BioHaven Floating Islands: Modeling and Their Role in Water Resource Recovery

Mark Reinsel[1], Apex Engineering, PLLC, Missoula, MT

BioHaven® floating islands remove excess nutrients and other contaminants from lakes, streams and wastewater lagoons, and are the flagship product of Floating Island International (FII). A BioHaven floating island or floating treatment wetland (FTW) is an example of biomimicry – the science of adapting designs from nature to solve modern problems. BioHavens leverage natural microbial processes to clean water, using a combination of microbial (bacteria and algae) and plant growth to effectively take up, precipitate and/or filter contaminants from water. The matrix and plant roots that grow through it provide an activated surface area for microbes. Producing a sticky biofilm, these microbes are responsible for breaking down nutrients and other contaminants.

BioHavens comprise layers of a non-woven, non-toxic durable matrix of fibers made from polyethylene terephthalate (PET). Dense and porous, the matrix is inert and coated with a UV-resistant resin that is compliant with U.S. EPA standards. An additional armor coating of polyurea is added to provide extra protection against environmental degradation and waterfowl damage.

BioHaven Floating Islands are currently improving water quality at sites around the world (Figure 1). Over 8,000 islands have been launched, and approximately 30 different applications/uses have been identified and evaluated. The purpose of this article is to: 1) describe a BioHaven treatment model that has been developed and used to date by FII, and 2) project how BioHavens can be used in the growing realm of Water Resource Recovery (WRR), where the treatment model is replaced or supplemented by a Return on Investment (ROI) model.

MODELING

The purpose of modeling BioHaven performance is to predict efficacy for various contaminants in new settings. When FII receives an inquiry from a potential client, inevitably one of the first questions is—how many floating islands will I need to budget for? An essential step to establish a budgetary estimate is to calculate the system size needed.

All of the modeling and results discussed are for BioHavens, the standard FTW embodiment for FII. Results cannot be extrapolated to FTWs produced by other manufacturers.

To develop its proprietary model, FII used contaminant removal data from numerous independently-monitored BioHaven studies since 2006. Removal rates are expressed in terms of pounds of contaminant removed per year per cubic foot of BioHaven (lbs/yr/ft^3). Cubic feet are used rather than square feet to account for possible different BioHaven thicknesses, although eight inches is typical.

An Excel spreadsheet model was developed to estimate BioHaven quantities, and subsequently costs, for new projects. The model addresses waterways with either continuous flow or no flow. A factor of $1.05^{(\text{new T} - \text{reference T})}$ is used to correct for temperature. This "theta" value of 1.05 is typically used for temperature correction. Since 2018, a

FIGURE 1. BioHavens are part of an industrial waterfront beautification project at the Urban Institute in Washington, DC. (Note: All photos for this article provided courtesy of Floating Island International, Inc. – permission granted March 22, 2019.)

1 Corresponding author contact: mark@apexengineering.us

different theta value for cold-weather performance derived from Canadian studies has been used when appropriate.

Model Input

Standard model input for design of a continuous-flow system includes:

- Flow rate (gallons per minute),
- Current and desired effluent concentrations (mg/L) for each contaminant of concern, and
- Water temperature (°C).

The same input is used for a no-flow ("batch") system, except that the flow rate variable is replaced by:

- Water volume (gallons),
- Startup time (months) - the time for BioHaven biofilm and plants to grow and become effective (e.g., typically estimated at three months), and
- Total time for restoration (months) - the time requested by the client for desired effluent concentrations to be achieved (note: a typical time might be 24 months; a shorter time requires more BioHavens and a higher capital cost).

The difference between startup and total times is the time the BioHavens are effectively treating water, or the remediation time.

Typical contaminants of concern include biochemical oxygen demand (BOD), total suspended solids (TSS), ammonia, nitrate, total nitrogen (TN), total phosphorus (TP) and total metals. FII has developed typical BioHaven removal rates for each of these contaminants, including both total and dissolved copper and zinc for metals.

Model Output

For each contaminant of concern, the model provides the minimum BioHaven volume required (ft^3). One of the contaminants will be the limiting variable, in that it requires the largest volume and determines the design volume. For example, where model results for a new application predict required volumes of 800, 300 and 600 ft^3 for TN, TP and BOD, respectively, the recommended design volume would be 800 ft^3. That volume should remove all of the TN required (the limiting variable), so the system would then be "over-designed" for removal of TP and BOD.

The volume required is then converted to the BioHaven area required (ft^2), using the typical thickness of eight inches. The area is converted to a number of islands required and a cost. Several BioHaven sizes are available, including standard, high-energy and wastewater-specific models.

FIGURE 2. Total Nitrogen (TN) removal rates for various BioHaven case studies in the United States and New Zealand. Total removal rates are much higher than net rates in most cases.

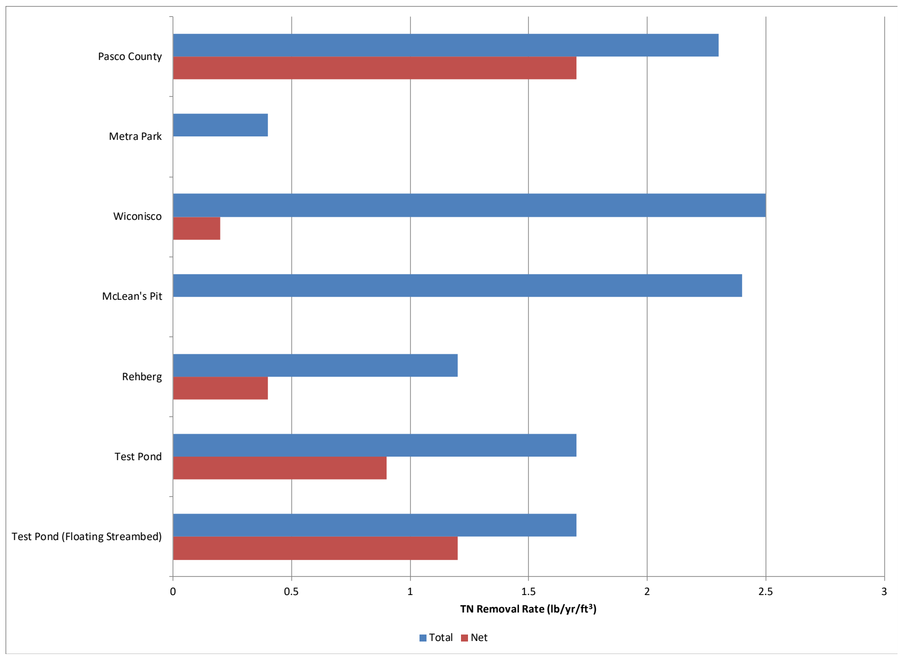
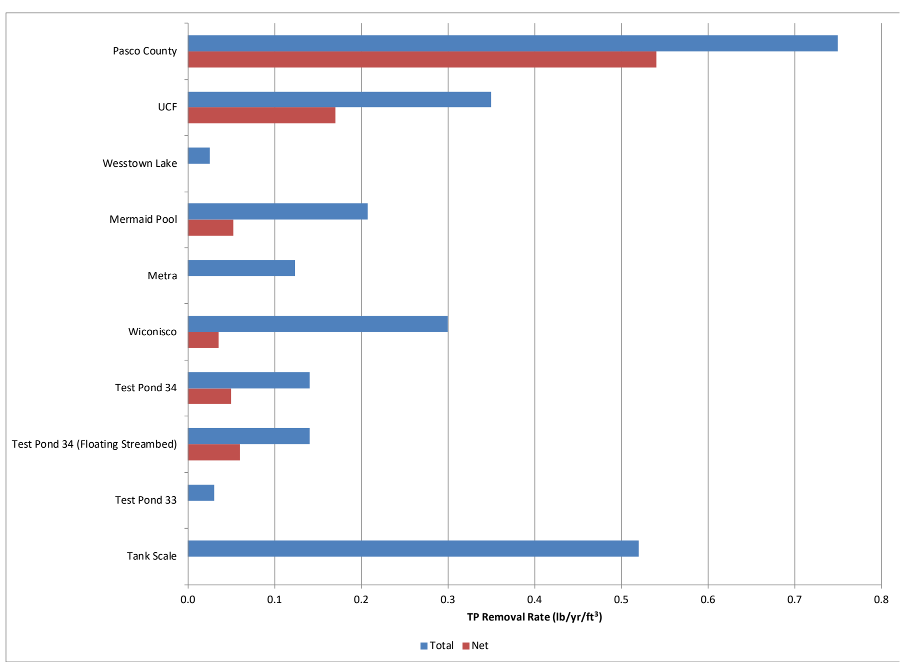


FIGURE 3. Total Phosphorus (TP) removal rates for various BioHaven case studies. TP removal rates are much lower than those for TN.



Total vs. Net Rates

It is necessary to explain the difference between what FII calls the "total rate" vs. the "net rate." The total rate includes effects of both the waterway and the BioHavens. The waterway will typically provide some removal by itself, called the "control rate." Net rate is the effect of the BioHaven only, which equals the total rate minus the control rate.

An example is the FII case study at the Rehberg Ranch subdivision wastewater ponds in Montana. Two parallel ponds were used for the study. The first pond contained BioHavens (the "island pond"), while the second contained no BioHavens (the "control pond"). The island pond removed 1.3 lbs/yr/ft^3 of ammonia (the total rate), while the control pond removed 0.9 lbs/yr/ft^3 (the control rate). Therefore, the net BioHaven rate for Rehberg Ranch was 1.3 – 0.9 = 0.4 lbs/yr/ft^3, which would be the removal rate attributed to BioHavens and the rate used for system design.

Total and net removal rates for total nitrogen (TN) are shown in Figure 2 for several FII case studies. Applications include wastewater treatment, wastewater polishing, stormwater and landfill leachate. Rates for total phosphorus (TP) are shown in Figure 3.

Typical BioHaven rates ("net removal") are shown in Table 1. Removal rates are higher for higher concentrations, as would be expected. A linear increase in rate with concentration would mean first-order kinetics. No change in rate with a change in concentration would mean zero-order kinetics. Since bacteria have been shown to provide at least 80 percent of contaminant removal in BioHavens (Gersberg et al. 1986), and bacterial activity typically follows Monod[2] kinetics (Characklis and Marshall 1990), BioHaven removal rates would be expected to also follow Monod kinetics. Monod kinetics fall between first-order kinetics (where the rate varies linearly with concentration) and zero-order (where the rate is independent of concentration).

TABLE 1. Typical removal rates for BioHavens per cubic foot of island matrix. "High concentration" cases are for wastewater, with "low concentration" cases for lake water or stormwater.

Typical Removal Rates		
	Net Removal Rate (lb/yr/ft3)	
Parameter	**High Conc.**	**Low Conc.**
TN	1.7	0.40
TP	0.54	0.052
TSS	26	1.5
BOD	15	0.8
NH3-N	2.8	0.1
NO3-N	0.9	0.02
Total Cu	NA	0.01
Total Zn	NA	0.06

Verification of Model Results

Since the model has been used in numerous applications, it is appropriate to review how model results compare to actual performance. FII continues to collect data to obtain as complete a picture as possible. The data to-date are quite promising.

At Moonlight Basin near Big Sky, MT (Figure 4), a BioHaven system was installed in 2016 using the best available rate at the time of 0.3 lbs/yr/ft^3 for TN. TN removal measured in 2018

was 1.2 lbs/yr/ft^3, so the actual rate exceeded the design rate by a factor of four. This greatly pleased the client, with the only possible downside being that the system could have been smaller (less expensive) to meet the client's requirements. If FII were to design this system today, it would use the TN net removal rate for wastewater of 1.7 lbs/yr/ft^3 from Pasco County (Figure 2). Using the selected temperature correction factor discussed earlier, for the average water temperature of 10^{o}C at Moonlight Basin, provides a rate of 0.9 lbs/yr/ft^3. This is slightly below the measured rate of 1.2 lbs/yr/ft^3, and appears to be an ideal solution in that the system exceeds design performance at little extra cost.

Comparison data for various parameters are being collected at several other sites where BioHavens were installed in 2017-18: 1) a wastewater lagoon (Joliet, MT), 2) an estuary impacted by wastewater (Guayaquil, Ecuador), and 3) Levings Lake (Rockford, IL).

Other Modeling Tools

Alternative BioHaven modeling is being developed for other cases. An alternative modeling tool for urban stormwater was published in Australia in 2016 after extensive

FIGURE 4. BioHavens located in a high-elevation wastewater pond near Big Sky, MT, one year after installation.

2 $\mu = (\mu_{max} * S)/(K_s + S)$, where μ_{max} = maximum specific growth rate
K_s = rate (saturation coefficient)
S = substrate concentration

testing on a BioHaven FTW system. That model uses the catchment area of the stormwater pond as a key sizing variable. When compared with the FII sizing model, a promising correlation was noted. FII is also developing a model for the BioHaven Streambed (the forced-flow embodiment), which is currently in use in a wastewater trial.

FII continues to refine the Excel spreadsheet model as more case study data become available. A Water Resource Recovery (WRR) modeling tool that focuses on return on investment (ROI) rather than performance is in its early stages of development by FII.

WATER RESOURCE RECOVERY

This initiative launched nationally over the last decade and has been applied primarily to large wastewater facilities. The basic concept is to turn waste into revenue. In principle, it targets value recovery from wastewater that typically occurs in two forms, energy conservation and product generation.

FII is bringing WRR to small lagoon-based wastewater facilities, which comprise 93% of all U.S. wastewater treatment facilities and serve about 27% of the U.S. population (National Science Foundation et al. 1995). Both of the value recovery forms can be used by the BioHaven WRR system.

Modeling for minimal volume of island required to provide a solution has been the standard until now. Today, however, the best "solution" may also incorporate a commercial endeavor. Instead of modeling to limit the costs of a project, WRR suggests that spreadsheet calculations tracking ROI can become the basis for project scale. Other considerations such as regional market may become the standard (the limiting variable) for wastewater projects. This premise assumes that wastewater and its nutrient load are indeed valuable.

Solar Energy Harvest System

Simply placing a BioHaven system in a lagoon can take the pressure off aeration systems to keep the lagoon in compliance. However, FII's WRR-specific energy conservation design represents an innovative way of using solar panels and BioHavens to retain heat and enhance system performance in cold temperatures.

The WRR energy conservation design places solar panel arrays between rows of high-energy BioHavens, set end-to-end, with a four-feet-wide channel between the rows. The solar panel housing is mounted over the channel, within which a proprietary air-blower system provides circulation within and around the BioHaven module perimeters, and the perennial plant roots in place under the modules. Air flow can be adjusted depending on the output desired.

Waste heat from the solar panels plus compression heat from the air blower combine to boost air temperature inside the solar frame structure by about 55-60°F over ambient temperature. The solar panels are fixed at a 62° angle to optimize for solar energy harvest during winter around the 45th parallel. This solar energy harvest system is designed to operate only during daytime hours, to minimize battery expense. However, a battery is needed to facilitate daily startup, which otherwise requires a large power draw by the solar power-driven air blowers that could restrict operation hours.

This solar design is not intended to heat an entire wastewater lagoon, but to provide a small amount of additional heat around the BioHaven matrix and plant roots, boosting biofilm performance. Air blowers used in this design can draw water from any depth; they would target the stratified zone where water temperature is typically near 39°F. Per FII modeling projections, adding a few degrees of heat to 39°F water within the channel defined by the solar panel mounting structure is projected to measurably reduce the island size required to remove ammonia in cold weather.

This energy conservation system is designed to be used on the final pond of an in-series lagoon layout, but could also be used earlier in a system. To optimize for the 39°F temperature, lagoon systems must be at least eight feet deep. Aeration/circulation systems currently in operation could be shut down and replaced with the FII solar-powered air blower system.

Cost savings associated with shutdown of existing aeration/circulation systems (typically up to one-third or half) are projected to save clients substantial O&M expense, which can be projected in typical spreadsheet calculations, and which represent an important component of FII's WRR initiative.

Generation of Saleable Products

The second FII WRR component is product generation. Over the course of thousands of island launches around the world, a broad variety of plants and trees have been successfully grown on BioHavens. While most of these macrophytes can be described as plants that enjoy "wet feet" (obligate hydrophytes), many facultative plants that grow both in wetlands and terrestrial habitats also succeed on BioHavens. Examples of trees that will be targeted as commercial prospects in FII's WRR system include willow, poplar, cottonwood, specific forms of oak, elm, birch and alder, and melaleuca/tea trees.

FII has developed a system for steering plant roots towards vertical growth down into water, rather than laterally (Figure 5). This prevents them from integrating into

BioHaven matrix and allows for straightforward plant harvest. Projections indicate that valuable landscape trees and plants can be grown on BioHaven WRR modules designed for human access.

BioHaven buoyancy can be customized to support various levels of human activity. For example, a 40,000-square-foot BioHaven in California supports 9,000 tons of gravel. Other BioHavens support rigidified walkways and buildings (Figure 6). Integration of optimal walkways to enhance for plant nursery activities on FII modules is a key design feature in this WRR system.

Growth of macrophytes and other biota on and in wastewater has several important advantages, including relatively high nutrient density associated with inflow water, an ample water supply, and favorable water temperatures. Disadvantages include potential hygiene issues associated with wastewater, and public perception of products derived from wastewater.

Forage Fish Growth and Harvest

Another prospective product that could be aligned with lagoon-based wastewater facilities is forage fish, such as fathead minnows (*Pimpephales promelas*). The fathead is noted for resilience, and an ability to sustain and flourish in poor-quality water including wastewater (B. Kania, Michigan DNR, pers. comm. 2018). It has also been used for biological mosquito larvae control (Irwin and Paskewitz 2009). FII has operated a fathead production pond at its headquarters; the pond's nutrient inflow contains nonpoint agricultural fertilizer.

SUMMARY

FII has created an Excel spreadsheet model incorporating contaminant concentrations and goals, flow rates and remediation times for its BioHaven floating islands. Model predictions are then translated to a number of islands and budgetary cost for a given application. The model accurately predicts total nitrogen performance at a cold-weather application in Montana, while other verification testing is underway.

Water Resource Recovery is an emerging field and FII is seeking to apply it to small lagoon-based wastewater facilities. The FII WRR initiative is in its initial stage, with efforts focusing on solar energy generation, tree harvest and fathead minnow production. ■

REFERENCES

Characklis, W.G. and K.C. Marshall. 1990. *Biofilms*. John Wiley & Sons, Inc., New York, NY.

Gersberg, R.M., B.V. Elkins, S.R. Lyon, and C.R. Goldman. 1986. Role of aquatic plants in wastewater treatment by artificial wetlands. *Water Research* 20:3:363-368.

Irwin, P. and S. Paskewitz. 2009. Investigation of Fathead Minnows (*Pimephales promelas*) as a Biological Control Agent of *Culex* Mosquitoes under Laboratory and Field Conditions. University of Wisconsin-Madison, Department of Entomology, Madison, WI.

National Science Foundation, U.S. Department of Energy, and U.S. Environmental Protection Agency. 2015. Energy-Positive Water Resource Recovery Workshop Report. Workshop Date: April 28-29 2015. Arlington, VA.

FIGURE 5. Vertical root growth seen on plants installed into BioHavens.

FIGURE 6. BioHavens along walkway on Fish Fry Lake near Shepherd, MT.