CONSTRUCTED WETLANDS FOR WASTEWATER TREATMENT

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Summary

Efforts towards controlling water pollution focused mainly on expensive centralized collection and treatment systems for municipal wastewater. Conventionally, wastewater treatment is accomplished by physical, chemical and biological processes that are capital and energy-intensive. There is a critical global need for cost-effective, long-term

wastewater treatment technologies and approaches to deliver public health and environmental protection. Attempts in this direction always revolved around using only the natural components devoid of any mechanical requirements. Consequently, many natural systems that use the ability of plant species in uptaking or degrading pollutants from wastewater were developed. Among the natural systems, constructed treatment wetlands appear to be an appropriate alternative that can be employed both in developed and developing countries. Environmental engineers have made significant advances in the creation of constructed wetlands that can closely imitate the specialized treatment functions that occur in the natural wetland ecosystems, and have employed them in water pollution control and reuse.

1. Introduction

The World Health Organization (WHO) reports that more than 80% of the diseases affecting the human kind are water-borne. The pathogens causing these diseases often reach their water carrier due to discharge of fecal-polluted wastewater. Though the role of wastewater treatment in disease reduction is not always apparent, it can be said that discharge of wastewater into rivers and lakes with no or inadequate treatment can reduce the effectiveness of drinking water treatment systems downstream. They can also be a direct health hazard to those who come in physical contact with such waters. Groundwater can be contaminated due to disposal of inadequately treated wastewater. For these reasons, it is essential to properly treat and dispose of wastewater.

For the past 30 years or more, efforts towards controlling water pollution in industrialized countries have almost exclusively focused on implementation of expensive centralized collection and treatment programs of municipal wastewater. For example, currently less than 1% of all municipal wastewater is discharged untreated in the US. However, it has been estimated that over one-third of its surface waters do not fully support their designated uses. Due to the highly technical and mechanical nature of "concrete and steel" treatment facilities, the service life of such facilities is less than 25 to 30 years. And hence, most of the treatment facilities in these countries are already in need of overhaul or complete replacement and there is a burgeoning dilemma on how to address the funding needs for this cause.

Issues associated with wastewater treatment (or non-treatment) are different for developing countries as compared to the industrialized countries. In developing countries, where still an estimated 2 billion people do not have access to "adequate" sanitation facilities, the biggest cause of water pollution is disposal of untreated domestic wastewater and its most important effect is on human health. Rivers of Asia are among the most polluted in the world and contain ten times as many bacteria from human wastes as compared to the developed countries. It is clear that the course of action taken by the developed countries is not a viable alternative for developing nations. Due to the high cost of infrastructure investment, continual replacement and ongoing operation costs of conventional treatment plants, such technologies are beyond the financial grasp of most developing countries. Thus there is a critical global need for cost-effective, long-term wastewater treatment technologies and approaches to deliver public health and environmental protection.

2. Natural Systems for Wastewater Treatment

Conventionally, wastewater treatment is accomplished by physical, chemical and biological processes. Typically, these processes are supported by natural components such as microbial organisms, but in a complex array of energy-intensive mechanical equipment. Conventional treatment systems, therefore, contribute to i) depletion of nonrenewable fossil fuel sources, and ii) environmental degradation that occur due to extraction of nonrenewable resources, and also due to the by-products/final products of these technologies, such as biosolids and sludge. Therefore, attempts at developing a cost-effective treatment approach always revolved around using only the natural components devoid of any mechanical requirements that use up energy.

Using plants to purify wastewater has always fascinated researchers and holds intuitive appeal to the general public as well. Consequently, many natural systems that use the ability of plant species in uptaking or degrading the pollutants were developed.

The natural treatment systems are available under three major categories:

(i) aquatic or pond/ lagoon systems;
(ii) terrestrial or land application systems;
(iii) wetland systems.

The aquatic natural treatment systems involve impounding wastewater in ponds or lagoons for sufficient period so that pollutants and pathogens in wastewater are removed through natural biological degradation processes. Floating plant species such as algae, duckweed and water hyacinth may also be present in these systems to support the biological processes. Oxidation ponds, facultative lagoons and waste stabilization ponds are some of the examples for aquatic treatment systems.

Terrestrial or land application natural wastewater treatment systems involve utilizing unsaturated soil layer to provide either direct filtration and assimilation of pollutants or a rooting medium for plant growth that aid in filtration and uptake of pollutants from wastewater. On-site water filtration systems, low-rate and high-rate land application systems and overland flow systems are examples of terrestrial treatment systems.

Wetland treatment systems use either the natural wetlands or purpose-built wetlands (constructed wetlands) for treatment of wastewater.

3. Wetland Systems

Natural wetlands are the areas of transition between terrestrial and aquatic systems (Figure 1). These are land areas that are wet during part or all of the year because of their location in the landscape. Historically, wetlands were called swamps, sloughs, marshes, bogs or ecotones depending on the types of plants in these areas as also their geographic locations. There is no single definition that can correctly describe wetlands of all types and for all purposes. A widely acceptable definition of wetlands for scientific purposes was developed by the US Fish and Wildlife Service, which describes wetlands as the transition areas between terrestrial and aquatic systems where water is the dominant factor determining development of soils and associated biological communities. The definition specifies that wetlands need, at least periodically, to fulfil one or more of the following four requirements:

- Areas where, the water table is at or near the surface or the land is covered by shallow water.
- Areas supporting predominantly hydrophytes (water-tolerant plant species).
- Areas with predominantly undrained hydric soils. Hydric soils are those that are wet enough for long enough to produce anaerobic conditions that limit the types of plants that can grow on them.
- Areas with a non-soil substrate such as rock or gravel that are saturated or covered by shallow water at some time during the plant growing season of plants.

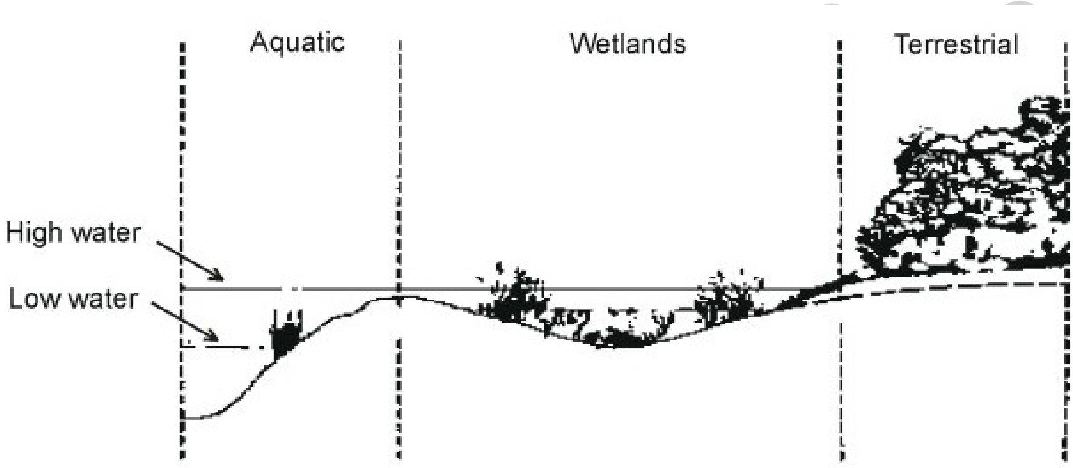

Figure 1. Wetland zone formation on landscapes

Wetlands that are dominated by water-tolerant woody plants are generally called *swamps*; those with soft-stemmed plant species as *marshes;* and those with mosses as *bogs*. Swamps and marshes can be of either salt water or freshwater type. Saltwater swamps are popularly known as *mangroves.*

Wetlands have a high rate of biological activity and hence a high rate of vegetative growth as well as zooplanktons. Wetlands along the shores of seas, lakes and riverbanks play a valuable role in their stabilisation and protection from erosive tides, waves, storms, floods and winds. They also function as groundwater recharge areas and sometimes as discharge areas where the water table touches the surface level. It is because of these attributes and also of aesthetic and wildlife values, environmentalists appeal for wetland preservation.

4. Constructed Wetlands

Wetlands have been "engineered" and "constructed" for one or more of the following reasons:

- **Constructed habitat wetlands**. These are the wetlands that are constructed to compensate for and help offset the rate of conversion of natural wetlands resulting from agriculture and urban development.
- **Constructed flood control wetlands.** These wetlands are constructed to act as a flood control facility.
- **Constructed aquaculture wetlands.** Wetlands that are constructed to be used for production of food and fiber.
- **Constructed treatment wetlands.** Wetlands that are constructed to act mainly as a wastewater treatment system and to improve water quality.

Though constructed wetlands are already being used in many parts of the world for various functions, it is their wastewater treatment capabilities that has attracted researches for a wide range of applications including treatment of domestic wastewater, industrial/agricultural flows, landfill leachates, etc. Constructed wetlands for other than treatment and water quality improvement functions will be described briefly, before detailing the constructed treatment wetlands.

4.4. Constructed Habitat Wetlands

Wetlands constructed primarily to develop a wildlife habitat are referred to as “constructed habitat wetlands.” Habitat wetlands are being constructed in all four major categories of wetlands, namely the salt marshes, saltwater swamps, freshwater marshes and freshwater swamps. Saltwater swamps and marshes are constructed close to estuarine waters so as to provide water in the correct salinity range to encourage the established species. Freshwater swamps and marshes are normally constructed near any upland location with the principal consideration being the availability of a predictable source of water for creating appropriate environmental conditions for the wetland plant species. However, there is a growing consideration and utilization of treated wastewater as the water source for freshwater constructed habitat wetlands.

The success of developing constructed wetlands for wildlife habitat purposes has been varied. In general, it can be said that greater success has been achieved in the establishment of freshwater and saltwater marshes and not in swamps.

4.5. Constructed Flood Control Wetlands

Flood control systems that include significant areas of wetlands vegetation are called constructed flood control wetlands. Varying sizes of impoundments are being used to store natural floodwaters to offset their losses due to urban and agricultural development. Emergent wetland plants either naturally or artificially colonize most of such systems. These systems are engineered to provide specific hydraulic functions for water storage and for bleed-off intervals following storms. Constructed flood control wetlands are sited generally at low elevations in the landscape to allow gravity inflows from the adjacent upland system generating runoff. In some cases, they may have to be located in floodplain areas, resulting in wetland functions in addition to flood control. Fluctuating water levels in these types of constructed wetlands may limit their use for any secondary functions such as habitat or water quality improvement.

4.6. Constructed Aquaculture Wetlands

Wetland systems have historically been used for husbandry of aquatic food species such as crayfish, shrimps and prawns and such other aquaculture activities. Water tolerant food plant species such as rice, cranberries, and water chestnuts are technically wetland plants and hence there is significant potential for compatible aquaculture within wetlands constructed for water quality management or for flood control. This potential is being explored for rice culture in Brazil and China. Increased fish and wildlife productivity in wetlands receiving elevated nutrients in wastewater inflows can be harvested for economic gains.

5. Constructed Treatment Wetlands (CTW)

Wetlands have been used as convenient wastewater discharge sites for as long as sewage has been collected (even 100 years for some locations). When monitoring was initiated at some of the existing wetland discharges, an awareness of the water quality purification potential of wetlands began to emerge. Since its initial "discovery" by K. Seidel and R. Kickuth of Max Planck Institute in Plon, Germany in 1950's, efforts to harness and develop the natural treatment ability of wetland systems have been undertaken by a wide range of government and private research interests around the world. Environmental scientists have made significant advances in the creation of artificial or "constructed" or "engineered" wetlands which can closely imitate the specialized treatment functions that occur in the natural wetland ecosystems, since that time.

5.8. Components of a CTW

The four major system components of constructed wetlands for treatment of wastewater are:

(i) wetland vegetation;
(ii) media or substrate supporting vegetation;
(iii) water column (in or above the media);
(iv) living organisms

5.1.1. Wetland Vegetation

A wide variety of aquatic plants can be used in constructed wetland systems designed for wastewater treatment. More often, constructed treatment wetlands are planned as marsh-type wetlands and are planted with emergent **macrophytes** (rooted plants that anchor to the substrate media) that are adapted to water-dominated environment. Most frequently used macrophytes species are cattails (*Typha sp.),* reeds (*Phragmites sp.*), bulrushes (*Scirpus sp.*) and sedges (*Carex sp.)*. These species are used because they help transform wastewater constituents so that quality standards for their discharge are met. Macrophytes play a major role in treatment of wastewater (Table 1). The biomass of the plant slows the pathway of wastewater enhancing sedimentation of solids. There is also uptake of some pollutants in wastewater as nutrients by these plants. The extensive root system provides a huge surface area to act as a filter for suspended solids and debris.

The root zone also provides extensive surface area for attached growth of microorganisms, which in turn are involved in transformation of pollutants. Oxygen diffused through the root membranes into the surrounding water environment creates an oxygen rich area around the root zone of the plants that drive many chemical transformations and result in the degradation of pollutants. Diffusion of oxygen through root zones also help to maintain partially aerobic conditions in the water column.

Wetland plant part	Role
Aerial plant tissues	• Light attenuation → reduced growth of phytoplanktons • Influence on microclimate → insulation during winter • Reduced wind velocity → reduced risk of resuspension of settled solids • Aesthetic appearance • Nutrient storage
Plant tissues in water	• Filtering effect → filter out large debris • Reduced current velocity → increased rate of sedimentation, reduced risk of resuspension of settled solids • Surface area for attached microorganisms • Excretion of photosynthetic oxygen → increased aerobic degradation • Nutrient uptake
Roots and rhizomes	• Stabilising the sediment surface → less soil erosion • Release of oxygen increase organic degradation and nitrification • Nutrient uptake • Release of antibiotics

Source: Brix H. (1997). Do macrophytes play a role in constructed treatment wetlands? *Water Science and Technology*, **35**(5), 11–17.

Table 1. Major roles of macrophytes in constructed wetlands

5.1.2. Supporting Media or Substrate

The media that physically supports vegetation in a constructed wetland is vital as it forms an integral link in treatment processes that occur in the wetland. Apart from vegetation, they also act as the principal storage of all biotic and abiotic components that exist in a wetland. While soil will be the support media in natural wetlands, engineered wetlands for treatment of wastewater more often are constructed with coarse and fine gravel. The bottom layers of constructed wetlands are normally of coarse gravel in the size range 30–40 mm. and upper layer of fine gravel in the size range 12–15 mm. The void spaces in the media serve as flow channels for wastewater.

Hydraulic conductivity of the substrate is a major factor in the performance of constructed treatment wetlands. Maintenance of hydraulic conductivity is required to stabilize the hydraulic retention time of the wetland system. Wetland systems with fine- and soil-based substrates will have low hydraulic conductivity, while coarse sand- and gravel-based medium display higher conductivity.

Soil is usually not recommended as a substrate for wastewater treatment wetlands. Several studies with soil-based treatment wetlands have reported problems of clogging, causing overflows of wastewater resulting in bed erosion and poor plant growth. Infilling and occlusion of interstitial spaces by solids will reduce the effective volume available within the substrate, leading to increasing flow velocities, decreasing hydraulic retention times, and short-circuiting. Therefore, in several countries, gravel has been the preferred medium for use in reed bed systems. Gravel allows through-flow of water from the start and, if the bed gradually starts to clog with solids, this can be counterbalanced by the growth of rhizomes and roots, opening up the bed. Soils will have a hydraulic conductivity value of 10^{-5} m/s or less, whereas a uniform gravel in the range of 3 to 6 mm, or 5 to 10 mm, will have an initial values in the order of 10^{-2} m/s or higher. Table 2 presents a range of media and the corresponding hydraulic conductivity.

Media type	**Effective size (D_{10}) mm**	**Porosity (η)**	**Hydraulic conductivity (k_s, m/s)**
Coarse sand	2	0.32	1.2×10^{-2}
Gravelly sand	8	0.35	5.8×10^{-2}
Fine gravel	16	0.38	8.7×10^{-2}
Medium gravel	32	0.40	11.6×10^{-2}
Coarse rock	128	0.45	115.7×10^{-2}

Source: Chen S., Malone R. F., and Fall L. J. (1993). A theoretical approach for minimization of excavation and media costs of constructed wetlands for BOD removal *Journal American Society of Agricultural Engineers*, **36**(6) 1625–1632.

Table 2. Media characteristics

The rate of clogging in gravel-bed wetlands will initially depend only on influent solids loading and efficiency of retention. In the longer term, factors such as the degradable fraction of the suspensoids and their rate of microbial and chemical degradation in the wetland environment will determine the rate of accumulation of solids and the pattern of clogging. Theoretical calculations show estimates for the service life of a hypothetical gravel-bed wetland in relation to clogging by organic and inorganic wastewater solids and microbial detritus (but ignoring plant litter contributions) to be in the order of 100 years. Measurements of hydraulic gradients in gravel-bed wetlands treating domestic wastewater at Richmond, Australia showed major reductions in substrate hydraulic conductivity at the head of the wetlands during the first year of operation, whereas the downstream permeability remained relatively stable over the two-and-a-half year monitoring period, with no indication of advancement of solids accumulation along the length of the bed.

Microbial organisms also grow attached to the media as in a trickling filter. However, due to high flow rates that are often maintained in constructed wetland systems, the microbial growth does not result in thick layers of biofilm and hence clogging of media due to biofilms are not a problem. The top layer of the substrate that falls in the root zones of macrophytes, is the biologically most active part of the constructed wetland.

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Biographical Sketches

M. Sundaravadivel is an Environmental Engineer with the Central Pollution Control Board, Ministry of Environment and Forests, Government of India. He holds a Bachelors Degree in Civil Engineering and a Masters Degree in Environmental Engineering. He has been working in the field of environmental management and industrial pollution control since 1989, particularly in the area of environmental audit, waste minimization and cleaner production in agro-based industries. He has also been an engineering consultant for planning, design and development of wastewater collection and treatment systems for many large cities of India. Currently, he is engaged in research on environmental economic approaches for liquid and solid waste management in small and medium towns of developing countries at the Graduate School of the Environment, Macquarie University, Sydney, Australia.

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