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Small-Scale Natural Wastewater Treatment Systems: Principles and Regulatory Framework[1]

Kiara Winans, Shanin Speas-Frost, Mike Jerauld, Mark Clark, and Gurpal Toor[2]

Introduction and Purpose

Natural systems used for treating wastewater are known by many names, including constructed wetlands, artificial wetlands, biofilters, and various trademarked names. In this article, these systems will be referred to as small-scale natural wastewater treatment systems (abbreviated as "natural systems"). Natural systems both transform and hold on to many of the common pollutants that occur in household wastewater. These pollutants include disease-causing pathogens, suspended sediments, organic matter, nutrients such as nitrogen (N) and phosphorus (P), heavy metals, and trace organic chemicals (Kadlec and Knight 1996).

The major natural processes occurring in natural systems include sedimentation (settling of solids), plant uptake, bacterial degradation, and chemical adsorption (fixation). These processes help remove physical, biological, and chemical contaminants from wastewater. This is important because various contaminants found in untreated wastewater must be removed before the effluent can be safely reused or released to the environment. Here wastewater refers to wastewater prior to the removal of contaminants produced by domestic, municipal, industrial, or agricultural activities, while effluent refers to wastewater following primary, secondary, tertiary, or advanced treatment.

Removing contaminants from wastewater before the effluent is released or reused will ensure that no harm is caused to the environment. Untreated wastewater in the environment can cause eutrophication (algae growth in water bodies), depressed oxygen levels (which will kill fish), accumulation of toxic chemicals and heavy metals in aquatic organisms, and human health concerns.

Some conventional treatment systems with advanced technologies actually use many of the principles of natural systems. Examples of conventional treatment systems include septic tanks, aeration tanks, porous filter media, chemical polymers, distribution pumps, rock beds, earthen mounds, dispersion fields, and plastic chambers. However, when natural systems are incorporated into a landscape or building design, they can provide added benefits compared to a conventional treatment system.

Wetlands have been used numerous times to treat wastewater, and they have proven to be a well-suited, cost-effective, and environmentally friendly treatment alternative to conventional systems (DeBusk 1999). Constructed wetlands for small flows (from individual or community households or businesses) have been a wastewater treatment option for at least 18 years. The principles described in this article apply to either vegetated submerged bed wetlands or wetlands with an open water surface, even though there are

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2. Kiara Winans, Ph.D., Department of Soil and Water Science; Shanin Speas-Frost, water reuse/wastewater wetlands coordinator, Florida Department of Environmental Protection, Tallahassee, FL; Mike Jerauld, research scientist 3, DB Environmental, Inc., Rockledge, FL; Mark Clark, associate professor, Department of Soil and Water Science; and Gurpal Toor, assistant professor, Department of Soil and Water Science, Gulf Coast Research and Education Center, Wimauma, FL; Florida Cooperative Extension Service, Institute of Food and Agricultural Sciences, University of Florida, Gainesville, FL 32611.

differences between the two. Wallace and Knight (2004) found that vegetated submerged bed wetlands are more commonly used for small-scale applications than wetlands with an open water surface because of the decrease in exposure to pathogens. (Note: Vegetated submerged bed wetlands are also known as submerged flow, horizontal subsurface flow wetlands, and root zone systems. These wetlands are designed to create subsurface flow through a permeable medium, usually a gravel bed that is then planted with wetland vegetation.)

This document briefly describes the principles and added benefits of natural systems. It then focuses on the use of natural systems for treating small municipal wastewater flows from commercial and residential sites (i.e., septic systems or decentralized wastewater systems). This document is not intended as a "how to" of treatment system design. Instead it is an introduction to the use of natural processes (common in wetland ecosystems) for the purpose of treating wastewater. The target audience for this publication includes community developers and city, county, or state personnel who may have the authority to approve use of natural systems in select areas.

Natural vs. Conventional Treatment Systems

Individual residential and small commercial wastewater flows are usually treated using an onsite wastewater treatment system (i.e., septic system). Septic systems typically provide adequate treatment for pathogens, and, if designed properly, they will provide adequate treatment for both nutrients and pathogens. In fact, several advanced onsite treatment systems incorporate the principles of natural systems (i.e., aerobic and anaerobic pretreatment). For an overview of wastewater flow and quality in septic systems, consult Toor et al. (2011) EDIS article "Onsite Sewage Treatment and Disposal Systems: An Overview" available at http://edis.ifas.ufl.edu/ss549.

Compared to conventional onsite wastewater treatment systems, natural systems are generally more ecologically and economically efficient but are relatively more design-intensive. In these systems, pretreating the wastewater by aerobic and/or anaerobic digestion allows microorganisms to biologically process the contaminants in the wastewater so that wetland plants and algae in the water column can take up and further process the contaminants. In contrast, conventional wastewater treatment methods used to further reduce contaminants such as nutrients become increasingly expensive to implement. These often require a large amount of chemical inputs and result in sludge as a byproduct of the treatment process. The natural systems may be especially effective and practically feasible in rural areas where homes can be clustered together (for example, one system can serve a number of structures with more than one and up to hundreds of connections).

Using natural processes to treat wastewater provides added benefits. These systems can be designed to be aesthetically appealing and can be incorporated into the landscape or a greenhouse. Similar to a fertilizer, the high nutrient content of the wastewater supports a dense plant growth. It is best to use native plants that will either persist throughout the winter or regrow or reseed in the spring. However, it is possible to use multipurpose plant species, including ornamentals; these can provide a pleasing aesthetic and bring a wildlife benefit (e.g., bird habitats) that conventional systems rarely provide.

Deciding which type of system to use (traditional or one that employs a constructed wetland component) is based on environmental and regulatory requirements as well as physical constraints of the site.

Principles of Small-Scale Natural Wastewater Treatment Systems

System Design of Small-Scale Natural Wastewater Treatment Systems

Small-scale natural systems are designed on ecological principles. The goal is to maximize the function of relevant ecological processes within a limited area. The hydraulic residence time (i.e., the amount of time the wastewater remains in the system) is a key design factor. It is affected by (1) the size of the components in the system, (2) the concentration of contaminants entering the system and the level of treatment required, and (3) the flow of wastewater through the system. There are typically two and sometimes three stages of treatment: pretreatment, biological polishing, and, in some cases, effluent disinfection. Water quality testing should be incorporated before and after each stage to ensure optimal performance and compliance.

The **pretreatment stage** involves breaking down of organic matter and settling of solids. Water quality testing done during the pretreatment stage measures the 5-day Biological Oxygen Demand (BOD_5) and total suspended solids (TSS). (The 5-day Biological Oxygen Demand test is fairly easy to conduct and measures the rate of oxygen uptake by microorganisms in water over a period of five days.)

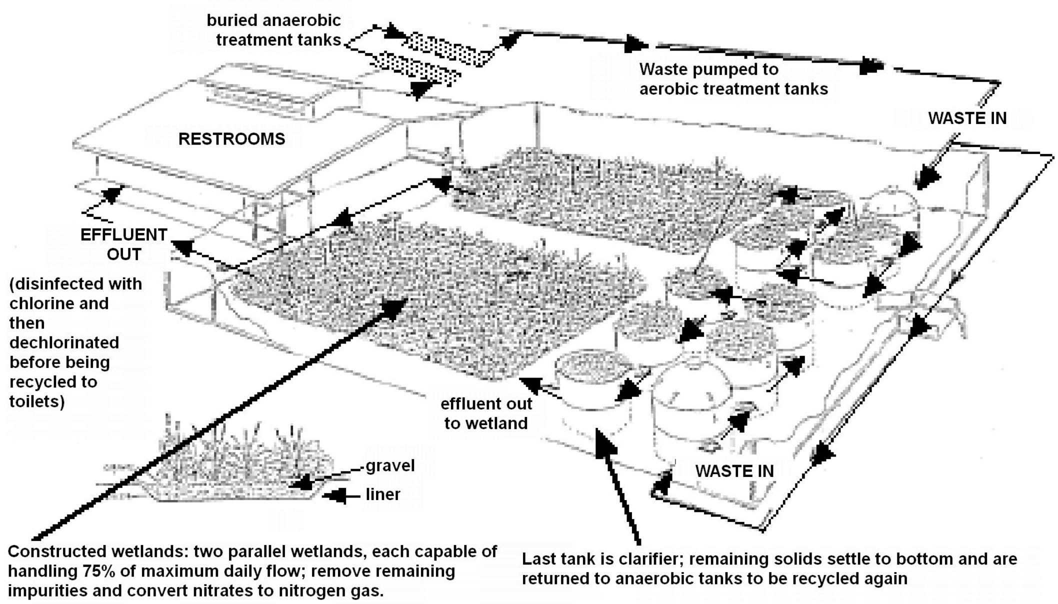

Figure 1. Schematic of constructed wetland at Corkscrew Swamp Sanctuary.
Credits: Living Machine®

Pretreatment helps to reduce organic matter and suspended solids. This can be achieved either through anaerobic (no oxygen) digestion using a traditional septic tank or aerobic (with oxygen) digestion using an aerobic treatment unit. Anaerobic digestion (in the septic tanks) is the most common pretreatment method for small onsite wastewater treatment systems and requires the least amount of energy. The detention time in a septic tank must be long enough to allow for microorganisms in the absence of oxygen to break down the organic matter and settle to the bottom. Detention time, similar to hydraulic residence time, is the time required for a small amount of water to pass through a tank at a given flow rate. Therefore, the size of the tank has the largest effect on detention time for a given flow rate (i.e., longer detention times require larger tanks).

Anaerobic digestion happens at a slower pace than aerobic digestion because it is done by different organisms. However, if the system is designed correctly, anaerobic digestion alone has been shown to reduce BOD_5 by 30% and TSS by 50%. Aerobic digestion, however, is better at removing organics and suspended solids and with shorter detention times (and, therefore, using smaller tanks). Untreated municipal wastewater has a BOD_5 of approximately 300–600 mg/L, and a TSS of approximately 200 mg/L. BOD_5 and TSS measurement for wastewater flowing out of an aerobic treatment system is usually between 10–30 mg/L. However, this improved treatment comes at an increased cost of infrastructure, energy, and maintenance. The clarified wastewater (meaning it is reduced of organics and suspended solids) will exit the pretreatment stage and flow to the **biological polishing stage**.

The **biological polishing stage** consists of a vegetated compartment for the pretreated wastewater to pass through. This stage is the constructed "natural" process treatment portion of the treatment. This stage's primary function is to remove nutrients from the wastewater, although it also reduces many other contaminants (pathogens, suspended solids, heavy metals, and trace organic chemicals). Water quality testing done for this stage should measure the BOD_5 and TSS, as well as nutrients of concern such as nitrogen and phosphorous. It is important to measure not only total nitrogen and total phosphorous but also the various forms of each nutrient, such as organic nitrogen (e.g., urea), ammonium nitrogen (including the un-ionized form), nitrate/nitrite, and orthophosphate. The only way to reduce total nitrogen levels in the wastewater is to remove one or more of the nitrogen forms that make up total nitrogen, as seen in the equation below:

Total Nitrogen = Organic Nitrogen + Ammonium Nitrogen + Nitrate/Nitrite

Although ammonium nitrogen is the most preferred form of nitrogen for plant uptake, the un-ionized form of ammonia is toxic to aquatic life even in low concentrations (Kadlec and Knight 1996). Because of the pretreatment stage, levels of both organic nitrogen and ammonium nitrogen (including the un-ionized form) should be reduced, having been converted to nitrate/nitrite. However, ammonium nitrogen levels will be higher coming from a septic tank versus an aerobic treatment unit since the conversion process happens much slower under low oxygen conditions.

Nitrate/nitrite is an important parameter to measure because nitrate/nitrite is dangerous to humans and the environment. The release of nitrate/nitrite to the surface and groundwater (1) can cause excess algae growth in surface water and (2) is toxic to infants, causing "blue baby" syndrome if ingested. The current federal regulation for nitrate in groundwater and drinking water is no more than 10 mg/L.

One benefit of natural wetland treatment systems is that they are excellent at either taking up nitrate/nitrite in the plants or changing it to gaseous forms of nitrogen (our air is predominantly nitrogen gas). The reduction of nitrates in effluent is what usually drives the desire to use a natural treatment system in the first place. The process of converting nitrate/nitrite to nitrogen gas (the denitrification process) takes place in small pockets in the vegetated compartment, usually in the soils or around the base of the roots, where oxygen is absent. For this reason, oxygen should never be introduced into the biological polishing stage of the natural treatment system. Wetland plants are well adapted to low levels of oxygen that happen as a result of soggy or flooded soils.

Phosphorus removal is a difficult task using any treatment technology, including natural treatment systems (Kadlec and Knight 1996). Orthophosphorus is the inorganic form of phosphorus used by plants and converted to the organically-bound form. Conventional systems typically require a chemical or polymer addition to remove (bind up) orthophosphorus from wastewater, which creates a lot of sludge (solid waste). Removal of orthophosphorus in a natural wetland system is limited by how much the soil can take up and the small amount that the plants and other living organisms in the wetland ecosystem use for growth. The more total phosphorus needed to be removed from the wastewater (to achieve low effluent limitations, for example), the larger the vegetative component will need to be.

Other parameters that can help gauge the health of the system are pH, water temperature, and dissolved oxygen levels. Water quality testing is typically done for the last point of outflow from the system. Check local regulations for current water quality standards.

Environmental factors that affect treatment performance must be considered when designing the "natural" portion of natural systems. These systems operate best when there are no sudden changes to operating variables such as temperature, pH, flow, organic loading, etc. Some of these variables change depending on whether the system is placed indoors or outdoors. As a result, this component of the system is the most "customizable" feature, accommodating the characteristics of the site and the wastewater. The features of the chosen site and effluent criteria will determine the size, shape, substrate (surface or material where the plants grow or are attached), plant species, and detention time. A ballpark range of retail costs for constructing a vegetated component of the treatment process can be anywhere from $6 to $21 for every gallon per day treated, depending on site-specific considerations.

After treatment by a properly designed natural system consisting of a pretreatment and biological polishing stage, the effluent will be of very high quality. An **effluent disinfection stage**, however, may also be required by local regulations. Depending on how the effluent will be reused or where the treated effluent will be discharged into the environment, there may be additional treatment required for disinfection. Standard methods for disinfection (see state, county, and city regulations) include the use of ultraviolet light or a chlorination-dechlorination process.

Operation and Maintenance of Small-Scale Natural Wastewater Treatment Systems

The biological polishing stage (or the "natural" portion of the natural systems) is relatively maintenance-free when compared to other wastewater treatment systems that achieve high effluent standards. The septic tank or anaerobic component will need to be pumped every three to five years, depending on particulate load in the wastewater. If the raw wastewater contains lots of grease (such as from a restaurant), a grease interceptor before the septic tank should be installed to reduce the pump-out frequency as well as the risk of grease and scum getting into the constructed wetland component. If an aerobic treatment unit is used, then the aeration blowers and pumps will need to be inspected and maintained regularly. Any outlet filters that are used on the effluent coming from either a septic tank or aerobic treatment unit will also need to be changed regularly (monthly to once every three years). Effluent filter alarms are recommended to alert the system operator or homeowner(s) in the unfortunate event of sewage backing up into the home(s) or business when the effluent filter is clogged. Also, homeowners and employees occupying the structures serviced by these systems need to be educated on the materials that cannot be introduced into the system. Certain chemicals (e.g., large quantities of harsh cleaners, fuels, oil-based paints, pesticides, solvents, kerosene, and other flammables), as well as dry cleaning chemicals, should not be flushed down the toilets or washed down the drains.

Vegetation is a critical component of the natural system, and successful performance depends on a relatively dense stand of healthy plants. Disease and insect infestation can cause problems, but this has not been experienced to date at operational constructed wetlands in the United States. Very high concentrations of nutrients in the wastes can overwhelm the oxygen transfer capability of the plants. Affected plants may decline and die, which is why a properly functioning pretreatment stage is needed. This has occurred in only a few systems around the inlet end of the wetland cell when un-stabilized deposits of sludge were allowed to accumulate. Routine harvest of the vegetation is not necessary for constructed wetland systems. However, removing accumulated plant debris may be desirable on an infrequent basis to avoid restriction of flow in the system. Also, replanting the system is usually not necessary, especially if particular care was used in plant selection as described earlier. However, for aesthetic purposes, attractive seasonal species of flowers and ornamentals can be replanted as desired.

Depending on how the natural portion of the treatment system is designed, burrowing rodents and other critters could pose a threat to the integrity of the system, and it will require regular inspections. Rodent control can be achieved by periodically changing the water levels to flood their habitats. Another special requirement may be mosquito control, even though mosquito habitat is stagnant water. A properly designed system should allow for continuous water flow and prevent the formation of a mosquito habitat.

Regulatory Framework for Small-Scale Natural Wastewater Treatment Systems

National Regulation

In accordance with United States Environmental Protection Agency regulation (40 CFR Part 122.2), when a natural system referred to as a "constructed wetland" is designed, built, and operated for the purpose of wastewater treatment, they are not considered waters of the U.S. Therefore, they are not subject to meeting the water quality standards of the Clean Water Act within the constructed wetland boundaries and are only subject to state regulations. Each state, however, regulates constructed wetlands created for wastewater treatment differently.

State Regulation

In Florida, state regulation of municipal wastewater is split between two agencies, the Department of Health (DOH) and the Department of Environmental Protection (DEP). Whether a natural system is regulated under the DOH or the DEP depends on the estimated amount of wastewater flow and the type of wastewater treatment proposed.

The DOH typically regulates natural systems or "constructed wetland treatment systems" as described in this publication. In accordance with 381.0065 of the Florida Statutes (F.S.), DOH has jurisdiction over municipal flows of 10,000 gallons per day or less (5,000 gallons per day or less for commercial-type wastewater such as from a restaurant) provided that the treatment system is composed of closed tanks, is buried underground, and uses a subsurface treatment and disposal mechanism such as a subsurface flow wetland (wetland is covered with a mulch layer to the necessary depth) and drainfield. Because of these statutory requirements, proposing a constructed wetland treatment system presents distinct permitting hurdles through the DOH.

To receive a permit for a constructed wetland from DOH, an applicant needs to contact the appropriate local office (i.e., county health department) for the necessary forms and associated fees. Contact information for each county health department can be found at http://www.doh.state.fl.us/chdsitelist.htm. Because the system will most likely fall under DOH's Innovative System rule (found in 64E-6.026 of the Florida Administrative Code, F.A.C.), contact DOH's Bureau of Onsite Sewage Programs, located in the State Health Office in Tallahassee, for useful information on design and permitting assistance. For more information on DOH permitting, including rules and forms, go to http://www.doh.state.fl.us/environment/ostds/index.html.

If the constructed wetland treatment system falls outside the jurisdiction of DOH because it is either over 10,000 gallons per day (or 5,000 gallons per day for commercial) or the design does not meet DOH's Innovative System requirements, a DEP wastewater permit is required in accordance with Chapter 403, F.S. To apply for a DEP wastewater permit, individuals must submit the Wastewater Permit Application Form 2A for Domestic Wastewater Facilities (62-620.910(2), F.A.C.) to one of the six regional districts offices (or branch office, where appropriate) or one of DEP's delegated local programs.

Chapter 403.182, F.S., authorizes DEP to delegate its permitting authority to issue state wastewater permits, under Chapter 403, F.S., to local environmental programs. As of this article's date of publication, DEP's local delegated programs are as follows: Palm Beach County Health Department, Broward County Environmental Protection Department, Miami-Dade County Department of Environmental Resources Management, Hillsborough County Environmental Protection Commission, and Sarasota County Natural Resources.

For DEP district contact information, go to http://www.dep.state.fl.us/secretary/dist/default.htm.

Most natural systems will not discharge to surface waters, but if the system does, it requires a federal or federally-delegated National Pollutant Discharge Elimination System (NPDES) permit. Constructed wetlands that do not discharge to surface waters are permitted by DEP in accordance with all applicable criteria found in Chapters 62-600 and 62-620, F.A.C. These criteria include but are not limited to meeting at least the secondary effluent treatment standards (20 mg/L for both $CBOD_5$ and TSS), basic level disinfection (200 fecal coliform per 100 mL), minimum levels of operator staffing and effluent monitoring, as well as providing reasonable assurance that standards will be met with proven treatment technology.

If the constructed wetland system has the potential to impact groundwater, then the groundwater permitting requirements of Chapter 62-522, F.A.C., must be implemented, including groundwater monitoring and a mounding analysis. A mounding analysis is used to determine if the capacity of soils beneath the discharge site is capable of distributing the effluent without causing hydraulic failure. This typically requires the collection of appropriate site-specific hydraulic data and the application of an appropriate modeling technique. A constructed wetland that percolates to groundwater will be held to meeting acceptable groundwater quality standards. Because of these criteria, permitting a constructed wetland treatment system of any scale for municipal wastewater through DEP presents multiple challenges.

Other states, such as Ohio and Tennessee, have embraced regulations for small-scale natural systems. Beginning in the mid-1980s, the Tennessee Valley Authority began research on constructed wetlands for treatment of wastewater (US EPA 1993). They have since outlined criteria for subsurface flow wetlands designed for wastewater treatment, including for small flows. In 2007, the Ohio EPA issued guidelines on design standards and maintenance issues to be addressed for subsurface flow constructed wetland systems that treat up to 10,000 gallons per day of domestic wastewater and whose overflow structures only discharge to the soil (Ohio EPA 2007). These guidelines, however, may not be applicable to larger systems or those that discharge to surface waters, which need to meet other criteria, such as lower effluent limits. The Tennessee regulations and Ohio guidelines are both good points of reference for designing a small-scale natural treatment system, even if it won't be located in either of those states.

County or City Regulation

While DOH and DEP (and its delegated local authorities) are the only agencies with jurisdiction over state wastewater regulations, Florida's counties and cities may also have adopted local regulations, in accordance with 403.182, F.S., that are more stringent than state requirements. This is the case for Miami-Dade and Broward Counties and could be the case for other local governments in Florida. As stated above, the county health departments, while located in each county, are in fact part of the state Department of Health and not county government. Furthermore, DEP has delegated the authority to issue state wastewater permits under Chapter 403, F.S., to one such county health department — Palm Beach County. In other states, regulation over small-scale natural systems may only reside at the county level.

Successful Case Studies of Using Natural Wastewater Treatment Systems

Case Study 1: Corkscrew Swamp Sanctuary

Located in Naples, Florida, Corkscrew Swamp Sanctuary operates a 7,500 gallons per day (gpd) maximum monthly average daily flow system under the provisions of Chapter 403, F.S., and applicable rules of the F.A.C. To operate the "natural" process domestic wastewater treatment plant and associated reuse disposal system, an engineer must complete and file a full report with the DEP, South District every five years. The Corkscrew system includes two 10,000 gallon septic tanks (anaerobic pretreatment septic tanks), two parallel series of five circular aerated tanks (27,600 gallons of aeration volume), dual blowers, two clarifiers, two living filters, a chlorine contact chamber, a dechlorination chamber, and an effluent sump with dual pumps that pump reclaimed water to reused water storage or to the drainfield disposal.

The system is placed outdoors in a screened room, and the reused water in this system is used to flush toilets at Corkscrew Swamp Sanctuary. An outside water quality testing consulting firm conducts monthly testing to ensure standards are maintained. Staff members at the Corkscrew Swamp Sanctuary receive on-site training to learn about the system. Also, educational tours are provided for visitors on a regular basis. For more information about this system, go to http://www.corkscrewsanctuary.org/Information/LivingMachine.html.

Case Study 2: Oberlin Living Machine®

Oberlin College, located in Oberlin, Ohio, installed a small-scale constructed wetland based on sustainability standards in the Adam Joseph Lewis Center for Environmental Studies. The system is in a greenhouse within the Center. A series of community workshops helped to establish the specific design and purpose of the building and the constructed wetland. The Living Machine® (or constructed wetland) serves as a research and education tool for Oberlin students and meets the same regulatory standards as conventional treatment systems at the Oberlin campus. Design parameters include a flow rate of 2,470 gpd. Components include one anaerobic tank, one closed aerobic tank, three open aerobic tanks, a clarifier, a gravel tank (or marsh), an effluent tank, a UV filter, and a pressurized storage tank (for immediate reuse in the toilets and landscape). Research projects are conducted regularly to analyze the biological processes in the system. A team of students operates, maintains, and monitors the system, and educational tours are provided regularly.

For more information about this system, go to http://www.oberlin.edu/ajlc/.

Case Study 3: The Fields of St. Croix

The Fields of St. Croix is an award-winning residential community located in Lake Elmo, Minnesota. It is the first development in Minnesota to use wetland treatment in a clustered septic system, which is designed to treat a total of 45,100 gallons per day. Using the wetland cluster treatment system helps preserve open space while protecting the rural character of the community (not allowing high-density development that tends to come with a regional treatment system). The Fields of St. Croix community wetland cluster treatment system was designed and built in two phases, which resulted in two separate systems. The two systems both employ septic tanks for pretreatment (solids settling and filtration) of the wastewater. The first phase was completed in 1997 for roughly $340,000 in today's dollars, and it serves 48 homes (design flow based on 50 gallons per day per capita), conserving around 1.5 acres where the system is used. The system uses two lined and gravel-filled subsurface flow constructed wetlands (9,000 square feet each) for wastewater treatment followed by two unlined wetland infiltration beds (also 9,000 square feet each and gravel-filled) for effluent dispersal. The detention time in the constructed wetlands component is 5–6 days.

The second phase became operational in 2000 for a total cost of $670,000 in today's dollars and serves 88 homes (design flow based on 100 gallons per day per bedroom). The second treatment system uses two vertical flow recirculating (targeted for five to seven times recirculation) gravel-filled wetland cells of 5,100 square feet each with Forced Bed Aeration™ followed by a 51,700 square foot infiltrator chamber drainfield for effluent dispersal. The Minnesota Pollution Control Agency regulates both systems, after the residential community spent months working with the state and local officials in the Pollution Control Agency as well as the local county Environmental Services Department. Even today, the Fields of St. Croix is regarded as one of the most innovative approaches to residential development in Minnesota. This is due in part to its use of the relatively small-scale constructed wetland treatment systems.

For more information about this system, go to http://www.engstromco.com/prev_fields.

Summary

1. Natural wastewater treatment systems are living systems that through ecologically engineered design promote a range of natural processes that treat wastewater.

2. These systems use some of the conventional treatment system technology (i.e., the septic tank), yet are less expensive than conventional treatment systems.

3. Natural systems can be designed to be aesthetically pleasing and fit into a landscape or a greenhouse setting.

4. In Florida (and possibly other states such as Minnesota), there are permitting hurdles for natural systems. These hurdles can be overcome with the proper coordination and planning.

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