Application of Engineered Wetlands in Stormwater Management

By David Whitney, Mark O. Liner, and Evan Fitzgerald

Three case studies show wetlands in action.

What are wetlands, really? And why does everyone talk about them when the topic of stormwater is brought up? In the past, wetlands were considered a nuisance: a blight on the landscape that contained cold, slippery creatures; a lot of mud; and a tangle of plants that, if you weren't careful, would swallow you whole. If you were a landowner unfortunate enough to have wetlands on your property, you had but one option: Drain those darn wetlands and turn that land into something–anything–but the soggy patch of existence that it previously was. Oh, how times have changed.

In a glimmer of hope for humankind, it appears we are beginning to give wetlands the respect they deserve in our landscapes. After all, they are the kidneys of our environment. But what is a wetland? What makes it unique, and how can we harness the natural benefits for use in our constructed environments?

Wetlands Defined

The USEPA defines wetlands as follows [taken from the EPA regulations listed at 40 CFR 230.3(t)]:

> *Generally, wetlands are lands where saturation with water is the dominant factor determining the nature of soil development and the types of plant and animal communities living in the soil and on its surface (Cowardin, December 1979). Wetlands vary widely because of regional and local differences in soils, topography, climate, hydrology, water chemistry, vegetation, and other factors, including human disturbance. Indeed, wetlands are found from the tundra to the tropics and on every continent except Antarctica.*
>
> *For regulatory purposes under the Clean Water Act, the term wetlands means "those areas that are inundated or saturated by surface or ground water at a frequency and duration sufficient to support, and that under normal circumstances do support, a prevalence of vegetation typically adapted for life in saturated soil conditions. Wetlands generally include swamps, marshes, bogs and similar areas."*

Based on this definition, it is clear that wetlands are not a distinct, unique element within the landscape; rather, they take on a diversity of forms. Wetlands are commonly defined by soils that are saturated with water for a sufficient time period to sustain wetland vegetation. In nature, these ecosystems have been observed to have higher rates of biological activity than most ecosystems, and as a result they are capable of transforming common pollutants from wastewater into harmless byproducts or essential nutrients that are used to feed additional biological productivity (Kadlec and Knight 1996). Typically, these systems evolved over time as a result of natural flow patterns and self-organized into an essential component within the environment.

How Are Constructed Wetlands Different?

The greatest difference between constructed wetlands and natural wetlands

Figure 1: Slope-side condominiums at Jay Peak Ski Resort in Vermont

is the hydraulic regime. In natural wetlands, the flow in and out is a result of random meteorological events and groundwater patterns. Conversely, in constructed wetlands, the hydraulic regime is strictly controlled by inlet distribution headers, outlet collection systems, water-level control devices, and liners to prevent the influence of groundwater. Additionally, constructed wetlands are designed with a purpose: to remove specific pollutants, whether sediment, organic matter, or nutrients. When these systems are designed and installed appropriately, they will perform better than a natural wetland of equal size that receives similar waste.

In general, there are two types of constructed wetlands. The first is a free-water-surface (FWS) wetland. These wetlands resemble shallow ponds in which the water is no deeper than 3 feet. Emergent, submerged, and floating plant species are typically planted in these systems. The second type is a subsurface-flow (SF) wetland. In subsurface-flow systems, water is maintained at a constant depth below the surface of the growing medium, which is usually gravel, and is typically 0.45 meter deep throughout the wetland. The gravel medium ranges in depth from between 0.6 and 0.9 meter. Typically an impermeable liner is installed beneath the gravel to prevent seepage and contamination of the groundwater. In cold-weather regions, approximately 6 inches of mulch are applied to the top of the gravel, providing essential insulation during the winter months and minimizing water loss during warmer, drier periods. Plant species used in SF wetlands are currently limited to emergents and others that can tolerate saturated soil conditions for extended periods of time.

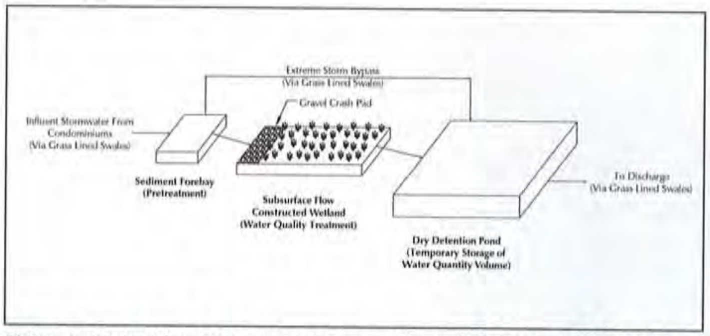


Figure 2: Typical Jay Peak stormwater system using SF wetland technology

How Are Constructed Wetlands Used for Stormwater?

Before we can discuss how constructed wetlands are used for stormwater, we first need to understand how stormwater regulation has evolved in the US. In general, an efficient stormwater management system includes water-quality and water-quantity controls (Vermont Agency of Natural Resources 2002). The specific requirements for each element vary from state to state. In Vermont, for example, the water-quality treatment standards have been developed to remove 80% of the average annual post-development total suspended solids (TSS) load and 40% of the total phosphorous (TP) load. The regulations then prescribe standard treatment practices that, when followed according to the rules within the manual, are presumed to meet these treatment standards. Water-quantity controls deal with the capture of extreme storm events and the controlled release back into the environment so that postdevelopment discharge from project sites equals the predevelopment, or undeveloped, runoff.

Constructed wetlands are typically used for water-quality treatment. However, some forms, such as the FWS, can be designed to control water-quantity events as well. The form of constructed wetlands can be as diverse as that of natural wetlands. The application of constructed wetlands in stormwater systems depends on a myriad of parameters, including but not limited to location within the landscape, topography, solar orientation, and personal preference. An additional consideration, which is not typically addressed in stormwater management guidelines, is the source of the stormwater and the expected levels of constituents to be treated (e.g., TSS, TP). The consistency of stormwater can be as varied as that in natural wetlands and as a result should be a design consideration.

This article focuses on the use of SF constructed wetlands for the water-quality treatment of stormwater. Three case studies are presented that detail different treatment and design considerations for this type of wetland, based on the varied constituents encountered in stormwater from a residential development at a ski resort, agricultural runoff, and commercial/industrial runoff from an airport. The design considerations, construction experiences, and lessons learned are presented below in greater detail.

Case Study #1

Jay Peak Ski Resort: Stormwater Treatment for Residential Runoff

The Jay Peak Ski Resort is located in northern Vermont, just miles from the Canadian border. Like many ski resorts, it has been expanding rapidly with a boom of condominiums constructed adjacent to ski trails on slopes of 15% and greater (Figure 1). Resort developers wanted to minimize the amount of disturbed area on the hillside in an effort to preserve the mountain landscape while protecting the environment at the same time. A conventional stormwater design comprising large ponds was considered but ruled out because of safety concerns, as well as the amount of downslope fill that would be required to reach existing grade. Additionally, a portion of the stormwater system was being designed as a retrofit for existing buildings that were not compliant with current regulations.

The Design Challenges. Subsurface-flow constructed wetlands were designed for water-quality treatment of the runoff generated from the slope-side condominiums, with dry detention ponds for temporary storage of extreme storm events (Figure 2). Unlike the ponds, the wetlands do not present safety concerns because they have no standing water. The siting challenges created by the existing buildings were minimized as well by the smaller footprint of the wetland stormwater treatment systems.

The SF constructed wetlands designed for Jay Peak's condominiums are not more than 4 feet deep, and the sideslopes are nearly vertical, which allowed the wetlands to be cut into the hillside and drastically reduced the amount of downslope fill required. Each wetland was lined with an impermeable EPDM rubber membrane to maintain a permanent water level below a stone media. The wetland was filled with 2- to 4-inch stone and topped off with pea stone for planting. Additionally, infiltration chambers are used to redistribute flow within the inlet end of the wetland, and water is collected at the bottom of the outlet end to ensure that all of the water entering the wetland passes through the stone media.

The minimum sizing criteria for these wetlands was based on the following requirement listed in the Vermont Stormwater Management Manual (Vermont Agency of Natural Resources 2002).

Equation 1: Vermont stormwater manual SF wetland sizing requirement

$$SA = \left(\frac{3}{d}\right) \times 0.0025 \times A$$

Where

SA = surface area (footprint), acres
D = stone depth, feet
A = drainage area, acres

It is important to stress that the wetland design process does not stop here. The guideline provided in the manual is a minimum requirement. Prudent design requires the further investigation of hydraulic loading rates to ensure that 100% of the water-quality volume design flow passes through the media. Furthermore, consideration should be given to treatment; in this case it is presumed that 80% of the postdevelopment TSS and 40% of phosphorous will be removed. Solids removal is a function of pore space, wetland dimensions, and flow. Phosphorous removal is more complicated (see sidebar).

Figure 3: Example SF constructed wetland with integrated water-quality treatment

The water-quality design storm was analyzed using HydroCAD based on watershed subcatchment area characteristics. The resulting influent flow intensities were then modeled in PTC, a groundwater modeling software, to determine whether the storm surge would pass through the wetland or overflow the media. As a result of this analysis, an inlet "crash" zone was created by installing large, 2- to 4-inch stone media up to the surface of the wetland. This stone had sufficient void space and a high enough hydraulic conductivity to allow the peak water-quality design storm flow to infiltrate the wetland. An extreme-storm-event bypass was installed to prevent larger flows from passing through the wetland and potentially damaging the system.

Water-level control is another important design consideration for SF constructed wetlands. Initial plantings require elevated water levels during the first growing season to establish root systems. The water should be incrementally drawn down to the desired design level beneath the top of the media. This is most easily accomplished with an adjustable standpipe on the outlet end. Manufactured adjustable water-level control systems such as the DOS-IR are available as well.

Plant selection is another important design consideration. Plants are often

Figure 4: Typical constructed wetland at Jay Peak. The sediment forebay is shown in the foreground, followed by the SF constructed wetland and dry detention pond.

an afterthought in these types of systems, which is ironic, because without them the systems would not be wetlands. The first consideration for plants is the location of the treatment system within the landscape. Is it shaded? What direction is it facing? What aesthetic impact will it have? In general, native plant species should be used because they will have the best chance for survival. It is recommended that a variety of plants should be planted initially, evenly distributed throughout the wetland to minimize die-off due to plant disease, nuisance pests, or other environmental parameters. It is not uncommon, however, that over time certain plants will outperform others and begin to take over the wetland. Lastly, it is important to find a local source for wetland plants to ensure they are appropriate for your regional planting zones. In the case of Jay Peak, plants also had to be appropriate for its microclimate, which is characterized by an extended winter season with extremely low temperature and heavy snowfall. Fortunately, Jay Peak was able to purchase its wetland plants from a local wetland plant nursery called Ambler Living-Design in Hyde Park, VT.

Lessons Learned. The constructed wetlands at Jay Peak have been operating for more than two years. Jake Webster, the vice president of development at Jay Peak, oversaw much of the stormwater construction at the resort and offered the following lessons learned with regard to these innovative stormwater solutions. The process begins with establishing a professional working relationship between the members of the design team, the regulators responsible for issuing the permits, the general contractor, and the owner. Because the SF constructed wetlands at Jay Peak were the first to be approved and installed in the state of Vermont, there was a bit of a learning curve for all parties involved to understand the system that was being proposed.

Once the design and permitting challenges were satisfied, it was a matter of finding contractors with an eye for detail and a keen enthusiasm for creating something new. Webster emphasizes the importance of skilled labor and a knowledgeable general contractor, especially when the job site is located in a remote mountain hollow. These systems require specialized components, such as the liner. EPDM rubber was selected because of the availability of an experienced roofing contractor that was already onsite installing membrane roofs for the condominiums. Additionally, it is important to have an excavation crew with an understanding of the technology and attention to detail. The construction sites at Jay Peak were fraught with challenges, including limited tree clearing, existing buildings, steep terrain, high

Figure 5: View of the CWCREO with Potash Brook buffer in background

groundwater, and shallow bedrock. In the end, Jay Peak's owners are excited by the constructed wetlands that have been integrated throughout their landscape and are planning on additional wetlands for future resort expansions and upgrades. Figure 3 shows a constructed wetland treating runoff from a cluster of single-family homes, and Figure 4 shows a typical constructed wetland at Jay Peak.

Case Study #2

The University of Vermont Constructed Wetlands Center for Research, Education, and Outreach: Stormwater Treatment for Agricultural Runoff

The Constructed Wetlands Center for Research, Education, and Outreach (CWCREO) is located at the University of Vermont (UVM) in Burlington, at the Paul Miller Research Complex. The CWCREO was established in 2003 by the UVM Department of Civil and Environmental Engineering and the Department of Plant and Soil Science to study the treatment efficiency of an SF wetland for concentrated runoff from the dairy facility (Figure 5). The dairy facility is located in the upper reaches of Potash Brook, a stormwater-impaired surface-water body that drains directly to Lake Champlain. Lake Champlain is one of Vermont's many valuable natural resources and is the drinking-water source for about a third of the state's population. Potash Brook is known to carry high concentrations of sediment, nutrients, and bacteria to the lake, which has led to numerous beach closings in recent years. The dairy facility maintains a herd of about 250 milking cows for research and production, and a thorough inspection of the runoff from the open-air barnyard indicated a potential source of nonpoint pollution in the watershed.

The Design Challenges. The farm setting and scale of production presented many challenges for the CWCREO wetland design. In light of these challenges, an interdisciplinary team with members from the Department of Civil and Environmental Engineering, the Department of Plant and Soil Science, and the College of Agriculture and Life Sciences was assembled to approach the design. The two principal design challenges were the cold climate conditions of New England and the high concentration of pollutants found in the farm runoff.

Vermont's cold climate was a principal factor influencing the decision to use a subsurface-flow constructed wetland. Treatment wetlands have not typically been used in northern climates, because it was believed they were not capable of providing consistent treatment efficiency throughout the year, especially during the winter months. It is well known that the biological processes of wetland systems are temperature dependent. The optimal temperature range for bacteria associated with wastewater treatment is between 30°C and 35°C, and below 4°C their metabolism virtually stops, inhibiting wastewater treatment (Davis and Cornwell 1998). Previous attempts to use constructed wetlands in cold climates were done using free-water-surface designs. Often these systems would freeze solid, or nearly solid, severely constricting the wastewater flow and preventing treatment. Recent attempts using SF wetland treatment systems have been more successful. In an SF system, the water flows at least 6 inches below the gravel surface, and a layer of mulch is placed on top of the gravel to provide critical insulation. Temperature monitoring performed on wetlands in Minnesota and Wyoming has shown that even with air temperatures as low as −25°C, the wetlands did not freeze. These encouraging results prompted the CWCREO design team to use this technology to treat barnyard runoff and milkhouse rinsate from the dairy facility to promote the use of inexpensive

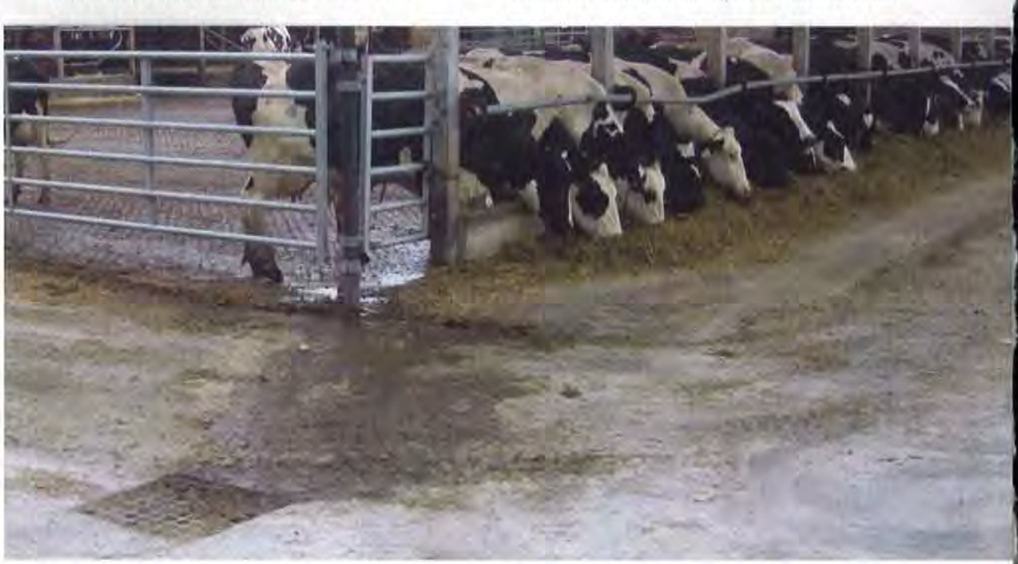


Figure 6: Catch basin collecting runoff from the open-air barnyard

Table 1. UVM Dairy Farm Water-Quality Test Results

Constituent	Unit	UVM Dairy Farm		Typical Municipal Wastewater
		Barnyard	Milkhouse	
BOD$_5$	mg/L	> 4,000	1,200	250
Total Suspended Solids	mg/L	2,500	2,600	220
Ammonia	mg/L - N	346	52	25
Nitrate	mg/L - N	1	1	0
Total Phosphorous	mg/L	44	44	12

biological treatment systems in cold climates.

The high concentration of nutrients and bacteria in the farm runoff was an additional factor that led the team to select an SF design. Water-quality tests performed on the barnyard runoff, sampled from various locations on the farm, confirmed that the runoff was a significant source of nutrient and organic loading to nearby Potash Brook.

In fact, the waste was so concentrated that it was analogous to industrial waste and more than 10 times stronger than typical untreated sewage flowing into a municipal wastewater treatment plant. Further tests on the washwater from the milkhouse produced similar results. The water-quality test results of runoff from the barnyard catch basin (Figure 6) and samples from the milkhouse settling tank are shown in Table 1 along with typical values observed for untreated municipal wastewater.

The CWCREO design consists of four full-scale SF treatment cells with a forced bed aeration system designed by North American Wetland Engineering LLC. Runoff and effluent from the dairy operation enters a series of settling tanks, where it is evenly divided to each of the four cells using a tipping bucket system (Figure 7). Each of the cells is equipped with aeration tubing, water-quality monitoring wells, and thermisters. The cells have a surface area of 223 square meters and a gravel media depth of 0.6 meter with a bottom liner to prevent seepage into the groundwater. The influent side of each cell (one-third of each cell) is composed of coarse gravel, with the remaining area consisting of fine gravel. For research purposes, two of the cells were planted with river bulrush (*Schoenoplectus fluviatilis*), and two cells were left free of vegetation.

Lessons Learned. The use of an SF constructed wetland design proved very effective for treating the dairy farm runoff and waste. Initial research carried out on the efficiency of the system through the winter season, which was a critical concern during the design, showed that the wetland vegetation contributed to thermal protection and the aeration increased temperature and mixing. This mixing and temperature maintenance helped prevent clogging and preferential flow patterns, which are known to reduce treatment efficiency (Munoz, Drizo, and Hession 2006).

Ongoing research at the CWCREO is exploring the following areas of wetland treatment and design:

1. Assessment of the nutrient treatment efficiency and evaluation of changes in seasonal performance
2. Investigation of nitrogen (N) transformations in the wetlands and ways N removal can be improved
3. Evaluation of greenhouse gas emissions from the system
4. Investigation of the microbial populations at the plant-substrate interface

More information on the ongoing research is available at http://www.uvm.edu/~cwrc/.

Case Study #3

Buffalo Niagara International Airport (BNIA): Stormwater Treatment for Commercial/Industrial Runoff

An innovative approach using aerated wetlands is currently being designed for treatment of deicing fluid at the Buffalo Niagara International Airport (BNIA) (Figures 8 and 9). The below-grade gravel beds are designed to treat spent glycol found in the stormwater. Aeration of the gravel is critical. The system is designed to supply oxygen to bacteria attached to the gravel and can be controlled relative to the level of glycol being treated. Currently, the system is designed for 10,000 pounds of oxygen demand per day and is roughly the size of four football fields.

The Design Challenges. At full build-out, the wetland will consist of eight wetland cells excavated from an existing open area near the airport's main runway. At ground level, only a field of grasses will be observable, growing from a "dry" mulch surface. An important factor of the design is the size of the gravel used and the porosity of the bed. The relatively large size of gravel, 0.5 to 0.75 inch in diameter, allows for accumulation of

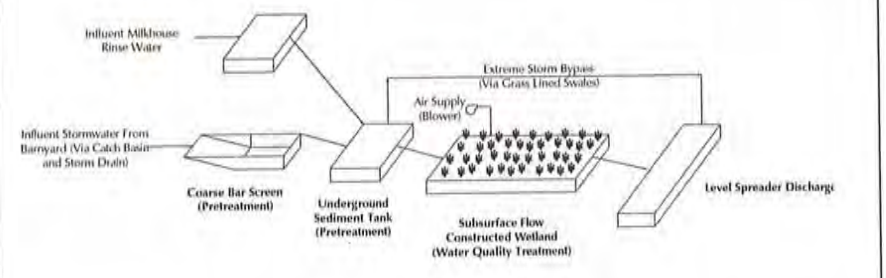


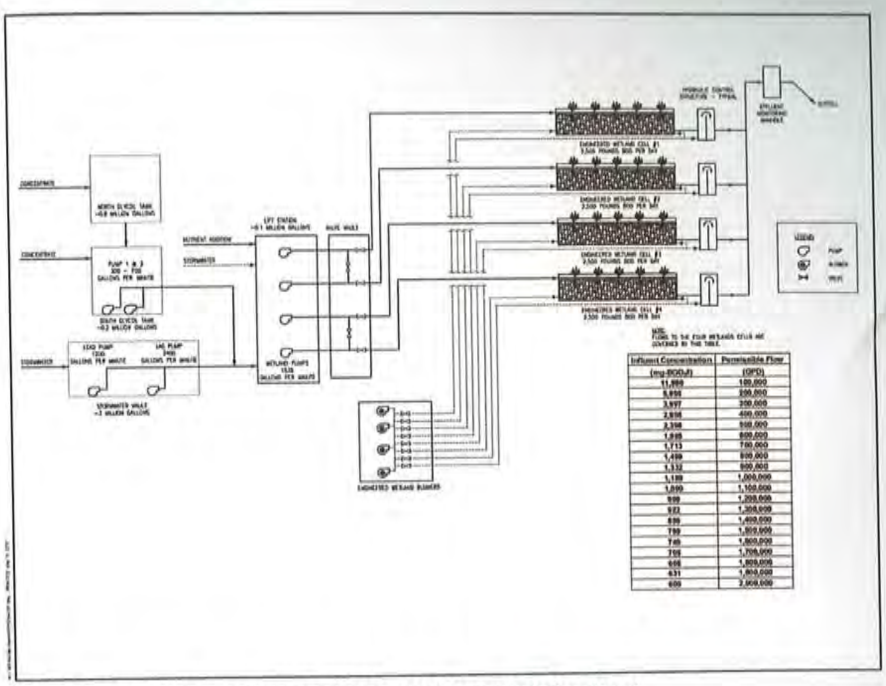
Figure 7: Simplified process flow schematic for the UVM CWCREO SF constructed wetland

Figure 8: A wetland for treating deicing fluid is being designed for BNIA.

bacterial biofilm (aka, slime), which grows during the deicing season and degrades in the summer. A detailed analysis of biomass growth, storage, and decay was undertaken to ensure that the gravel beds would not clog. Based on the analysis, a vertical flow configuration was selected in which stormwater is distributed uniformly over the beds and flows downward to an underdrain system. The large application area coupled with the large gravel voids minimizes the probability of clogging.

The flow and concentration of the stormwater will be closely monitored and, as necessary, controlled to optimize performance of the wetland. Air and nutrients will be supplied to the system to match the pounds of glycol measured. The system is engineered to maintain an active biomass within the wetland throughout the winter. It is built belowground with an insulating mulch layer on top to maximize water temperature. During the warmer summer months, the accumulated biomass will degrade and be consumed by larger "bugs" that graze on the slime-covered gravel. This natural digestion of biosolids is a seasonal means for managing "sludge" generated in the treatment of the glycol.

The driver of the BNIA project is compliance with a State of New York stormwater permit. Specifically, the discharge permit limits the concentration of biochemical oxygen demand in stormwater to 30 mg/L. Not all airports have limits like BNIA's, although that could change. The EPA is currently developing a regulation that will cover deicing at



NOTE:
FLOWS TO THE FOUR WETLAND CELLS ARE GOVERNED BY THE TABLE.

Influent Concentration (mg-BOD5/l)	Permissible Flow (GPD)
11,990	100,000
5,995	200,000
3,997	300,000
2,998	400,000
2,398	500,000
1,998	600,000
1,713	700,000
1,499	800,000
1,332	900,000
1,199	1,000,000
1,090	1,100,000
999	1,200,000
922	1,300,000
856	1,400,000
799	1,500,000
749	1,600,000
705	1,700,000
666	1,800,000
631	1,900,000
600	2,000,000

Figure 9: Process flow schematic for the BNIA constructed wetland

airports across the United States.

Under the Clean Water Act, the EPA establishes technology-based national regulations, termed *effluent guidelines*, to reduce pollutant discharges from categories of industrial facilities that discharge to waters of the United States. The guidelines are designed to provide uniform guidance for National Pollutant Discharge Elimination System permit writers so that there will be a level regulatory playing field from state to state. The guidelines will establish a baseline with which airports must comply and offer permit writers new, uniform guidance. Currently, the EPA is working with airports to collect survey data and conduct detailed sampling programs. This work will be used to identify the best available technology (BAT) that is economically achievable for treatment of deicing and anti-icing fluids. Typically, the BAT is the basis on which numerical discharge limitations are developed. The EPA plans to publish the proposed rule in June 2008 and take final action two years later.

The BNIA wetland is scheduled for construction at the same time, although it will not be a candidate for BAT because it will not have sufficient operational history.

Another regulatory restriction on the project is the volume of stormwater discharge to Scajaquada Creek to the south of the airport. The discharge from the southern half of the airfield is limited to a maximum flow rate of 181 cubic feet per second, which effectively translates to 154 cubic feet per second for the project area. To meet this restriction, the airport previously constructed a stormwater system with a 3-million-gallon vault. Pumps from the vault discharged to a culvert feeding Scajaquada Creek.

Lessons Learned. Stormwater management and wastewater treatment are two different disciplines with different goals. The BNIA wetland project involved a marriage of both. Whereas the stormwater engineer is focused on storage volume and flood prevention, a wastewater engineer looks at tank volume for equalizing flow and concentrations. Throughout the design process, both are gaming to maximize tank volume dedicated to meet their respective goals. In the end, management of stormwater volume wins out because it affects the core of airport operations and airfield safety. But in the case of BNIA, there is also volume for equalization. The airport has more than 1 million gallons of tanks dedicated for glycol storage, and these will be pressed into service to smooth out the peaks and pace the discharge of glycol-contaminated stormwater to the wetland system.

Although it may appear that the wastewater and stormwater engineers are at odds, it is not always the case. Come spring and the close of deicing season, the wetland treatment system will be used as a tool in the management of stormwater volume. The water level in the gravel beds is fully adjustable, allowing the operator to utilize the beds to buffer the flow from summer storm events. Because the system is already piped for managing peak flows, no additional infrastructure modifications are necessary. The beds provide treatment in the winter and storage in the summer.

Conclusion

Constructed wetlands are effective tools for treating stormwater runoff. Similar to the natural wetlands that this technology has evolved from, every system is unique and can take on many different manifestations, while still being considered a "wetland." Although simplified design guidelines exist as best management practices, it is important to recognize that these are the minimum design requirements. To harness the natural benefits offered through the use of constructed wetlands in our built environment, it is paramount we consider how the system will function in the landscape. Design guidelines including flow rate, waste strength, and effluent water quality need to be clearly defined. Furthermore, consideration needs to be given to construction feasibility, which includes material availability, cost, and qualified labor. Lastly, we need to consider the ongoing operation and maintenance requirements to ensure that the design guidelines are met and exceeded.

A typical SF constructed wetland configuration at Jay Peak

References

Cowardin, L.M., Carter, V., Colet, F.C., and LaRoe, E.T. 1979. *Classification of Wetlands and Deepwater Habitats of the United States.*

Davis, M., and D. Cornwell. 1998. *Introduction to Environmental Engineering.* Boston: McGraw-Hill.

Kadlec, R.H., and R.L. Knight. 1996. *Treatment Wetlands.* Boca Raton, FL: Lewis Publishers.

Munoz, P., A. Drizo, and W.C. Hession. 2006. "Flow Patterns of Dairy Wastewater Constructed Wetlands in a Cold Climate." *Water Research* 40: 3209–3218.

Vermont Agency of Natural Resources. 2002. *The Vermont Stormwater Management Manual.* Volume I, Stormwater Treatment Standards. 5th Printing.

David Whitney, P.E., is president and principal engineer with EcoSolutions LLC in Burlington, VT. ***Mark O. Liner****, P.E., is a senior engineer with Jacques Whitford NAWE Inc. in St. Paul, MN.* ***Evan Fitzgerald*** *is a principal watershed scientist with Fitzgerald Environmental LLC in Colchester, VT.*