Design Optimization in Floating Treatment Wetlands: An Examination of Key Challenges and Solutions

Josh Clark[1], Terrapin Water, Owen Sound, Ontario, Canada

INTRODUCTION

The use of Floating Treatment Wetlands (FTWs) for a number of important environmental remediation applications is rapidly gaining traction both in North America and elsewhere. As more diverse applications for FTWs emerge there is a natural and necessary process of refinement and optimization of design that must occur. This process is all the more challenging in the context of climate change as we face increasingly severe storm events on a more frequent basis. The following article is intended to provide a brief overview of some of the key challenges and failures in full scale deployment of FTWs as well as the design optimization process that Terrapin Water used to develop a modular components-based FTW system called "PhytoLinks." Two key PhytoLinks installations in particular were at the center of a 100-year storm event in Toronto, Ontario Canada on July 8, 2013 and have provided invaluable insight into how FTW systems respond to the unforgiving forces of nature. It is hoped that by providing this type of information we can help both fellow FTW practitioners and end-users in the refinement and ongoing management of their own technologies and/or installations.

Terrapin Water has over ten years of professional and research and development experience with FTWs in a variety of different settings. We worked extensively with three commercially available FTW systems from 2008-2011 and immediately began to compile a list of key challenges that none of those systems was fully able to address including:

- Cost (both upfront and replacement)
- Ease of plant establishment
- Anchoring
- Maintenance
- Flexibility
- Durability.

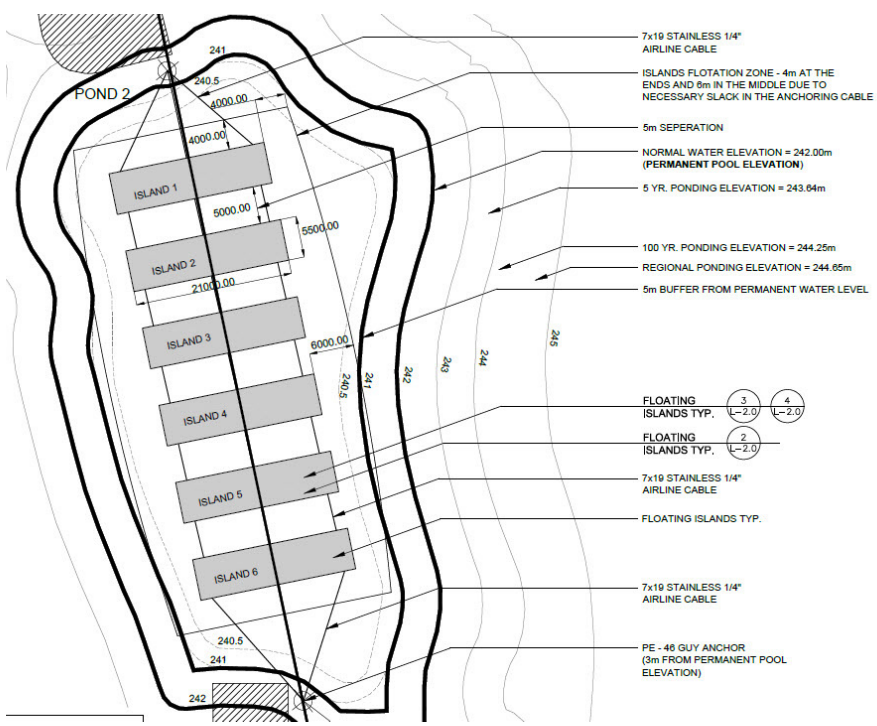
Based on this experience, we initiated a program to develop our own modular, components-based FTW technology that would be capable of meeting as many of the identified challenges as possible. We selected urban stormwater management ponds as the key application to build our design around since we felt it placed the most demanding set of constraints on FTW design. More specifically, stormwater ponds provide a unique combination of rapidly changing water levels, periods of relatively high water velocity, ice-locked winter conditions (in northern locations), periods of intense strong winds and presence of large numbers of herbivorous animals such as Canada geese and muskrats.

Three installations have provided the necessary full-scale performance data for our design optimization process, the details of which are briefly summarized below.

POND 10 FTW THERMAL MITIGATION

The Pond 10 FTW installation was a collaborative pilot project with the Credit Valley Conservation Authority for which Terrapin Water installed approximately 7,452-square

FIGURE 1. Anchoring layout for Pond 10 Thermal Mitigation Project, Brampton, Ontario (Single helical piles were installed at the north and south ends of the FTWs).



1 Corresponding author contact: josh@terrapinwater.com

feet of FTW constructed primarily of a 2-inch thick recycled foam board. The FTW was installed in August 2010 into a municipal stormwater management pond in Brampton, Ontario Canada. The main purpose of the installation was to reduce the temperature of water being discharged from the pond. A total of six rectangular modules where installed in a suspension bridge pattern using 7x19 ¼-inch stainless aircraft cable and a helical earth anchor at either end (Figures 1 and 2). Key failures at this installation included:

- Failure of helical earth anchor and partial foam board collapse after a severe wind storm in Year 2 (winds gusting in excess of 63 mph or 100 km/hour);
- Failure of hardware attaching modules to main anchor line in Year 5;
- Localized damage (holes) in foam board matting due to muskrat digging starting in Year 5;
- Failure of the main anchor lines in Year 6 and again in Year 8;
- Failure of foam board module in Year 8 (Figure 3).

The key lessons learned from this installation included:

- Wind-induced shock loading can pose a significant problem for FTWs using non- stretching anchoring/support lines such as stainless steel cables or chain;
- Suspending multiple large FTW modules from a single anchor/support line is not an optimal anchoring strategy;
- Recycled foam board lacks sufficient integrity to stand up to the long-term rigors of FTW deployment in an urban stormwater pond;
- Large-scale modules are cumbersome and difficult to adjust in full-scale FTW installations when troubleshooting;
- Goose and muskrat deterrent fencing must be maintained permanently on FTW installations in areas where these animals are common to prevent excessive damage.

LAKE WABUKAYNE FTW PILOT PROJECT

This municipal storm water installation located in Mississauga, Ontario Canada was a collaborative pilot project with the Credit Valley Conservation Authority and the City of Mississauga. In May 2013 Terrapin Water installed approximately 912-square feet of FTW comprised of 114 individual hexagon-shaped PhytoLinks modules that were anchored using a total of six 100lb concrete anchors fastened to the modules by means of a vinyl buoy and 5/16 inch chain (Figures 4 and 5). On July 8th, 2013 (2 months post installation) the Greater Toronto Area experienced a severe storm event that dumped approximately 5 inches (126 mm) of rain in the span of a few hours and caused hundreds of millions of dollars in infrastructure damage. Both the Lake Wabukayne and Jannock Pond (see below) FTW installations were near the center of this event which would have been expected to produce a rapid increase in water level of approximately 7-10 feet (2-3 meters) and water velocities approaching 17 feet per second (5.4 m/second). This provided us with an invaluable test of our design. The module layout and location of this installation was eventually changed to create a more stable configuration and eliminate flipping (Figure 6).

FIGURE 2. Pond 10 Thermal Mitigation FTW, Brampton, Ontario (Fall 2011, 1 year post installation).

FIGURE 3. Pond 10 Thermal Mitigation FTW, Brampton, Ontario (Spring 2018, broken module)

FIGURE 4. Lake Wabukayne FTW pilot project design layout (Anchor buoys located at the center of each cluster of modules).

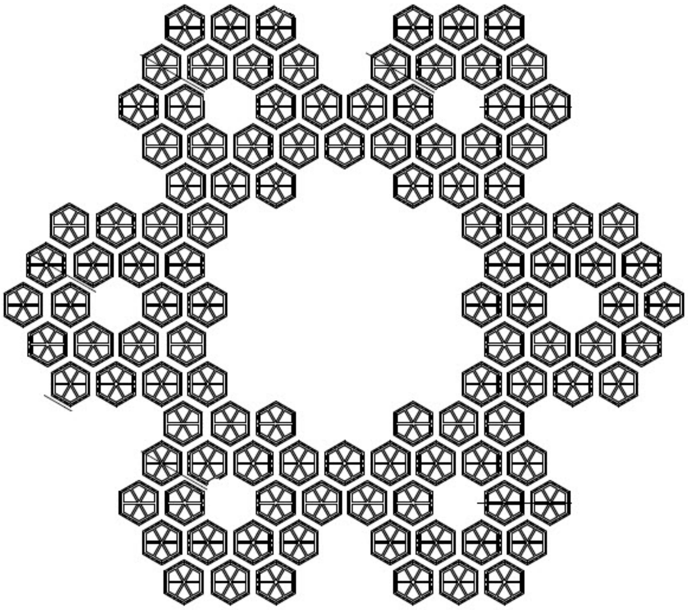
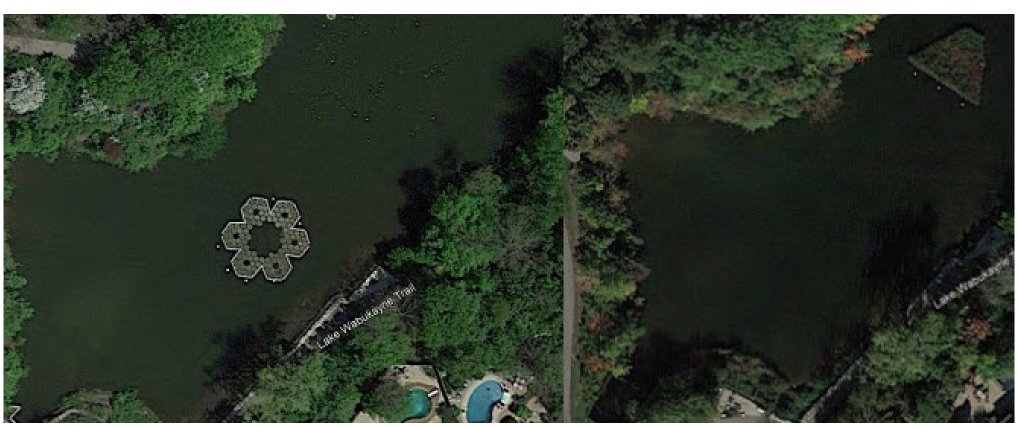


FIGURE 5. Lake Wabukayne FTW pilot project, Mississauga, Ontario Canada (Summer 2015).

FIGURE 6. Lake Wabukayne FTW pilot project, Mississauga, Ontario Canada. Left view is initial configuration summer 2015. Right view shows the same modules reconfigured and relocated in Summer 2016.



Key failures at this installation included:

- Destruction of greater than 75% of plants following 100-year storm event in Year 1;
- Flipping of approximately 20 modules during the same storm event (Figure 7);
- Failure of approximately 10% of polyethylene (PE) foam rod flotation due to ice damage during the first winter.

The key lessons learned from this installation included:

- Use of stretchable nylon rope instead of cable for module-module connections was able to reduce wind induced shock-loading and withstand the severe forces of a 100-year storm event with no failures;
- Anchoring systems must provide support to each and every module on the leading edge that is exposed to rapidly flowing water to avoid flipping (Figure 8);
- FTW floatation requires rigid structural support to resist the crushing force associated with ice;
- Removable components-based construction of modules allowed for complete onsite replacement of PE floats with more robust high-density polyethylene (HDPE) encased floats in 1 day;
- Small-scale modules are much easier to work with and provide greater flexibility for troubleshooting including complete layout change (Figure 6);

Goose and muskrat deterrent fencing should be checked after all moderate to severe storm events as most FTW modules will tend to partially submerge under high flow conditions.

JANNOCK POND FTW PILOT PROJECT

This municipal storm water installation located in Mississauga, Ontario Canada was a collaborative pilot project with the Credit Valley Conservation Authority and the City of Mississauga. In May 2013 Terrapin Water installed approximately 1,112-square feet of FTW comprised of 264 individual hexagon-shaped PhytoLinks modules that were anchored using ground screw-type anchors fastened to the modules by means of a vinyl buoy and 5/16 inch chain (Figure 9). Similar to Lake Wabukayne, this location was exposed to the 100-year storm event approximately 2 months post installation. Another significant challenge with this location was the resident year-round population of more than 50 Canada geese. Fence failures in early 2015 allowed access by geese which rapidly eliminated the majority of the vegetation. Subsequently, all modules were removed from the pond in late summer 2015 and transferred to a nursery pond (Figure 10). All modules were successfully reinstalled, fully vegetated in a new more stable configuration in late 2016 (Figure 11).

Key failures at this installation included:

- Destruction of greater than 90% of plants following 100-year storm event in year 1;
- Flipping of approximately 60 modules during the same storm event (Figure 12); and,
- Elimination of approximately 85% of viable plants by Canada geese following a fence failure (Figure 11).

The key lessons learned from this installation included:

- Transplanting of fully vegetated FTW modules from a nursery pond is a viable approach to mitigate risks associated with onsite plant establishment;
- In areas with abnormally high populations of geese fencing must be checked on a regular basis;
- Canada geese can quickly eliminate all viable vegetation from fully mature FTW modules in a matter of months if fences are not maintained (Figure 11).

PROJECT DESIGN CONSIDERATIONS

The importance of having pilot projects like these to expose FTWs to full-scale forces cannot be overstated. It is virtually impossible to artificially recreate the conditions and forces that a 100-year storm event creates. The patience and support that was provided by both the Credit Valley Conservation Authority and the City of Mississauga were essential to the success of this program and have allowed Terrapin Water to make significant improvements in our overall understanding of the practical side of FTWs.

FIGURE 7. Lake Wabukayne FTW pilot project, Mississauga, Ontario Canada after 100-year storm event. Modules were flipped but module-module tethering system and anchor lines were all intact.

FIGURE 8. Revised PhytoLinks anchoring system for urban stormwater ponds (each module on the leading edge has a support line that connects it to the anchor line to eliminate flipping).

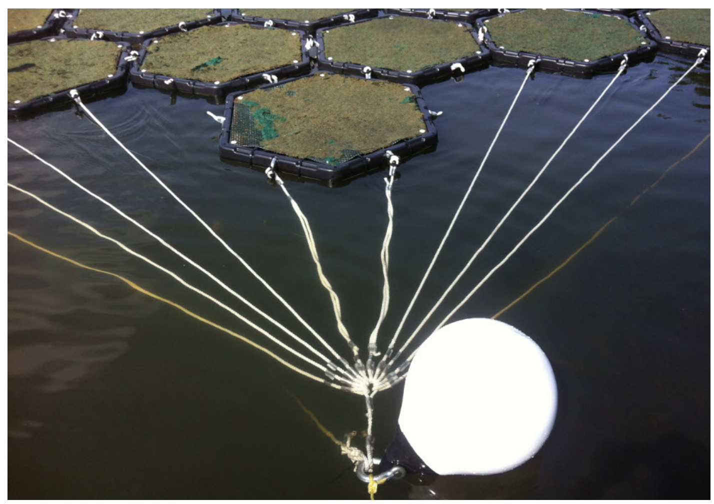


FIGURE 9. Initial configuration of Jannock Pond FTW pilot project, Mississauga, Ontario (September 2013).

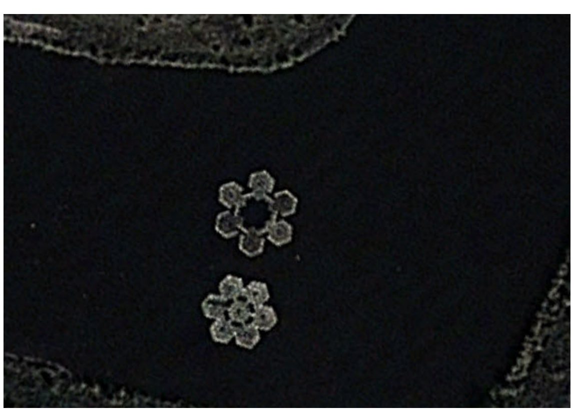


FIGURE 10. PhytoLinks FTW modules being grown in a nursery pond prior to reinstallation in Jannock Pond.

The key aspects of FTW design optimization based on our experience to date are summarized below.

Cost (Initial & Replacement)

The most likely end-users of FTW technology (municipalities) are already tasked with managing increasingly complex infrastructure with finite financial resources. Any investment in new technology such as FTWs, regardless of the potential benefits, will therefore require a careful analysis of all the associated short-term and long-term costs. A second key consideration with regards to cost is that size in FTWs is generally very important. The realization of significant treatment effects (in most cases) will require large-scale FTW installations. These are the main reasons that our design process used both initial and replacement costs as a key constraint. The way in which we addressed this constraint was very straight forward, we used the bare minimum of materials in our module construction in order to reduce the overall cost. Buoyancy in particular was noted as a relatively expensive component of the FTW system. Therefore we conducted a number of tests to determine the exact amount of buoyancy we needed to float fully mature vegetated modules. Our relatively small module size (approximately $8ft^2$) and quick attach module-module connection system meant that we did not need to provide enough buoyancy for people to walk on the modules in order to perform routine maintenance activities (Figure 13) .

We also factored in that FTWs deployed in outdoor environments will have a finite lifespan of approximately 10-15 years for locations where winter is a reality. With many of the commercially available systems we studied and installed, the entire FTW system including plants would need to be replaced at the end of that lifespan which would introduce a significant financial challenge for end-users. We addressed this challenge by making the compo-

FIGURE 11. Reconfigured module layout, Jannock Pond FTW pilot project, Mississauga, before (right) and after (left) goose damage due to fence failures.

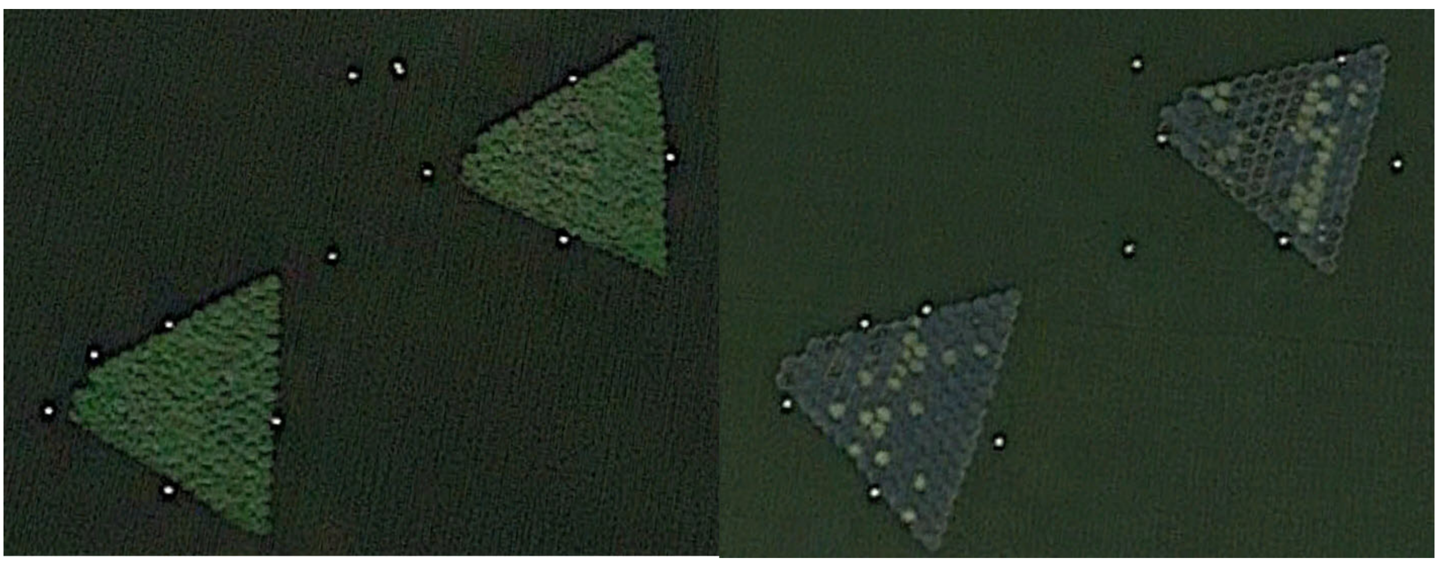


FIGURE 12. Jannock Pond FTW pilot project, Mississauga, Ontario after 100-year storm event. Multiple modules were flipped but module-module tethering system and anchor lines were all intact.

nents that wear out, namely buoyancy and module-module connection systems fully replaceable; in effect reducing the cost of system replacement at the end of the expected lifespan by greater than 65%. Based on our experience to date we also know that we can conduct this manual components replacement onsite without sacrificing the vegetation resulting no significant lapse in treatment effect.

Ease of Plant Establishment

Our experience with FTWs has shown that getting plants established is one of the most significant challenges to overcome. Even locations with obvious symptoms of eutrophication such as excessive algae blooms and odors may lack sufficient sustained quantities of dissolved nutrients to allow for optimal hydroponic growth and establishment of plants in the first year of deployment. In northern locations plants must attain a certain minimum amount of root growth in Year 1 to avoid excessive winter mortality. Some FTW systems address this by adding growth media to the surface of their modules to provide additional nutrients to establish plants. However, we decided against this approach since it requires additional buoyancy and hence adds cost to the FTW design. Instead we opted for a module size (approximately 8-square feet or 1-square meter) that was small enough that even a fully vegetated and mature module could be moved by hand. This has allowed us to rear our FTW modules offsite in a nursery pond environment where we can control nutrient levels and predation pressures much more effectively (Figure 10). In most cases we now deliver fully established vegetated FTW modules to the job site at the end of their first year of growth. This design feature has provided several key benefits including:

- Reduced plant mortality in first winter;
- Reduced predation pressure by geese (mature vegetation is much less attractive than immature vegetation);
- Reduced opportunity for colonization by invasive species (fully established modules have virtually no space for invasive plants); Greater success with plant establishment in low nutrient conditions such as newly built ponds.

Anchoring

For the purposes of FTWs we define anchoring as both the means of tethering individual modules together as well as the system used to attach groups of tethered modules to the bottom of a waterbody. Anchoring is a key constraint for design since keeping the modules in their desired location is necessary both from a functional and a liability perspective. The anchoring system must not only keep the modules connected to each other and the bottom but also help to absorb and dissipate the significant forces associated with gusting winds (termed “shock loading”).

Based on our experiences with several anchor failures at our Pond 10 installation we elected to incorporate the module-module tethering system into the underside of the plastic frame that forms each individual module. We selected stretchable rope as opposed to cabling to effectively mitigate shock loading from gusting winds. Our tethering system and quick-attach connectors also allow for spacing and subtle movements between adjacent modules which in turn contributes to the active dissipation of force (Figure 13).

During the design process we also embraced the reality that tethering and anchoring systems can and will fail periodically regardless of how robust the design may be. Accordingly, we incorporated redundancy into our connection system such that each module in a typical PhytoLinks layout is connected to six adjacent modules (Figure 13). This

FIGURE 13. Mature PhytoLinks modules showing module-module tethering and quick attach connections.

FIGURE 14. PhytoLinks FTW installation Brampton, Ontario Canada (2017) showing 6 anchor lines (white buoys) per grouping of modules.

effectively means we can experience a failure in multiple module-module connections without having a catastrophic system failure where all tethered modules come loose from their anchor point. We also employ multiple anchors for any one group of tethered modules to provide a similar system of redundancy (Figure 14). Our experience has shown that both concrete deadman-style anchors as well as helical ground piles are effective for use with FTWs.

The last consideration for anchoring of FTWs in stormwater ponds is the ability of the system to withstand rapidly moving water during severe storm events. Because our modules make use of the bare minimum of buoyancy, they tend to ride relatively low on the water surface which initially made them susceptible to flipping during severe storm events (Figures 7 and 12). We were able to overcome this challenge by tethering each individual module that is exposed to the rapidly moving stormwater flow back to an anchor (Figure 8). This relatively simple adjustment has eliminated the issue of flipping during severe storm events.

The combination of forces acting on FTWs in stormwater ponds in northern locations is arguably one of the most challenging situations imaginable. However, the end result of designing and testing our system in this environment is an anchoring system that is both reliable and cost-effective and can be changed and adapted to meet other less demanding applications with relative ease.

FIGURE 15. PhytoLinks FTW installation Brampton, Ontario Canada (2017) modules frozen in place.

FIGURE 16. PhytoLinks module showing HDPE-encased flotation system.

Maintenance

Maintenance is crucial to the long-term success of FTW installations but rarely gets an appropriate amount of consideration. For the purposes of this article we define maintenance as all activities that occur post installation once plants have reached maturity. In stormwater pond installations the primary maintenance activities are visual inspections of anchoring and tethering systems and minor fencing repairs. Visual inspections need to be conducted in spring immediately following ice-out, during fall just prior to ice-up as well as following severe storm events to assess both the anchoring and fencing systems for problems. In locations with resident populations of geese, inspections may have to be conducted on a more regular basis during the growing season to ensure that the fencing is not breached.

Our design strategy with regards to maintenance was to make our FTW system as simple to work with as possible. As a result both our module-to-module quick attach tethering and anchoring systems require no special tools or technical skills to assess and/or maintain. In the majority of cases a simple visual inspection is sufficient to be able to quickly and accurately assess overall system integrity. This means that municipal staff or other end-users can quickly and easily be trained to conduct visual inspections and even carry out minor repairs or adjustments themselves. In rare instances requiring replanting or other adjustments to individual modules, the quick-attach connections can be easily removed to allow for easy access to the problem modules.

FTWs like any other type of infrastructure are certainly not maintenance-free, and, as such, they need to be designed with the end-user in mind. Making tethering and anchoring systems simple and straight forward makes it less intimidating for the end-user to effectively maintain their FTW system and may ultimately lead to wider spread investment in the technology.

Flexibility

FTWs like any other infrastructure can and will experience problems and failures whether it be due to severe weather, wildlife, or even vandalism. The ease with which one can trouble shoot a particular FTW system and solve the kinds of unforeseen challenges encountered in aquatic systems is a characteristic we define as system flexibility. Not surprisingly, the simpler the system, the easier and more flexible it is to work with. This is precisely why we opted for tethering and anchoring systems that can be manipulated by hand without the need for specialized tools. We also selected a relatively small and simple hexagon module shape and quick-attach module-to-module tethering system to give ourselves the ability to completely change both the shape and location of the groupings of tethered modules with minimal effort (Figure 6). In practice this has generally been applied in response to system failures or in an effort to improve treatment effects. We have found this attribute to be particularly important in new FTW applications where the optimal layout to achieve a certain treatment goal may not yet be known. The ability to adapt and change a particular FTW installation in response to challenges or data analysis is a critical component of long-term success.

Durability

The challenge of designing a sustainable FTW system capable of withstanding the punishing forces of nature is all the more daunting in the context of climate change. More frequent storms of increasing severity mean that the 100-year event is no longer just an abstract design concept but rather a reality that will likely be experienced in the short-term. Our strategy to mitigate this challenge was two-fold. First we accepted the humbling reality that severe weather events can and will cause all FTW systems to fail at some point. As a result we abandoned the concept of trying to make our system absolutely indestructible and instead made the components that bear the brunt of storm forces quickly and easily replaceable. This approach allowed us to recover rapidly from the severe weather event in 2013 without the need for total system replacement. The second element of our strategy was to eliminate cable and/or chain from our module-to-module tethering system in favor of rope. The subtle stretching ability of rope provides much needed protection against the types of severe shock loading from wind gusts that are so often associated with severe weather events.

Winter conditions create a unique set of challenges for FTWs with modules and flotation often becoming completely frozen in place (Figure 15). Repeated freeze-thaw cycles can lead to crushing type deformation of buoyancy and loss of flotation in some installations. As a result, we switched our buoyancy from PE foam rods to more robust HDPE-encased flotation (Figure 16). This change has significantly improved the durability of the PhytoLinks flotation system.

Ultimately, durability in FTW design is only attainable through subtle changes and adjustments in response to repeated exposure to the most challenging conditions available. In that sense we were extremely fortunate to have had multiple full-scale systems exposed to such conditions in 2013. However, we are certainly not of the opinion that our system or any other system is infallible, and we will undoubtedly adapt and change our system in response to future challenges in order to continuously improve the durability.

CONCLUSION

The use of FTWs to solve any number water-related environmental challenges shows outstanding promise. However, we are clearly still in the early stages of acceptance and widespread application. To overcome this hurtle key end-users such as municipalities will need to be convinced that FTW system designs embrace and address the various elements discussed in this article in a way that ensures a sustainable long-term solution.

At a glance, the open discussion of failures of FTW technologies by a FTW practitioner may seem counter-intuitive. However, we have come to understand through our various experiences that the success of environmental technologies such as FTWs is much more about embracing failure than it is about touting success. The design optimization program utilized to develop PhytoLinks has allowed us to achieve a simple, cost-effective, durable, flexible and portable FTW system that we have successfully used to solve a number of environmental challenges. That being said, we are by no means convinced that we know everything there is to know about FTW systems. Instead we are committed to a continuous process of learning, refinement and improvement that has allowed us to stay at the forefront of the FTW industry in Canada.

It is hoped that by providing this type of information we can help both FTW practitioners and end-users in the refinement and ongoing management of their own technologies and/or installations. ■