Evaluation of In-Lake Management Options for Lake Carmi, Franklin, Vermont

Final Report

Prepared for the

Vermont Department of Environmental Conservation

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1.0 Introduction

Lake Carmi is a large (surface area = 1,402 acres) and relatively shallow lake (maximum depth = 33 ft) located in the Town of Franklin, Vermont. The lake is heavily used for recreation, including fishing, boating, and swimming. Lake Carmi has a long history of water quality problems related to high phosphorus loading. Problems include late summer algal blooms, poor water clarity, and heavy aquatic plant growth. As a result of those problems, the Vermont Department of Environmental Conservation (VTDEC) listed the lake as impaired by high phosphorus concentrations under Section 303(d) of the Clean Water Act. This led to preparation of a Total Maximum Daily Load (TMDL) analysis by the Vermont Agency of Natural Resources (VTANR, 2008).

Lake Carmi has a watershed area of 7,710 acres. A land use analysis conducted as part of the TMDL (VTANR, 2008) indicated the major land uses in the watershed were wooded areas and wetlands (45%) and tilled or untilled farm land (44%). Intensive shoreline development and low-density residential development spread throughout the watershed comprised the remainder of the land use. The TMDL used export coefficients based on land use to estimate P loading through runoff from the watershed at 1,333 kg/yr, with an additional 88 kg/yr contributed by direct precipitation on the lake surface. Separate estimates were made for internal P loading (97 kg/yr), P loading from septic systems (15 kg/yr), and the Lake Carmi State Park wastewater treatment facility (1.5 kg/yr). The modeling effort relied on the Wisconsin Inland Lakes Modeling Suite (WILMS). WILMS (WIDNR, 2001) uses a number of common, published lake phosphorus models to estimate in-lake phosphorus concentrations from loads.

As a result of concerns over algal blooms, the Franklin Watershed Committee was formed in 1994 (originally as the Carmi Watershed Committee) to investigate and address sources of phosphorus to Lake Carmi. The committee initiated several projects to improve water quality, including some that addressed specific issues noted in the TMDL analysis. These included an Integrated Crop Management assessment that focused on nutrient needs and manure management of crop and hay fields for three farms in the watershed. Other projects included a septic tank pumping cost share and a septic survey to understand the relative suitability of existing septic systems and the extent to which camp owners knew about their septic systems and how to take care of them. Stream assessments, shoreline stabilization projects, and a lay monitoring program that collected data on Lake Carmi since prior to 1980 were also conducted.

The nutrient reductions recommended by the Lake Carmi TMDL will take several years to be fully implemented. In the meantime, the observed water quality problems are continuing and there is growing concern over the nuisance algal blooms. As a result, the Vermont DEC funded the current study to investigate in-lake methods that can potentially reduce internal phosphorus loading and reduce algal blooms.

In-lake restoration measures are aimed at enhancing the viability of lakes by alleviating specific symptoms of eutrophication. These restoration measures may provide short-term relief to existing water quality problems because, while they provide limited control for nutrients and other pollutants, they can substantially improve the aesthetic and recreational potential of the

lake and help gain public support for the restoration program while long-term management practices are being implemented.

Wagner (2001) listed 18 potential in-lake management options, but those methods vary widely in cost, effectiveness in addressing various water quality problems, effects on other lake uses, and potential side effects. For example, chemical treatments can control nuisance algal growth but do not reduce nutrient concentrations and may have adverse long-term effects on other aquatic organisms. In contrast, dredging may reduce internal nutrient loading if enough nutrient rich-sediments can be removed, but it is expensive and is unlikely to control algal growth as long as significant external nutrient loading is occurring.

Reservoir Environmental Management, Inc. (REMI) evaluated existing water quality data from Lake Carmi to determine the type of in-lake treatment that has the greatest probability of both improving lake water quality by controlling internal phosphorus loading and reducing or controlling the problems associated with nuisance cyanobacterial blooms. The various types of aeration/oxygenation systems that are available, as well as alum treatment, were the restoration methods evaluated.

2.0 Restoration Methods Under Consideration

Three main methods restoration methods were considered for Lake Carmi, and they are discussed in detail below:
- Artificial circulation
- Hypolimnetic aeration/oxygenation
- Phosphorus binding with aluminum (alum treatments)

A recent review of aeration/oxygenation systems used in water treatment reservoirs (Wagner, 2015) identified seven basic methods for increasing oxygen concentrations in lakes and reservoirs. The typical goal of aeration/oxygenation methods is reducing internal loading of phosphorus and other nuisance parameters, including ammonia, iron, manganese, and hydrogen sulfide, by increasing dissolved oxygen concentrations in the water column. In addition, some of these methods have also shown the ability to reduce nuisance blooms of cyanobacteria.

There are three basic artificial circulation methods:

1) direct release of diffused air into the water column at a rate sufficient to mix the water column,
2) updraft pumping systems, and
3) downdraft pumping systems.

The primary objectives of an artificial circulation system are to completely mix the water column and increase dissolved oxygen concentrations. Increasing oxygen levels oxidizes iron and manganese to convert them from soluble to insoluble forms, which also helps bind sediment phosphorus. Oxidation also converts ammonia to nitrate and sulfide to sulfate. In addition, mixing the water column may reduce algal growth.

Several different methods have been proposed for controlling algae and cyanobacteria through artificial circulation (Lorenzen and Fast, 1977; Pastorak et al., 1981; Cooke et al. 2005; Wagner; 2015).
- Mixing increases the mixed depth to reduce algal growth through light limitation
- Mixing also interferes with growth by subjecting algae to turbulence and rapid changes in hydrostatic pressure
- Mixing may reduce internal nutrient loading by eliminating the anaerobic conditions that favor phosphorus release.

Reductions in concentrations of cyanobacteria are common, even in those cases when there was an overall increase in algal biomass. Potential explanations for the control of cyanobacteria include:

- Increased circulation eliminates the competitive advantage that cyanobacteria have by being able to use buoyancy to reach optimum light levels.
- Dominance by cyanobacteria is favored by high pH and low levels of free carbon dioxide, but complete circulation usually results in a decrease in surface pH and increases in carbon dioxide as surface and bottom waters are mixed

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- Algal sinking rates are reduced with increased mixing, favoring heavier algal species that do not have buoyancy adaptations
- Mixing can also increase concentrations of both oxidized (nitrate) and reduced (ammonia) forms of nitrogen in the epilimnion by mixing surface and bottom waters. This can eliminate the advantage that cyanobacteria gain by being able to fix atmospheric N_2 under low nutrient conditions.

In addition to the artificial circulation methods, there are four types of hypolimnetic aeration/oxygenation systems that increase oxygen levels in the bottom layers of a lake without mixing the water column. These include:

4) direct release of oxygen gas at the bottom of the water column (typically through porous hose),
5) hypolimnetic aeration, which releases air into submerged chambers and transfers oxygen to the water as the bubbles rise,
6) downdraft bubble contact, which injects oxygen into water being pumped downward in a chamber, with most of the oxygen being absorbed by the water before it is released into the target zone of water depth, and
7) sidestream supersaturation, which adds oxygen to a shore-based pressurized chamber to produce a super-saturated solution that is released to the target zone.

Hypolimnetic aeration systems are designed to maintain stratification in the water column and increase dissolved oxygen concentrations in the lake's hypolimnion, with maintenance of a cold-water fishery often being one of the goals. Hypolimnetic aeration systems are usually expensive to install and maintain and are more suited to deep lakes with relatively large hypolimnia.

Alum treatment was also considered because it has been demonstrated to control internal phosphorus loading and to reduce the water column concentration of phosphorus. Alum is highly effective at binding (inactivating) phosphorus and making it unusable for algal growth. Different application strategies are used to sequester P in the lakebed sediments (internal loading control) and/or to strip P from the water column. The best strategy (e.g., full dose, split dose, annual low dose) is dependent on the sources and timing of the lake's P loads. In a recent review of full dose alum treatments, Huser et al. (2016), reported that the water quality benefits of the alum application lasted an average of 21 years in lakes throughout the world.

Preliminary cost estimates were obtained for the following restoration methods:

1) Circulation
   - Diffused air circulation (Mobley Engineering)
   - Updraft pumping (Medora Corporation - Solar Bee)
   - Downdraft pumping (WEARS)
2) Aeration/Oxygenation
   - Downflow bubble contact (Eco2 - Speece Cone)
   - Sidestream supersaturation (BlueInGreen)
3) Alum treatment (HAB Aquatics)

No cost estimates were requested for direct release of oxygen gas at the bottom of the water column (typically through porous hose) or for hypolimnetic aeration. Lake Carmi is too shallow for either of these methods to work effectively, and diffused air circulation through a porous hose system would be more effective and less costly in solving the observed water quality problems than direct release of oxygen through a similar system.

The cost estimates below are subject to revision; actual costs cannot be determined until a final engineering assessment is completed. The estimates below were based on preliminary information from the listed vendors and stated assumptions. The estimates were based, in part, on areas and volumes calculated by REMI from the available bathymetric map. A more accurate assessment of the areas and volumes at various depths in Lake Carmi is required for final design.
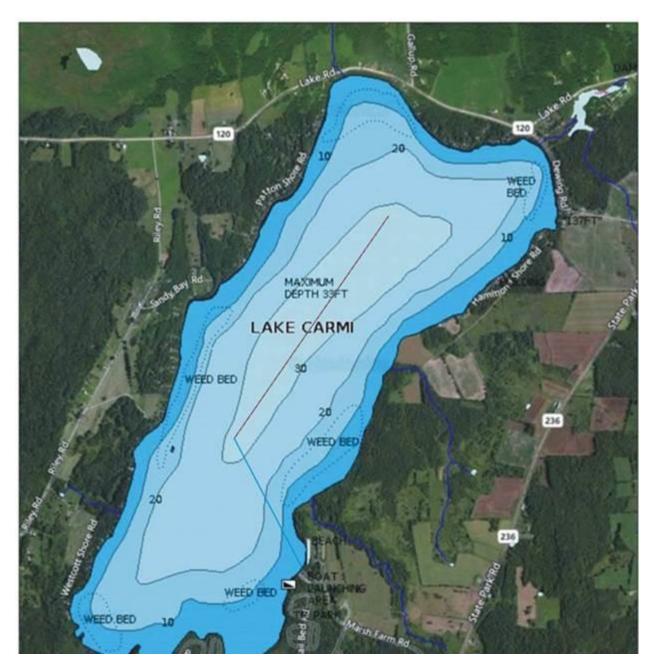
2.1 Diffused Air Circulation

A preliminary analysis of a diffused air circulation system was performed by applying a bubble plume model to develop an approximate design capacity that could circulate Lake Carmi. These systems are comprised of porous hose similar to the hose sold locally for irrigating gardens and landscaping around homes and commercial buildings. For aeration applications the hose is used to act as a diffuser that can release small air or oxygen bubbles into a lake water column so that dissolved oxygen can be added to the water and the water column can be mixed to the desired extent. To circulate a lake, air is distributed through a site-specific designed system of porous hose to optimize the lake mixing effectiveness. Lake Carmi water quality data were reviewed to develop a preliminary design to provide the basis for a preliminary cost estimate. The purpose of the design was to add dissolved oxygen to the water as well as circulate the lake to reduce cyanobacteria and enhance opportunity to replace these growths with more desirable algae.

The developer of the porous hose diffuser system, Mobley Engineering, Inc., developed a preliminary design for Lake Carmi. He came up with a system comprised of about 5,400 feet of diffuser (40 active 90 foot diffuser sections) with 600 cfm (150 HP) to break through thermal stratification. About 200 cfm would be sufficient to keep it mixed once destratified. The diffuser deployment at Lake Carmi would likely be as shown in Figure 1.

Mobley's cost estimate was $633,536 for the diffuser installation and $886,160 for the air supply facility installation, with both cost figures including contingencies at 25%. Annual O&M costs for the diffused air circulation system are expected to be a maximum of $15,000 for compressor operation based on a cost for electricity of $0.015/kWh ($10,000 or less is more likely) and $1,500 for compressor maintenance.

2.2 Updraft Pumping

Cost estimates were obtained from Medora for the installation of their Solar Bee pumps in Lake Carmi. Because each Solar Bee is designed to treat a maximum of about 35 acres, an estimated 20 units would be required to treat Lake Carmi. Each unit costs approximately $45,000 and comes with a 2-year warranty. Volume discounts for the units would be likely based on the large number expected to be required. Operation and Maintenance are handled through service contracts from Medora, which include two visits per year and are estimated at $2,580/unit/year.

In addition, monthly cleaning of the solar panels by local personnel would probably be required.

Figure 1 – Proposed diffuser line deployment in Lake Carmi.

Solar Bee costs were based on the assumption that 20 units would be required. Medora recommended that the units should be placed around the lake perimeter for optimum algal control. Note that this would not control internal phosphorus loading

Solar Bee Cost Summary

Capital cost: 20 units x $45,000 = $900,000
Annual O&M cost: 20 units x $2,580 = $51,600
Note: Additional costs for local personnel will also be required to clean solar panels.

2.3 Downdraft Pumping

A cost estimate for downdraft pumping was received from WEARS Australia. This is a preliminary estimate based on the following caveats.

- Site inspection has not been completed, so access to site, electricity (availability and location), proximity to services, etc. are assumed as being standard.

- Pricing was supplied by WEARS based on a standard installation. No allowances were made for the inclusion of third parties or having to manage other trades or services throughout.

Assumes power cable to be laid by others to WEARS specifications on time and in full.

- Assumes one trip to USA for up to 2 weeks for a WEARS crew to complete/supervise installation. No allowance was made for return trip/s or delays.

- Assumes smooth transition through contract and installation processes.

- No allowance has been made for permits, charges, fees or other state, local or federal charges in Vermont.

- Assumes that the State will provide an appropriately sized and secured build and set-down site at a location nominated by WEARS.

- No allowance has been made for crane hire, USA assembly crew or contractor (if required) or other local requirements, such as planting, tools, etc.

- Once more information is known, the above can be either priced, eliminated, or otherwise agreed on. WEARS can complete all of the excluded items and they can be priced accordingly, if required.

Based on the information provided, the best solution for Lake Carmi will be installation of a ResMix 3000CC. The ResMix 3000CC is a specifically designed application of two ResMix 3000 systems in a 'Close Coupled' arrangement. This system is used for lakes and reservoirs where flow requirements are high, but where depth prevents the use of a larger system such as the ResMix 5000. The systems are connected via a footbridge that allows transit between the two units for servicing, etc., with ease.

Although it may not be necessary (depending on modeling results), a ResMix 1000 system could be installed in the northeast part of the lake to provide additional mixing for more immediate control of algal blooms, if the budget allows. The ResMix 1000 system would provide an additional mixing capacity of 9,800 gal/min (37,300 L/min) for only 3HP (2.2kW). This would be additional targeted flow for a more rapid localized effect.

Capital costs include a ResMix 3000CC system, including foot bridge, electrical control panel including variable speed drives, and full SCADA compatibility; installation supervision by WEARS, including crew, travel, accommodations, and meals (up to 2 weeks); and international freight for shipping from Australia to USA and road transport from the nearest port. The total cost for a fully engineered solution, installation report, and Operations and Maintenance manual would be $424,700.

Each unit will be fitted with a very efficient 2.2 kW (3 HP) motor and gearbox. The ResMix 3000 system is able to achieve required flow and pumping velocity without high power needs. Operational costs assume that each unit draws approximately 1.6 kW for 24 hours per day, 365 days per year. Assuming an average annual cost of $0.15/kWh for electric power. The cost for each unit operated would be approximately $14,000/unit/year, or $28,000/year for the ResMix 3000 Closed Couple system. The ResMix 1000 system also uses a 2.2 kW motor, resulting in an additional operating cost of $14,000/year.

The cost for the ResMix 1000 system, including the same factors as the ResMix 3000CC system, would be $114,900. Some savings on shipping and installation costs could be realized if the ResMix 1000 system was ordered and installed at the same time as the ResMix 3000CC systems

Generally the systems require a visual inspection twice per year, which can be easily completed by the operator, and a mechanical service once each year. The mechanical service includes the changing of the food grade oil, greasing coupling and bearing, checking all connections (under and above water) and general cleaning and maintenance. WEARS completes this work in their domestic market relatively cheaply (~$3,500 per year), and generally without issue. Similar costs would be expected here.

The WEARS systems are designed to operate in excess of 20 years. WEARS suggests a refit after 10 years to replace barrier netting, entry cone panels and draft tubes, and perform any upgrades, etc. WEARS carries spare parts for all components and provides ongoing support, as required.

2.4 Downflow Bubble Contact

A cost estimate for installing a Speece Cone at Lake Carmi was provided by Eco2. Costs were based on treating the hypolimnetic volume of 470 acre-ft, which was calculated to require 3,536 pounds of oxygen per day. The cost for the Eco2 system, which includes a 10-ft diameter stainless steel cone with a life expectancy of 20 years, and an 84-hp (5,400 gallon/minute) pump is $480,000 for the basic system and $100,000 for the pump.

Operating costs will depend upon whether the liquid oxygen (LOX) is purchased locally or generated by on on-site oxygen generator. If the LOX is purchased locally, the gas supplier typically maintains the LOX tank and related equipment. Annual O&M cost for that option are

estimated at $27,100 for pumping, $5,420 for pump maintenance, $29,000 for LOX, and $12,000 for the equipment lease.

The on-site LOX generator has an estimated cost of $250,000, but oxygen would be produced on demand and the other costs would be reduced. After the initial outlay, annual O&M costs are estimated at $27,100 for pumping, $12,800 for oxygen, and $8,000 for maintenance.

Eco2 Cost Summary
Capital Cost: $480,000 for Eco2 system + $100,000 for pump + $250,000 for on-site LOX generator (optional)

Annual O&M cost: $73,520 for pumping, maintenance, and LOX purchased from local vendor or $47,900 with the on-site LOX generator

2.5 Sidestream Supersaturation

A cost estimate for sidestream supersaturation (SSS) was received from BlueInGreen, The cost estimate for the SSS system assumed a typical design point for sediment oxygen demand of 1 g O_2/m^2/day (a typical range is $0.5 - 3$ g O_2/m^2/day). BlueInGreen can provide a basic unit (with O_2 supplied by others, either as LOX or generated on-site) for about $300,000 to $350,000 delivered to site with start-up assistance. A completely containerized injection system could be supplied, if requested, which would simplify installation considerably. Installation and site preparation costs were not included in the estimate received.

BlueInGreen also has a lease option that includes service and support if the client would prefer not to own the equipment. Contracts for the lease option are typically provided on a yearly basis (1-year minimum) and are typically about $20,000/month, not including oxygen costs. Lower prices could be available for longer term commitments.

For a system of this size, BlueInGreen recommended using LOX. The LOX requirement was estimated to be 10,000 to 12,000 lb O_2/day through the BlueInGreen dissolution and injection system. This would result in yearly pumping costs of $256,100 (230hp @$0.17/kWh) and an annual LOX cost of $228,860 at maximum flow (12,000 lb/day).

BlueInGreen Cost Summary
Capital Cost: $300,000-350,000 for a basic system. Potential additional costs were not itemized.
Annual O&M cost: $484,960 at maximum flow.

2.6 Alum Treatment

The historic annual hypolimnion total phosphorus increase during summer oxygen reduction and the TMDL external and internal loads were reviewed. Assuming an annual internal load of 560 lbs/yr, a dose of 168,000 lbs of aluminum was calculated for a full dose application. This dose would be applied to areas of the lake with depths >20 ft in the form of a buffered alum application due to the low alkalinity of Lake Carmi. Alum and the buffer (sodium aluminate) would be applied a ratio of 2 gallons alum-to-1 gallon buffer. The estimated cost for this application is $660,000. We recommend that the concentration of available phosphorus in the

lake sediments be determined to confirm the alum dose. There are no annual O&M costs associated with an alum application.

A second alum application strategy could also be implemented. Instead of the traditional, full dose application, annual low dose applications are conducted to inactivate phosphorus in the water column. The annual dose would be designed to inactivate approximately 611 kg of phosphorus. This is equal to the required annual load reduction reported in the Lake Carmi TMDL. The annual cost of this application strategy would be approximately $150,000 to $160,000/yr. A benefit of this strategy is that it immediately meets the annual TMDL load reduction as long-term watershed work to control external phosphorus sources are ongoing. The annual application dose could be lowered (or stopped) once the external load controls were realized.

2.7 Cost Summary

Costs for the six methods described above are summarized in Table 1. Note that costs for diffused air circulation included costs for site preparation and other engineering costs that were not included in the estimates for the other five methods. In addition, all of these costs are preliminary estimates only and may be expected to change as more information becomes available.

Table 1 – Estimated costs for various restoration methods

Restoration Method	Capital Costs	Annual O&M Cost
Diffused air circulation	$633,536 for diffuser installation $886,160 for air supply facility installation	$15,000 (max.) for compressor operation $1,500 for compressor maintenance
Updraft pumping	20 units x $45,000 = $900,000	Maintenance contract - 20 units x $2,580 = $51,600
Downdraft pumping	$424,700 for a ResMix 3000CC, including shipping and installation supervision. $114,900 for an optional ResMix 1000 system for the northeast corner of the lake, including shipping and installation supervision	$28,000 electrical cost $3,500 for mechanical service $14,000 electrical cost $3,500 for mechanical service
Downflow bubble contact	$480,000 for Eco2 system $100,000 for pump $250,000 for on-site LOX generator (optional)	$73,520 for pumping, maintenance, equipment lease, and LOX purchased from a local vendor $47,900 with the optional LOX generator
Sidestream Supersaturation	$300,000-350,000 for a basic system. Additional costs for pumps and other system components may be required.	$256,100 yearly pumping costs $228,860 annual cost for LOX at maximum flow
Alum treatment (full dose)	$660,000 for application of 168,000 lbs of aluminum	$0
Alum treatment (annual, low dose)	$150,000 to $160,000 per year	$0 other than application cost

Please note that the costs listed in Table 1 are not directly comparable. The costs for diffused air circulation are the most complete because they include engineering fees for site preparation, testing, and other fees, plus they provide additional costs for contingencies and eventual diffuser replacement. None of the other estimates included these costs, which are not insignificant.

3.0 Evaluation of Listed Alternatives

The treatment alternatives listed above were evaluated both on their ability to reduce phosphorus loadings to Lake Carmi and on their ability to potentially control nuisance blooms of cyanobacteria; however, phosphorus loading does not appear to be a significant factor in deciding on the most appropriate treatment method. All of the aeration/oxygenation methods would reduce internal loading by oxidizing iron in the hypolimnion and immobilizing phosphorus. Alum treatment would be even more effective in binding phosphorus, but the Lake Carmi TMDL (Vermont ANR, 2008) estimated internal P loading as 97 kg/yr, which is only 6% of the total calculated P load of 1,595 kg/yr. The TMDL further calculated that a reduction in P loading of 611 kg/yr would be required to meet water quality objectives. While the actual internal P loading may be greater than that calculated by the TMDL (see Further Considerations below), differences in internal P control among the methods evaluated would be very small and control of cyanobacteria became the major evaluation criterion. As a result, alum treatment is not recommended at this time.

Because of its success in a large number of lake restoration projects, aeration has become one of the most common lake management techniques. Numerous surveys describe the benefits of aeration/circulation and provide information on design, costs, and other considerations (Lorenzen and Fast, 1977; Pastorak et al., 1981; Cooke et al., 2005; Wagner, 2015).

Several conclusions can be drawn on the effects of artificial circulation projects on algae. In most cases, algal biomass decreases or remains unchanged if mixing is complete, but often increases if mixing is incomplete. Even in cases where overall algal biomass increases or remains unchanged, artificial circulation usually reduces the concentration of cyanobacteria.

Although downflow bubble contact (Speece Cone) and sidestream supersaturation would increase oxygen levels in the hypolimnion of Lake Carmi to reduce internal P loading, neither of these methods is designed to completely mix the water column and control of algae and cyanobacteria would be limited to that achievable through control of internal nutrient loading, which is a minor portion of the overall nutrient loading to Lake Carmi. As a result, these methods were also eliminated from consideration.

Of the three remaining methods, updraft pumping (Solar Bee) may be the least suited to large lakes and the proposed installation would have limited impact on internal loading. Wagner (2015) reported that the actual amount of water pumped through these systems typically amounts to 30% of the total capacity listed in product literature, and even that value may be reduced if the pumps do not operate continuously at maximum capacity. Consequently, most updraft pumping systems will be underpowered if manufacturer specifications are applied. Because of relatively high costs, the large number of units that would be required, and a good possibility that the units would have limited effects on internal P loading, updraft pumping was also eliminated as a possible treatment method for Lake Carmi.

The remaining two alternatives, diffused air circulation and downdraft pumping, both could be potentially successful in improving water quality and decreasing cyanobacterial blooms in Lake Carmi. Modeling (see Recommendations below) is recommended to more accurately determine the pumping requirements, and therefore the costs, for these two alternatives.

Diffused air circulation is a well-developed technique that has been successfully used in many applications across the country. Design requirements are understood. The porous hose required for the diffused air system may be snagged by boat anchors or fishing lines, but the method presents no surface obstructions to recreation.

Some diffused air circulation systems add alum to further reduce P concentrations, but that is not recommended for Lake Carmi. There was concern among stakeholders that reductions in phosphorus concentrations could increase water clarity enough to cause dramatic increases in plant growth. That has been reported in some instances (Souza, personal communication).

A 2010 aquatic plant survey conducted by the Darrin Fresh Water Institute (Eichler and Boylen, 2010) listed elodea (*Elodea Canadensis*), wild celery (*Vallisneria americana*), Eurasian watermilfoil (*Myriophyllum spicatum*), and coontail (*Ceratophyllum demersum*), found in 33%, 24%, 19%, and 9%, respectively, of all survey points, as the most frequently-identified plants. Aquatic plant growth extended to a depth of 6 m (20 ft), with elodea, Eurasian watermilfoil, and coontail all found at depths of 5-6 m. Under these conditions, a significant increase in water clarity could result in more extensive plant growth.

Downdraft pumping was one of the early methods used for artificial circulation, but the current ResMix system developed by WEARs potentially represents a significant improvement. The number of installations in the United States is limited and there may be a risk of sediment suspension because Lake Carmi is more shallow than many of the successful applications of this system. The system does require a surface unit(s) in the lake, which may be subject to vandalism or interfere with boating, and this should also be considered. Costs are likely to be lower than those for diffused air circulation, but there is less certainty of success because the number of installations is more limited.

4.0 Recommendations

Diffused air circulation or downdraft pumping are the two methods that appear most suitable for improving water quality and reducing the occurrence of cyanobacterial blooms in Lake Carmi. Water quality modeling is suggested for evaluating these two alternatives in the next phase to guide the decision for selecting the best approach for achieving the objectives for Lake Carmi. Water quality modeling has been used to size and evaluate the performance of alternative aeration and water management systems and to design such systems to achieve water quality objectives. Modeling internal nutrient loading rates could evaluate the application of alum as a logical treatment method after sources of P loading in the Lake Carmi watershed are controlled.

The CE-QUAL-W2 model has been used to simulate water quality and selected aeration systems in lakes and reservoirs. Such models can quantify physical, ecosystem, and water quality processes in site-specific waterbodies accounting for hydrological and meteorological conditions and processes. These models can simulate the effects and performance of selected water quality management approaches. In cases where models can be limited in simulating aeration and mixing processes, they can assist in providing information that can cost much less and is much easier to obtain than expensive field testing.

Models can assist in designing aeration systems for a portion of the lake to focus on a lake area with higher frequency and likelihood of cyanobacteria occurring. This focusing approach can reduce cost for aeration and mixing. Also, such models can simulate the degree of stratification occurring in the lake in different years so that aeration and mixing systems can be designed and operated most cost-effectively.

The CE-QUAL-W2 model can assist in the design of alum applications regarding placement and size of the application to cost-effectively manage nutrient and algal objectives. The model can simulate a range of nutrient release rates from the sediments within each aerial segment of the model layout, and the model can represent over time the nutrients released within each segment. In addition, the model can be used to assess the effects of thermal stratification that can vary between years to assist in evaluating the performance of alum applications over a range of conditions.

5.0 Additional Considerations

While in-lake treatments can provide immediate relief from lake water quality problems, they are not a permanent solution. Regardless of the in-lake system that is selected, continued implementation of the Lake Carmi TMDL is recommended to reduce phosphorus loading. Continued phosphorus loading from the Lake Carmi watershed is a concern and can potentially reduce the effectiveness of any in-lake treatment method.

Although the load analysis was very thorough, we see two significant areas of concern that may warrant further investigation to guide future management efforts. The TMDL noted that there were five dairies in the watershed but apparently did not account for the additional P loading that can be produced by confined animal operations. It is our experience that those loadings can be significant and treatment of those relatively concentrated sources can be more productive in reducing phosphorus loadings that treating more diffuse non-point sources.

A recent watershed survey identified several streams in the Lake Carmi watershed with high P concentrations (Figure 35 in Gerhardt, 2015). We recommend that the Franklin Watershed Committee work with the local Natural Resource Conservation Service (NRCS) or similar agencies to identify possible areas where agricultural operations are creating high nutrient loadings. The NRCS can often provide a cost-share to implement management recommendations and this would be the most cost-effective approach to meeting TMDL goals.

Four different approaches were used to estimate an internal P load of 97 kg/yr for the TMDL, but the estimate from *in situ* phosphorus increases in the fall (1,011 kg/yr) was not used in calculating the average internal P load because the results may have been confounded by fall rains in 2006. Higher internal loading rates could make alum a logical treatment method after sources of P loading in the Lake Carmi watershed are controlled. While the long-term effectiveness of alum would be limited by continual P loading from the watershed, it could be still be a useful in-lake management technique if internal P loading is higher than the current estimate indicates.

The REMI team recognizes shortcomings of estimating internal P loading from *in situ* phosphorus increases in the fall, but we have had good success in applying this method to other lakes. Available water quality data from 2006, 2007, 2016, and 2017 could be used to refine internal P loading estimates for this method if alum treatments are seriously considered.

Note that the increase in hypolimnetic nutrient concentrations can result from both internal regeneration from lake sediments and from the sedimentation and decomposition of organic material originating in lake surface waters. Burns and Ross (1970) attributed approximately 50 percent of the hypolimnetic nutrient increase in Lake Erie to each of these factors. We have successfully used this value to estimate internal nutrient loading in a variety of lakes across the country.

Two additional approaches to refine the TMDL internal P load estimates are available. The pool of P in the lakebed that is potentially available for internal load events can be defined by collecting sediment cores various representative locations in the lake. The cores are then sectioned at different depths and the samples are analyzed for the various fractions of P that constitute the available pool. In addition, intact cores can be transported to a lab for P flux studies. In these studies, the actual P release rate from the lake sediments is measured under oxic and anoxic conditions. These approaches would not only refine the internal load estimates, but would also be important in finalizing alum doses.

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