

Wetlands for Water Quality Management – The Science and Technology

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1. Introduction

Wetlands are defined as water systems with marsh or fen and with water that is static or flowing, fresh or brackish, the depth of which at low tide is below 6m [5]. Natural wetlands are characterized by emergent aquatic vegetation such as cattails (typha), rushes (*Scirpus*) and reeds (*Phragmites*), and by submerged and floating plant species. Wetlands are categorized into three main categories: (1) fresh water coastal wetlands, (2) flood – plain wetlands and (3) constructed wetlands. These are valuable ecosystems as they support services which contribute significantly to human well - being. Some of these services are fish and fiber, water supply, water purification, flood regulation, recreational opportunities and tourism.

In this chapter, we focus our attention to potential of wetlands as water purifiers. This is important because harmful substances enter into wetland systems through animal waste from farms, toxic chemicals from factories and pesticides present in rain water. The large and diverse population of bacteria which grow on the submerged roots and stems of aquatic plants play an important role in removing BOD₅ from waste water. Wetland plants take up harmful substances into their roots and change the harmful substances into the less harmful ones before they are released into the water body. Harmful substances partly get buried in the wetland soil. The soil bacteria convert these into substances, which are not harmful. Soil microbes (*Bacillus subtilis* and *Pseudomonas fluorescens*) convert pesticides into simpler non-toxic compounds. This process of degradation of pesticides and subsequent conversion into non-toxic compounds is known as “biodegradation”. The biodegradation is influenced by factors such as moisture, temperature, pH and organic matter content.

The chapter is organized as follows. In the next section, we present a study of a natural wetland of flood – plain type. This section summarizes a previous study of this natural wetland by the author and presents some new results. Section 3 discusses the design and construction of constructed wetlands.

2. Keoladeo National Park, Bharatpur, India: A case study

Keoladeo National Park ($27^{\circ}10'N$, $77^{\circ}31'E$), a World Heritage Site, is situated in eastern Rajasthan. The park is 2 kilometers (km) south-east of Bharatpur and 50 km west of Agra (cf. Figure 1). Figure 1 provides a location map for the park. The Park is spread over 29 square kilometres area. One third of the Park habitat is wetland system with varying types of trees, mounds, dykes and open water with or without submerged and emergent plants. The uplands have grasslands (savannas) of tall species of grass together with scattered trees and shrubs present in varying densities. The area consists of a flat patchwork of marshes in the Gangetic plain, artificially created in the 1850s and maintained ever since by a system of canals, sluices and dykes. Water is fed into the marshes twice a year from inundations of the Gambira and Banganga rivers, which are impounded on arable land by means of an artificial dam called Ajan Bund, located in the south of the park (cf. Fig. 2). It was developed in the late 19th century by creating small dams and bunds in an area of natural depression to collect rainwater and by feeding it with an irrigation canal.

The 29 km (18 mi) reserve, locally known as Ghana, is a mosaic of dry grasslands, woodlands, woodland swamps, and wetlands. These diverse habitats serves as homes to 366 bird species, 379 floral species, 50 species of fish, 13 species of snakes, 5 species of lizards, 7 amphibian species, 7 turtle species, and a variety of other invertebrates. Keoladeo National Park is popularly known as "bird paradise". Over 370 bird species have been recorded in the park. The park's location in the Gangetic Plain makes it an unrivalled breeding site for

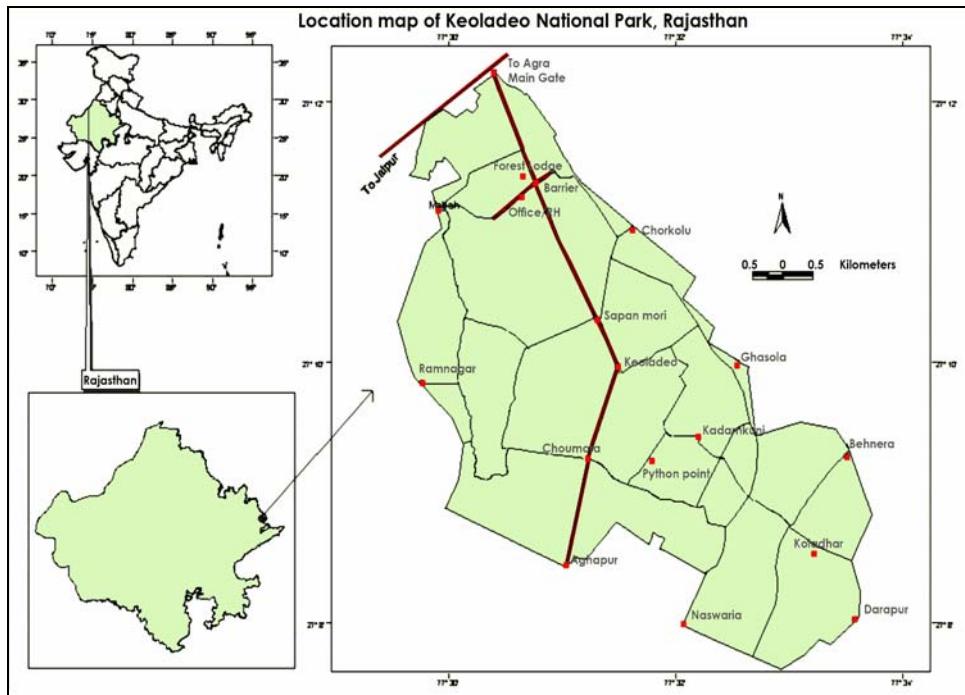


Fig. 1. Location map of the Keoladeo National park, a World Heritage site

herons, storks and cormorants, and an important wintering ground for large numbers of migrant ducks.

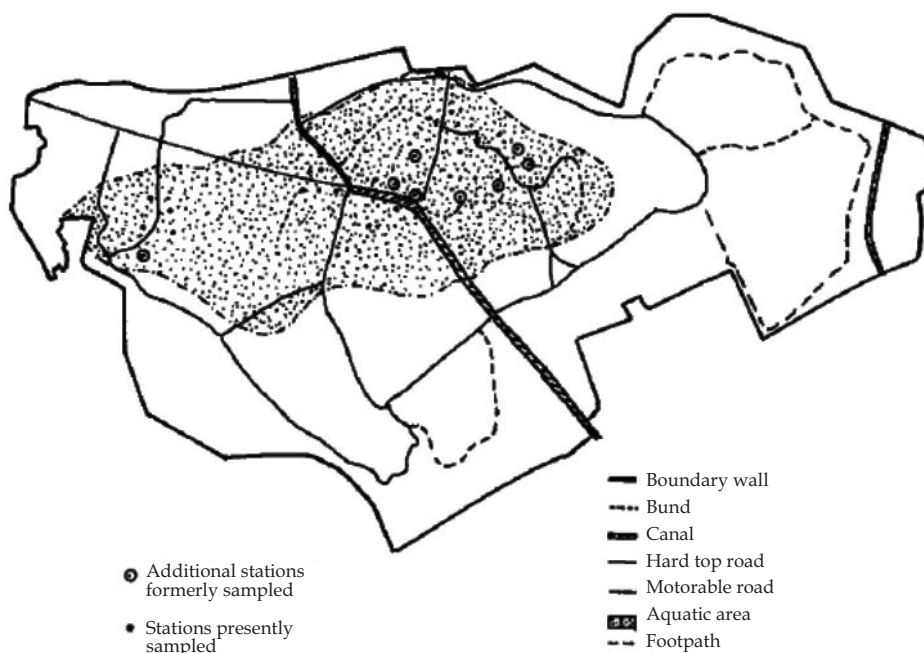


Fig. 2. Situational map of Keoladeo National Park

Light vs nutrient supplies

It is known that the population persistence boundaries in water column depth–turbulence space are set by sinking losses and light limitation [1]. In shallow waters, the most strongly limiting process is nutrient influx to the bottom of the water column (e.g., from sediments). In deep waters, the most strongly limiting process is turbulent upward transport of nutrients to the photic zone. Consequently, the highest total biomasses are attained in turbulent waters at intermediate water column depths and in deep waters at intermediate turbulences. These patterns have been found insensitive to the assumption of *fixed versus flexible algal carbon -to - nutrient stoichiometry*. They arise irrespective of whether the water column is a surface layer above a deep water compartment or has direct contact with sediments. This helps us understand the relevant dynamical processes in the physical systems in natural as well constructed wetlands.

Biotic part of Keoladeo National Park

KNP is a natural wetland which can be categorized as a flood - plain type. The economic value of the park is dependent on tourist activities. The tourists are mainly attracted by Siberian Crane, the migratory bird which adds aesthetic value to KNP. It provides a large habitat for migratory birds; Siberian crane being the flagship species. With reference to migratory birds, the biomass is divided into two categories: “Good” and “Bad”. The excess

growth of the wild grass species, *Paspalum distichum* restricts the growth of bulbs, tubers and roots, on which avifauna feed on.

Paspalum distichum is known to deplete oxygen in the natural aquatic systems is the dominant species. The paspalum and its family acts as a bad biomass for the birds and the floating vegetation. The following species of the floating vegetation, *Nymphoides indicum*, *Nymphoides cristatum*, *Nymphaea nouchali*, *Nymphaea stellat*, and other useful species are categorized as "good" biomass [7, 8]. The fishes and the water fowl are the most suffered species. Although visits of the tourists bring revenue to the state, it also creates a disturbance gradient.

2.1 Good biomass, bad biomass and birds in the Keoladeo National Park: The biotic system

Rai [6] modeled the dynamics of the biotic system of the wetland part of KNP by the following set of ordinary differential equations.

$$\begin{aligned}\frac{dG}{dt} &= aG - bG^2 - cGB - d\frac{GP}{G+D}, \\ \frac{dB}{dt} &= eB - \frac{B^2}{W_1} - a_2GB, \\ \frac{dP}{dt} &= -\theta P + \phi\frac{GP}{G+D_1}.\end{aligned}\tag{1}$$

With

G : density of the good biomass, g/cm³,

B : density of the bad biomass, g/cm³,

P : density of resident birds joined by migratory ones.

This system can be broken into two subsystems. (i) The competition system with "good" and "bad" biomass as component populations. (ii) The prey - predator system with good biomass and the bird population. Oscillatory dynamics are possible in the subsystems, but it is sensitive to initial conditions. The prey-predator subsystem performs oscillatory motion in significant region of the parameter space. The subsystem is essentially a Rosenzweig - MacArthur kind of system [9]. It is known to produce oscillatory dynamics in a significant region of the parameter space.

The good biomass and the resident birds occasionally joined by migratory ones constitute a subsystem. It is given by the following set of ordinary differential equations

$$\begin{aligned}\frac{dG}{dt} &= aG - bG^2 - d\frac{GP}{G+D}, \\ \frac{dP}{dt} &= -\theta P + \phi\frac{GP}{G+D_1}.\end{aligned}\tag{2}$$

With

D : a measure of the half-saturation constant,

a : reproductive growth rate of the good biomass,

- b : measures the severity of the intra-specific competition among individuals of good biomass,
 ϕ : conversion coefficients for the bird species (resident as well as migratory),
 t : time measured in days.

Critical Points for the subsystem (2) are $(0, 0)$, $\left(\frac{a}{b}, 0\right)$, $\left(\frac{\theta D_1}{\phi - \theta}, \frac{(a - bG)(G + D)}{d}\right)$.

For the following parameter set, the nature of these critical points $(0,0)$, $(100,0)$, $(20,12.8)$ turn out to be as follows.

$$a = 0.2, b = 0.002, c = 0.005, d = 0.5, D = D_1 = 20, \theta = 0.05, \phi = 0.1 \quad (3)$$

$(0, 0)$ is a saddle point. $(100, 0)$ is an unstable node. The critical point located at $(20, 12.8)$ is an unstable focus.

2.2 The biotic part of the wetland system in space and time

$$\begin{aligned} \frac{dG}{dt} &= aG - bG^2 - cGB - d \frac{GP}{G + D} + \frac{\partial^2 G}{\partial x^2} \\ \frac{dB}{dt} &= eB - \frac{B^2}{W_1} - a_2GB + \frac{\partial^2 B}{\partial x^2} \\ \frac{dP}{dt} &= -\theta P + \phi \frac{GP}{G + D_1} + \frac{\partial^2 P}{\partial x^2} \end{aligned} \quad (4)$$

Equal diffusivity constants were assumed for good and bad biomasses. The value of the diffusion coefficient for the avian predator (birds) was taken to be 10^{-6} . The vegetation diffusion coefficient is 10^{-7} . Figures show contours of equal densities on a suitably chosen spatial scale. We assume that the horizontal extent of the wetland system is large compared to the depth of the wetland system. Each figure is accompanied with a scale specifically tailored to the species it represents. Dark blue represents small spatial densities, light blue represents slightly higher spatial densities, yellow and red represent higher spatial densities. The results show that “good” biomass has uniform spatial distributions in certain domains. The spatial distribution of “bad” biomass contains two distinct humps.

The “good biomass” acquires stable stationary patterns (Figure 3). The “bad” biomass performs swinging motion and selects a steady state spatial pattern given in Figure 4. Figure 5 presents stationary spatial distribution of the species clubbed under the category “bad” after the model system is allowed to run after a long period of time. Simulations in two - spatial dimensions are needed to unravel mysteries of system’s spatio-temporal dynamics.

The complete system displays three kinds of oscillatory motion which represents three different health conditions of the wetland [6]. The per capita availability of water to “bad biomass” is known to be the control parameter. An earlier study by one of the authors (VR) may be helpful in this regard as vegetation plays a critical role in BOD₅ removal and denitrification of the available nitrogen. The crucial factor for constructed wetland design for waste water treatment would be to control the density of the good and bad biomass; the

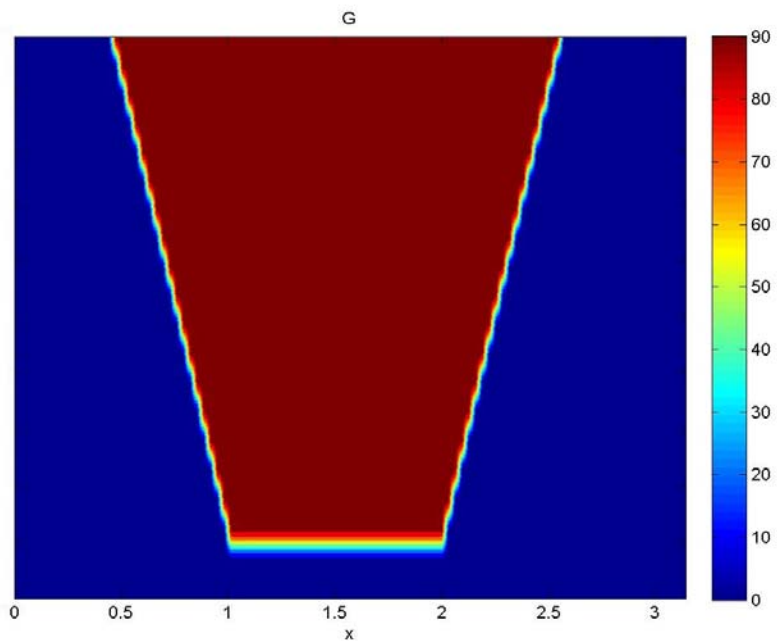


Fig. 3. Spatial distribution of the "good" biomass (G)

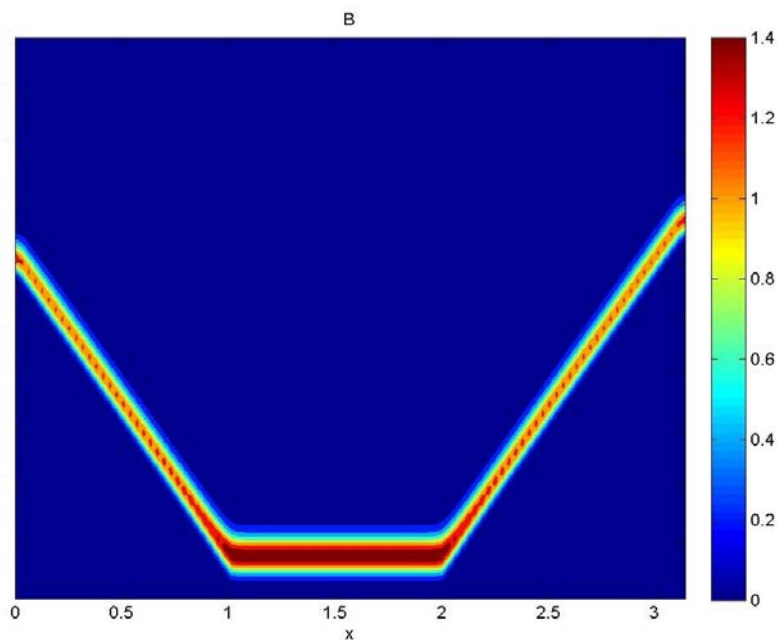


Fig. 4. The distribution of the "bad" biomass (B) - see section 2, para 2

vegetation component of the system. The chemical fertilizer upstream deteriorates the water quality (WQ) of the wetland. Construction of an artificial wetland in the vicinity of the natural one would restore the water quality standards.

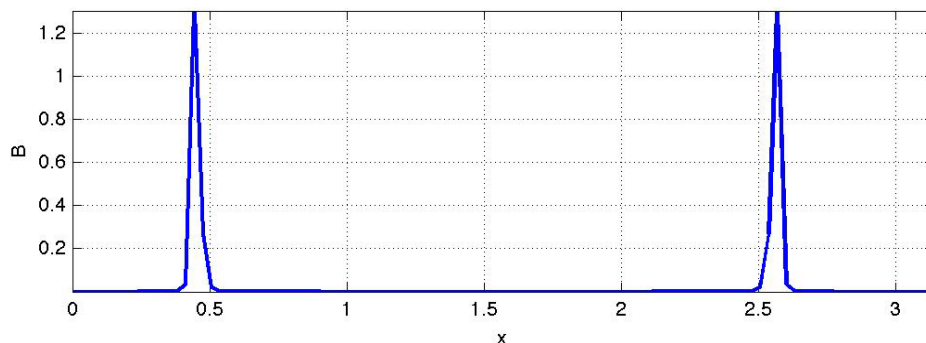


Fig. 5. The spatial distribution of the “bad” biomass after the system is run for a long period of time

3. Constructed wetlands for water pollution management

These man-made wetlands are used to treat aquaculture and municipal water, to regulate the water quality of shrimp ponds and manage pollution from pond effluents. The wetland treated effluents satisfy standards for aquaculture farms. Since the technology to use the constructed wetlands to treat waste water of high BOD₅ is limited, these are generally used to polish secondary effluents. Other applications of constructed wetlands are (a) to treat acid mine drainage, (b) to treat storm water, and (c) the enhancement of existing wetlands.

The suggestion to use wetland technology for waste water treatment is attractive for both ecological and economic reasons. Constructed wetlands are efficient in removing pathogens [2]. It performs better than conventional waste water treatment methods although the lack of knowledge of principles of pathogen removal in plants hampers optimum performance. Interactions between soil matrix, micro-organisms and plants and higher retention time of the waste water in these biologically complex systems make phyto-remediation more effective than conventional systems. Phyto-remediation involves complex interactions between plant roots and micro-organisms in the rhizo-sphere. The efficient functioning of wetland systems is hampered due to following factors:

- High redox potentials,
- Acidity of effluents, i. e., low pH and
- Microbial degradation of organic substrates (i.e. BTEX, petroleum-derived hydrocarbons, HET, phenols).

Wetland systems efficiently treat water polluted by heavy metals, chromium and magnesium.

The metal removal in these systems involves following mechanisms:

- Filtration and sedimentation of suspended particles,

- Incorporation into plant material,
- Precipitation by microbial mediated biogeochemical processes, and
- Adsorption on the precipitates.

Constructed wetlands are either free water surface systems with shallow water depth or subsurface flow systems with water flowing laterally through the land and gravel. These wetlands have been used for wastewater treatment for nearly 40 years and have become a widely accepted technology available to deal with both point and non-point sources of water pollution. They offer a land-intensive, low-energy, and low-operational-requirements alternative to conventional treatment systems, especially for small communities and remote locations. Constructed wetlands also prove to be affordable tools for wastewater reclamation, especially in arid and semi-arid areas. Although the emission of N_2O and CH_4 from constructed wetlands is found to be relatively high, their global influence is not significant towards their contribution to global warming.

Three main components of an artificial wetland are as follows:

(a) Construction practices

While design should be kept as simple as possible to facilitate ease of construction and operation, the use of irregular depths and shapes can be beneficial to enhance the wildlife habitat. The site for construction should be properly chosen so as to limit damage to local landscape by minimizing excavation and surface runoff during construction and, at the same time, maximize flexibility of the system to adapt extreme conditions.

(b) Soil

The chosen soil must not contain a seed bank of unwanted species. The permeability of the soil should be carefully controlled as highly permeable soils may allow infiltration and possible contamination of ground water. High permeability is not conducive for development of suitable hydrological conditions for wetland vegetation. Use of impermeable barriers may be suggested in certain instances.

(c) Selection of vegetation

Plant species among native and locally available species should be chosen keeping in mind water quality and habitat functions. The use of weedy, invasive and non-native species should be avoided. Plants ability to adapt to various water depths, soil and light conditions should also be taken into consideration.

In the following, design and construction of two kinds of artificial wetlands which are used for water purification will be described.

3.1 Free water surface (FWS) wetland systems

These systems consist of basins or channels with subsurface barrier to prevent seepage, soil or another medium to support the emergent vegetation and water at a shallow depth flowing through the unit. The shallow water depth, low flow velocity and presence of plant stalks and litter regulate the water flow [3]. The soil permeability is an important parameter. The most desirable soil permeability is 10^{-6} to 10^{-7} meter per second. The uses of highly permeable soils are recommended for small waste water flows by forming narrow trenches and lining the trench walls and bottom with clay or an artificial liner.

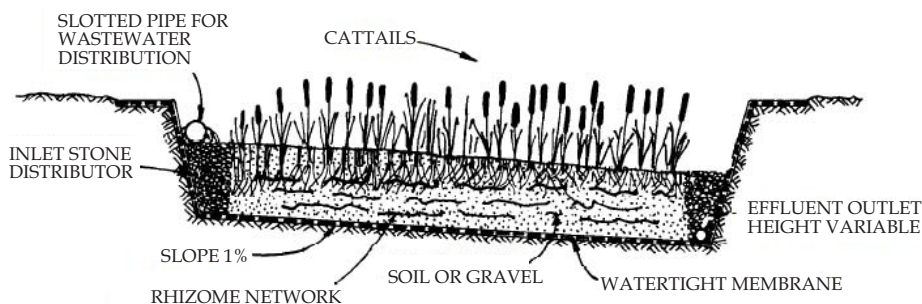


Fig. 6. A cross - sectional view of a Free Water Surface Wetland system (reprinted from the US Environmental Protection Agency design manual)

The hydrologic budget is an important part of design of constructed wetlands. The following water balance equation is generally used

$$Q_i - Q_o + P - ET = \frac{dV}{dt}, \quad (5)$$

Where:

- Q_i influent waste water flow, volume/time
- Q_o effluent waste water flow, volume/time
- P precipitation, volume/time
- ET evapo-transpiration, volume per unit time
- V volume of water, and
- t time.

Ground water inflow and infiltration are excluded from the above equation as impermeable barriers are used. Historical climatic records can be used for estimating the precipitation and evapo-transpiration. Infiltration losses can be estimated by conducting infiltration tests [3].

Typical dimensions of a FWS are:

- Length \approx 64 meters
- Bed width = 660 meters.
- Bed depth = 0.3 meters,
- Retention time is 5.2 days.

Divide the width into individual cells for control of hydraulic loading rate. Vegetation used in United States is Cattails, reeds, rushes, bulrushes, and sedges. Physical presence of this vegetation transports oxygen deeper than it would reach through diffusion. Submerged portions serve as home for microbial activity. The attached biota is responsible for treatment that occurs.

3.2 Constructed wetlands with horizontal subsurface flow (HF)

Horizontal Subsurface Flow systems (submerged horizontal flow) consist in basins containing inert material with selected granulometry with the aim to assure an adequate hydraulic conductivity (filling media mostly used are sand and gravel). These inert

materials represent the support for the growth of the roots of emerging plants (cf. Fig. 7). The bottom of the basins has to be correctly waterproofed using a layer of clay, often available on site and under adequate hydro-geological conditions or using synthetic membranes (HDPE or LDPE 2 mm thick). The water flow remains always under the surface of the absorbing basin and it flows horizontally [11]. A low bottom slope (about 1%) obtained with a sand layer under the waterproof layer guarantees this.

During the passage of wastewater through the rhizo-sphere of the macro-phytes, organic matter is decomposed by microbial activity, nitrogen is denitrified. In the presence of sufficient organic content, phosphorus and heavy metals are fixed by adsorption on the filling medium. Vegetation's contribution to the depurative process is represented both by the development of an efficient microbial aerobic population in the rhizo-sphere and by the action of pumping atmospheric oxygen from the emerged part to the roots and so to the underlying soil portion, with a consequent better oxidation of the wastewater and creation of an alternation of aerobic, anoxic and anaerobic zones. This leads to the development of different specialized families of micro-organisms. It also leads to nearly complete disappearance of pathogens, which are highly sensitive to rapid changes in **dissolved oxygen content**. Submerged flow systems assure a good thermal protection of the wastewater during winter, especially when frequent periods of snow are prevented.

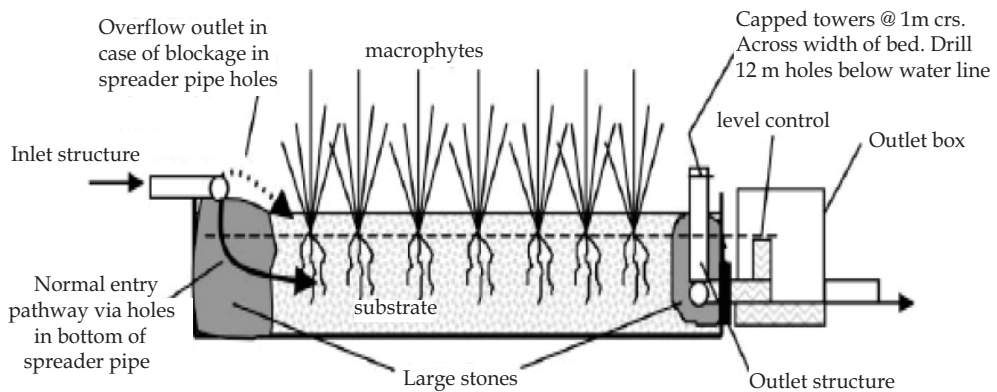


Fig. 7. Sketch of a subsurface flow wetland showing the working principles (reprinted from reference [10])

Key design parameters of horizontal subsurface flow constructed wetlands

- hydraulic loading rate (HLR),
- aspect ratio,
- size of the granular medium, and
- water depth.

Hydraulic linear loading rate is the volume of waste water that the soil surrounding a waste water infiltration system can transmit far enough away from the infiltration surface such that it no longer influences the infiltration of additional waste water. It depends on the soil characteristics. In principle, the hydraulic loading rate is equal to the particles settling

velocity. A greater surface allows capture of particles with smaller settling velocities. Typical hydraulic rates in subsurface flow wetlands vary from 2 to 20 cm per day.

The aspect ratio defines the length to width ratio. This is considered to be of critical importance for the adequate flow through the wetland. Constructed wetlands are designed with an aspect ratio of less than 2 to optimize the flow and minimize the clogging of the inlet.

3.3 Performance evaluation

Wetland systems significantly reduce biological oxygen demand (BOD₅), suspended solids (SS), and nitrogen, as well as metals, trace element, and pathogens. The basic treatment mechanisms include sedimentation, chemical precipitation, adsorption, and microbial degradation of organic matter, Suspended solids and nitrogen, as well as some uptake by the vegetation.

Microbial degradation (also expressed as biological oxygen demand BOD₅) in a wetland can be described by a first-order degradation model

$$\frac{C_e}{C_o} = \exp(-K_T t) \quad (6)$$

Where:

C_o influent BOD₅, mg/L

C_e effluent BOD₅, mg/L

K_T temperature-dependent first-order reaction rate constant, d⁻¹

t hydraulic residence time, d

Hydraulic residence time can be represented as

$$t = \frac{LWd}{Q} \quad (7)$$

Where:

L length

W width

d depth

Q average flow rate = (flow_{in} + flow_{out}) ÷ 2

Equation (7) represents hydraulic residence time for an unrestricted flow system.

In a FWS wetland, a portion of the available volume will be occupied by the vegetation; therefore, the actual detention time is a function of the porosity (n). The porosity is defined as the remaining cross-sectional area available for flow.

$$n = \frac{V_v}{V} \quad (8)$$

With:

V_v volume of voids,

V total volume.

The ratio of residence time from dye studies to theoretical residence time calculated from the physical dimensions of the system should be equal to the ratio.

Combining the relationships in Equations (7) and (8) with the general model (Equation 6) yields

$$\frac{C_e}{C_o} = A \exp \left[-0.7 K_T (A_v)^{1.7} \frac{LWdn}{Q} \right] \quad (9)$$

Where:

A fraction of BOD₅ not removable as settling of solids near head works of the system (as decimal fraction),

A_v specific surface area for microbial activity, m²/m³

L length of system (parallel to flow path), m

W width of system, m

d design depth of system, m

Q average hydraulic loading of the system, m/d

n porosity of system (as a decimal fraction).

$$K_T = K_{20} (1.1)^{(T-20)}, \quad (10)$$

where K_{20} is the rate constant at 20°C.

Other coefficients in equation (5)

$$A = 0.52$$

$$K_{20} = 0.0057 \text{ d}^{-1}$$

$$A_v = 15.7 \text{ m}^2/\text{m}^3$$

$$n = 0.75$$

In most of the SFS wetlands, the system is designed to maintain the flow below the surface of the bed where direct atmospheric aeration is very low. The oxygen transmitted by the vegetation to the root zone is the major oxygen source. Therefore, the selection of plant species is an important factor. The required surface area for a subsurface flow system is given by

$$A_s = \frac{Q(\ln C_o - \ln C_e)}{K_T dn} \quad (11)$$

The cross - sectional area for the flow for a subsurface flow is calculated according to

$$A_c = \frac{Q}{k_s S}, \quad (12)$$

Where $A_c = d \times W$, cross - sectional area for wetland bed, perpendicular to the direction of the flow, m²,

d bed depth, m

W bed width, m

k_s hydraulic conductivity of the medium, $\frac{\text{m}^2}{\text{m}^3} \text{ d}$

S slope of the bed, or hydraulic gradient.

The bed width is calculated by the following equation

$$W = \frac{A_c}{d}$$

Cross - sectional area and bed width are established by Darcy's law

$$Q = k_s A_s S \quad (13)$$

The value of K_T is calculated using

$$K_T = K_{20} (1.1)^{(T-20)} \quad (14)$$

$K_{20} = 1.28 \text{ d}^{-1}$ for typical media types.

4. Conclusion

Constructed wetlands are a cost-effective technology for the treatment of waste water and runoff. Operation and maintenance expenditure are low. These systems can tolerate high fluctuation in flow; with wastewaters with different constituents and concentration. Free water systems (FWS) are designed to simulate natural wetlands with water flow over the soil surface at shallow depth. FWS are better suited for large community systems in mild climates. The treatment in subsurface flow (SF) wetlands is anaerobic because the layers of media and soil remain saturated and unexposed to the atmosphere. Use of medium - sized gravel is advised as clogging by accumulation of solids is a remote possibility. Additionally, medium - sized gravel offers more number of surfaces where biological treatment can take place. Thus SF types of wetlands perform better than FWS. A properly operating constructed wetland system should produce an effluent with less than 30 mg/L BOD, less than 25 mg/L of total suspended solids and less than 10,000 cfu per 100 mL, fecal coliform bacteria.

In sum, we note that artificial wetlands are known to perform better as far as removal of nitrogen is concerned. The removal of phosphorous and metals depend critically on contact opportunities between the waste water and the soil. Performance of both kinds of constructed wetlands is poor as contact opportunities are limited in both of them. The submerged bed designs with proper soil selection are preferred when phosphorous removal is the main objective. In contrast to this, removal of suspended solids is excellent in both types of artificial wetlands. Constructed (artificial) wetlands assume special significance as natural wetlands are degrading at a rate faster than the other ecosystems. Two primary ecological agents which cause degradation of natural wetlands are

1. eutrophication and
2. introduction of invasive alien species.

The water in the wetland must be shielded from sunlight in order to control algae growth problems. Algae is known to contribute to suspended solids and cause large diurnal swings in oxygen levels in the water.

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