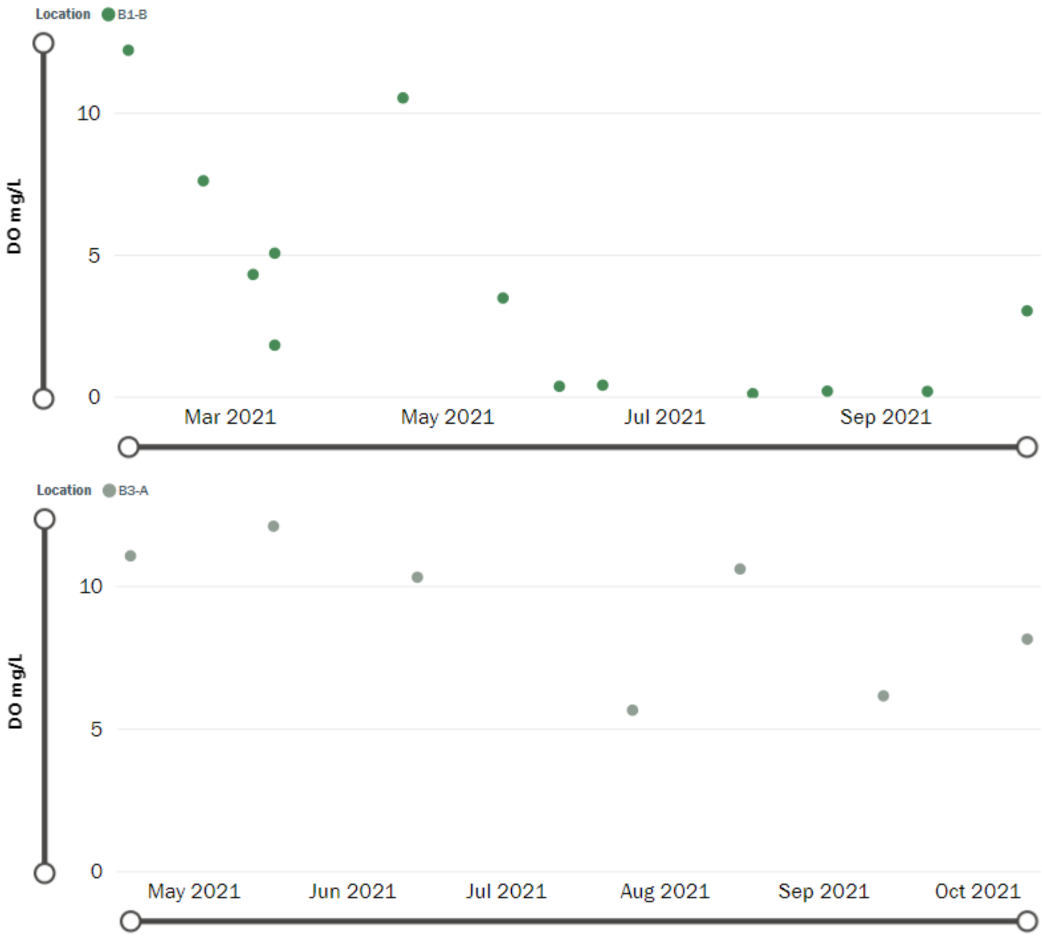


**Figure 7 Dissolved oxygen concentrations at the deepest parts of B1-B (20 feet) and B3-A (7 feet) during the 2021 monitoring program**

### Water Clarity (Secchi Disk Depth)

- A measurement of water clarity was collected using the Secchi Disk method, wherein a disk is lowered into the water column, and volunteers recorded the depth at which the disk was no longer visible.
- Average Secchi disk depth in Basin 1 remained relatively constant through the spring at around 10 feet but dropped to a low of around 5 feet in the summer before increasing in the fall.
- Variations in Secchi disk depth were greatest in Basin 2, fluctuating over time from around 12 feet to a low of 5 feet.
- Secchi disk depths in Basins 3 and 4 had low variability. Observed values were generally around the depth of the lake at the monitored locations, 7 feet and 5 feet, respectively. Observations are shown in Figure 8.



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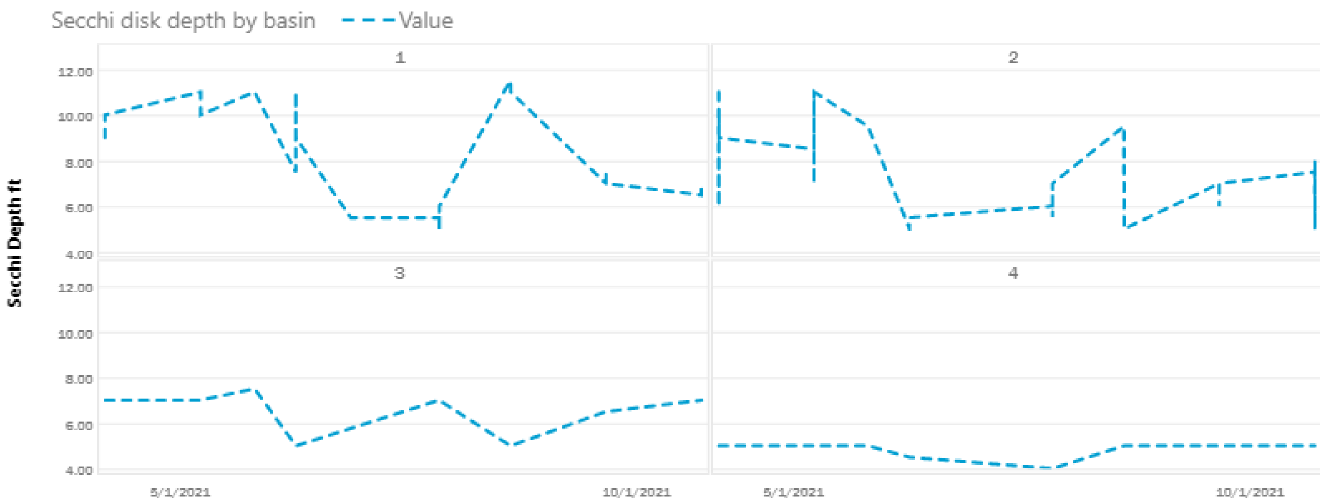


**Figure 8 Secchi Disk Depth in each basin during the 2021 monitoring program**

### Chlorophyll A

- Chlorophyll *a* is a is a measurement of the amount of algae growing in a waterbody and the measurements can be used to classify the trophic condition of a waterbody (USEPA).
- Samples were collected and analyzed for chlorophyll *a* from each basin during the monitoring program. Generally, samples were collected monthly, but no samples were collected in June.
- Analytical results indicated a seasonal pattern, with analytical results at or below the detection limit (<2 mg/m$^3$ or ppb) in April and May. Analytical results indicated increasing concentrations throughout the summer months with peaks in October. Multiple samples were collected during algal blooms during October 2021.
- The maximum concentrations of chlorophyll a, 159 mg/m$^3$ was detected in Basin 1 on October 6, 2021, as shown in Figure 9. The corresponding sample was collected on the eastern shore, and at the time of sampling, volunteers observed “very dense and paint-like algae in the coves.” This sample tested negative for blue green algae.

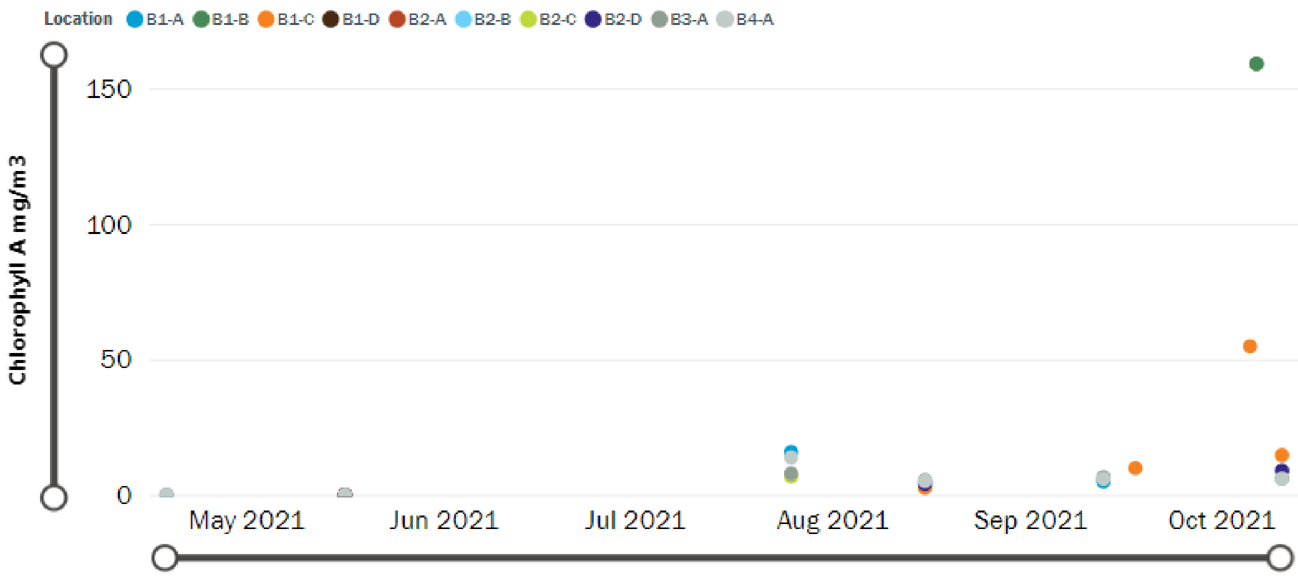


**Figure 9 Chlorophyll A results over time during the 2021 monitoring program**

## Nitrogen

- Nitrogen is a nutrient present in plants, soil, sewage and animal waste, fertilizers, and fossil fuels. Nitrogen can enter a lake through groundwater, stormwater runoff, and the atmosphere.
- High concentrations of nitrogen in a lake are generally associated with health and environmental concerns, and may be correlated with increased plant growth, algal blooms, and lake acidification. However, nitrogen is not typically a limiting nutrient for algal blooms in freshwater lakes. Unlike other nutrients, like phosphorus, there is not a single regulatory threshold for nitrogen concentration that applies to all lakes in Massachusetts. Instead, limits are temperature and pH dependent and are based on toxicity to aquatic life (see EPA 822-R-18-002).
- Nitrogen cycles through different forms. Samples were collected and analyzed for four forms of nitrogen: *ammonia, Total Kjeldhal Nitrogen (TKN), nitrate, and nitrite*. Analytical results for samples analyzed for *nitrate* were below the detection limit. Trends in these compounds over the monitoring program are shown in Figure 10 below.
- In lakes, nitrogen is typically present in the form of *nitrate* ($NO_3$) and *organic nitrogen*, but the dominant form varies over time because of inflow and biological processes and based on the aerobic conditions of a waterbody (Minnesota Pollution Control Agency, 2013). On the average, *nitrate* represented about 35% of the measured nitrogen forms in the lake over the 2021 monitoring period.
- Algae and other organisms can uptake nitrate and convert it to *amino compounds* ($NH_2$-*R*) and *organic compounds*. When these organisms die and decompose, nitrogen is released as *ammonia* ($NH_3$). The highest observed ammonia concentration was from a sample collected from B1-B on October 6, 2021, as shown in Figure 10. This analytical result, which was twice as high as values from other sampling events, may have coincided with a die-off period of an algal bloom observed around the same time.
- *Total Kjeldhal Nitrogen (TKN)* represents the concentration of *organic nitrogen* plus *ammonia* and *ammonium*. During the monitoring program, the dominant form of nitrogen in the lake was TKN

(65%), with about 15% of the measured TKN in the form of *ammonia*. Ammonium was not analyzed during the monitoring program.

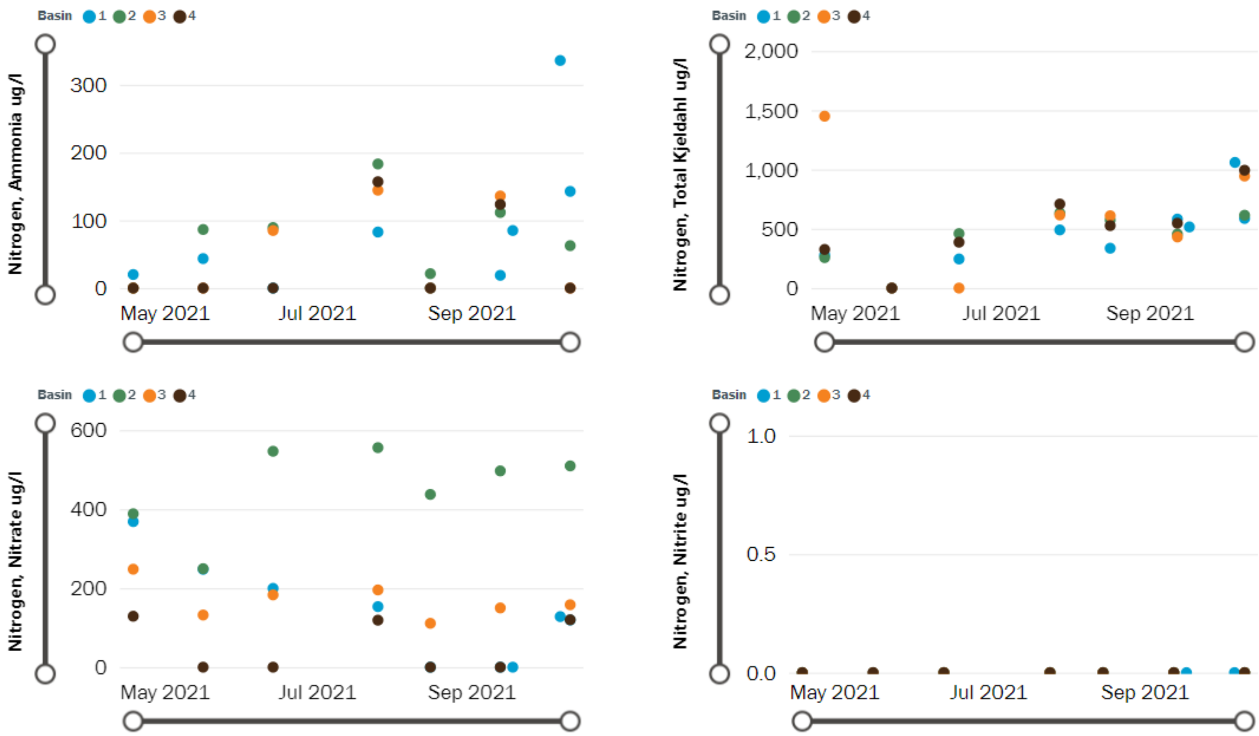


Figure 10 Concentration of nitrogen in each of the basins in Lake Boon (2021 Monitoring Program)

## Conductivity and Chloride

- The median in-lake measured conductivity from was 477.4 µS/cm. Average observed values of conductivity varied by basin. Basin 2 had the highest median value at 496 µS/cm and Basin 4 had the lowest median value at 424.4 µS/cm.

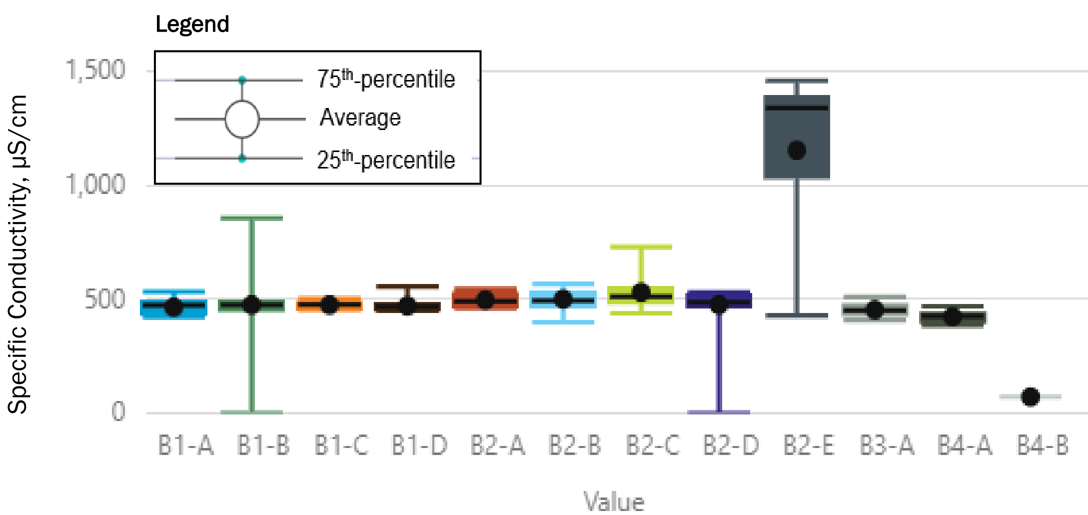


Figure 11 Conductivity measurements from each monitoring location (Spring 2021)

- Specific conductivity was highest at B2-E, which prompted additional investigations of the sub-watershed area. Volunteers measured high conductivity at locations in the tributary upstream of the Monahan's Cove culvert at B2-E. Additional investigations identified multiple potential pollutant sources including industrial and roadway runoff.
- A linear relationship between specific conductivity and chloride was derived for Lake Boon, as shown in Figure 12. The correlation was like those of freshwater lakes of similar nature. The relationship indicated an approximately 3:1 ratio between specific conductivity and chloride, or that for every 100 µS/cm of specific conductivity, one might expect a concentration of chloride of approximately 38 mg/L. Few chloride samples were available from outside of 2021 monitoring results but based on this empirical relationship between specific conductivity and chloride, observed values at B2-E, at times, probably exceeded USEPA's chloride criteria for aquatic life protection of 230 mg/L (4-day average) and 860 mg/L (1-hour average).

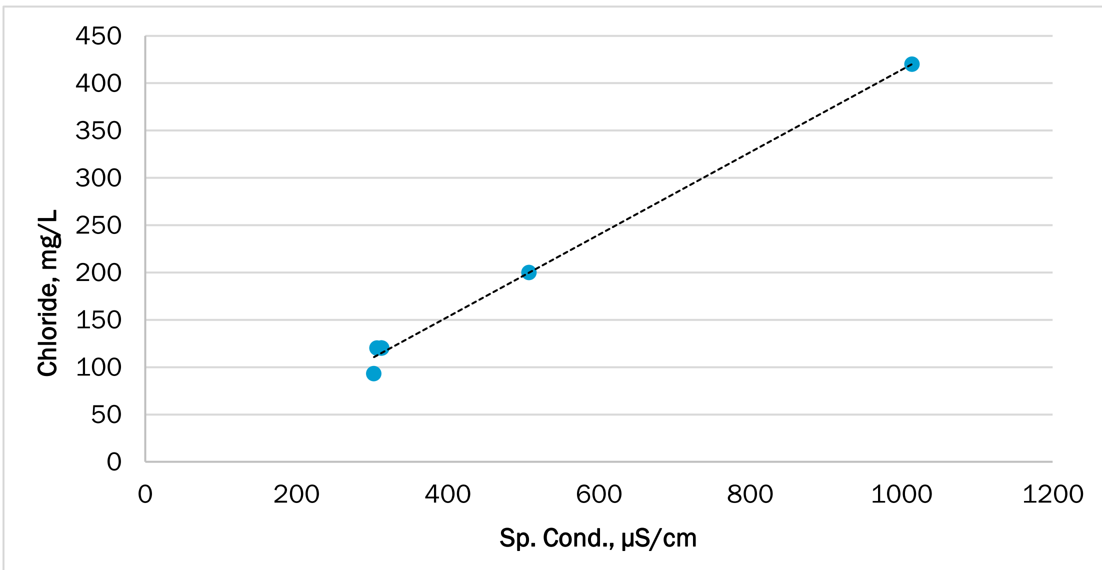


**Figure 12 Correlation between paired observations of specific conductivity, as measured with a YSI, and analytical laboratory results chloride, from grab samples (collected on August 16 and 17, 2021)**

**Phosphorus**

- 35 of the 120 samples analyzed for phosphorus concentration were below the analytical detection limit (10 ug/L) during the monitoring program
- MassDEP's Total Maximum Daily Load (TMDL) goal for Lake Boon was 20 ug/L. 20 samples analyzed for phosphorus concentration in 2021 had results above this threshold. Samples from each basin exceeded this threshold.
- The highest concentrations of phosphorus were collected from B4-B on June 1, 2021 (142 ug/L), at B1-C on 10/5/2021 (126 ug/L), and B1-B on October 6, 2021 (111 ug/L). The latter two analytic sample results correspond to samples collected during a late-summer algal bloom and may be related to a release of phosphorus from the sediment into the water column. The flux of phosphorus is partly controlled by the aerobic conditions at the lake's bottom, as discussed in the Technical Memorandum submitted by SMAST.
- The median concentration of phosphorus was 14 ug/L, including samples that were below the detection limit.

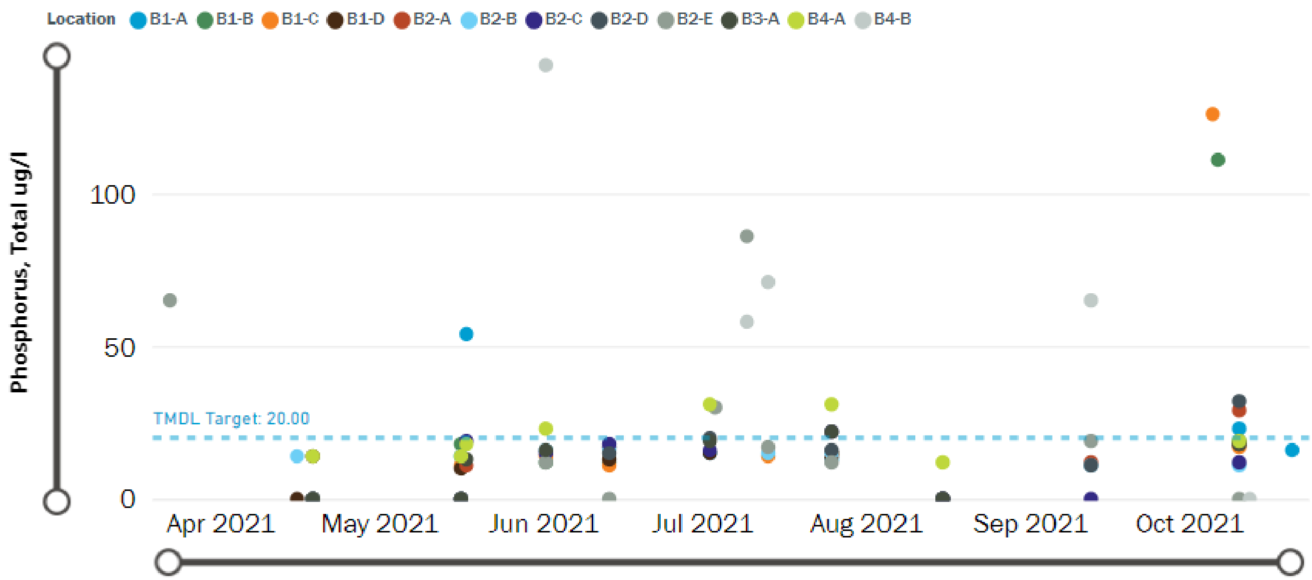


**Figure 13 Phosphorus grab sample analytical results during the 2021 monitoring program**

Trends in in-lake phosphorus concentrations generally indicate that phosphorus concentrations have decreased since 1980, as illustrated by a decreasing proportion of samples with phosphorus greater than the TMDL goal of 20 ug/L (Figure 14). This finding is discussed in further detail in subsequent sections (see Eutrophication Analysis). However, the concentration of phosphorus in-lake may not be directly comparable due to changes in analytical laboratory detection and reporting limits (which were lower for the samples collected during the 2021 monitoring period) and timing and location of sampling over time.

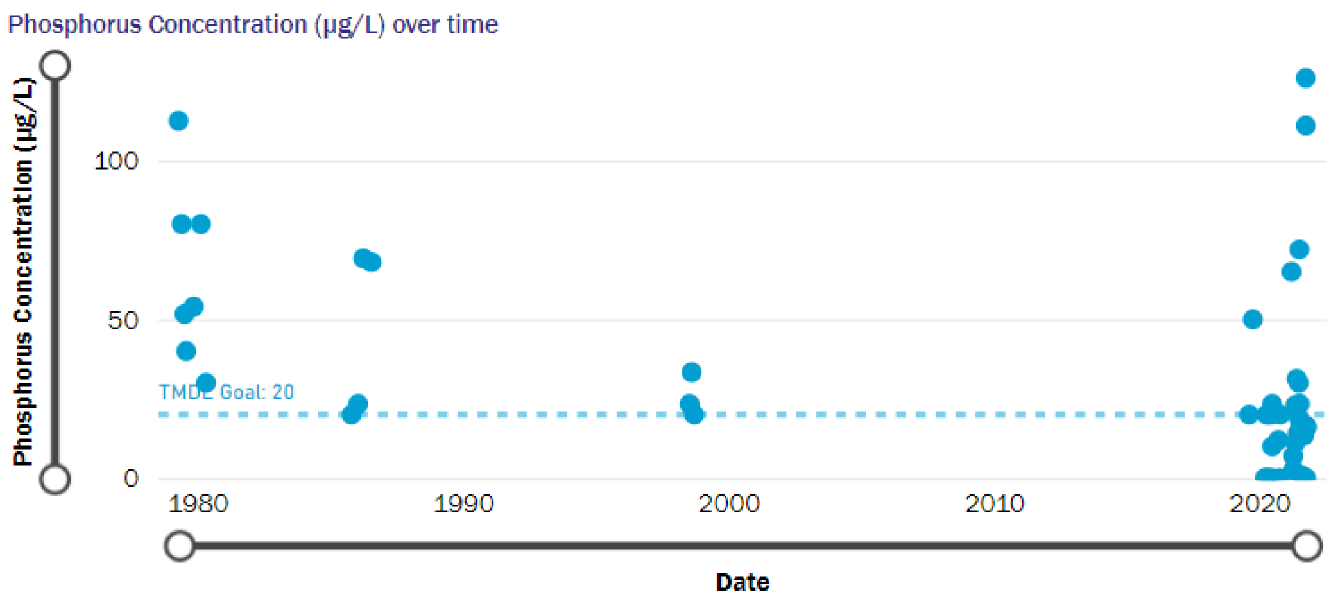


**Figure 14 Comparison of in-lake phosphorus concentrations over time (1979-2021)**

# Section 2: Modeling Process

Brown and Caldwell completed a multi-phase modeling program that included models of the hydrology, eutrophication potential analysis, and a phosphorus loading model of the watershed. The modeling process is described in the sub-sections below.

## 2.1 Hydrology Model

A hydrology model is a tool that can be used to characterize real-world systems and hydrologic processes. The hydrology model of Lake Boon was developed to answer key questions that will inform recommended lake and watershed management practices, such as "What proportion of nutrient loading in the Lake is from groundwater versus surface water sources?"

### 2.1.1 Methods

BC developed a model of the hydrology of Lake Boon using a spreadsheet tool. The model uses basic inputs, such as precipitation, temperature, lake geometry, and measured streamflow to estimate how water moves through the watershed and through the lake. The model relies on a water balance and was based on research by Thomas (1981). The model provided estimates for runoff and recharge, saturation levels of the soil, the ratio between groundwater recharge and surface water runoff, and the rate of groundwater discharge (Walker, 2014). A depiction of these parameters is shown in Figure 15.

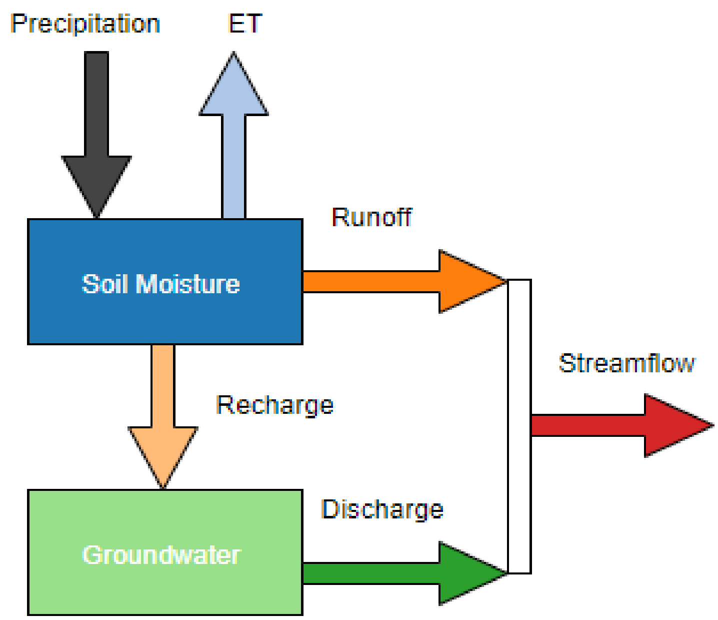


**Figure 15 A depiction of the hydrology model (graphic from: Walker, J.)**

### 2.1.2 Supporting Data

A summary of data used in this model is provided in Tables 1 and 2. Table 1 provides a summary of time-series data from the monitoring program or from publicly accessible sources, whereas Table 2 summarizes physical properties that were held constant over time These constants were estimated from measurements collected through the monitoring program or derived from publicly available sources. Details on streamflow data collected through the monitoring program are also provided in this section.

**Table 1. Time-series data used in the hydrology model**

| Input Parameter | Units | Location(s) | Date Range | Source |
|---|---|---|---|---|
| Staff Gage height | Feet | Pine Point Road | 2020-2021 | Volunteer-collected data (see monitoring program) |
| Streamflow (culverts) | Million Gallons per Day (MGD) | Culverts into basins 2, 3, and 4, labeled B2-E, B3-B, B4-B | April – October 2021 | Volunteer-collected data (see streamflow sub-section below) |
| Temperature (daily minimum, average, maximum) | Degrees F | Acton Weather Station | 2020-2021 | National Centers for Environment Infor-mation (NOAA) Global Summary of the Day, Hanscom Field |
| Precipitation (daily) | Inches | Pine Point Road | 2020-2021 | Volunteer-collected (see monitoring pro-gram) |

**Table 2. Constants used in the hydrology model**

| Input Parameter | Value | Units | Source |
|---|---|---|---|
| Sub-watershed area of Monahan's Cove | 283 | Acres | GIS - Derived from Streamstats |
| Sub-watershed area excluding Monahan's Cove and the Lake surface area | 947 | Acres | GIS - Derived from Streamstats |
| Lake surface area | 161 | Acres | GIS - Derived from Streamstats |
| Seepage from the dam | 0.004 | MGD | Assumed based on streamflow data collected at the dam out-let on 7/11/2021 |
| Side Weir Crest | 2.9 | Feet | Measurement |
| Side Weir Length | 1.33 | Feet | Measurement |

### Streamflow data

Brown and Caldwell identified three locations in which culverts discharge surface water into Lake Boon. These locations are labeled B2-E, B3-B, and B4-B in Figure 16. Flow rates at B2-E averaged 0.84 MGD, as measured by volunteers on 17 dates between April-October 2021. Both culverts into Basins 3 and 4 were blocked at the start of the monitoring program in 2021. The Town of Stow removed debris from culvert B4-B in April 2021, and streamflow was measured at this location on 3 dates, with an average flow rate of 0.35 MGD. It should be noted, however, that this culvert remains damaged, and ponding occurs at the upgradient end. As a result of this defect, flow was only observed and measured at this location during or shortly follow-ing major storm events, which may skew estimates. Additionally, volunteers noted that surface water was accumulating upstream of the culvert and the culvert was partially blocked at various periods. Flow was not observed or measured from B3-B during the monitoring program.

Based on the large differences in measured streamflow, the hydrology model was sub-divided into two areas – one for Monahan's Cove, which has significant measured surface water flows, and one for the Primary sub-basin, or the remainder of the Lake's watershed area, which had lower amounts of observed surface water inflows. The subwatershed for Monahan's Cove is shown in Figure 16 as the shaded region, while the overall watershed is outlined in dark blue.

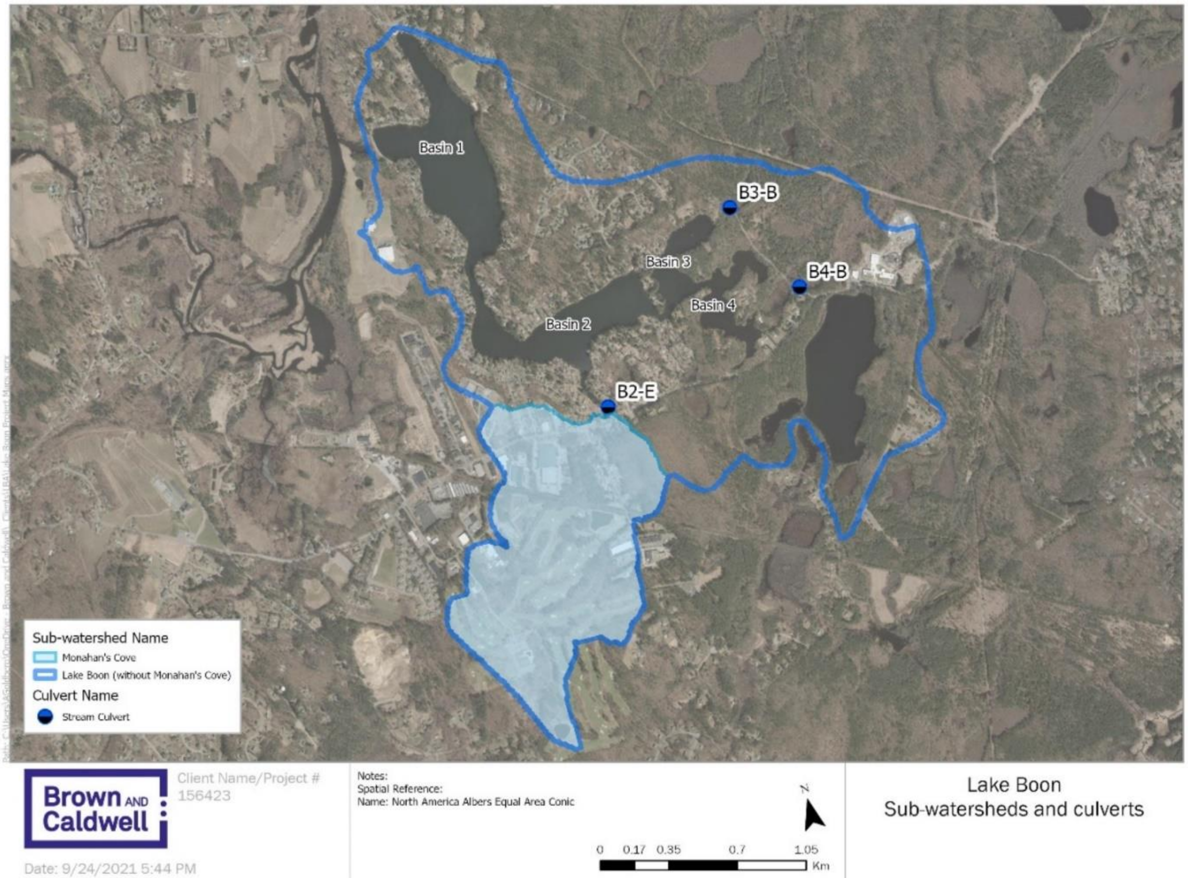


**Figure 16 The Primary Lake Boon watershed (outline) and the Monahan's Cove sub-watershed (shaded region)**

### 2.1.3 Calibration and Validation

The model was calibrated against observed streamflow values and water level elevations in 2021. 2020 served as the validation period (checking the model parameters against different climate conditions without changing them to test their validity beyond the calibration period). BC used measured flow rates at culverts to calibrate the hydrology model, which in turn, was used to estimate the proportion of surface water and groundwater that moved through this system in 2020 and 2021. The measured and estimated streamflow values for Monahan's Cove are shown in Figure 17**Error! Reference source not found.** and the calibrated hydrology model for Lake Boon is shown in Figure 18.



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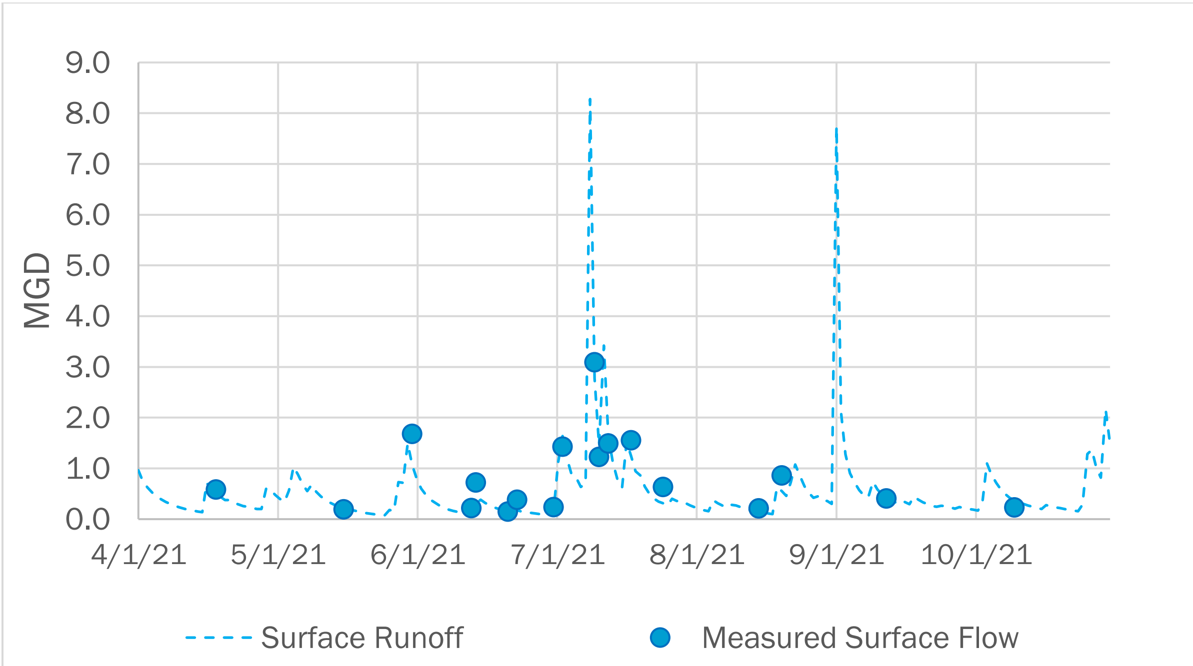


**Figure 17 Measured and estimated streamflow for Monahan's Cove (B2-E) during the 2021 monitoring program**

The model performance during the calibration and validation periods represented observed conditions with reasonable accuracy, as shown in Figure 18 and Figure 19 below.

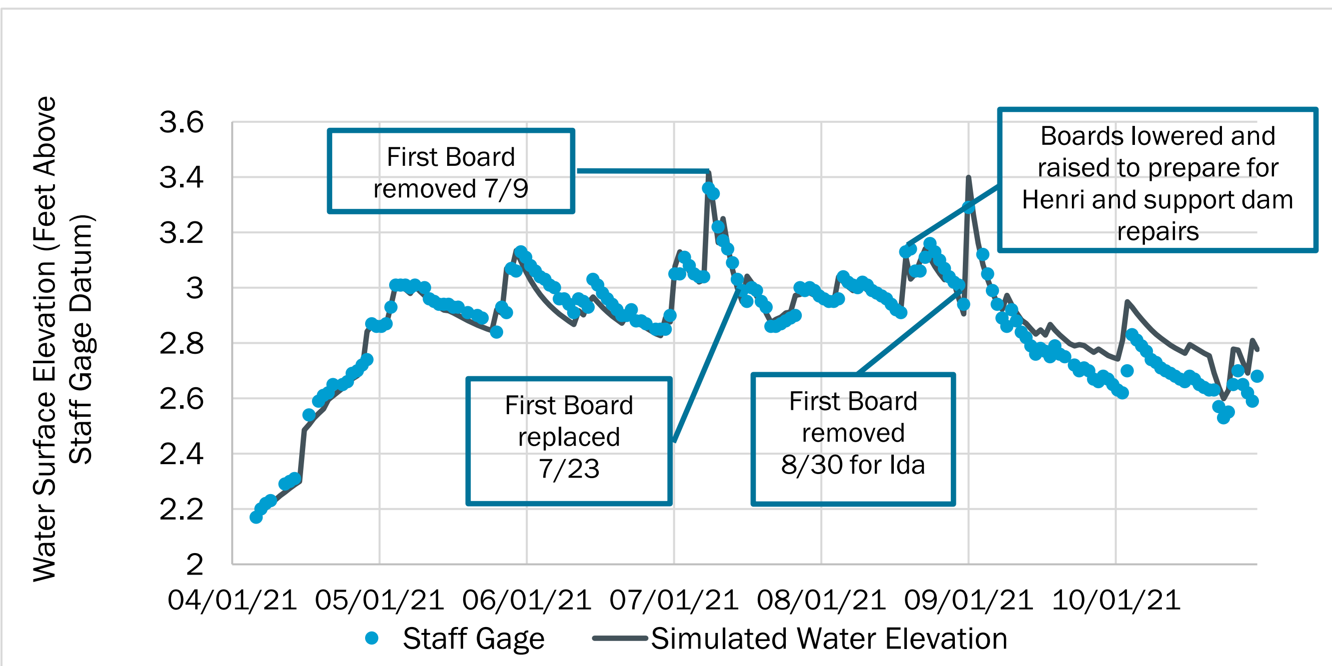


**Figure 18 Simulated vs. observed water levels in Lake Boon for the calibration period (4/2021-10/2021)**

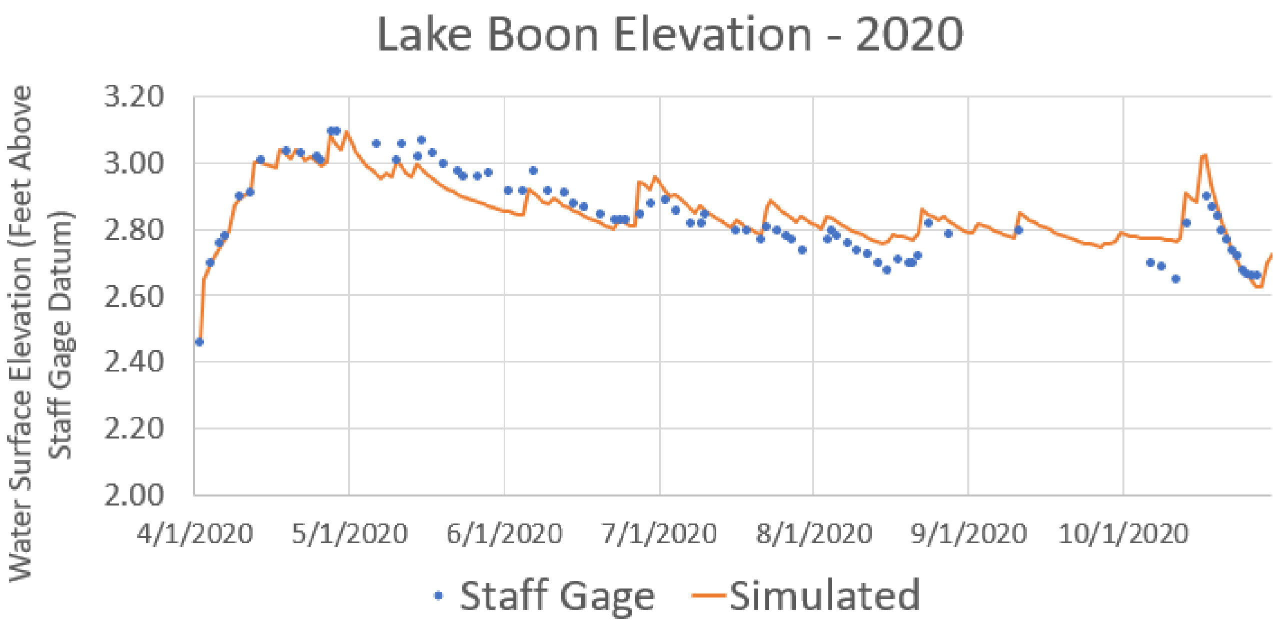


**Figure 19 Simulated vs. Observed water levels in Lake Boon for the validation period (4/2020-10/2020)**

Each of the calibrated parameters has a real-world significance, which can be plotted over time and compared against expected results, for validation purposes. Two groundwater-related model predictions, groundwater storage and soil moisture storage, were examined for reasonableness given their sensitivity to seasonal variability in precipitation, which was measured in this study. The reasonableness of these predictions for the primary subbasin and Monahan's Cove Subbasin is discussed below.

In 2021, groundwater storage was predicted to increase during 2021, which was a wetter than normal year. During periods without significant precipitation, the groundwater storage was predicted to decrease toward the initial value specified in the model. Similarly, as shown in Figure 20, soil moisture was predicted to stabilize over the simulation period and was sensitive to smaller storm events, as expected.

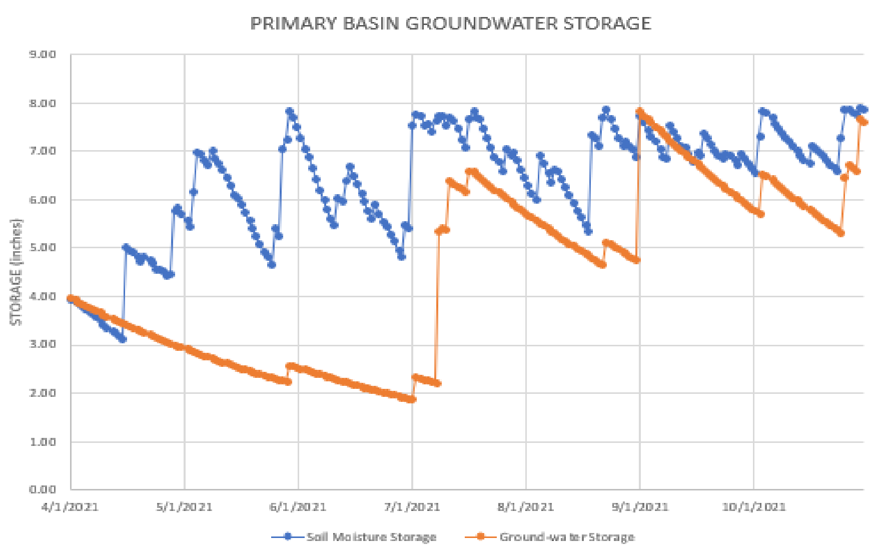


**Figure 20 Predicted values of groundwater-related variables (storage and soil moisture during the calibration period, 4/2021-10/2021)**

Conversely, in 2020, a drier than average year, groundwater storage was predicted to decrease steadily over nearly the entire validation period, though it was predicted to recover towards the end of the period. Soil moisture was predicted to decrease during the summer but increase with storm events in the fall.

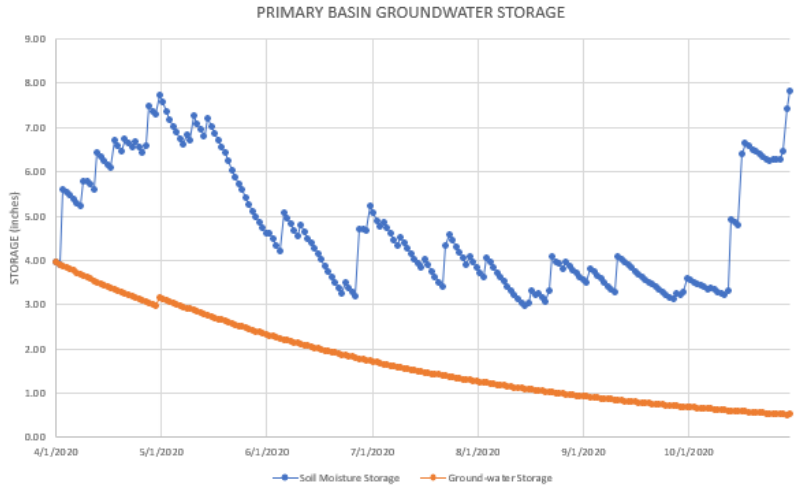


**Figure 21 Predicted values of groundwater-related variables (storage and soil moisture during the validation period, 4/2020-10/2020)**

A similar comparison of the groundwater and soil moisture parameters in 2021 and 2020, respectively, are shown in Figure 22 and Figure 23 for Monahan's Cove Subbasin. Stable seasonal patterns that follow rain-fall patterns were predicted in both years. Groundwater and soil moisture were both predicted to approach their initial condition toward the end of the calibration period, suggesting a reasonable long-term average and appropriate selection of initial conditions. Overall, the reasonableness of the predicted values and sea-sonal patterns in these groundwater-related variables suggest that the model is well specified in this regard.

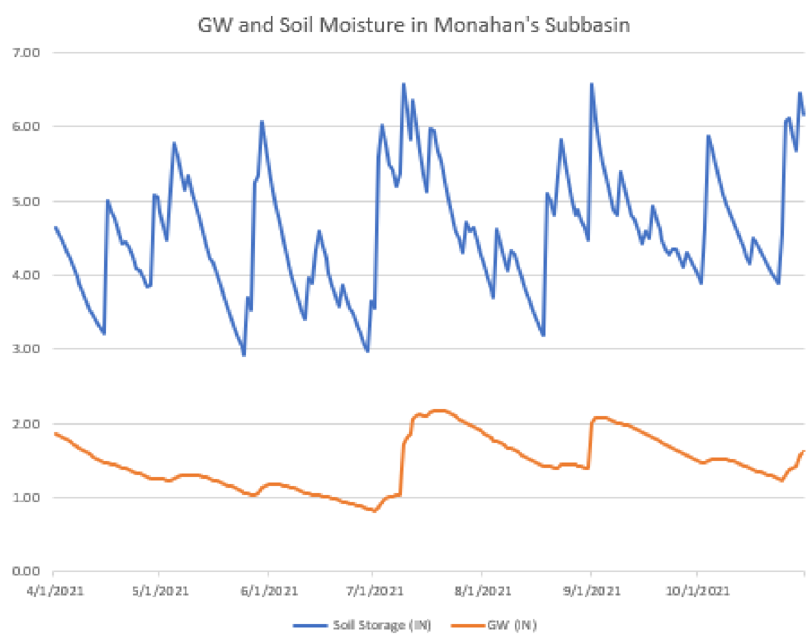


**Figure 22 Predicted values of groundwater-related variables (storage and soil moisture during the calibration period, 4/2021-10/2021)**



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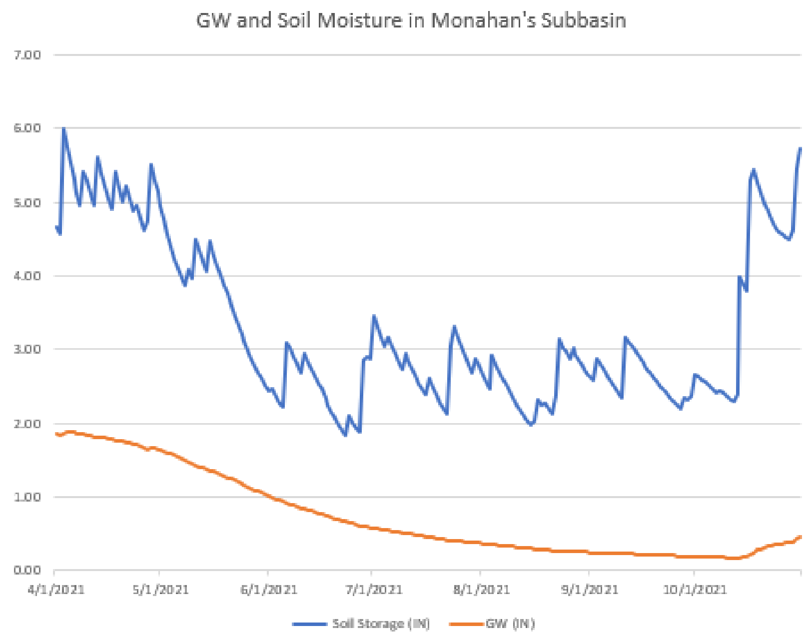


**Figure 23 Predicted values of groundwater-related variables (storage and soil moisture during the validation period, 4/2020-10/2020)**

## 2.2 Eutrophication Analysis

### 2.2.1 Background and Purpose

One way to classify lakes is based on trophic state, which ranges from oligotrophic (good water quality) to mesotrophic (moderate biological productivity and fair water quality), to eutrophic or hypereutrophic (high rates of biological productivity resulting in poor water quality). Eutrophication is a long-term condition that relates to aquatic health and the usability of the lake for recreational purposes. Eutrophication occurs when a water body becomes over-enriched with nutrients in a state where they can grow into harmful algae, deplete the water of oxygen, and pose toxic threats to both people, fish, and wildlife. Algal blooms and toxic cyanobacteria have been observed in Lake Boon in recent years, which indicates that the lake may, at times, be eutrophic (for example, during late summer). The purpose of this analysis was to determine if Lake Boon is eutrophic or could be classified under a different trophic state under present-day conditions.

Prior studies have measured the concentration of nutrients in Lake Boon and estimated the nutrient loading rates that may be contributing to eutrophication in the Lake. It is understood, however, that land development, landscaping, septic system upgrades and maintenance, and other watershed management practices have changed since these studies were conducted and that more recent water quality data may provide an updated view on the health of the Lake Boon.

Data were incorporated into a simple trophic model of the Lake based on the Vollenweider model. This model is an empirical relation between annual phosphorus loads, lake hydraulics, morphology, and lake trophic state (Vollenweider, 1975). This model can be used to predict the present-day eutrophication potential of Lake Boon. The Vollenweider model is a more powerful method predicting trophic state than use of phosphorus concentrations alone because it considers how trophic responses would be affected by factors such as lake depth and the hydraulic residence time of the lake. Later in the project, this model will also be used to assess how changes in management practices might impact eutrophication potential.

### 2.2.2 Methods and Data

The Vollenweider equation is based on four parameters, which are summarized in Table 3 below.

| Table 3. Constants used in the hydrology model | | | |
|---|---|---|---|
| Input Parameter | Value | Units | Source |
| Lake Mean Depth | 10.7 | Feet | MassDEP TMDL Report |
| Lake Surface Area | 163 | Acres | GIS |
| Residence time | Varies | Years | Hydrologic model |
| Annual phosphorus loading rate | Varies | Pounds | Hydrologic model |

A plot of the relationships described by the Vollenweider Model is shown in Figure 24. In the model, annual phosphorus loads are plotted as a function of depth/residence time. Lake with higher phosphorus loading and lower ratios of mean depth to residence time are more likely to experience higher phosphorus and chlorophyll-a (or algae) concentrations, and lower water clarity.

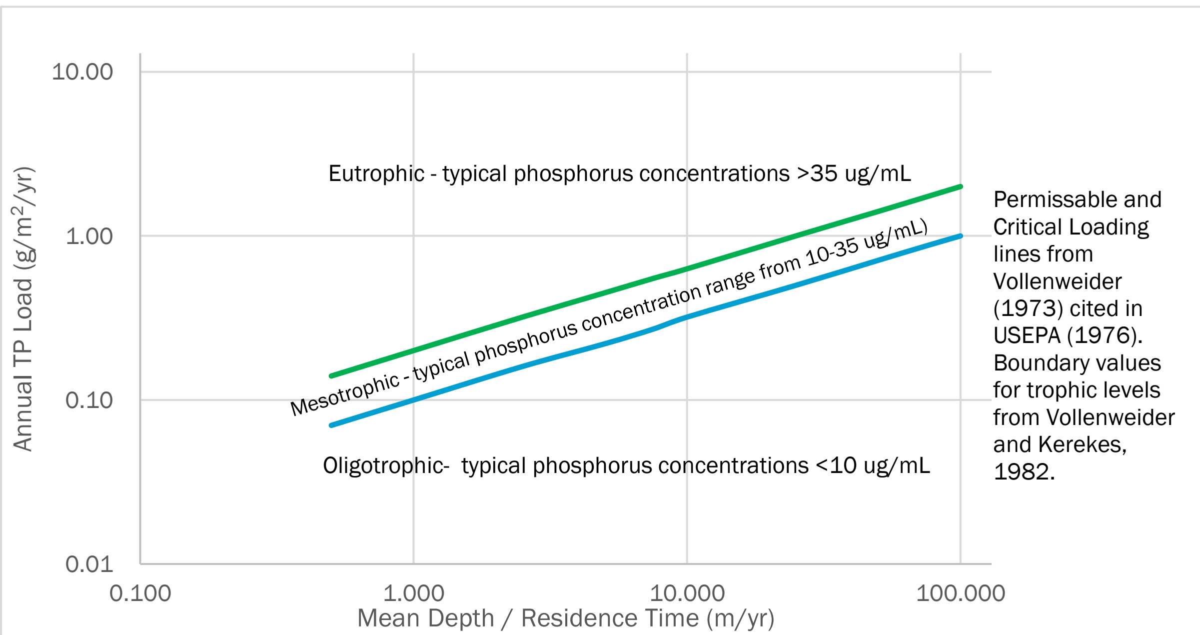


**Figure 24 Vollenweider model (log-log scale)**

BC used multiple calculations to determine where the present-day Lake Boon would plot on the Vollenweider chart shown in Figure 24. Ranges of likely parameter values were established for each parameter in the Vollenweider Model based on available monitoring data and a review of literature and prior studies on Lake Boon. For example, Notini and Morrison (1981) estimated a wide range of annual phosphorus loading rates from prior studies, with the high end of the loading rate (896 kg/year) approximately 7.5 times greater than the low-end (119 kg/year). A more recent study by MassDEP (2002) estimated loading rates around 366 kg/year, and more recent studies reference this estimate. Similarly, estimated values for residence time vary from year to year based on annual precipitation rates.

### 2.2.3 Preliminary Findings

Figure 25 shows the preliminary results of analysis of trophic status under a variety of conditions and a range of likely values for residence time and phosphorus loading. Because residence time is a function of precipitation, estimated values for trophic levels varied significantly between 2020 (when low precipitation increased residence time) and 2021, when there was a lower residence time. This possible range in values, which varies based on the value of residence time, is represented as a dashed vertical line. Similarly, because phosphorus loading rates are uncertain, Figure 25 displays results for various potential phosphorus loading rates.

Most combinations of model inputs resulted in a trophic state that is near the border between mesotrophic and eutrophic. Using inputs from the TMDL report, the Lake was predicted to fall within the eutrophic range. However, this preliminary screening step suggested that the lake could fall into the mesotrophic range if phosphorus loading was at lower end of the potential range, and in wetter years. The screening results suggest the potential for the lake to move between mesotrophic and eutrophic conditions depending upon annual rainfall rate and other factors affecting phosphorus load.

It should be emphasized that the preliminary eutrophication screening step was based on the empirical relation defined by the Vollenweider model, unadjusted based on water quality results measured in Lake Boon. Individual lakes can depart significantly from the Vollenweider model, and thus the screening results might not represent the true status of Lake Boon. The following section of this report describes how monitoring data from Lake Boon were used to calibrate the empirical relations and improve the understanding of Lake Boon's trophic state.

The calculated residence time for 2021 was lower than prior years, at only 0.74 years due to higher-than-average observed rainfall. Thus, the flux of phosphorus out of the lake was faster than in prior years, particularly during summer months, and results for this year may not provide a reliable indicator of the trophic status of the lake in a year with typical amounts of precipitation. However, this result suggests that the trophic status of the lake is within a range that managing phosphorus loading and hydrology could reduce the risk of eutrophication.

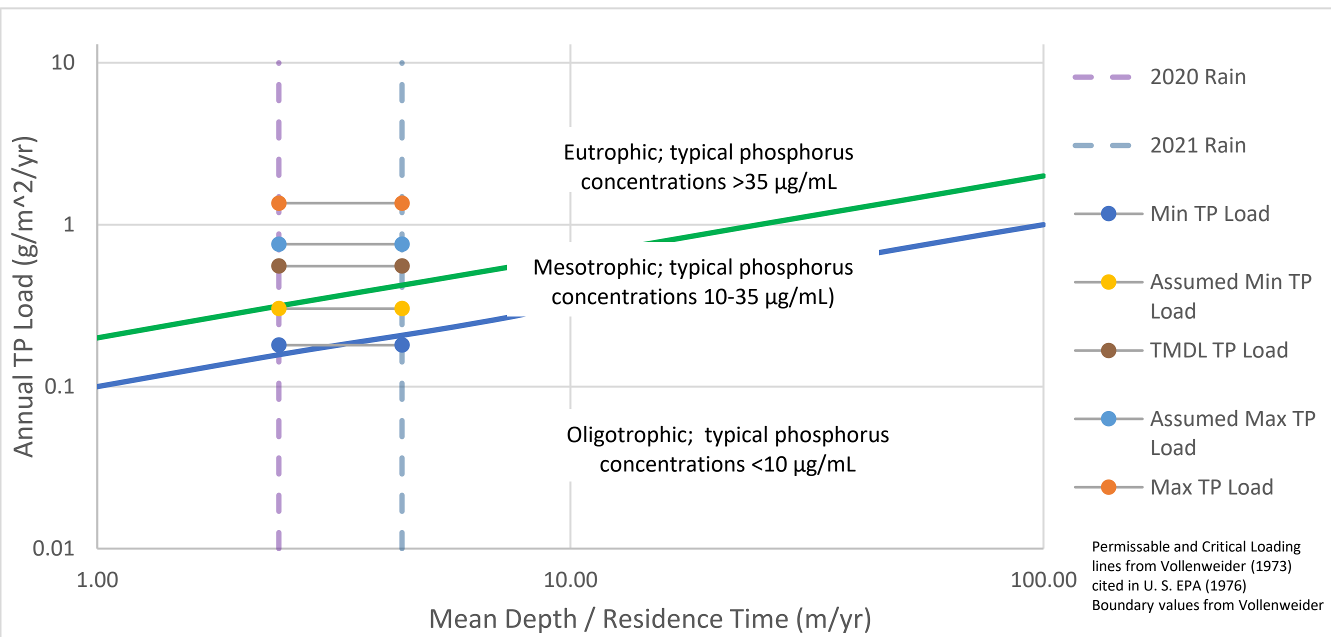


**Figure 25 Vollenweider model preliminary results (log-log scale)**

## 2.3 Phosphorus Loading and Watershed Model

The preliminary eutrophication analysis described in section 2.2 utilized the (uncalibrated) Vollenweider Model and previous estimates of phosphorus loading to the lake. The screening step had considerable uncertainty in both model inputs and predictions of trophic state. The next step in the project was to refine the predictions of phosphorus loading and lake trophic state using the hydrologic model and water quality collected in 2021. The hydrologic model described in section 2.1 was used in conjunction with the 2021 monitoring data to create a simple phosphorus loading model. A simple lake quality model was also created that was conceptually like the Vollenweider Model but could be validated based on lake phosphorus concentrations measured in 2021. The model was created to answer key management questions such as (1) what proportion of phosphorus loading to the lake comes from groundwater vs. surface water; and (2) how the lake's trophic status would change under different climatic or management scenarios.

### 2.3.1 Phosphorus Loading Analysis

The phosphorus loading analysis was based on the hydrologic model described in section 2.1. As represented in that model, Lake Boon has two main inflows that contribute phosphorus loads: groundwater and surface inflow. Phosphorus monitoring data were used characterize the phosphorus concentrations of these different inflows, and thereby estimate phosphorus loads in 2021. The hydrologic model has a daily time step; phosphorus loads were calculated on a daily time step and then summed to estimate monthly and annual loadings.

To model phosphorus from surface inflows, phosphorus measurements sampled at the stream inflow points were paired with the modelled inflow at the time of measurement. From these pairings, a relationship was established through linear regression of concentration versus the log of the flow as seen in Figure 26 below.

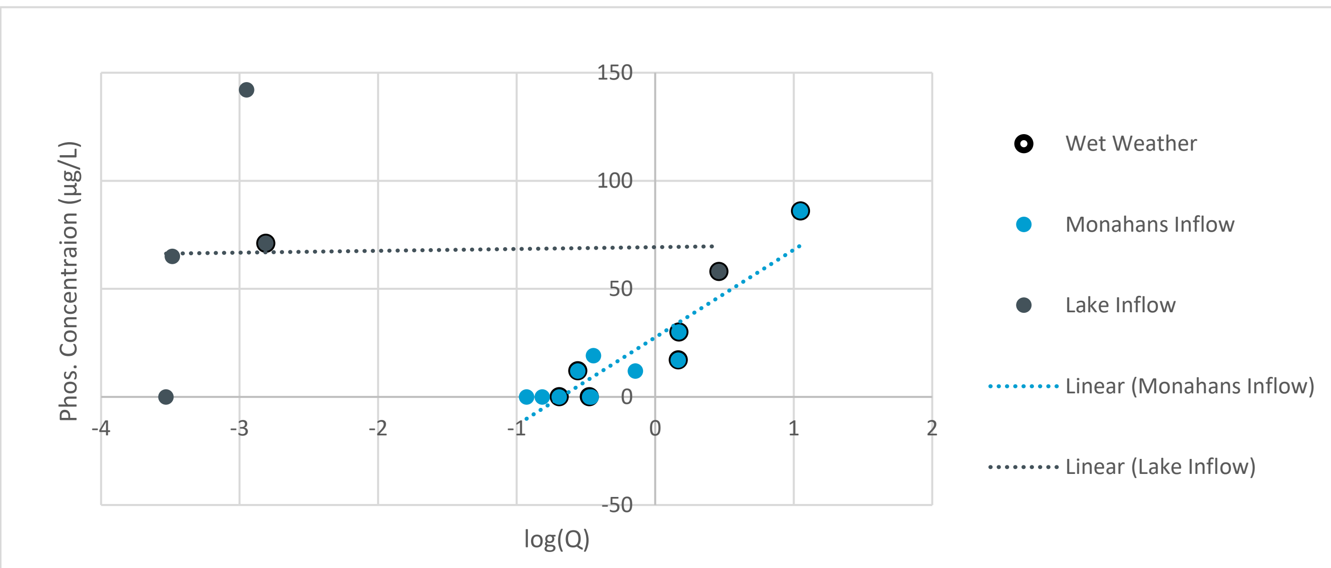


**Figure 26 Relationships between log of flow (Q) and phosphorus for Lake Inflows**

The relationship between the log of the surface inflow from Monahan's Cove and the measured phosphorus was significant and applied to estimate the phosphorus concentration of the stream inflow from the Monahan's Cove basin for each day of the hydrologic model simulation. Surface runoff into the lake excluding that from Monahan's Cove (indicated in dark blue in Figure 26) did not have a significant relationship with phosphorus, so an average phosphorus value was used for a linear relationship between concentration and flow.

Most groundwater samples from shallow wells did not have detectable levels of phosphorus. Therefore, the phosphorus concentration in groundwater was set to a constant of half the detection limit, or 5 ug/L. This was then multiplied by the modeled groundwater flow to determine total groundwater loading.

Phosphorus loading rates were calculated by multiplying the modelled daily concentrations by the estimated flow value. These daily loading rate values (in grams) were summed to calculate total phosphorous loading for the monitored period and extrapolated to winter months that were outside of the monitoring period using historical rainfall amounts during that period.

### 2.3.2 Preliminary Findings of the Loading Analysis

Total seasonal and annual loading values are below in Table 4. Preliminary estimates of phosphorus loading showed a seasonal increase in loading rates during summer months. Refer to Figure 16 for an illustration of the Primary Basin and Monahan's Cove Basin.

**Table 4: Estimated Seasonal and Annual Phosphorus Loading Values**

| | Jan* | Feb* | Mar* | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov* | Dec* |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Primary Basin Surface water (g of phosphorus/month) | 0.0 | 0.0 | 0.0 | 0.0 | 50.7 | 0.0 | 4283.5 | 95.5 | 3615.2 | 1332.4 | 0.0 | 0.0 |
| Primary Basin Groundwater (g of phosphorus/month | 267.6 | 257.5 | 321.6 | 502.4 | 387.3 | 321.2 | 768.3 | 770.1 | 992.1 | 918.9 | 321.6 | 331.6 |
| Monahan's Cove Basin Surface water (g of phosphorus/month | 267.6 | 257.5 | 321.6 | 118.2 | 766.8 | 141.2 | 5940.6 | 400.3 | 3472.4 | 1684.8 | 321.6 | 331.6 |
| Monahan's Cover Basin Groundwater (g of phosphorus/month | 62.9 | 60.6 | 75.6 | 116.8 | 123.1 | 101.9 | 180.5 | 159.0 | 183.3 | 146.1 | 75.6 | 78.0 |
| Total Monthly (g of phosphorus/month | 598.0 | 575.6 | 718.8 | 737.5 | 1327.9 | 564.2 | 11172.9 | 1424.9 | 823.1 | 4092.2 | 718.8 | 741.2 |
| Total Annual Phosphorus Loading | 30,935 g/year | | | | | | | | | | | |

*Values estimated using historical rainfall data and comparison to similar monitored months

### 2.3.3 Preliminary Findings of the Lake Water Quality Model

The annualized loading of phosphorus calculated in the previous section and the 2021 rainfall data was incorporated into the Vollenweider graph to compare 2021 to prior studies, shown below in Figure 27. The placement on the Vollenweider plot indicates the 2021 phosphorous loading from surface and groundwater values is minor compared to prior studies, and oligotrophic in classification.

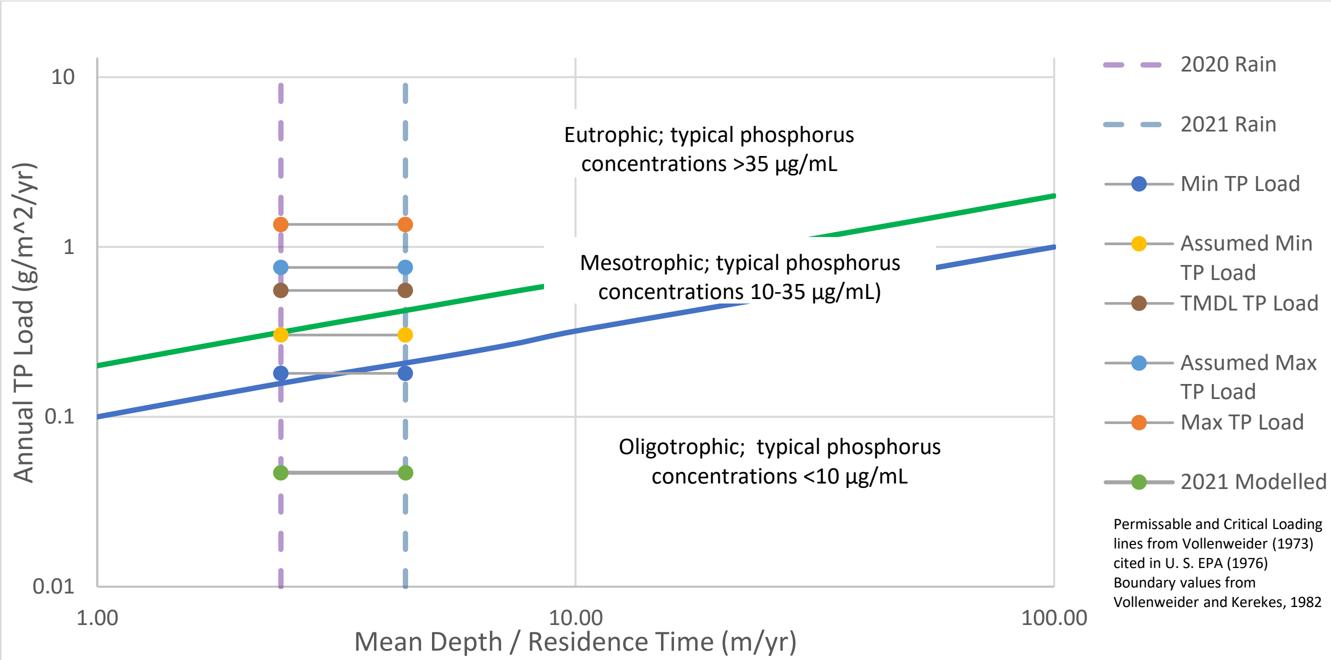


**Figure 27 Updated Vollenweider Results (log-log scale)**

The Vollenweider equation relates total phosphorous inflow to total lake concentration, which allowed BC to calculate the total lake concentration if groundwater and surface water were the sole source of phosphorus to Lake Boon. After completing measurement-based loading calculations, we compared the modeled concentrations of the lake to values that would be expected from the Vollenweider equation (relationship between total loading in and total phosphorus in the lake, using empirical relationships with hydraulic retention time and biologic uptake of phosphorus). The two rate coefficients used are used to represent the biological processes within the lake, with 0.45 being the standard and 1.16 derived from the hydraulic retention time. The comparisons of the model-predicted phosphorus concentrations to those measured in 2021 is shown in Table 5 below.

**Table 5. Predicted vs Observed Lake Phosphorus Concentration (µg/L)**

| Season | Modeled Lake Phosphorus Concentration (Rate coefficient = 1.16) | Modeled Lake Phosphorus Concentration (Rate coefficient = 0.45) | Measured Lake Phosphorus Concentration |
|---|---|---|---|
| Spring | 3.24 | 4.52 | 16.97 |
| Summer | 5.53 | 7.70 | 14.01 |
| Fall | 4.74 | 6.61 | 12.78 |
| Year | 4.53 | 6.31 | 15.29 |

The results of this comparison indicate that the phosphorous values within the lake are higher than the Vollenweider predicted values. This indicates a source of loading into the lake was unaccounted for in this model. One potential source of in-lake phosphorus, releases from sediment, is described below.

### 2.3.4 Sediment Phosphorus Results

Sediments can be a large source of phosphorus in freshwater systems, especially when conditions in bottom waters become anoxic. The Coastal Systems Program (CSP) within the School of Marine Science and Technology at UMass Dartmouth was asked to quantify the uptake and release of phosphorus in Lake Boon's sediment under aerobic and anoxic conditions. Sediment was collected from Lake Boon in the form of sediment cores and then incubated in a laboratory under both aerobic and anoxic conditions.

The CSP provided a report describing the findings of the incubation result. The uptake and release rates determined is shown in Table 6. These rates are separated into three categories: aerobic (sediment uptake under aerobic conditions), anaerobic (biological release under anoxic conditions), and Fe-bound (chemical release beginning 6 days after anoxia and continuing for 30 days). These values were provided in µMoles/m²/d and were converted to g/m²/d. Table 7 provides the specific release rates at the corresponding depths and areas for each basin.

**Table 7. Summary of Sediment Uptake and Release of Phosphorus and Applicable Surface Area in Lake Boon**

| Incubation Conditions | Depth Interval (ft) | Phosphorus Flux (µMol/m²/d) | | Surface Area of contour interval (m²) | Phosphorus Flux (g/m²/d) | |
|---|---|---|---|---|---|---|
| | | Mean | S.D. | | Mean | S.D. |
| Aerobic | 0-20 | -75.1 | 44.8 | 199134 | -0.002326147 | 0.001387635 |
| Aerobic | >20 | -59 | 13.3 | 49510 | -0.001827466 | 0.000411954 |
| Fe-Bound P | 0-20 | 12.73 | 5 | 199134 | 0.000394299 | 0.00015487 |
| Fe-Bound P | >20 | 121.04 | 30 | 49510 | 0.003749093 | 0.00092922 |
| Anaerobic | 0-20 | 21.6 | 4 | 199134 | 0.000669038 | 0.000123896 |
| Anaerobic | >20 | 29.3 | 20 | 49510 | 0.000907538 | 0.00061948 |

*Note: negative flux represents orthophosphate uptake by sediments

**Table 8. Sediment Uptake and Release of Phosphorus Adjusted to Corresponding Basin Geometry**

| Basin | Depth Interval (ft) | Represented Surface Area (m²) | Fe-Bound Rate (g/d) | Aerobic Rate (g/d) | Anaerobic Rate (g/d) |
|---|---|---|---|---|---|
| Basin 1 | >20ft | 49510.00 | 185.62 | -90.48 | 44.93 |
| | 0-20ft | 57250.92 | 22.57 | -133.17 | 38.30 |
| Basin 2 | 0-20ft | 73437.23 | 28.96 | -170.83 | 49.13 |
| Basin 3 | 0-20ft | 51725.35 | 20.40 | -120.32 | 34.61 |
| Basin 4 | 0-20ft | 16720.49 | 6.59 | -38.89 | 11.19 |

The dissolved oxygen conditions collected throughout the monitoring period seen in Figure 7 were used to identify aerobic and anoxic conditions for each basin and depth interval. The identified periods were used to calculate the total sediment exchange of phosphorous in Lake Boon using the rates in Table 8. The total sediment flux can be found below in Table 9. The sediment primarily produces a negative flux, meaning more phosphorous is being absorbed into the sediment than released. However, due to the anaerobic conditions primarily occurring from mid-June to mid-August, the sediment produces a positive flux in July and August.



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It is important to recognize that these rates were determined in a laboratory setting without the constraints one might see in a natural environment. Therefore, these rates can be used as representations of the processes happening within the lake, but the associated loading values are greater in magnitude than those occurring naturally in the lake.

**Table 9. Monthly Sediment Flux for Monitored Period from Laboratory Determined Rates**

| Month | Sediment Aerobic Uptake (g) | Sediment Anaerobic Release (g) | Sediment Fe-Bound Release (g/d) | Total Month Flux (g) |
|---|---|---|---|---|
| April | -13897 | 1348 | 5569 | -6980 |
| May | -14360 | 1393 | 5754 | -7213 |
| June | -10065 | 2450 | 5817 | -1798 |
| July | -3730 | 4450 | 7466 | 8186 |
| August | -9216 | 2872 | 7556 | 1212 |
| September | -13897 | 1348 | 6382 | -6166 |
| October | -13897 | 1348 | 5569 | -6980 |

### 2.3.5 Lake Phosphorus Balance

The modelled inflow and outflow were paired with the relationship identified in the phosphorous study to determine the primary contributors to phosphorus flux in the lake. Phosphorous addition to the water column was represented through the surface inflow from the primary basin and Monahan's Cove basin, groundwater inflow from both sub-basins, the anaerobic release from the sediment, and the Fe-Bound release from the sediment. Phosphorous removal from the water column was represented through the outflow from the weir at the dam and through the aerobic uptake into the sediment.

A balance done for only the water-based inflows and outflows of phosphorus shows a loading of approximately 7000g into the lake. As there was no apparent trend in the concentration of phosphorous in the lake outside of daily and seasonal variation, the sediment release and uptake rates were scaled to the expected sediment uptake of 7000g from the water-based inflows to approximate scale of flux from each source or sink. The weights (or amounts) of the modeled mechanisms for phosphorus fluxes into and out of the lake's water column is shown in Figure 28, and the corresponding values in Table 10.

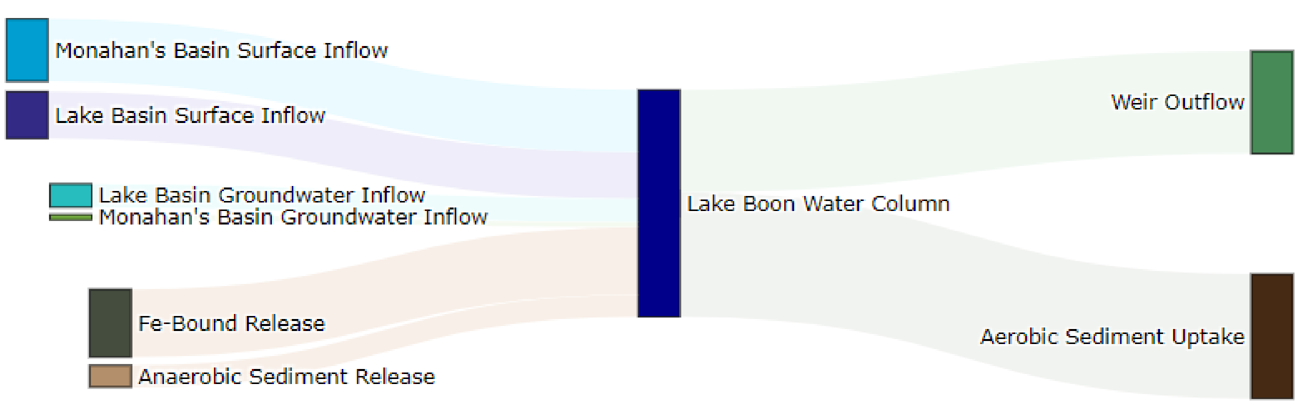


**Figure 28 Mechanisms and estimated weight of phosphorous transport into and out of the lake's water column**

| Table 10. Phosphorus Balance for Water-Based Inflows, Raw and Scaled Sediment Rates | | | | | |
|---|---|---|---|---|---|
| Water-Based Inflow | | Raw Sediment Rates | | Scaled Sediment Rates | |
| Source/Sink | Phosphorus Flux (g) | Source/Sink | Phosphorus Flux (g) | Source/Sink | Phosphorus Flux (g) |
| Lake Basin Groundwater | 4660.30 | Aerobic Sediment Uptake | -81423 | Aerobic Sediment Uptake | -24994 |
| Lake Basin Surface Inflow | 1044 | Anaerobic Sediment Release | 14311 | Anaerobic Sediment Release | 4393 |
| Monahan's Groundwater | 9377 | Fe-Bound Sediment Release | 44298 | Fe-Bound Sediment Release | 13598 |
| Monahan's Surface Inflow | 12534 | - | - | - | - |
| Weir Outflow | -20612 | - | - | - | - |
| TOTAL | 7003 | TOTAL | -22815 | TOTAL | -7003 |

During most months, the phosphorous flux of the lake is well balanced due to a high rate of uptake from the sediment during aerobic conditions. However, when the lake bottom becomes anoxic during summer months, a large amount of phosphorous is released into the water column. Due to the temperature gradient in the lake, much of the phosphorous stays in the colder waters in the bottom portion of the lake (the hypolimnion). As the lake turns over in the fall, the released phosphorus is mixed into the water column and becomes available for algal growth. These patterns resulted in the algal blooms that were seen during fall of 2021.

# Section 3: Next Steps

On February 16, 2022, BC met with the Steering Committee to review the information presented in this draft Technical Memorandum. BC will incorporate feedback from this group into future analyses and the draft Project Report. Our team will continue to refine the models used to develop these results and will use future iterations to conduct a sensitivity analysis, which will provide insight on how sensitive the models are to the measurements taken during the monitoring program. Additionally, as these models used present-day data, BC will develop scenarios to assess the Lake's response to a variety of future likely climate conditions. These findings will inform recommended best management practices for Lake Boon to be implemented. In a future phase of this project, BC will also evaluate the potential impact of implementing recommendations on the Lake's Health.

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# Attachment A: Field Investigation Notes from David Gray

Investigation of Monahan's Cove Tributary

Revised Shoreline Conductivity Surveys (8/30/21, 12/10/21 and 12/15/21)

Lake Boon Algae Blooms (12/22/21)



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# Attachment B: Phosphorus Release from Sediments of Main Basin Boon Pond, Stow MA

Technical Memorandum from Dr. Brian Howes, Director Coastal Systems Program
(Date Revised: February 1, 2022)