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MANMADE WETLAND FOR WASTEWATER TREATMENT WITH SPECIAL EMPHASIS ON DESIGN CRITERIA

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ABSTRACT

Manmade wetlands are planned systems designed and constructed to employ wetland vegetation to assist in treating wastewater in a more controlled environment as compared to that which occurs in natural wetlands. Hammer (1990) defines constructed wetlands as a designed, manmade complex of saturated substrate, emergent and submerged vegetation, animal life, and water that simulate wetlands for human uses and benefits. Manmade wetlands are an "eco-friendly" alternative for secondary and tertiary municipal and industrial wastewater treatment. The pollutants removed by manmade wetlands include organic materials, suspended solids, nutrients, pathogens, heavy metals and other toxic or hazardous pollutants. In municipal applications, they can follow traditional sewage treatment processes. Different types of manmade wetlands can effectively treat primary, secondary or tertiary treated sewage. Manmade wetlands are practical alternatives to conventional treatment of domestic sewage, industrial and agricultural wastes, storm water runoff, and acid mining drainage.

Key words: Constructed wetlands, Phytoremediation, Conventional treatment, Pollutants, Effluents.

INTRODUCTION

Manmade wetlands for wastewater treatment can be classified as either Free Water Surface (FWS) or Subsurface Flow (SSF) systems. In FWS systems, the flow of water is above the ground, and plants are rooted in the sediment layer at the base of water column (Fig. 1).

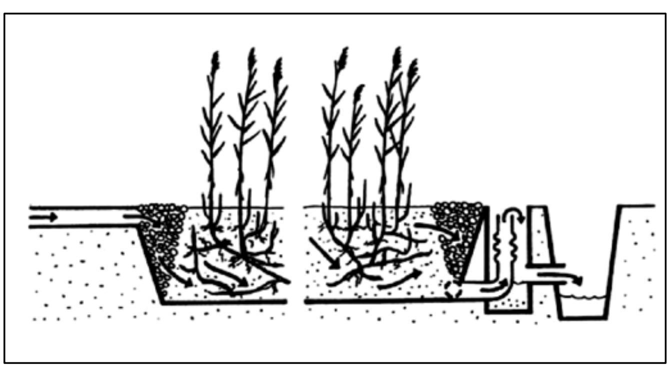

Fig. 1: Emergent macrophyte treatment system with horizontal sub-surface flow (After Brix 1993)[1]

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In SSF systems, water flows through a porous media such as gravels or aggregates, in which the plants are, rooted (Fig. 2). Table 1 illustrates the type of wetlands, vegetation types and water column contacts in constructed wetlands.

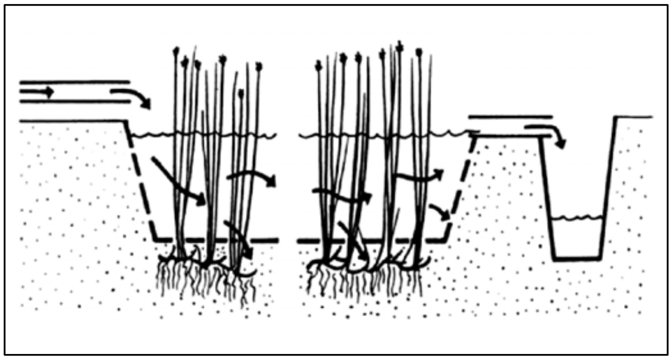

Fig. 2: Emergent macrophytes treatment system with surface flow (After Brix 1993)[1]

Table 1: Vegetation type and water column contact in constructed wetlands

Constructed wetland type	Type of vegetation	Section in contact with water column
Free water surface (FWS)	Emergent	Stem, limited leaf contact
	Floating	Root zone, some stem / tubers
	Submerged	Photosynthetic part, possibly root zone
Sub-surface flow (SSF)	Emergent	Rhizome and root zone

SSF systems are most appropriate for treating primary wastewater, because there is no direct contact between the water column and the atmosphere. There is no opportunity for vermin to breed, and the system is safer from a public health perspective. The system is particularly useful for treating septic tank effluent or grey water, landfill leachate and other wastes that require removal of high concentrations organic materials, suspended solids, nitrate, pathogens and other pollutants. The environment within the SSF bed is mostly either anoxic or anaerobic. Oxygen is supplied by the roots of the emergent plants and is used up in the Biofilm growing directly on the roots and rhizomes, being unlikely to penetrate very far into the water column itself. SSF systems are good for nitrate removal (denitrification), but not for ammonia oxidation (nitrification), since oxygen availability is the limiting step in nitrification.

There are two types of SSF systems: horizontal flow SSF (hSSF) and vertical flow SSF (vSSF). The most common problem with hSSF is blockage, particularly around the inlet zone, leading either to short circuiting, surface flow or both. This occurs because of poor hydraulic design, insufficient flow distribution at the inlet, and inappropriate choice of porous media for the inlet zone. Properly-designed SSF systems are very reliable.

The objective of using manmade wetlands is to remove organic matter, suspended solids, pathogenic organisms, and nutrients such as ammonia and other forms of nitrogen and phosphorus. The growing interest in wetland system is due to the fact that natural systems offer advantages over conventional activated sludge and trickling filter systems. When the same biochemical and physical processes occur in a more natural environment, instead of reactor tanks and basins. This review paper is concerned with the design and operation of wetlands.

Advantages and disadvantages of manmade wetlands

Advantages of manmade wetlands are as follows –

(i) Relatively inexpensive to construct and operate

(ii) Easy to maintain

(iii) Provide effective and reliable wastewater treatment

(iv) Relatively tolerant of fluctuating hydrology and contaminant loading rates (optimal size for anticipated waste load), and

(v) Provide indirect benefits such as green space, wildlife habitats and recreational and educational areas.

The disadvantages of manmade wetlands are as follows –

(i) The land requirements (cost and availability of suitable land)

(ii) Proper design and operation criteria

(iii) Biological and hydrological complexity and our lack of understanding of important process dynamics

(iv) The costs of gravel or other fills, and site grading during the construction period

(v) Possible problems with pests, Mosquitoes and other pests could be a problem for an improperly designed and managed SSF.

The system may be used for small communities and, therefore, may be located close to the users.

Configuration, zones and components of manmade wetlands

Influents to manmade wetland can range from raw wastewater to secondary effluents. Most manmade wetlands have the following zones: inlet zone, macrophyte zone, and littoral zone and outlet zones. The components associated in each zones are as shown in Table 2, and can include substrates with various rates of hydraulic conductivity, plants, a water column, invertebrate and vertebrates, and an aerobic and anaerobic microbial population. The water flow is maintained approximately 15-30 cm below the bed surface. Plants in wastewater systems have been viewed as nutrient storage compartments where nutrient uptake is related to plant growth and production. Within the water column, the stems and roots of wetland plants significantly provide the surface area for the attachment of microbial population.

Wetland plants have the ability to transport atmospheric oxygen and other gases down into the root to the water column. Most media used include crushed stones, gravels, and different soils, either alone or in combination. Most beds are underlain by impermeable materials to prevent water seepage and assure water level control. As wastewater flows it gets purified during contact with media surface and vegetation roots. The sub-surface zone is saturated and generally anaerobic, although excess DO conveyed through the plant root system supports aerobic microsites adjacent to the root and rhizomes.

Processes in manmade wetlands

Wetland can effectively remove or convert large quantities of pollutants from point sources (municipal, industrial and agricultural wastewater) and non-point sources (mines, agriculture and urban runoff), including organic matter, suspended solids, metals and nutrients. The focus on wastewater treatment by manmade wetlands is to optimize the contact of microbial species with substrate, the final objective being the bioconversion to carbon dioxide, biomass and water.

Table 2: Wetland zones and their associated components

Zones	Components	Functions
Inlet zone	Inlet structure, splitter box	Flow distribution across the full width at a minimum of 3-5 m interval
Macrophyte zone	Porous bed/substrate, open water, vegetation, island, mixing baffles, flow diversion	To provide the substrate with high hydraulic conductivity; to provide surface for the growth of Biofilm; to aid in the removal of fine particles by sedimentation or filtration; to provide suitable support for the development of extensive root and rhizome system for emergent plants.
Deep water zone	Usually deeper, non-vegetated	Reduce short circuiting by re-orienting flow path; reduce stagnant areas by allowing for mixing by wind; enable UV disinfections of bacteria and other Pathogens; provide habitat for waterflow.
Littoral zone	Littoral area	Littoral vegetation protects embankment from Erosion; littoral vegetation serves to break up wave action.
Outlet zone	Collection devices, spillway, weir, outlet structures	Control the depth of the water in the wetland; collect the effluent water without creating of dead zones in the wetlands; provide access for sampling and flow monitoring.

Wetlands are characterized by a range of properties that make them attractive for managing pollutants in water. These properties include high plant productivity, large adsorptive capacity of the sediments, high rates of oxidation by micro flora associated with plant biomass, and a large buffering capacity for nutrients and pollutants. Table 3 provides an overview of pollutant removal mechanisms in constructed wetlands[2].

Table 3: Overview of pollutant removal mechanism

Pollutant	Removal processes
Organic material (measured as BOD)	Biological degradation, sedimentation, microbial uptake
Organic contaminants (e.g., pesticides)	Adsorption, volatilization, photolysis and biotic/abiotic degradation
Suspended solids	Sedimentation, filtration
Nitrogen	Sedimentation, nitrification/denitrification, microbial uptake, volatilization
Phosphorous	Sedimentation, filtration, adsorption, plant and microbial uptake
Pathogens	Natural die-off, sedimentation, filtration, predation, UV degradation, adsorption
Heavy metals	Sedimentation, adsorption, plant uptake

Biological processes

There are six major biological reactions involved in the performance of manmade wetlands, including photosynthesis, respiration, fermentation, nitrification, denitrification and microbial phosphorus removal. Photosynthesis is performed by wetland plants and algae, with the process adding carbon and oxygen to the wetland. Both carbon and oxygen drive the nitrification process. Plants transfer oxygen to their roots, where it passes to the root zones (rhizosphere). Respiration is the oxidation of organic carbon, and is performed by all living organisms, leading to the formation of carbon dioxide and water. The common microorganisms in the manmade wetland are bacteria, fungi, algae and protozoa. The maintenance of optimal conditions in the system is required for the proper functioning of wetland organisms. Fermentation is the decomposition of organic carbon in the absence of oxygen, producing energy-rich compounds (e.g., methane, alcohol, volatile fatty acids). This process is often undertaken by microbial activity. Nitrogen removal by nitrification/denitrification is the process mediated by microorganisms. The physical process of volatilization also is important in nitrogen removal.

Wetland microorganisms, including bacteria and fungi, remove soluble organic matter, coagulate colloidal material, stabilize organic matter, and convert organic matter into various gases and new cell tissue. Many of the microorganisms are the same as those occurring in conventional wastewater treatment systems. Different types of organisms, however, have specific tolerances and requirements for dissolved oxygen, temperature ranges and nutrients.

Chemical processes

Metals can precipitate from the water column as insoluble compounds. Exposure to light and atmospheric gases can break down organic pesticides, or kill disease-producing organisms[3].

The pH of water and soils in wetlands exerts a strong influence on the direction of many reactions and processes, including biological transformation, partitioning of ionized and un- ionised forms of acids and bases, cation exchange, solid and gases solubility

Physical processes

Sedimentation and filtration are the main physical processes leading to the removal of wastewater pollutants. The effectiveness of all processes (biological, chemical, physical) varies with the water residence time (i.e., the length of time the water stays in the wetland). Longer retention times accelerate the remove of more contaminants, although too-long retention times can have detrimental effects.

Limitations of wetland processes

Process rates

The chemical and biological processes occur at a rate dependent on environmental factors, including temperature, oxygen and pH. Metabolic activities are decreased by low temperature, reducing the effectiveness of pollutant uptake processes relying on biological activity. Low oxygen concentrations limit the processes involving aerobic respiration within the water column, and may enhance anaerobic processes, which can cause further degradation of water quality. Many metabolic activities are pH-dependent, being less effective if the pH is too high or low.

Hydrological limitations

The capacity of wetlands to treat wastewater is limited, both in terms of the quantity of water, and the total quantity of the pollutants. Hydraulic overloading occurs when the water flow exceeds the design capacity, causing a reduction in water retention time that affects the rate of pollutant removal. Pollutant overloading occurs when the pollutant input exceeds the process removal rates within the wetland[4]. Hydraulic overloading may be compensated for by using surcharge mechanisms, or the design may be based on a flush principle, whereby large water flows bypass the wetland when used for storm water treatment[3]. Inflow variations are typically less extreme for wetlands treating municipal wastewaters, with incoming pollutant loads also being more defined and uniform.

Process design for manmade wetlands

Hydrology

It is not safe to ignore water exchanges with the atmosphere, mainly because they can significantly contribute to water flows. Rain causes two opposing effects, including;

(i) Dilution of waters, thereby reducing material concentrations and

(ii) Increased water velocity, increasing the water retention time within a wetland.

The presence of vegetation may retard the evapotranspiration, although wetland evapotranspiration is usually 0.8 times the Class A pan set at an adjacent open site. Preparation of an accurate hydrological budget is needed to properly design a constructed wetland.

The water balance to a wetland can be calculated as follows –

$$dV/dt = Q_i + Q_e + P - ET$$

Where Q_i is the influent wastewater flow (volume/time), Q_e is the effluent wastewater flow (volume/time), P is the precipitation (volume/time), ET is the evapotranspiration (volume/time), V is the volume, and t is time.

The equation does not consider the inflow from, and to, the groundwater, since the SSF wetlands should be lined.

Design approaches for constructed wetlands

Sizing based on equation

The wetland might be sized based on the equation proposed by Kickuth:

$$A_h = \frac{Q_d (\ln C_i - \ln C_e)}{K_{BOD}}$$

Where, A_h = Surface area of bed (m^2), Q_d = average daily flow rate of sewage (m^3/d), C_i = influent BOD^5 concentration (mg/L), C_e = effluent BOD^5 concentration (mg/L), K_{BOD} = rate constant (m/d)

K_{BOD} is determined from the expression –

$$K_T dn$$

Where, $K_T = K_{20} (1.06)^{(T-20)}$, K_{20} = rate constant at 20°C (d-1), T = operational temperature of system (°C), d = depth of water column (m), n = porosity of the substrate medium (percentage expressed as fraction).

K_{BOD} is temperature dependent and the BOD degradation rate normally increase about 10% per °C. Thus the reaction rate constant for BOD degradation is expected to be higher during summer than in winter. It is also been noted that K_{BOD} increases with the age of the system.

Sizing based on specific area requirement per population equivalent (PE)

The specific area requirement per PE holds true where there is uniformity in the specific wastewater quantity and quality. In general, the rules of thumb suggested by several works can be served as a safe bed (depending on the climatic conditions). However the investment costs tend to be higher due to conservative aspects of this approach.

Specific area requirement for Horizontal Flow (HF) and Vertical Flow (VF) constructed wetland has been calculated for various specific wastewater discharges for a certain population. The BOD contribution has been taken as 40 g BOD/pe.d, 30% BOD load is reduced in the primary treatment and the effluent concentration of BOD is taken as 30 mg/L. The K_{BOD} for HF and VF wetlands are taken as 0.15 and 0.20, respectively. It is seen that a specific area requirement of 1-2 m^2/pe would be required of HF constructed wetlands where as a specific area of 0.8-1.5 m^2/pe for the VF wetland.

Depth

In general, the depth of substrate in a subsurface flow constructed wetland is restricted to approximately the rooting depth of plants so that the plants are in contact with the flowing water and have an effect on treatment. However, Hydraulic Retention Time – HRT (time the wastewater is retained in the wetland) is to be considered in the selection of the depth of the wetland.

HF wetland

Most HF wetlands in Europe provide a bed depth of 60 cm.[6] In the United States, HF wetlands have commonly been designed with beds 30 cm to 45 cm deep.[6] An experimental study carried out in Spain showed that shallow HF wetlands with an average depth of 27 cm were more effective than deep HF wetlands with an average water depth of 50 cm.[7] It is recommended to use an average depth of 40 cm taking into considerations of the precipitation which could cause surface flow.

VF wetland

Generally, VF systems are built with larger depths compared to HF systems. Most VF systems in UK are built 50-80 cm deep.[5] In contrast to that, depth greater than 80 cm is recommended in Germany.[8] Similarly, in Austria a depth of 95 cm is recommended.[9] A minimum of 100 cm depth is recommended in Denmark.[10] The VF systems in Nepal were also built about 100 cm deep but nowadays shallower depths are being practiced.

In a subtropical climate, it is possible to increase the applied loading rates above guidelines issued in Central Europe and achieve nitrification in VF system. The average results by vertical beds of 75 cm depth showed better performance in comparison with vertical beds of 45 cm depth.[11]

It is recommended to use substrate depth of 70 cm, which can provide adequate nitrification in addition to the organic pollutants removal.

Bed cross section area (Only for HF wetland)

Dimensioning of the bed is derived from Darcy's law and should provide subsurface flow through the gravel under average flow conditions. Two important assumptions have been made in applying the formula:

Hydraulic gradient can be used in place of slope, and the hydraulic conductivity will stabilize at 10^{-3} m/s in the established wetland.

The equation is –

$$A_c = Q_s / K_f \, (dH/ds)$$

Where, A_c = Cross sectional area of the bed (m^2), Q_s = average flow (m^3/s), K_f = hydraulic conductivity of the fully developed bed (m/s), dH/ds = slope of bottom of the bed (m/m).

There is no hard and fast rule on the width of the wetland however it is recommended to have a width more than 15 cm. Also the wetland cell should be divided to avoid short circuiting. Also it is desirable to have more than one wetland cell.

In VF wetlands, since the flow is vertical, the width and cross-sectional area of VF beds are not set by a requirement to keep the flow below surface and prevent surface flow.

Media selection

The media perform several functions. They are rooting material for vegetation, help to evenly distribute/collect flow at inlet/outlet, provide surface area for microbial growth, and filter and trap particles. Very small particles have very low hydraulic conductivity and create surface flow. Very large particles have high conductivity, but have little wetted surface area per unit volume of microbial habitat. Large and angular medium is inimical to root propagation. The compromise is for intermediate-sized materials generally characterized as gravels. It is recommended that the gravels are washed because this removes fines that could block the void spaces. It is reported that the diameter size of media used in HF wetlands varies from 0.2 mm to 30 mm.[6, 12-16]

It is recommended that the media in the inlet and outlet zones should be between 40 and 80 mm in diameter to minimize clogging and should extend from the top to the bottom of the system. For the treatment zone, there does not appear to be a clear advantage in pollutant removal with different sized media in the 10 to 60 mm range[16].

VF Wetland

The substrate properties, d10 (effective grain size), d60 and the uniformity coefficient (the quotient between d60 and d10) are the important characteristics in the selection of the substrate. There is not one uniform standard substrate design for the construction of VF wetland. Various literatures reports effective grain size should be $0.2 < d10 < 1.2$ mm, uniformity coefficient $3 < d60/d10 < 6$ and hydraulic conductivity Kf 10^{-3} to 10^{-4} m/s.[10, 17, 20]

The rate of decrease in permeability for similar SS influent characteristics is highest for porous media with smaller pore sizes. Compared to the gravel, the sands show a relatively more rapid reduction in their permeability due to effects of sediment accumulation at the surface of the sands. However, the depth of clogging is higher for larger particle sizes.[21]

Bed slope

The top surface of the media should be level or nearly level for easier planting and routine maintenance. Theoretically, the bottom slope should match the slope of the water level to maintain a uniform water depth throughout the bed. A practical approach is to uniformly slope the bottom along the direction of flow from inlet to outlet to allow for easy draining when maintenance in required. No research has been done to determine an optimum slope, but a slope of 0.5 to 1% is recommended for ease of construction and proper draining.

Sealing of the bed

Subsurface flow wetlands providing secondary treatment should be lined to prevent direct contact between the wastewater and groundwater. Liners used for wetlands are the same as those typically used for ponds.

Native soils may be used to seal the wetlands if they have sufficiently high clay content to achieve the necessary permeability. The thickness of the linings depends on the permeability of the soil. The advice given in the European Guidelines[22] was that if the local soil had a hydraulic conductivity of 10^{-8} m/s or less then it is likely that it contained high clay content and could be "puddled" to provide adequate sealing for the bed. As a general guide, the following interpretations may be placed on values obtained for the in situ coefficient of permeability:

- $K > 10^{-6}$ m/s: The soil is too permeable and the wetlands must be lined.
- $K > 10^{-7}$ m/s: Some seepage may occur but not sufficiently to prevent the wetlands from having submerged condition.
- $K < 10^{-8}$ m/s: The wetlands will seal naturally;
- $k < 10^{-9}$ m/s: There is no risk of groundwater contamination (if $k > 10^{-9}$ m/s and the ground water is used for potable supplies, further detailed hydrogeological studies may be required).

The soil could be mixed with ordinary Portland cement (8 Kg/m^2) to decrease the soil permeability and compacted to seal the wetlands. Bentonite mixed with the native soils and compacted has been used in the developed countries.

Other synthetic liners include:

- Polyvinyl chloride (PVC)
- Polyethylene (PE)
- Polypropylene

Liners should be selected based on its availability and cost effectiveness. Preparation of the subgrade under the liner is crucial for successful liner installation. The finished subgrade should be free from materials that might puncture the liner.

Systems layout

Components of the manmade wetlands include preliminary/primary treatment units and the wetland cell (or cells). The manmade wetlands includes substrate, vegetation and biological organisms contained within the physical configuration that can be described as an attached growth biological filter.

Configuration

Configuration should enhance wastewater distribution to maximize contact between wastewater, substrate and vegetation by minimizing short-circuiting. The configuration should consider the degree of pre-treatment, required treatment area, available land shape and slope, length- to-width ratio, desired bed slope, amount of excavation and grading to obtain cell depth and slope, substrate type, collection pipes, and operation and maintenance flexibility. There are three possible configurations for wetland cells used for wastewater treatment: In parallel, in series, or a combination of the two. The main advantage for cells in parallel is the flexibility and redundancy in operation, so that individual cells can easily be taken off-line for maintenance and repair. The water flow can be re-directed to other cells, allowing for ongoing operation of the wastewater treatment plant and the wetland. When the wetland cells operate in series, the water moves sequentially from one cell to next, forming a chain of wetland cells. The main operational advantage of cells in series is minimization of short-circuiting, leading to better overall treatment in the system. The selected configuration must be based on a clear understanding of the objectives, influent water quality, desired effluent water quality, hydraulic regime and site specific constraints and opportunities.[23] An L/W value as low as 1 is recommended for SSF[24], while an L/W ratio of at least10 is required for the SF. The bed slope for SSF should be 2% or less, while that for SF should be 0.5% or less. The substrate depth should be 0.6 m.

Preliminary/primary treatment

Manmade wetlands should be preceded with screens or comminution as preliminary treatment facilities. Imhoff tanks, septic tanks and stabilization pond(s) should be used as primary treatment facilities where necessary.

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