USE OF CONSTRUCTED WETLANDS FOR WASTEWATER TREATMENT AND WATER RECYCLING—APPLICATION TO SAUDI ARABIAN CONDITIONS

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ABSTRACT

Constructed wetlands are in common use in many parts of the world and provide a relatively economical and efficient polishing step and an important additional barrier to contaminants in municipal wastewater. Their ability to remove various classes of contaminants, especially wastewater-derived organic compounds are well-documented and can be maximized using appropriate design criteria and experience from ongoing treatment systems. The role of constructed wetlands as environmental barrier and as a psychological separation is especially important for indirect potable reuse, when combined with other appropriate barriers. In addition to wastewater treatment, wetlands provide additional benefits, including environmental enhancement, habitat for plants and animals and passive recreational opportunities for the community. Constructed wetlands are well suited to the environmental conditions in Saudi Arabia and the surrounding region.

KEYWORDS: Wetlands, Constructed Wetlands, Biological Treatment, Water Reuse

1. INTRODUCTION

Constructed wetlands are essentially inspired by natural processes in naturally occurring wetlands. Natural wetlands—marshes, swamps, bogs, everglades—are highly productive ecosystems storing large volumes of water, recirculating nutrients, providing habitats that support a diverse population of plants and animals, and removing pollutants from the water. Wetlands, under natural conditions, are capable of providing significant pollutant removal from influent streams of impaired waters—including stormwater, municipal and industrial wastewater, landfill leachates, and urban runoff. Treatment in wetlands occurs as a result of settling of suspended particles, oxidation of organic matter, metabolic activity by indigenous microorganisms, photolysis, and uptake of nutrients by plants growing within the wetlands. As long as the wetland is not overloaded, dried out, or subjected to extended cold periods, effluent quality can be expected to be suitable for most non-potable uses.

Natural wetlands have long been used for discharge of treated wastewater effluents—primarily as a disposal measure, but also as a means of reducing nitrogen and phosphorus concentrations in the effluent. However, intentional and planned use of constructed wetlands for wastewater treatment is relatively new. Use of wetlands is common in some parts of the United States, as shown in Table 1, in which some of the characteristics of several representative constructed wetlands are summarized.

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Table1. Representative Constructed Wetlands in the United States and Their Main Characteristics

Site Name and Location	Wet Area (hectare)	Source of Wastewater	Wildlife Habitat	Human Use
Arcata, California	15.2	Municipal	X	X
Beltway 8 (Harris County), Texas	89.0	Stormwater	X	X
Des Plaines, Illinois	10.1	Other	X	X
DuPont (Victoria), Texas	21.4	Industrial	X	X
Hayward, California	58.7	Municipal	X	X
Hemet/San Jacinto, California	14.2	Municipal	X	--
Hillsboro, Oregon	35.7	Municipal	X	X
Incline Village, Nevada	173.3	Municipal	X	X
Industrialian River County, Florida	75.3	Municipal	X	X
Iron Bridge (Orlando), Florida	494.0	Municipal	X	X
Mt.View Sanitary District, California	37.0	Municipal	X	X
Olentangy (Columbus), Ohio	2.0	Other	X	X
Phinizy Swamp (Augusta), Georgia	162.0	Municipal	X	X
Pinetop/Lakeside, Arizona	51.0	Municipal	X	X
Santa Rosa, California	4.1	Municipal	X	--
Show Low, Arizona	54.2	Municipal	X	X
Sweetwater (Tucson), Arizona	7.0	Municipal	X	X
Tres Rios, Arizona	4.2	Municipal	X	X
Wakodahatchee (Palm Beach County), Florida	21.0	Municipal	X	X

SOURCE: WateReuse Foundation, 2011, with permission.

Much has been learned from disposal practices in natural wetlands and used in the design and operation of constructed wetlands, primarily for polishing treated wastewaters. Constructed wetlands are credited with significant savings in wastewater treatment costs—both in construction and life-cycle operational costs—especially in smaller communities. They are designed specifically to maximize treatment capability within the available land area and for the flows anticipated to be treated. In some of the earlier designs of constructed wetlands, little attention was paid to performance criteria and limitations of natural processes under different loading conditions, with predictable negative consequences. Today, constructed wetlands are designed with much greater attention to detail, pre-treatment, provision for flow variations, and strict effluent quality control. With improved analytical methods now capable of detecting microconstituents at parts per billion and parts per trillion levels, the pollutant removal capability of treatment systems are more critically considered when deciding among alternative processes.

2. MATERIALS AND METHODS

The most critical component of constructed wetlands is land. Because of the relatively large surface area necessary for a given flow, use of constructed wetlands is generally limited to smaller communities, usually down to single-family or single-building settings. The land is shaped into basins, commonly (but not always) lined with impermeable membranes and sloped to provide a gentle flow from the inlet to the outlet of the treatment system. A gravel lining is built above the liner and it can vary in thickness from a minimal root zone to varying depths that might extend to above the water line.

In extremely hot and dry climates, a gravel or sand bed can help minimize evaporative loss of water. A mix of aquatic plant materials (cattails, bulrushes, reeds, etc.) growing either hydroponically or in a gravel substratum provide the media through which polluted water is filtered and biologically treated. A simplified schematic view of the constructed wetland treatment system is shown in Figure 1.

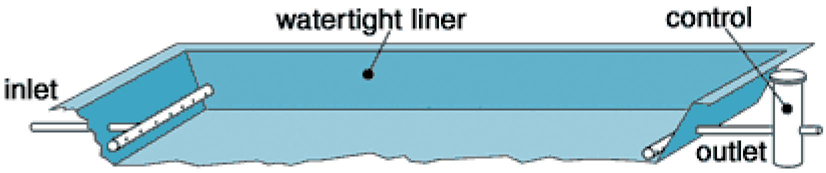

Figure 1. Schematic drawing of constructed wetland with optional impermeable liner

Small-scale constructed wetlands are typically intended for additional treatment or polishing of primary or secondary effluent from a mechanical system—such as Imhoff or septic tanks—receiving raw domestic wastewater. Effluent from the wetland is then discharged to surface waters, disposed of in a leach field, or reused for irrigation of crops and/or landscaping.

Large-scale constructed wetlands serve to polish effluent from municipal sewerage systems or to remove pollutants from urban runoff. Wadi Hanifa constructed wetlands (Figure 2) is an excellent example of such engineered biological treatment systems, achieving a high degree of nutrient removal from the flows in the Wadi.

Figure 2. Wadi Hanifa constructed wetlands, pictured in 2009

Flows into Wadi Hanifa are heavily influenced by wastewater disposal from individual wastewater treatment systems upstream in northern parts of the City of Riyadh. Thus, they carry high concentrations of biochemical oxygen demand (BOD), suspended solids, nitrogen and phosphorus that the wetlands can remove effectively. In addition, the Wadi Hanifa constructed wetlands provide an aesthetic resource to the people of Riyadh and visitors using the surrounding areas.

2.1 Types of Constructed Wetlands

Two main types of constructed wetlands are in common use: (1) free surface flow (FSF) and (2) subsurface flow (SSF), as depicted in Figure 3.

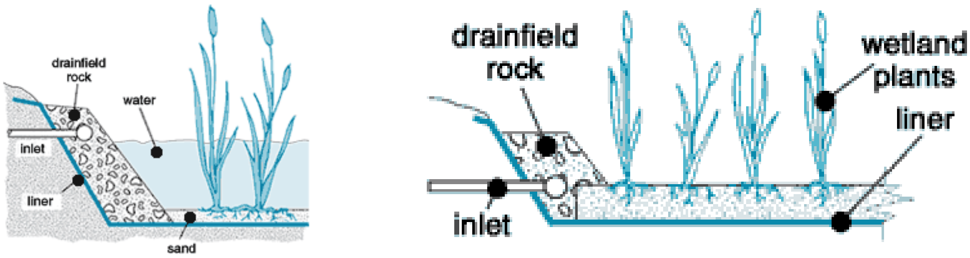

Figure 3 Two Types of Constructed Wetlands: Free Surface Flow (FSF), on the left and Subsurface Flow (SSF), on the right side of the figure

In the FSF type of wetland, the impoundment is constructed with an impermeable bottom and sides and the inlet allows polluted water into the pond, diffused from several points through a gravel embankment. This type of constructed wetland closely mimics natural wetlands in terms of vegetation and water flow regime. Vegetation covers most of the water surface, but some areas are left bare to maximize photolytic processes and to provide habitat for birds and access to recreational users of the wetland. Wastewater flows over the soil and through the thicket of vegetation rooted in the soil. Pollutant removal is achieved with sedimentation, filtration, oxidation, reduction, adsorption, and precipitation. Pollutant concentration decreases linearly or exponentially along the length of the flow path. Constructed FSF wetlands are adapted well for temperate and warm regions—such as in Saudi Arabia.

In the SSF type of constructed wetland, water flows below ground, or subsurface, through gravel or other media. These systems can be designed for horizontal or vertical flow through the media. In vertical-flow systems, underdrains are installed below the rooting media for collection of the effluent. Microbial populations adapted to the anaerobic environment provide for anoxic decomposition. Because of the larger surface area of exposure in SSF systems, greater densities of bacteria can work on some of the pollutants, such as BOD and organic compounds, resulting in a smaller footprint than the comparable FSF system. However, the effectiveness of the two systems is similar in removal of nitrogen, phosphorus, suspended solids, and trace metals. Flow through the SSF wetlands is slower than in the FSF wetlands because of the friction encountered in flowing through the media (sand, soil, gravel) and root systems of the aquatic plant. The additional removal benefit provided by the roots within the media is rather limited. Impermeable lining of the wetlands is necessary if it is desired to maximize the volume of treated effluent (TSE) for reuse. The SFF wetlands are better suited to cold climates and where

Vertical SSF wetlands provide the opportunity for both aerobic and anaerobic treatment by intermittent draining and filling of the media. During the drainage phase, air becomes entrapped within the porous media, creating many small pockets, which will stay aerobic after refilling of the wetland until the next cycle of drainage.

Small-scale, compact, constructed wetlands are now marketed by several manufacturers for use within commercial buildings especially for reuse of treated wastewater or graywater for landscaping. One example is the so-called "Living Machine", marketed by Worrell Water Technologies (Worrell, 2011) and represented in cross-sectional view in Figure 4.

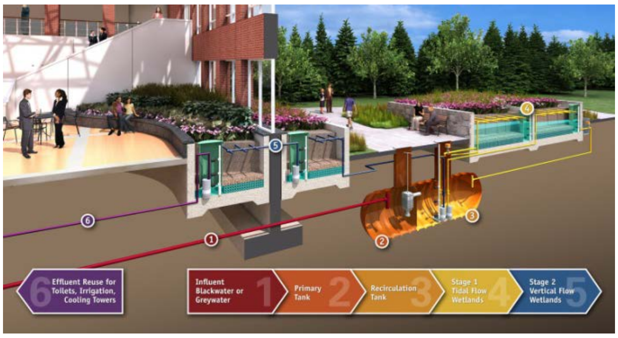

Figure 4. Worrell's Living Machine—Constructed Wetlands in An Upscale Office Building

3. RESULTS AND DISCUSSION

3.1 Degradation of Organic Matter

Decomposition of organic matter in the wastewater occurs as a result of different metabolic activities depending on type and operational mode of the constructed wetland, as shown in Table 2.

Table 2. Metabolic mode of decomposition of organic matter in constructed wetlands

Type of Wetland→ Mode of Operation↓	Free Surface Flow (FSF)	Subsurface Flow (SSF)
Without Aeration	Anaerobic	--
With Aeration (air diffusion or fountain)	Aerobic	--
Constant Flow	--	Anaerobic
Intermittent Flooding	--	Aerobic/Anaerobic

In aerobic decomposition, aerobic heterotrophic microbes convert soluble organic matter to carbon dioxide and water. In anaerobic decomposition, facultative or obligate anaerobic heterotrophs produce methane and water, after several biotransformation steps.

3.2 Suspended solids removal

Mechanisms responsible for removal of suspended solids include aggregation, sedimentation, and interception. The slow movement of water and the dense concentration of vegetative matter facilitate these processes in the FSF wetlands. In the SSF wetlands, it is the result of high surface contact area of the media through which water flows. Still, the smallest particles, including microorganisms, algal cells and colloids are not completely removed in a typical wetland, although their concentration is usually much reduced.

3.3 Nitrogen Cycling in Wetlands

Depending on the redox status of the wetland, several different forms of nitrogen can exist simultaneously at different and varying concentrations over time, including organic nitrogen, ammonia, nitrite, nitrate, and nitrogen gas. Nitrogen arriving at the wetland from municipal wastewater effluent is in two main forms, organic N and ammonia. Removal through the wetland involves a series of complex transformations including mineralization, nitrification, and denitrification. Some of the ammonia escapes as gas into the atmosphere.

In the first step, organic matter is converted to ammonia either aerobically or anaerobically. In the second step, ammonia undergoes progressive oxidation under aerobic conditions and changes into nitrite first, and nitrate later. Finally, in the denitrification process, nitrate is changed to nitrogen gas, which escapes to the atmosphere. Denitrification occurs only under anaerobic conditions through combination with organic matter in the wetland, requiring at least a 1:1 mass ratio of available carbon to nitrogen. Under nearly all conditions, there is adequate organic carbon available for this process in the wetland—except where wastewater is overloaded into the wetland. As water temperature rises, the rate of nitrogen transformation increases.

3.4 Phosphorus Cycling in the Wetlands

Phosphate is adsorbed onto the exchange sites of the wetland sediments. These sites are soon saturated and this mechanism is not available for sustained removal over the long term. Phosphate accumulation into the bottom sediments is the long-term mechanism for removal. Plants take up some of the phosphorus and return it to the bottom sediments as they die.

3.5 Pathogen Removal and Deactivation

Microbial pathogens (viruses, bactreia, protozoa, helminthes) in municipal wastewater are removed in wetlands through sorption on organic matter, predation by indigenous microorganisms, filtration, photo-deactivation by ultraviolet light, sedimentation, oxidation, and exposure to plant-produced biocides. The wetland environment is hostile to non-indigenous microorganisms. Human pathogens are generally unadapted to the temperatures in wetlands. They are readily used as food by the better-adapted wetland organisms and are easily trapped through sedimentation in the media through which water flows slowly. On the other hand, pathogens excreted by wetland animal (birds and mammals) contribute to high levels of fecal coliform counts of 50 to 2,000 colonies per 100 mL.

3.6 Metals in the wetlands

Metals are accumulated in the sediments and removed from the water column. But, they remain within the wetland and stored therein indefinitely. While some metals are adsorned on the sediment exchange sites, this process is not sustained. Plant uptake of metals can remove some of the metals if the plant material is harvested and removed from the wetland. Usually, when the plant material decomposes, the uptaken metals return to the wetland sediments.

3.7 Removal of Trace Organic Compounds

Many classes of hydrocarbons are removed, to varying extents, in wetlands. These include fuels, oils, aliphatic and aromatic hydrocarbons, halogenated hydrocarbons, oxygenated hydrocarbons, volatile organic compounds, herbicides, and insecticides. The dominant removal mechanisms include volatilization, photochemical oxidation, sedimentation, sorption, and biological degradation.

3.8 Removal of Wastewater-Derived Organic Compounds (WDOCs)

The ability of analytical laboratories reliably to detect and quantify microconstituents at extremely low concentrations has improved rapidly in recent years. While these compounds (pharmaceuticals, personal care products, fire retardants, herbicides, insecticides, plasticizers, etc.) have been present in waters tainted with waste for as long as these compounds have been in use, only in recent years have their presence become a subject of media attention and public concern. While any one or more of these compounds may be detected at such low levels in potable water, the precise human health impact of their presence is not as well established. Regulatory agencies are not likely to set limits for most of the over 40,000 chemicals currently manufactured and often detected at very low concentrations—assuming that their health impacts will be determined to be benign.

At higher concentrations, some of these compounds are known to have deleterious impacts on aquatic organisms. The most reported and often cited effect is feminization of male fish in surface water that receive significant amounts of wastewater effluent (Desbrow et al., 1998; Huang and Sedlak, 2001; Routledge et al., 1998). Even at trace concentrations, WDOCs may cause adverse effects on aquatic organisms. Many species of fish can detect and be guided by steroid hormones to identify fertile mates and to time reproductive activities. Natural hormones, such as testosterone, and manufactured hormones, such as medroxyprogestrone, are present in wastewater effluents at or above concentrations that elicit pheromonal responses in fish (Kolodziej et al., 2003). In addition, compounds, including the beta-blocker propranolol (Huggett et al., 2002) and the antibiotic triclosan (Reiss et al., 2002) may be present at concentrations near or above levels at which adverse impacts have been reported.

Knowledge about human health effects of WDOCs lags far behind knowledge about their environmental impacts. Fortunately, most WDOCs are effectively removed during drinking water treatment and the compounds that have been detected are usually at concentrations well below levels at which they might pose a health effect. Nonetheless, considerable research effort is underway to determine the health relevance of these compounds at prevailing concentrations in drinking water supplies. While human health is not the main reason for removing WDOCs, their removal is considered highly desirable as it helps take away the last hints of the water's partially wastewater origins.

Based on several recent research reports, removal rates observed and documented in constructed wetlands for a number of WDOCs are presented in Table 3.

Table 3. Removal of Wastewater-Derived Organic Compounds in Constructed Treatment Wetlands

Contaminant	Removal Percentage	Residence Time, days	Wetland Type
Alkylphenols	75±72	2.5	FSF
A+CAPnEC	8±48	2.5	FSF
Bromoacetic Acid	27	3.5	FSF
Caffeine	97	-	SSF (pilot)
Chloroform	80	3.5	FSF
Dichloroacetic Acid	87	3.5	FSF
17β-estradiol	36	3.5	FSF (pilot)
Ethinyl estradiol	44	3.5	FSF (pilot)
Galaxolide	52	-	SSF (pilot)
Gemfibrozil	58±103	2.5	FSF
Ibuprophen	47±37	2.5	FSF
Ibuprophen	87	-	SSF (pilot)
Naproxen	85	-	SSF (pilot)
Triclosan	68	4.3	FSF (pilot)

SOURCE: Adapted from WateReuse Research Foundation, 2011, with permission

Removal mechanism for WDOCs in constructed wetlands varies with the particular compound, and those for which data are available are listed in Table 4.

Table 4. Removal Mechanisms for WDOCs

Parameters	Physical	Chemical	Biological	Comments
Acetaminophen	NA	***Photolysis***	***Biotransformation***	Insufficient data to determine sorption effects
Atenolol	NA	Photolysis	***Biotransformation***	Insufficient data to determine sorption effects
Codeine	NA	***Photolysis; Sorption***	Biotransformation	
Diazepam	NA	Photolysis	Biotransformation	Insufficient data to determine sorption effects
Diltiazem	NA	***Photolysis***	Biotransformation	Insufficient data to determine sorption effects
Diphenhydramine	NA	Photolysis; ***adsorption***	***Biotransformation***	
Gemfibrozil	NA			Not available for microcosm study
Propranolol	NA			Not available for microcosm study
Estradiol (E2)	NA	Photolysis	***Biotransformation***	Insufficient data to determine sorption effects
Ethinyl Estradiol (EE2)	NA	Photolysis	***Biotransformation***	Insufficient data to determine sorption effects
Testosterone	NA		***Biotransformation***	Insufficient data to determine sorption effects
Progesterone	NA	***Photolysis***	***Biotransformation***	Insufficient data to determine sorption effects

Note. ***Significant removal*** mechanisms are italicized and bolded; NA = Not Applicable

SOURCE: Adapted from WateReuse Research Foundation, 2011, with permission

4. CONCLUSIONS

Constructed wetlands are a proven technology for removal of conventional pollutants in a variety of wastewaters and other impaired water streams. Thousands of wetland treatment systems have been constructed world-wide to reduce BOD, TSS, nitrogen, phosphorus, and trace metals. Best use of constructed wetlands is as the final step in an overall treatment train that includes primary and secondary pretreatment. Thus, constructed wetlands can provide the near-final step for producing an effluent that can meet advanced water treatment (AWT) standards.

Public use facilities are generally included in many of the large-scale constructed wetlands, such as at Wadi Hanifa, where passive recreational facilities and wildlife habitat are supported. Water produced at the discharge point is useful for a wide variety of non-potable applications

Design criteria for constructed wetlands are well-established for conventional parameters, based on geographical considerations and pollutant loading. Removal rates are predictable and reproducible across the world. Recent data have shown that constructed wetlands are capable of removing trace organic contaminants and wastewater-derived organic compounds. The extent and nature of removal of most microconstituents remains subject of future research. The long residence time in most constructed wetland systems is responsible for much of the removal of pharmaceuticals and steroid hormones. Other mechanisms for removal of various trace organics include biotransformation (for acetaminophen, atenolol, diphenhydramine, estradiol, ethinyl estradiol, testosterone, and progesterone) and photolysis (for acetaminophen, codeine, diltiazem, and progesterone).

Constructed wetlands are now playing an important role in indirect potable reuse where they are part of the overall system. This role is providing a robust barrier to microconstituents as well as an environmental buffer that serves as a psychological separation of the drinking water supply from the source water.

5. ACKNOWLEDGMENTS

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