Manual on

Constructed Wetland as an Alternative Technology for Sewage Management in India

सत्यमेव जयते

Department of Biotechnology
Ministry of Science & technology
Government of India

IN PURSUIT OF CLEAN ENVIRONMENT
cpcb

Central Pollution Control Board
Ministry of Environment, Forest & Climate Change
Government of India

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Content

PREFACE

Water, next to oxygen is arguably the most important resource to humans on the planet. However, too often, for too many people, water is either not readily available or is not safe to drink. Although more than two and a half billion people have gained access to improved drinking water sources since 1990, 663 million people still do not have access to clean water. It is estimated that 50% of the world's population will have to survive in water stressed conditions by 2020. Scarcity of water is bound to be associated with inadequate water management, sanitation, hygiene and occurrence of diseases.

Improving sanitation has been a key priority in the agenda of the Indian Government, for which several flagship programmes including the Swachh Bharat Abhiyan, and Namami Gange were designed and implemented to get holistic and sustainable water management into practice with time-bound targets. In this context, in order to reach the heart of the water scarcity dilemma, it becomes inevitable to reduce and recycle the amount of wastewater being generated. In a way to achieve these, various simple and affordable solutions need to be developed. Constructed wetlands (CW) are emerging as affordable technologies for treatment of wastewater in a decentralized framework. CW are ecologically engineered systems that have been designed and constructed to mimic the processes found in natural wetland ecosystems involving wetland vegetation, soils, and the associated microbial assemblages to assist in treating wastewaters. They are designed to take advantage of many of the same processes that occur in natural wetlands, but do so within a more controlled environment. CW as alternative or supplementary systems are simple to construct, operate and maintain by small or large communities.

This manual intends to cover in a consistent way, the current to most innovative and systematic advances specific to constructed wetlands. The manual provides a comprehensive idea about the wetlands, type of wetlands and applications and challenges to the treatment of sewage along with the plethora of new technological developments. Subsequently, the manual depict in detail the ways in which engineered wetlands can be constructed, with intent to provide guidance on the design, construction, operation and maintenance along with a few case studies. This manual will able to serve as reference for public health officials and water professionals in the domain of domestic wastewater management and sanitation.

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Dr. S. Venkata Mohan
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FOREWORD

The trajectory of our industrialization, urbanization and anthropogenic activities has led to an increase in the amount of wastewater generated, inexorably leading to water pollution and scarcity. Water pollution is one of the main causes of human health problems across the globe and it is responsible for causing more human deaths than collectively by any other means. Treating wastewater is a sustainable contribution to the environment. In the 17 Sustainable Development Goals (SDGs) of the United nations SDG 6 is dedicated to water and sanitation. It is also included in the health, disaster risk management, and environmental targets of other goals.

Although efforts to curb the menace of pollution are being pursued, more directed and focused approaches are required for improving access to water and sanitation with affordable technologies. Smaller, decentralized, wastewater management and treatment systems are essential alternatives for both urban and rural areas. Constructed Wetlands (CW) offer simple, self-adaptive, affordable and sustainable solutions for waste management specific to decentralized applications. This manual provides a comprehensive framework of information on the working principles, constructional aspects, operation and maintenance of CWs.

I congratulate the Editorial Team and Expert Committee for their effort in bringing out this State-of-Art compendium on Constructed Wetland specific to domestic wastewater management. I hope that this technically rich exploration on inexpensive and environmentally friendly 'Constructed Wetland Technology' for wastewater treatment would provide further direction to the waste management community to adopt a sustainable, and naturally effective way of wastewater treatment. This manual will be an important reference centerpiece of the government's campaign on improving sanitation and providing clean water to all.

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CENTRAL POLLUTION CONTROL BOARD
पर्यावरण, वन एवं जलवायु परिवर्तन मंत्रालय भारत सरकार
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FOREWORD

Water quality of aquatic resources is deteriorating due to discharge of untreated domestic and industrial wastewater. In India, sizeable gap exists between sewage generation and treatment capacity and substantial funding would be necessary to bridge the gap. In view of limited financial resources, however, it is desirable to consider alternate and natural treatment measures so that water quality of surface river bodies can be improved.

There is therefore an urgent need to develop effective and innovative technologies for treatment of a large variety of contaminants. Accordingly, need is felt to develop a document on alternate treatment technologies and constructed wetland technology is one such promising technology which can provide effective solution for wastewater treatment.

I congratulate the Editorial Team and Expert Committee for their untiring efforts for bringing out this State-of- Art report. I hope this manual on 'Constructed Wetland Technology' for waste water treatment would provide very useful information to the funding agencies and stakeholders for adopting an eco-friendly, clean and effective way of treatment.

(S.P Singh Parihar)

Date: 26/03/2019

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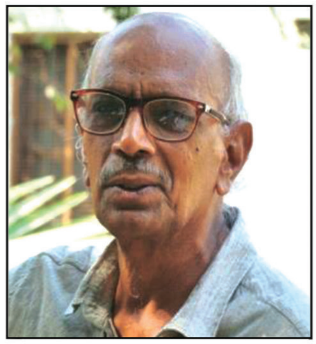
FOREWORD



The world, at large, is facing water crises, and the climate change may make the water availability scenarios bad to worse in many countries. India is a water deficit country and many urban centres are facing the acute water scarcity. One way to address the challenge of water scarcity is to recycle waste water, particularly sewage. Conventional techniologies such as the Sewage Treatment Plants are widely used in India, but the installed capacity of STPs is less than half of the total sewage generated in the country. Further, STPs have many limitations and are dysfunctional due to one or other reasons.

Natural wetlands have been in use for more than a Century in the treatment of waste water, including sewage. The Constructed Wetland (CW) is an engineered/designed wetland for the treatment of waste water, and is widely used across the world as primary/secondary/tertiary treatment for waste water and it is also considered as alternative to Conventional Technologies.

However, in India the use of Constructed Wetlands for sewage treatment is very limited and does not find place in CPCB manuals as one of the approved technologies for sewage treatment. This is because that CWs: (i) require more land, (ii) emit bad odours, (iii) clog the filtering system, and (iv) are duysfunctional after 1 or 2 years. Presently, design of CWs has been vastly improved and in-situ CWs can overcome all the limitations mentioned above. In fact, in-situ CWs are cost effective and the quality of treated water is much better than the STP treated water.

Realizing the need to promote CWs as alternative to conventional technologies, the Department of Biotechnology and Central Pollution Control Board, Government of India, jointly brought out this manual on "Use of Constructed Wetland Technology for Sewage Management in India". An Expert Committee was constituted to bring out this manual, and for which the Committee expresses its gratitude to the Secretary, Department of Biotechnology. The Committee also acknowledges the contributions made by Dr. Pradeep Sharma and Dr. Onkar Tiwari of the Expert Committee in the preparation of and bringing out this manual.

The present manual on the "Use of Constructed Wetland Technology for Sewage Management in India" gives a comprehensive account on different facets of CWs, including their designs and the available models in a simple language. I do hope that the Manual is useful to all stakeholders involved in the treatment of sewage, policy makers, planners and researchers.

C. R. Babu

(C R Babu)
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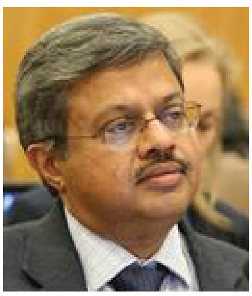

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LIST OF ABBREVIATIONS

ABR: Anaerobic Baffled Reactor

BOD: Biological Oxygen Demand

CW: Constructed wetlands

COD: Chemical Oxygen Demand

CEC: Cation Exchange Capacity

CPHEEO: Central Public Health and Environmental Engineering Organization

DO: Dissolved Oxygen

ET: Evapotranspiration

FWS: Free water Surface

HSSF CW: Horizontal Subsurface Flow Constructed wetland

HRT: Hydraulic Retention Time

HLR: Hydraulic Loading Rate

MoEF & CC: Ministry of Environment Forest and Climate Change

NRCS: Natural Resources Conservation Service

O&M: Operation & Maintenance

PE: Person Equivalent

PC: Prior Converted

SF: Surface Flow

SSF: Subsurface Flow

SS: Suspended Solids

TN: Total Nitrogen

TP: Total Phosphorous

TSS: Total Suspended Solids

TFAW: Tidal Flow Artificial Wetland

US EPA: United States Environment Protection Agency

VSSF CW: Vertical Subsurface Flow Constructed wetland

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1. Natural Wetlands And Their Role

1.1 Introduction

Natural wetlands are ecosystems that are either permanently or temporarily saturated in water, providing a natural habitat for biotic organisms and supporting conditions that promote the development of wetland soils. The structure of a natural wetland is shaped due to its surrounding abiotic conditions and these may be classified as: marshes, swamps, forested wetlands, bogs, and wet meadows, as well as coastal wetlands such as mangroves. The ability of wetlands to retain large volumes of water, which they release slowly, makes them significant for combatting extreme weather conditions such as flood control and drought mitigation, that occur more frequently as a result of climate change. Additionally, wetlands contribute to water purification, water regulation, biodiversity, aesthetics and recreation.

Within the natural wetlands many biological activities occur, therefore these are known to be as "biological supermarkets". Natural wetlands endowed shelter to many species by providing huge quantity of food for their survival. The life cycle in the natural wetland ecosystem shows similarity as in other ecosystems. For example, in wetlands, bacteria degrade the dead decay matter of plants and animals into organic form as they do in other ecosystems.

As stated by **Ramsar Convention**, natural wetlands are those "areas of marsh, fen, peat-land or water, whether natural or artificial, permanent or temporary, with water that is static or flowing, fresh, brackish or salt, including areas of marine water the depth of which at low tide does not exceed six meters."

As stated by **National Wetlands Working Group, (1988)**, wetland are those areas which are generally found in waterlogged condition to enhance the wetland and aquatic growth as denoted by poorly drained soils, hydrophytic flora and different types of biological activities which are conditioned to be grow in wet environment.

Natural wetlands are further divided into two sub-heads-

1. Organic soil wetland
2. Mineral soil wetland

Organic soil wetlands:

Organic soil wetlands are commonly known as peatland because of its ability to form peat. Peat is referred to the formation of organic soil by collecting plants material. Majorly peatlands are divided into two types i.e., fens and bogs both the type shows similarity in their climatic and geographical areas.

Fen- In this type of organic soil wetland the area is specified by peat soil, having surpassed vegetation like grasses, sedges, and reeds. In this wetland the soil is alkaline in nature and primarily obtains water from the sources like surface and ground water.

Bogs- This type of wetland specifically having wet, spongy, insufficiently drained peaty soil with surpassed vegetation of big mosses, *Sphagnum,* and heaths, particularly *Chamaedaphne.* This wetland contains acidic soil.

Mineral soil wetlands:

Mineral wetlands are found in mineral soil areas associated with shallow water, with a depth generally < 2 m.

Marsh – This type of wetland is insufficiently drained with mineral soils and grasses are the dominant plant species. The plants result in slowing down the water flow rate and allow the adherence of nutrient rich sediments and providing favorable condition for the further development of marshes.

Swamp – This type of wetland is insufficiently drained with mineral soils and trees are the dominant plant species. It is found all over, commonly in low lying areas next to river.

1.2 Types of Natural Wetlands

On the basis of its source, nutritious content, caloric/warmth virtue and vegetation the natural wetland are grouped into various types as stated in Figure 1.

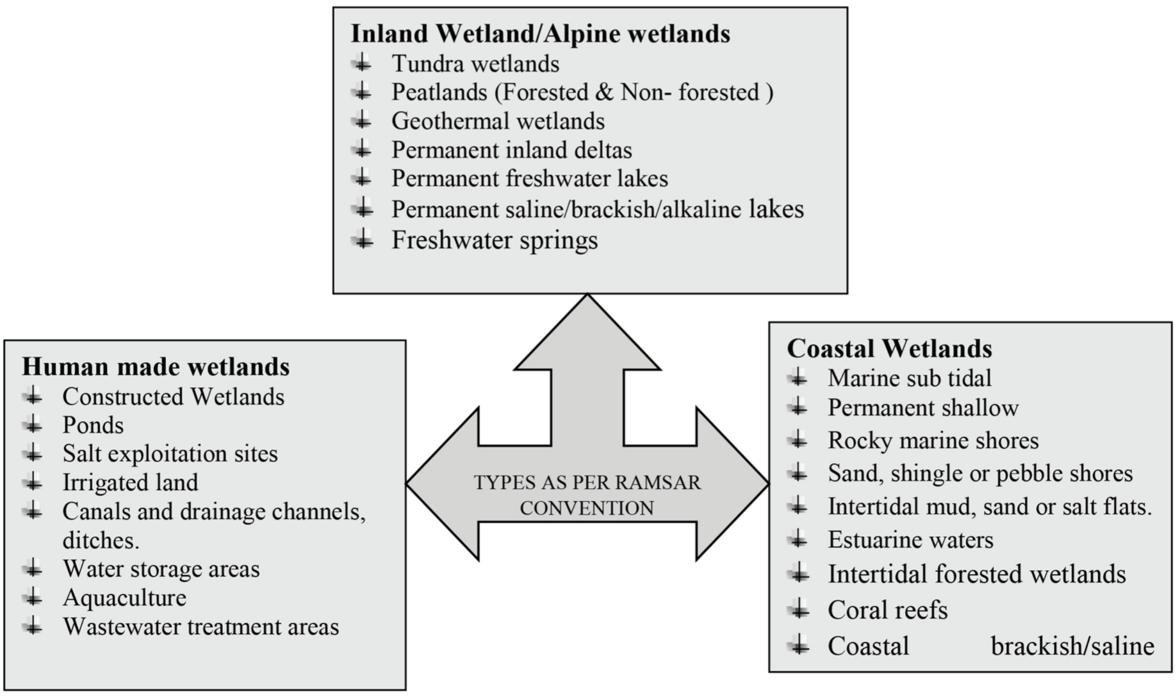

Figure 1: Various types of wetlands as per Ramsar convention

1.3 Process Mechanisms of Natural Wetland

In natural wetlands the wastewater is purified by means of various chemical, physical and biological processes. The water quality mainly improves by means of nutrient transformations as described in Figure 2.

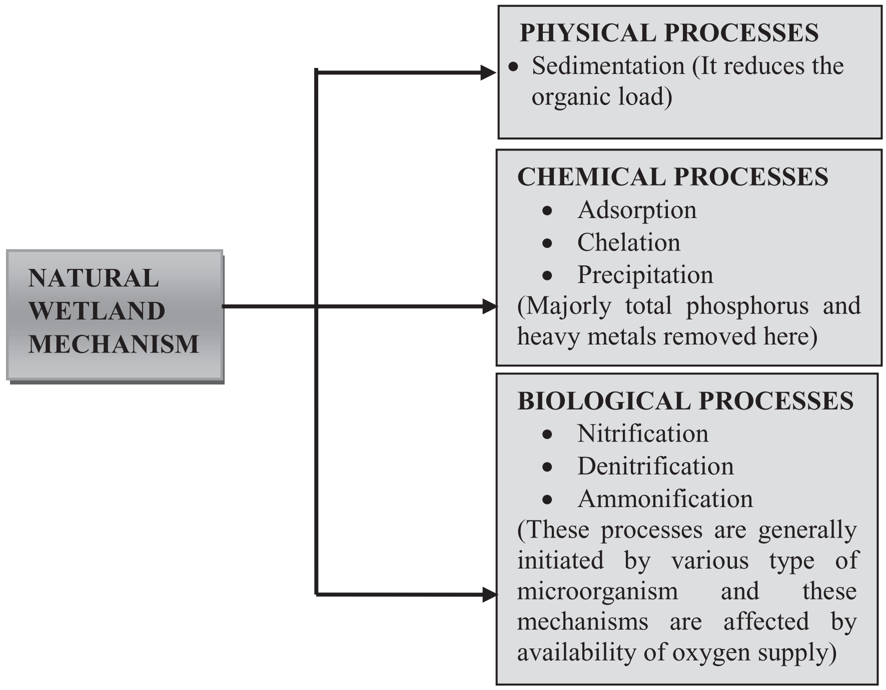

Figure 2: Working mechanism of natural wetlands

1.4 Distribution of Natural Wetlands

In India wetlands are spread in various geographical areas ranged from Himalayas to Deccan plateau (Table 1). Variation in seasonal conditions and topography results in remarkable diversity.

Table 1: State/Union Territory-wise wetland area in India (MoEF&CC, GOI)

S. No.	State	Wetland area (ha)	% of state geographic area
1	Jammu & Kashmir	391501	1.76
2	Himachal Pradesh	98496	1.77
3	Punjab	86283	1.71
4	Uttarakhand	103882	1.94
5	Haryana	42478	0.86
6	Delhi	2771	0.93
7	Rajasthan	782314	2.29
8	Uttar Pradesh	1242530	5.16
9	Bihar	403209	4.4
10	Sikkim	7477	1.05
11	Arunachal Pradesh	155728	1.78
12	Nagaland	21544	1.3
13	Manipur	63616	2.85

14	Mizoram	13988	0.66
15	Tripura	17542	1.59
16	Meghalaya	29987	1.34
17	Assam	764372	9.74
18	West Bengal	1107907	12.48
19	Jharkhand	170051	2.13
20	Orissa	690904	4.49
21	Chhattisgarh	337966	2.5
22	Madhya Pradesh	818166	2.65
23	Gujarat	3474950	17.56
24	Maharashtra	1014522	3.3
25	Andhra Pradesh	1447133	5.26
26	Karnataka	643576	3.36
27	Goa	21337	5.76
28	Kerala	160590	4.13
29	Tamil Nadu	902534	6.92
	Total	**15017354**	

S. No.	Union Territories	Wetland area (ha)	% of UT geographic area
1	Chandigarh	350	3.07
2	Daman & Diu	2068	18.46
3	Dadra & Nagar Haveli	2070	4.25
4	Lakshadweep	79586	96.12
5	Puducherry	6335	12.88
6	Andaman & Nicobar Islands	152809	18.52
		Total	**243218**

1.5 Importance of Natural Wetlands

- Functions as natural water filter/water quality improvement
- Helps in reducing the flooding condition and the desynchronization of storm rainfall and surface runoff
- Provide various water usages in irrigation, domestic needs, fisheries and recreational uses etc.
- Helps in ground-water recharge
- Reduces the algal bloom in the water body and provide nitrogen and phosphorus in needed form to the flora fauna
- Maintains the carbon cycle and cycling of nutrients and other materials
- Natural wetlands provide habitat to migratory birds
- Absorbs contamination at point source.

2. Introduction of Constructed Wetland Technology

2.1 Genesis of Constructed Wetland Technology

Constructed wetlands (CW) are the artificially created man made systems in which wastewater treatment take place by utilizing natural processes by involving soil, vegetation, and microbial communities. They resemble to the natural wetlands in treatment processes, but processes are carried out in a controlled environment **(Vymazal, 2010).**

The concept of constructed wetlands was given by **Kathe Seidel** in early 1950s. She studied CW system for treatment of different types of wastewater at Max Planck Institute. The early systems developed by Seidel comprised series of beds composed of sand and gravel with emergent vegetation (*Typha, Scirpus, and Phragmites*) and were named as hydrobotanical systems. Seidel used vertical flow in most of her experiments and excellent removal of BOD_5, TSS, N and P was claimed.

In early 1960s attempts were made to grow macrophytes in wastewater and sludge to improve the efficiency of septic tank or ponds and thus performance of wastewater treatment. **(Vyamzal, 2005).**

FWS CW was firstly developed in Hungary in 1968 for the treatment of town wastewater by preserving water quality of Lake Balaton. The North America also used free water surface constructed wetlands (FWS CW) for treatment of wastewater of natural wetlands using ecological engineering. This technology was utilized by North America for treatment of all types of wastewaters along with municipal wastewater **(Kadlec and Wallace, 2008).** Subsurface flow technology gained popularity later than FWS CW in North America but at present are in operation in high number.

In 1970s and 1980s the use of constructed wetlands was done merely for treatment of municipal and domestic wastewater. In 1975 Amoco Oil Company's Mandan Refinery in North Dakota used CW for treatment of process water and industrial storm water. In early 1980s use of FWS CW for treatment of urban wastewater started in California. First full scale constructed wetland for treatment of municipal sewage was developed in Othfresen, Germany **(Kickuth, 1977)**. Kickuth proposed the application of cohesive soils as filter medium with horizontal flow and *Phragmites plants as* vegetation. Theory behind his experiments was to open up-flow channels in the unified soil due to plants root/rhizomes growth which increased the conductivity of soil. Due to increased conductivity efficient removal of BOD_5, TSS, N, P and other organics was observed.

In 1985 many reed bed systems including gravel as bed media with sloping bottom and a flat surface were built in Great Britain based on Kickuth's concept soil **(Boon, 1985).** The purpose of using gravel instead of cohesive soil was to increase soil hydraulic conductivity while sloping bottom provided enough hydraulic gradients to make sure subsurface flow in the bed.

By 1990, about 500 of these 'reed bed' or 'root zone' systems were established in different parts of Europe. Since 1990s the constructed wetlands have been extensively built and operated for treatment of all kind of wastewater such as dairy farm **(Sharma *et al.*, 2013; Kato *et al.*, 2013)**, landfill leachate, runoff, food processing, industrial, agricultural farms, mine drainage and sludge dewatering **(Farooqi *et al.,* 2008)**. Historical development of this constructed wetlands is illustrated in Table 2.

Table 2: Historical developments of wetland treatment technology

	Flow	Year	Location	Application	References
Free water surface	Horizontal	1952-1970s	Plon, Germany	Removal of Phenols and dairy wastewater treatment with bulrush plants	**Seidel, 1966**
		1980s	California	Urban storm water treatment	**Chan *et al.*, 1982**
		1990-2000	USA Norway China Canada	For the treatment of Landfill leachate, industrial, stormwater and mine drainage	**Vymazal, 1998**
		2000 onwards	Canada USA Argentina Kenya, Greece Australia Spain UK, Sweden, Zambia New Zealand	For the treatment of Landfill leachate, pulp and paper, mine drainage, swine, dairy, domestic and industrial wastewater	**Hadad *et al.*, 2006**
	Horizontal	1960s	Germany	Various type of wastewater	**Seidel, 1966**
		1970s	Germany	Treatment of municipal sewage	**Kickuth, 1978**
		1980s	Germany, Australia	Treatment of municipal sewage and piggery effluent	**Kickuth, 1981 Finlayson *et al,* 1987**

		1990s	Worldwide, UK, USA, Australia, Slovenia, Germany China New Zealand Denmark Canada, Switzerland, Norway	For the treatment of municipal/ domestic, industrial, agricultural, run off and Landfill leachate wastewater	**Robinson *et al*., 1999**
		2000 onwards	UK, USA India Italy, Spain, Portugal, Kenya, Canada, Slovenia, Mexico Australia South Africa Lithuania Thailand, Germany France Taiwan, Italy, Poland	For the treatment of municipal/ domestic, industrial, agricultural, run off and Landfill leachate wastewater	**Bresciani *et al*., 2007**
	Vertical	1965	Germany	CW with vertical flow was used as pretreatment units before wastewater treatment in horizontal flow bed	**Seidel, 1965**
		1990s	Germany, Netherlands	For the treatment of municipal/ domestic, special organics, herbicides, dairy,and cheese dairy wastewater	**Kern and Idler, 1999**
		2000 onwards	Portugal, Canada,	For the treatment of municipal/	**Aslam *et al*., 2007**

			Australia Germany France Pakistan	domestic, special organics, leachate, and refinery wastewater	
	French - Hybrid	1979	France	The use of this system, developed by the CEMAGREF (now IRSTEA) in the early 1980's Used for treatment of raw sewage	**Liénard, 1987**
Subsurface	Hybrid	1965-1975	Krefeld, Germany		**Seidel, 1965**
		1990-2000	UK Nepal	Sewage wastewater, hospital	**Burka and Lawrence, 1990; Laber *et al.*, 1999**

2.2 Scope of Constructed Wetland Technology

2.2.1 Wastewater treatment

CW for Agriculture wastewater

Agriculture wastewater has been widely managed using constructed wetland systems in different countries (**Maddox and Kingsley, 1989; Hammer *et al.*, 1993; Du Bowy and Reeves, 1994; Cronk, 1996; Sun *et al.*, 1998; Kern and Idler, 1999; Knight *et al.*, 2000; Newman *et al.*, 2000; Nguyen, 2000; chaafsma *et al.*, 2000; Koskiaho, 2003; Mantovi *et al.*, *2003;* Poach *et al.*, 2003)**. CWs served as alternatives to conventional treatment options to eliminate/reduce contaminant and nutrient concentration in agricultural wastewaters **(Cronk, 1996; Peterson, 1998: Geary and Moore, 1999; Knight *et al.,* 2000; Borin *et al.,* 2001; Hunt and Poach, 2001; Szogi and Hunt, 2001; Braskerud, 2002)**. Several constructed wetlands have been studied for their capability to hold or alter nutrient inputs specifically from dairy and swine wastewaters. Further, many other dairy wetlands have been built in many states of the USA **(Holmes *et al.*, 1995, Chen *et al.*, 1995, Kadlec and Knight, 1996).** In Ireland, over a dozen dairy farms use integrated CW to handle farmyard waste water **(Dunne *et al.*, 2005).**

CW for domestic wastewater treatment

In many countries due to mountainous topography many rural communities were short of wastewater collection and treatment facilities. In the 1980s, USEPA gave consent to employ constructed wetlands for treatment of domestic wastewater **(Bastian *et al*., 1987).** Low operational cost, effective treatment capabilities along with aesthetic properties of surface or subsurface flow wetlands made a suitable choice for homeowners in individual or small group residential community **(Hiley, 1995; Knight, 1993; Knight *et al*., 1993; Steiner and Combs, 1993; Mitsch and Gosselink, 2000).** In Ohio, USA constructed wetland (CW) were also evaluated for water treatment of a single family system **(Steer *et al .,* 2002**). In Czech Republic, there were 62 constructed wetlands treating domestic or municipal sewage water by 1995 **(Vyamazal, 1998).**

CW for industrial wastewater treatment

Use of constructed wetland technology is not well recognized for treatment of industrial effluents **(Kao and Wu, 2001; Garcia *et al.,* 2004; Worall *et al*., 1997).** Perhaps the most promising application of constructed wetlands is for the control of many organic compounds in the landfill leachates. CWs have been used for advanced tertiary treatment of refinery wastewaters at Amoco's Mandan, ND facility for over 20 years **(Litchfield and Schatz, 1989; Litchfield, 1990, 1993)**. Wetland wastewater treatment in the petroleum industry is not confined to U.S. The Petrochemical Company in China stated decline in phenol and oil by wetlands system using water hyacinth **(Tang and Lu, 1993).**

Wetlands have been reported to successfully removal of metals from mine drainage water, and were recommended an economical, self-maintaining substitute to conventional methods for treatment of different kinds of wastewater **(Erten *et al*., 1988; Gopal, 1999; Weis and Weis, 2004)**. Similarly, In Argentina a pilot scale wetland was built to evaluate the possibility of treating the wastewater from a tool industry **(Hadad *et al.,* 2006).**

Various wetlands exist for treating different types of industrial wastewater such as tannery wastewater **(Calheiros *et al.,* 2007)**, textile waste **(Mbuligwe, 2005),** pulp and paper wastewater **(Knight, 1993),** acid mine drainage **(Kleinmann and Girts, 1987.)** etc.

2.2.2 Enhancement of aesthetic value of site with landscape

Constructed wetlands can provide intagible benefites by increasing the aesthetic value of the site and enhancing the landscape by presence of water, vegetation and associated wildlife. This appeals tourists throughout the world. The CW incorporates appropriate land forming design during construction to make it appealing aesthetically.

Understanding of existing topography and local landscape is required for CW land forming. Efforts are also needed to make mound or ridge in a curve/linear form in order to make landscape attractive at site from distance too. Ease of access for visitor/tourist to CW habitat can further increase the value of site.

Moreover, flora growth further enhances the appearance of site. Proper CW land forming according to the landscape minimizes CW maintenance and thus improves its functional prolonged existence.

2.2.3 Restoration of habitat diversity and nature management

Constructed wetland can be used in restoration of habitat biodiversity. Habitat restoration can be maximized by paying attention at the stage of designing. Infrastructural details needed to restore habitat includes following points:

- For greatest floral and faunal diversity, wide, deep and low elevated boundaries to the embankment should be used.
- Native vegetation should be incorporated wherever possible.
- Depth of water should be managed.
- The performance of plant species of CW depends on soil and water properties.
- Most common plant genera used in CW includes: *Juncus, Phragmites Acorus, Carex, Eleocharis, Glyceria, Iris, Scirpus, Sparganium, Ranunculus, and Typha.*
- The selection of plant species depends upon depth of water, conductivity of the water turbidity, organic matter, pH and concentration of ammonium ion.
- For selection of plant, factors like plant growth, physiology of plant, physical appearance and adaptability of plant for survival must be considered.

2.3 Components of Constructed Wetlands

Water, substrate/Media and plants are major components of constructed wetlands. These components can be engineered during the constructing of wetland. Communities of microbes and aquatic invertebrates develop naturally.

Water: Wetlands are likely to form where landforms direct surface water to shallow basins and where a relatively impermeable subsurface layer prevents the surface water from seeping into the ground (**A handbook of constructed wetlands volume 1: general considerations USDA - NRCS, EPA - Region III**). These conditions can be created to construct a wetland. A wetland can be built almost anywhere in the land-scape by shaping the land surface to collect surface water and by sealing the basin to retain the water. Hydrology is the most important design factor in the construction of wetlands because it links all the functions.

Substrate/Media : The substrate that physically supports vegetation in a constructed wetland is vital as it forms an integral link in treatment processes that occur in the wetland (**Stankovic,**

2017). Apart from vegetation, they also act as the principal storage of all biotic and abiotic components that exist in a wetland. Soil or graded gravel or sediments support many of the living organisms and substrate permeability affects the movement of water through the wetland. Many chemical and biological (especially microbial) transformations take place within the substrates (**Stankovic, 2017**). Gravel and sand are also used as filtering materials. Bound filtering materials were also used in the past but, today, their use is discouraged due to a high clogging hazard. In a saturated substrate, water replaces the atmospheric gases in the pore spaces and microbial metabolism consumes the available oxygen. Since oxygen is consumed rapidly it will be replaced by diffusion from the atmosphere. This eventually creates anoxic (without oxygen) condition (reducing environment) which is important in the removal of certain pollutants such as nitrogen and metals (**A handbook of constructed wetlands volume 1: general considerations USDA - NRCS, EPA - Region III**).

Vegetation: Wetlands have individual and group characteristics related to plant species and to their adaptations to specific hydrological, nutrient, and substrate conditions. Both vascular plants (the higher plants) and non-vascular plants are important in constructed wetlands(**A handbook of constructed wetlands volume 1: general considerations USDA - NRCS, EPA - Region III**). The rooted class is subdivided into emergent, floating, and submerged classes. The adaptation of certain plant depends on the design criteria of wetland, morphological and physiological features of plant (**Venkata Mohan et al., 2010**). Vegetation play an integral role in wetland treatment system by transferring oxygen through their roots to the bottom of treatment basins, and by providing a medium beneath the water surface for the attachment of microorganisms that perform the biological treatment (**Qasaimeh et al., 2015**). Aquatic plants are divided into free floating and rooted forms. Plants contribute to the treatment of wastewater and stabilize substrates and limit channelized flow with slow velocities, allowing suspended materials to settle, they take up carbon, nutrients, and trace elements and incorporate them into plant tissues and they transfer gases between the atmosphere and the sediments (**Venkata Mohan et al., 2011**). They create the oxygenated microsites within the substrate by leakage of oxygen from subsurface plant structures (**A handbook of constructed wetlands volume 1: general considerations USDA - NRCS, EPA - Region III**). The stem and root systems provide sites for microbial attachment and create. Most frequently used macrophytes species are cattails (*Typha sp.)*, reeds (*Phragmites sp.*), bulrushes (*Scirpus sp.*), sedges (*Carex sp.)* and several broad-leaved species. These species are used because they help transform wastewater constituents so that quality standards for their discharge are met. Photosynthesis by algae increases the dissolved oxygen content of the water which in turn affects nutrient and metal reactions.

Table 3:Major roles of macrophytes in constructed wetlands (Brix, 1997)

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

Microorganisms: A fundamental characteristic of wetlands is that their functions are largely regulated by microorganisms and their metabolism (**Wetzel, 1993**). Microorganisms include bacteria, yeasts, fungi, protozoa and algae. The microbial biomass is a major sink for organic carbon and many nutrients. The microbial consortia have transformed a great number of organic and inorganic substances into offensive or insoluble substances. They are improve reduction/oxidation (redox) conditions of the substrate and thus affects the processing capacity of the wetland and involved in the recycling of nutrients. Some microbial transformations are aerobic while others are anaerobic. Many bacterial species are facultative anaerobes, that is, they are capable of functioning under both aerobic and anaerobic conditions in response to changing environmental conditions. The microbial community of a constructed wetland can be affected by toxic substances, such as pesticides and heavy metals, and care must be taken to prevent such chemicals from being introduced at damaging concentrations (**A handbook of constructed wetlands volume 1: general considerations USDA - NRCS, EPA - Region III**).

Aquatic Animals: Constructed wetlands can provide habitat for a rich diversity of invertebrates and vertebrates. Invertebrate animals, such as insects and worms. contribute to the treatment process by fragmenting detritus and consuming organic matter (**Venkata Mohan et al., 2010**). The larvae of many insects are aquatic and consume significant amounts of material during their larval stages, which may last for several years. Invertebrates also fill several ecological roles; for instance, dragonfly nymphs are important predators of mosquito larvae. Although invertebrates are the most important animals as far as water quality improvement is concerned, constructed wetlands also attract a variety of amphibians, turtles, birds, and mammals.

2.4 Advantages of Constructed Wetlands

- Estimated cost of wetland construction is comparatively less than other treatment methods
- Construction does not need expensive materials
- Operation and maintenance of the system is easy
- Once established process is consistent.
- Process does not require fossil fuels and chemicals for treatment.
- Besides purification, facility can be used for fish cultivation, production of biomass, agriculture, recreation, flora and fauna conservation and water supply for different purposes **(Santer, 1989; EPA, 1993; Knight, 1997).**
- Able to meet the target effluent quality.

2.5 Limitations of Constructed Wetlands

- For construction needs large area.
- Land availability and affordability is a constraint.
- Knowledge of wetland ecology and native wetland species is a pre-requisite.
- Optimizations of parameters become difficult when different wastewater get mixed together.
- Periodic harvesting of the biomass is essential to maintain consistent performance.
- Design criteria still in development for different kind of wastewater in different climatic conditions.

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3. Types of Constructed Wetlands

There are various design configurations of constructed wetlands **(Haberl, 1999)** and they can be classified on the basis of following parameters, as illustrated in Figure 3.

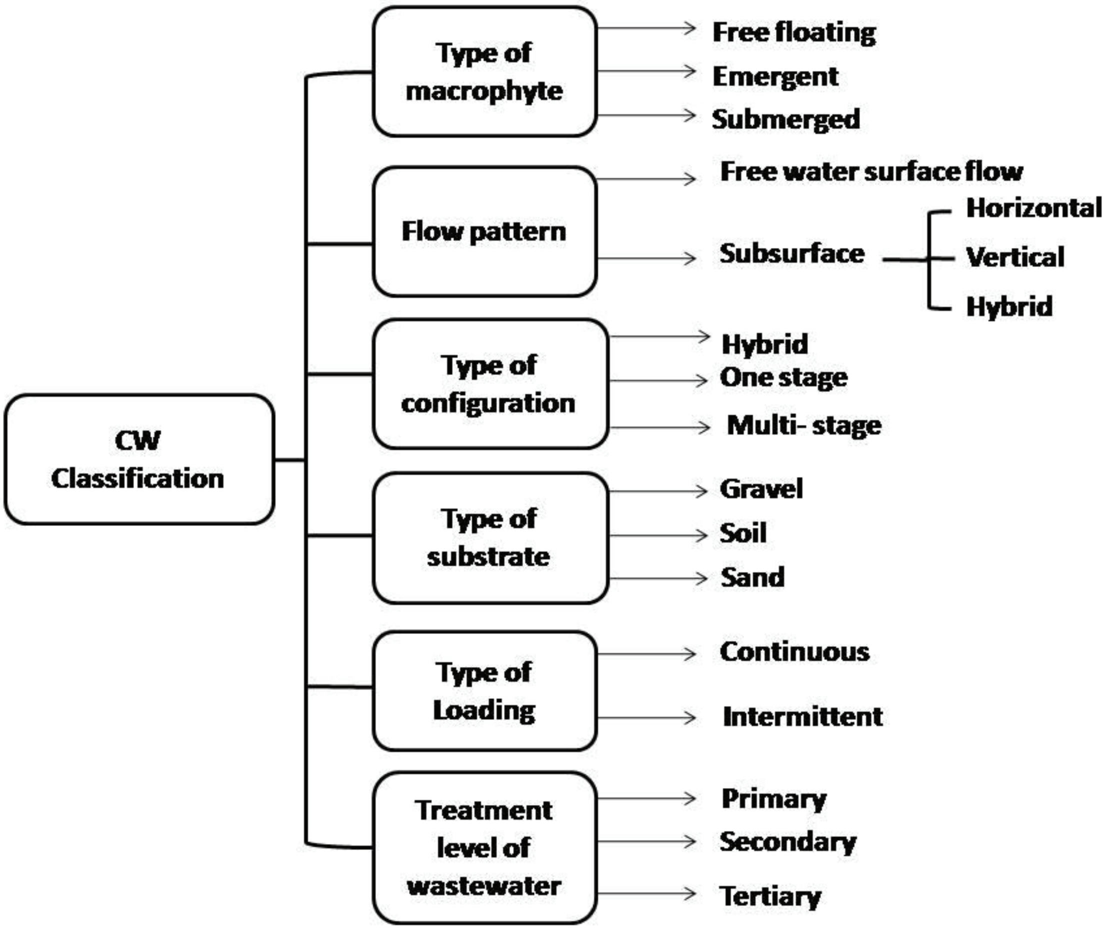

Figure 3: Classification and Types of Constructed Wetland Systems

Constructed wetlands are categorized as surface/free water surface flow and subsurface flow systems. Free Water Surface (FWS) wetlands/ surface flow wetlands are heavily planted systems in which water flow is above the media bed. Subsurface flow treatment wetlands are categorized into Vertical Flow (VF) and Horizontal Flow (HF) wetlands on the basis of the direction of water flow. HF and VF wetlands are not suitable for primary treatment due to risk of clogging of the filter media and are often used for secondary treatment of wastewater. In the past years, modified VF wetlands termed as 'French Systems' have also been introduced and adopted for treatment of screened raw wastewater. The French VF wetlands save construction cost by eliminating the pre-treatment structures and thus wastewater treatment in a single system.

3.1 Free Water Surface (FWS) Constructed Wetland

FWS wetlands appear similar to natural wetlands. FWS wetlands are deep basins planted with emergent and rooted vegetation. FWS wetlands are less loaded with requirement of large surface area. The flow of wastewater in FWS is across the surface of beds and therefore named as free water surface (FWS) wetland.

Water in FWS flows at depth of 6 to 18 inches from surface, depth of water depends upon the type of vegetation and design of wetland. The slope of bottom may have slight gradient (from inlet to outlet) or must be flat. A range of plant genera can be utlized: a) Emergent (*Typha, Phragmites, Scirpus)*, (b) Submerged (*Potamogeon, Elodea*, etc), (c) Floating (*Eichornia*, *Lemna).*

Most of the treatment in FWS wetland occurs from the microbial activities (bacteria and fungi), that reside in wetland environment. Most of the organisms become adsorbed to stems of submerged plant and litter, while others get incorporated in the soil/plant-root matrix. Besides this the whole water column is loaded with microorganisms that are involved in the treatment process. Suspended solids removal occurs rapidly in FWS wetland system. The major removal mechanisms include surface adhesion, sedimentation and aggregation **(QDNR, 2000)**. Wetland vegetation enhances sedimentation process by minimizing water column mixing and desorption of particles from the sediment surface.

Settleable organic compounds are removed by deposition and filtration in FWS CW while soluble organic compounds are degraded by suspended and attached microbes by aerobic and anaerobic mechanisms.

The mechanisms for phosphorous removal in FWS include adsorption, absorption and precipitation, however P-removal take place at slow rate in comparison to subsurface CW. Substantial storage of P also occurs in peat/litter. Plant and biotic retention of phosphorous may be high but is a short duration process, desorption from debris occurs back to water.

In FWS CWs nitrogen removal occur by nitrification and subsequent denitrificaton in aerobic water conditions and anoxic litter layer on the bed surface respectively. Volatilization also plays a major role for N elimination in constructed wetlands (CWs) with free water surface where high pH values are created due to algal photosynthesis.

FWS wetlands are mainly employed for tertiary treatment. They have also been used to treat effluent generated from treatment lagoons, waste storage ponds, acid mine drainage, dairy farms, croplands runoff and discharges from aquaculture facilities. Moreover, SF wetlands in comparison to floating aquatic plant systems are relatively easy to manage and maintain. Surface flow wetlands works efficiently throughout the year with slight reduction in efficiency in winter season in cold climate.

3.2 Horizontal Flow (HF) Constructed Wetland

Horizontal flow wetlands are also termed as 'Reed beds' (In Europe), "Reed bed treatment system" (In the United Kingdom) and "Vegetated Submerged Beds" (In the United State). HF CW requires land area 5-10 m^2 PE^{-1} (PE- population equivalent). In HF CW water level is managed to flow at sub-surface and it flows horizontally through sand or gravel based substratum. During this passage the wastewater become exposed to network of aerobic, anoxic and anaerobic zone but degradation processes are restricted mainly to anaerobic and anoxic zone due to the water-saturated condition. Aerobic zone is limited only around root and rhizomes that leaks oxygen into the substrate.

Organic compounds degradation majorly occurs by anoxic and anaerobic decomposition by bacteria attached to roots/rhizomes of plants. Due to insufficient oxygen transport capacity of reed plants limited organic compounds degradation take place by aerobic process. In HF CW limited removal of Phosphorous takes place due to the fact that media used (crushed stones, pea gravel) for HF CW contains low quantities of Fe, Al or Ca, which help in sorption/precipitation of Phosphorous. Nitrogen in HF CW is removed primarily by nitrification/ denitrification reactions however studies have shown that due to insufficient oxygenation of rhizosphere incomplete nitrification occurs **(Brix and Schierup 1990; Vymazal, 2007).**

HF CW is used for secondary or tertiary treatment. In these systems, a well-designed primary treatment is necessary for eliminating particulate matter to avoid clogging of the wetland filter beds. They are often used to treat on site domestic water, municipal sewage, industrial, agricultural wastewater as well as landfill leachate.

3.3 Vertical Flow (VF) Constructed Wetland

VF CW requires less area for operation (1-3 m^2 PE^{-1}) in comparison to HF CW but needs more maintenance and operational efforts. Emergent macrophytes are used in VF CW. In VF CW wastewater is sporadically applied on the filter media surface which further percolates vertically down through the filter media. Mainly aerobic degradation processes occur due to entry of air into the pores of media between two loadings. Therefore, Vertical CWs are considered as aerobic filters which in turn enhance the nitrification process in the wastewater. VF CW provides a good removal of suspended solids (SS), organics and ammonia but slight denitrification takes place and therefore NH_3-N is generally only converted to NO_3^-N. Elimination of phosphorus in Vertical CW is generally low and can be increased using media with high sorption capacity. The early VF CWs were made up of several beds connected in series or parallel. Now days, VF CWs are usually constructed with one bed only and termed as "compact system".

Similar to HF CW, VF CWs also need efficient primary treatment to get rid of suspended particles to prevent filter clogging. VF CWs are mostly operated to purify domestic and municipal wastewater. However, in the literature, various reports are available on the use of VF CWs for treating different kind of wastewater such as composting leachate, refinery effluent, airport runoff and dairy effluent.

3.4 French Vertical Flow Constructed Wetland

French VF are type of VF wetlands used for treatment of wastewater after pre-treatment. Two beds of wetlands function in series arranged in parallel manner. Primary treatment unit is not essential in French VF wetland. Treatment area requirement for French VF is 2.0 – 2.5 m^2PE^{-1}. Removal efficiency of French VF for organic matter, suspended solids and ammonia nitrogen, total nitrogen and total phosphorous is equivalent to VF CW. French VF wetlands saves construction costs by providing both sludge and wastewater treatment in one system.

3.5 Hybrid Constructed Wetland

Hybrid constructed wetlands are constructed by combining individual systems (VF & HF) for obtaining a higher treatment efficiency. Most of the hybrid CWs consists of VF and HF beds connected together. Currently hybrid CWs are in use across the world and selected particularly when there is a need of NH_4-N and total-N removal.

Apart from sewage, hybrid CWs have been employed for treatment of various kinds of wastewaters, such as, Dairy waste water **(Sharma *et al.,* 2013),** landfill leachate, compost leaching , slaughterhouse , shrimp and fish aquaculture or winery .

3.6 Some of The Advanced Versions of CW Systems

3.6.1. Baffled Subsurface-flow constructed wetland

Removal of nitrogen is an important consideration in any treatment system (Figure 4). In horizontal subsurface constructed wetlands nitrification/denitrification is major removal processes, wherein volatilization, adsorption and plant uptake play a much less important role **(Tee *et al.,* 2012).** Insufficient oxygenation of the rhizosphere leads to incomplete nitrification which becomes the major cause of limited nitrogen removal. Vertical Flow constructed wetlands have relatively higher oxygen transport capacity which allows ammonia nitrogen to be successfully removed but only limited denitrification occurs in such a system **(Tee *et al.,* 2012).**

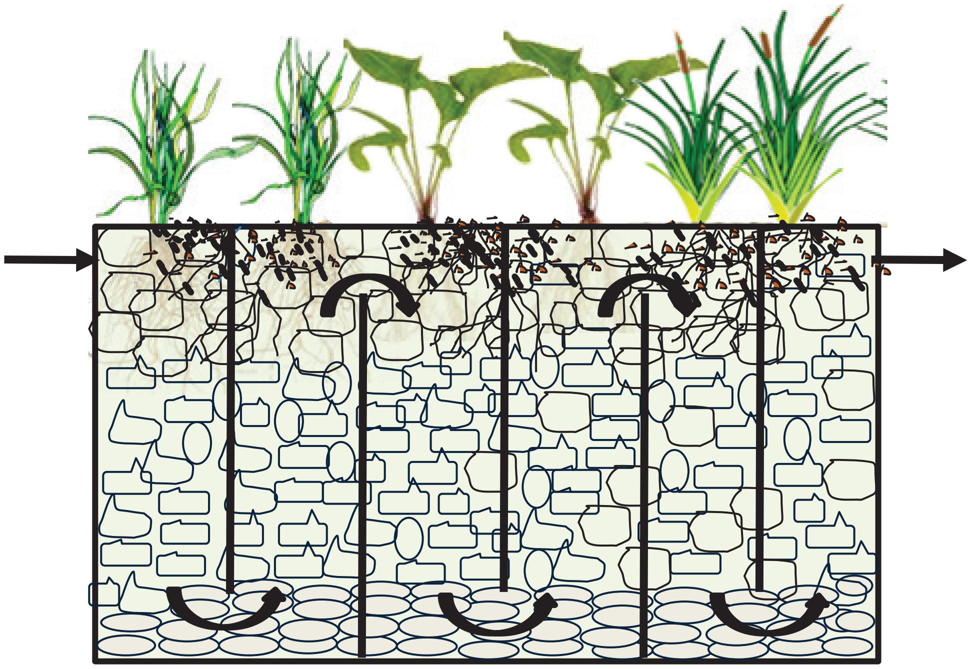

Figure 4: Baffled subsurface-flow constructed wetland.

In order to achieve high removal efficiency of nitrogen by providing both aerobic and anaerobic conditions simultaneously hybrid constructed wetlands are in operation with the requirement of a relatively large land area and a recycling system. A novel design for the horizontal subsurface constructed wetland incorporating up and down flow allowing treatment under multiple aerobic, anoxic and anaerobic conditions sequentially in same constructed wetland has been developed to enhance removal efficiency of the pollutants **(Tee *et al.,* 2012).** The design involves inserting vertical baffles along the width of the wetland thus forcing the wastewater to flow up and down instead of horizontally as it travelled from the inlet to the outlet (Figure 4). The baffles provides a longer pathway due to the up-flow and down-flow conditions sequentially thus allowing more contact of the wastewater with the rhizomes and micro-aerobic zones.

3.6.2 . Aerated Constructed Wetlands

Oxygen availability to support aerobic processes is the main limitation in CW, especially during nitrogen removal. To increase the oxygen availability, CWs can be installed with aeration system capable of transferring sufficient oxygen to perform aerobic processes **(Pascual *et al.,* 2019)** (Figure 5). Design variants spans from completely passive systems (HF), to moderately engineered systems (unsaturated VF systems with pulse loading) up to highly engineered or intensified systems, with increased pumping, water level fluctuation, or forced aeration (**Pascual *et al.,* 2019).**

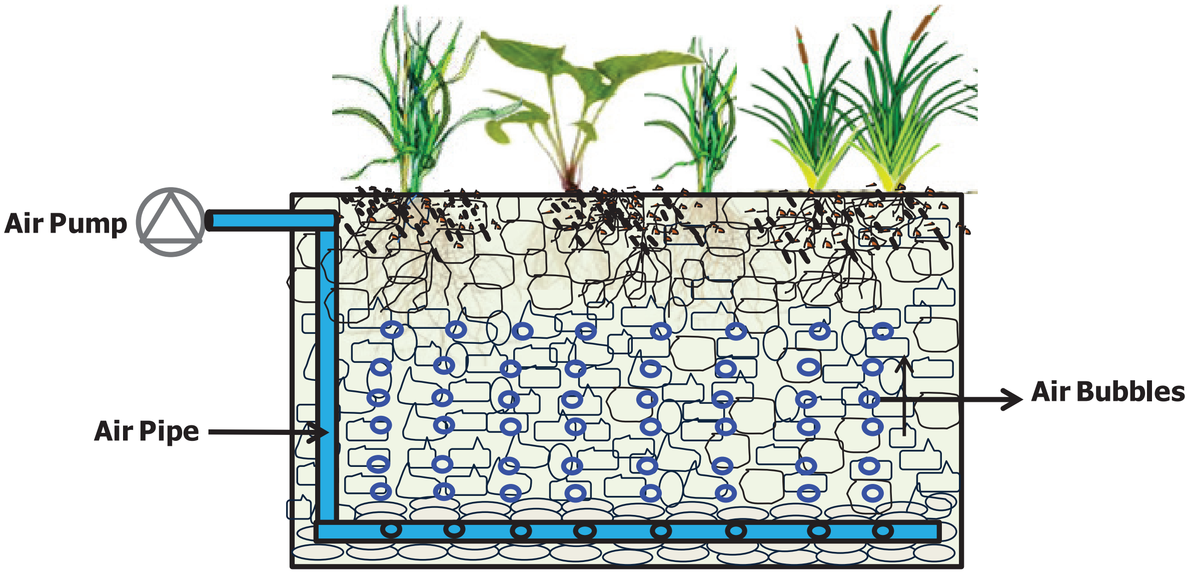

Figure 5: Aerated Wetlands

Artificial aeration can be classified as continuous aeration and intermittent aeration using tubing distributed across the bed of the wetland to create multiple coarse bubble through which wastewater has to pass. They are effective at nitrification even in cold climates. Aerated wetlands use less energy than conventional treatment processes. Passive processes remove BOD near the inlet zone, leaving much of the aerated wetland free for nitrification **(Pascual *et al.,* 2019)**. Recycle of nitrified effluent to the anoxic inlet zone can be implemented to promote denitrification. The need for aeration is derived from the strict need for mosquito control and odor control **(Pascual *et al*., 2019).** Aeration of the ponds helps maintain DO more than 1 mg/L for the fish in the system and minimizes H_2S gas production.

3.6.3 Multi-tropic Free-flow Engineered Wetlands

Miniature ecologically engineered constructed wetlands are principally designed to mimic the natural cleansing functions of the wetlands. It is flow through system segregated based on the tropic requirement for treatment in a defined sequence containing diverse biota viz., aquatic macrophytes, submerged plants, emergent plants, filter feeders, etc. connected in series **(Venkata Mohan *et al.,* 2010)** (Figure 6).

Figure 6: Multi-tropic Free Flow Engineered Wetlands semi-pilot scale (10 l/day) and Pilot scale facility (1000 l/day) [submerged plants, emergent plants, filter feeders, etc. connected in series) at CSIR-Indian Institute of Chemical Technology (CSIR-IICT), Hyderabad used for treatment of domestic sewage, lake water and industrial wastewaters.

This process brings about wastewater treatment by relying on the living systems in free-flow format. Natural abilities of living systems in synergy with the aquatic organisms will be considered in the design to breakdown and metabolize organics/nutrients at tropic levels balanced to perform their role by accelerating nature's own purification process using the principles of ecological engineering **(Todd *et al.,* 2003).** Floating aquatic plants such as water hyacinth (*Eichhornia crassipes*), duckweed (*Lemna* sp.), pennywort, etc. with submerged aquatic plants such as waterweed, water milfoil, water cress, etc. will be employed based on the availability and function. The plants provide a suitable habitation for bacteria that remove dissolved organics and nutrients. Introducing plants into constructed enclosures should be done carefully. This system is easy to implement and ideal for rural areas with relatively small foot prints. Plant biomass after harvesting can be used as a fertilizer, animal feed supplement, or source of biogas.

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4. Pollutant Removal Mechanisms In Constructed Wetlands

4.1. 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.

4.1.1 Sedimentation, Absorption and Adsorption

The floating matter is removed due to mechanical action of straining. Sedimentation is mainly used for removal of suspended solids in influent wastewater. Besides suspended solids, sedimentation is a major mechanism for elimination of microbial pathogens which mainly includes coliforms and other bacteria. Partial removal of organic matter also occurs by sedimentation process. Sedimentation process is driven by gravity which in turn depends upon shape size and gravity of particles along with consistency of fluid medium. Sedimentation or settling can be categorized into discrete and flocculent settling in view of no contact with other particles and interaction with other particles respectively. Solids settle down to the bottom of the constructed wetland and become part of the deposited material **(Norton, 2007; Dotro *et al.*, 2015).**

Sorption is a chemical process used to depict adsorption and absorption, which may be physical (using weak atomic and molecular interactions) or chemical (using stronger ionic-type bonds). Adsorption refers to retention of gas/ liquid/ dissolved substances on the surface of solids. Adsorption is an important mechanism for phosphorous removal **(LI jianbo, 2008).** Soluble inorganic phosphate becomes adsorbed to soil particles. Phosphorous adsorption is enhanced with increase clay content in soil owing to high cation exchange capacity in comparison to sandy soil. Apart from phosphorous heavy metals are also removed by adsorption to organic matter present in soil and water. Ammonium cation due to charged property also gets adsorbed to filter media. Size and chemical composition of filter media influence the adsorption of ammonium ion and can be enhanced by using specific media like zeolite **(Dotro *et al.*, 2015).**

Another mechanism of pollutant removal in CW is absorption by plants and microbial population. Phosphorous in its inorganic form i.e. orthophosphate is absorbed by macrophytes present in constructed wetland. Most of the phosphorous removal in constructed wetland occurs by absorption of plant roots. Absorption of P by other parts of plant (i.e. stems and leaves) is not significant. Microbial absorption of phosphorous occurs rapidly due to high multiplication rate however low storage capacity due to small size limits the amount of uptake **(Vymazal, 2006)**.

The mechanism responsible for each of the pollutant removal from the wastewater is summarized in Table 4.

4.2 Biological processes

The following major biological reactions are involved in the removal of contaminants from constructed wetlands including photosynthesis, fermentation, microbial removal, ammonification, nitrification, denitrification **(Mitchell, 1996b)**.

4.2.1 Ammonification

Ammonification is the primary step of nitrogen transformation in organic nitrogen rich wastewater received in CW systems. In ammonification process conversion of organic N to NH_4^+-N occurs by extracellular enzymes secreted by microbes **(Vymazal, 2007)**. It is energy yielding process where oxidative deamination of amino acids to NH_3 takes place. Ammonification is fast in upper layer of water due to prevalence of aerobic condition whereas it occurs slowly in lower layers due to change in environment from facultative anaerobic to obligate anaerobic **(Reddy and Patrick, 1984).** The rate of ammonification process also depends on pH (optimum pH-6.5-6.8) and temperature (ammonification doubles with temp. increase of 10°C) **(Patrick and Wyatt, 1964; Vymazal, 1995, Kadlec and Knight, 1996).**

4.2.2 Nitrification

Followed by ammonification, nitrification take place in nitrogen transformation in which oxidation of ammonium (NH_4^+) to nitrate (NO_3^-) is carried out by autotrophic bacteria with nitrite (NO_2^-) as a key intermediate product. Instead of organic nitrogen if NH_4^+-N predominates in water, the nitrification process starts directly without the need of ammonification. Nitrification takes place in two steps, in first stage conversion of NH_4-N to NO_2-N take place in presence of oxygen by chemolithotrophic microbes (e.g. Nitrosomonas, Nitrosococcus and Nitrosospira). In the second step NO_2-N is converted to NO_3-N by facultative chemolithotrophic bacteria (Nitrospira, and Nitrobacter) **(Reddy and Patrick, 1984)**

Nitrification process requires presence of desired microbes, O_2, alkaline conditions and micronutrients in the wastewater. Besides these requirements optimum temperature should be between 25-40°C **(Vymazal, 2007).** Most of the Nitrification is carried out by autotrophic microbes (Nitrosomonas and Nitrobacter). Apart from autotrophic bacteria heterotrophic bacteria are also involved in nitrification, however nitrification rate performed by heterotrophs are comparatively lower than autotrophic bacteria **(Gerardi, 2002).**

4.2.3 Denitrification

Denitrification is most effective mechanism of total nitrogen elimination in constructed wetlands (CWs) **(Chung *et al.,* 2008; Matheson and Sukias, 2010).** Denitrification converts nitrate into nitrogen gas (N_2), nitrous oxide (N_2O) or nitric oxide (NO); that is released to the atmosphere. The presence of high oxygen in VF systems results in poor denitrification, as the process need anoxic environment in the generation of N_2 (nitrogen) gas. Various bacteria are involved in denitrification process such as *Bacillus, Enterobacter, Micrococcus, Pseudomonas* and *Spirillum* **(Kadlec and Knight, 1996).**

Environmental parameters which influence denitrification rates include the level of dissolved oxygen (DO), pH, redox potential, type of media and organic matter concentration. Denitrifiers can use nitrates as electron acceptors but use oxygen preferably if present in water. Therefore, the desired DO concentration must be in range of <0.3-0.5 mg/L, to achieve nitrate reduction **(Bertino, 2010).** Denitrification process occurs in the anoxic environment with suspended and attached bacteria growth with low DO content **(Kadlec and Knight, 1996; Lee *et al.*, 2009).**

4.2.4 Photosynthesis

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 CW are bacteria, fungi, algae and protozoa.

4.2.5 Fermentation

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.

4.3 Microbial Degradation and Plant Uptake

Microbial degradation takes place to generate new cells by degrading soluble organic matter. The process involved in organic matter degradation may be aerobic and anaerobic but principally occurs by aerobic/facultative way. End products of organic matter degradation by aerobic and anaerobic method are carbon dioxide and water and carbon dioxide and methane, respectively **(Vymazal, 2006).** Decomposition rate depends upon dissolved oxygen concentration in wastewater. The soluble organic matter becomes attached to biofilm, which further decompose attached organic matter. The microbial population involved in organic matter decomposition includes bacteria, actinomycetes, and fungi.

Along with organic matter, organic forms of phosphorous such as phospholipids, nucleic acids (DNA, RNA) and phosphorylated sugars (easily decomposable organic phosphorus), and phytin (slowly decomposable organic phosphorus) are converted into inorganic phosphorous by microbial action.

Plant uptake is another important process for pollutants removal in constructed wetland. Plants can uptake and store inorganic nitrogen in the range of 0.2 to 0.8 g $N/m^2.d$ **(Vymazal, 2007)**, which depends upon the plant species and can be harvested (above ground biomass) intermittently. Along with above ground part nitrogen also remains stored in below ground parts of the macrophyte. Nitrogen absorbed by plant uptake is utilized in protein synthesis and thus increase plant biomass.

Metals are also eliminated by plant uptake. The metal uptake limit is governed by the type of macrophyte and type of heavy metal **(DeBusk, 1999b).** Metal accumulates in plant biomass and in the roots of plants. Some plants accumulate metals significantly for e.g. duckweed which can store a huge amount of metals such as Cu, Cd and Se. According to some researchers plant can uptake only 1-2 % of amount of metals present in constructed wetland, rest is removed by adsorbtion oxidation and sedimentation processes.

4.4 Chemical process

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 (EPA, 1995). 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.

Table 4: Major pollutants and their removal mechanisms

Pollutant	Main removal mechanism
Suspended solids	▪ Filtration ▪ Sedimentation
Nitrogen	▪ Ammonification followed by nitrification and denitrification ▪ Ammonia volatilization (mostly in SF system) ▪ plant uptake (only limited influence) and export through biomass harvesting
Phosphorous	▪ Retention in the soil by adsorption and precipitation reactions facilitated by filter media

	▪ Precipitation with calcium, aluminium and iron ▪ Plant uptake
Pathogens	▪ Sedimentation, ▪ Filtration ▪ Natural die-off due to long retention time ▪ Predation (carried out by protozoa and metazoa) ▪ UV irradiation (SF system) ▪ Excretion of antibiotics from roots of macrophytes
Heavy metals	▪ Precipitation and adsorption ▪ Plant uptake (partial) ▪ Cation exchange ▪ Complexation ▪ Microbial Oxidation /reduction
Organic matter	▪ Settling or filtration (Particulate organic matter). ▪ Microbial (aerobic/anaerobic bacteria) degradation (Soluble organic matter)
Organic contaminants	▪ Microbial adsorption and adsorption by clay particles ▪ Decomposition by aerobic/ anaerobic soil bacteria and due to long withholding

4.5 Abiotic Factors and their Influence on Wetlands

Oxygen: Oxygen in wetland systems is important for heterotrophic bacterial oxidation and growth. It is an essential component for many wetland pollutant removal processes, especially nitrification, decomposition of organic matter, and other biological mediated processes. It enters wetlands via water inflows or by diffusion on the water surface when the surface is turbulent. Oxygen also is produced photosynthetically by algae. Plants also release oxygen into the water by root exudation into the root zone of the sediments. Many emergent plants have hollow stems to allow for the passage of oxygen to their root tissues. The oxygen demand processes in wetlands include sediment-litter oxygen demand (decomposition of detritus), respiration (plants/animals), dissolved carbonaceous BOD, and dissolved nitrogen that utilizes oxygen through nitrification processes **(Kadlec & Knight, 1996)**. The oxygen concentration decreases with depth and distance from the water inflow into the wetland. It is typically high at the surface, grading to very low in the sediment water interface.

pH: The pH of wetlands is correlated with the calcium content of water (pH 7 = 20 mg Ca/L). Wetland waters usually have a pH of around 6-8 **(Kadlec and Knight, 1996)**. The biota of wetlands especially can be impaired by sudden changes in pH.

Temperature: Temperature is a widely-fluctuating abiotic factor that can vary both diurnally and seasonally. Temperature exerts a strong influence on the rate of chemical and biological processes in wetlands, including BOD decomposition, nitrification and denitrification.

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5. Designing of Constructed Wetlands

5.1 Preliminary Treatment

Pre-treatment of wastewater is essentially required before this wastewater is applied to the wetland beds because the sludge constituents such as oil, grease, and various solids (e.g., sand, fibers and trash) present in wastewater may clog the filter media of the wetland beds and subsequently interrupt the treatment processes. Therefore, the prevention and removal of these substances at initial stage is crucial for the long life of a CW treatment system. Pre-treatment processes such as screening, flotation, settling and filtration are considered as more efficient and are in use for treatment of variety of wastewaters including sewage. Some of the methods involved in pretreatment of wastewater are illustrated in the Figure. 7.

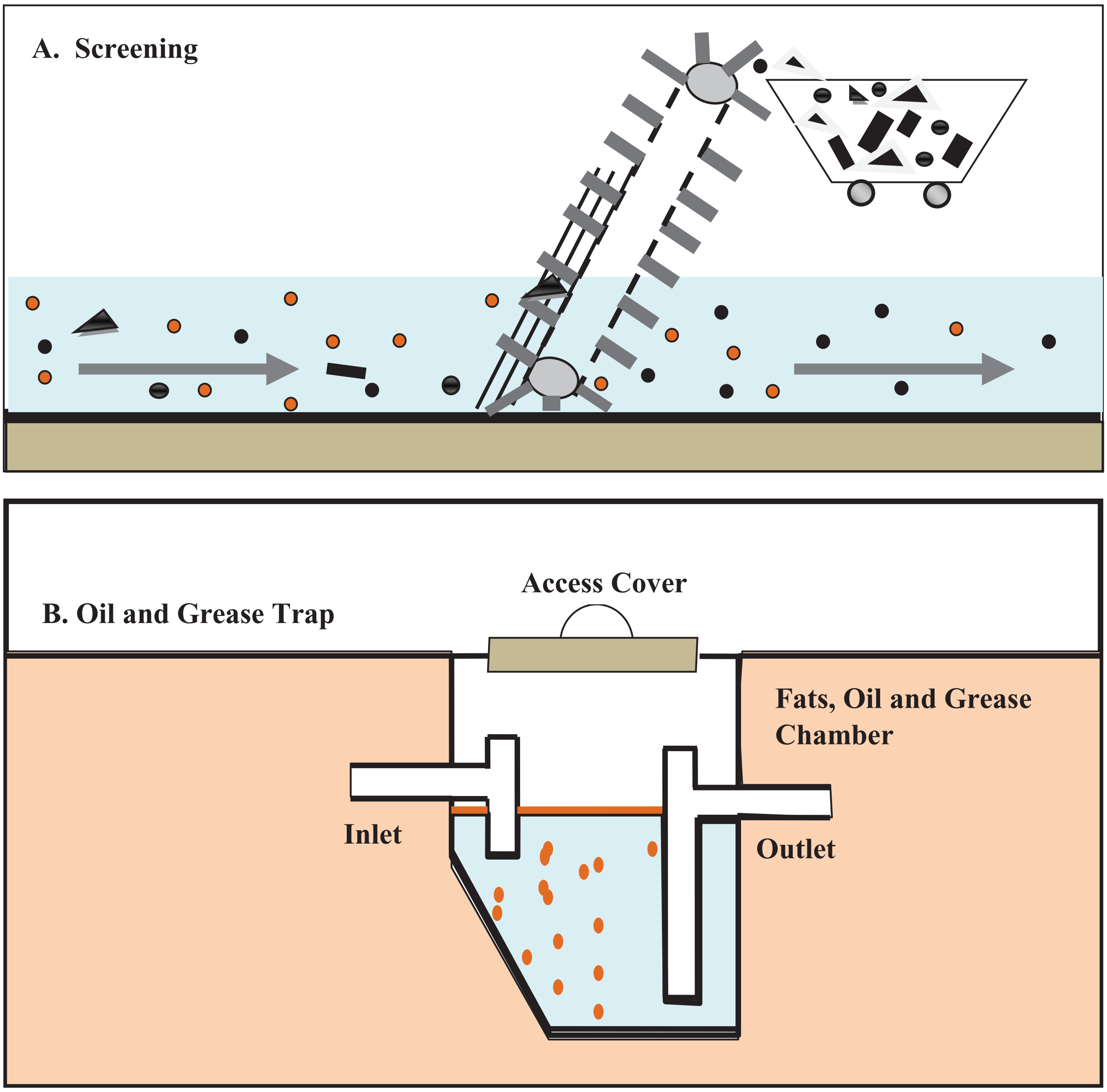


Figure 7: Layout of screening chamber and Oil & grease trap chamber (Tilley, *et al.*, 2014)

5.1.1 Grease Trap chambers

Presence of grease and oil in the wastewater obstructs the treatment process by clogging the filter media and by creating an anaerobic environment in the wetland bed, which is not desirable during the operation of a CW system. Therefore, the grease and oil should be removed from the wastewater during pre-treatment. Grease traps structures are the chambers made up of bricks, concrete or plastic, covered with an odor-tight cover at the top.

In a grease-trap chamber, baffles are constructed at the inlet and outlet points to prevent the turbulence at the water surface and to separate floating substances from the effluent. For small volumes of wastewater and small amount of oil and grease, an underground grease trap chamber is preferred whereas, for larger amounts of oil and grease, a bigger grease trap chamber can be installed above the ground.

Underground, small sized grease trap chambers are associated with an added advantage of relatively low construction cost, but require frequent cleaning (twice in a month), while a larger grease trap chamber has a drawback of higher capital cost, but it requires cleaning after a period of every 6 to 12 months. If designed properly, the grease trap chambers can also be utilized for removal of grit and other settleable solids through sedimentation.

5.1.2 Screening

Screening helps in intercepting the floating material from entering a sewage framework. These coarse particles if not removed can cause damage to the electric motors pumping the wastewater to the CW beds as well as might clog the top surface of wetland beds resulting into operational problems. The screening chamber is equipped with slanted screens or bar racks which help in obstructing coarse particles from wastewater. In a screening chamber, the spacing between the vertical bars should be fixed between 15 to 40 mm for an effective trap of solids.

5.1.3 Grit Chamber

A grit chamber is used for eliminating the suspended inorganic particles such as sandy and gritty matter from the wastewater. Grit chambers help in protecting the moving mechanical equipment from abrasion and wear as well as to prevent formation of heavy deposits in pipelines, channels and conduits. There are generally three kinds of grit chambers:

1. Horizontal-flow chambers
2. Aerated chambers
3. Vortex chambers

All the above grit chambers are potentially feasible to settle out the larger particles, while lighter ones remain in suspension form.

5.1.4 Compatibility

If there is high risk of clogging within the system, then grease traps are considered as an appropriate structure to be used. Grease traps are specifically applied whenever the oil and grease discharge quantity is very high in the wastewater. It can be included in the design for treating different kinds of wastewater.

Screening is also necessary to prevent the entrance of solid waste to sewer network. Trash traps, e.g., mesh boxes, likewise be connected at key locations like market drains. A grit chamber work efficiently in those areas where the roads are not paved and storm water get mixed directly with the sewer network by obstructing the deposition of sand and abrasion in wastewater.

5.1.5 Operation & Maintenance

For assuring the proper functioning of all the pre-treatment facilities the system should be routinely observed and cleaned. Less maintenance towards the treatment system results in degradation of sludge material, which gives pungent smell in the surroundings. It is also noted if the operation and maintenance of the system is not done properly then it will not work in an efficient manner or it may leads to failure.

The waste product during primary treatment should be disposed off in a manner that it does not harm the surrounding as well as environment. If the waste product is grease then it may be recycled and used for generation of energy.

5.2 Primary Treatment

5.2.1 Septic tank

Septic tank is mainly used for the primary treatment of sewage, which comprises of water tight chamber made up of concrete, fiber glass, PVC or plastic through which waste water flows. In a septic tank the degree of treatment is moderate as it only plays sedimentation and anaerobic processes to alleviate the removal of solids particles and organics. When the wastewater enters in the tank, the large particles settles at the bottom, while scum (mostly oil and grease) floats at the top. After some time period the settled solid starts degradation anaerobically.

In septic tank the sludge accumulation rate is fast compared to its decomposition rate, hence it is removed periodically. A well designed septic tank gives the removal rate of 30 to 40 % for BOD and 50 % for solid particles. The efficiency of the septic tank depends on its maintenance and operation as well as seasonal conditions.

5.2.1.1 Design considerations

Septic tank generally consists of two chambers. First chamber is measured at least half of the total length. If there are only two chambers to be built in septic tank, it should be two third of total length. In the first chamber all the solid particles get accumulated. Presence of baffle between the chambers helps in hindering the oil and grease particles which comes out with the effluent. Furthermore, T-shaped outlet pipes also prevent the discharged solids and scum.

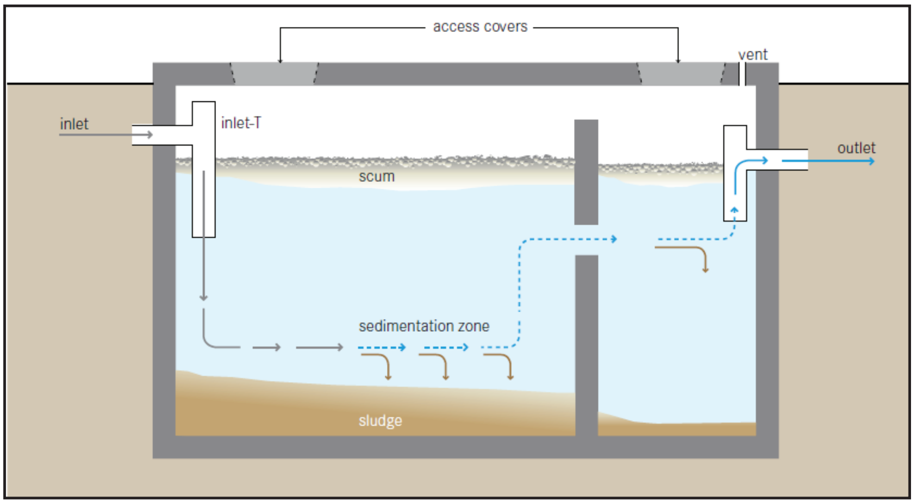


Figure 8: Cross-sectional view of the septic tank (Tilley, *et al.*, 2014)

All the chambers in the septic tank has to be assessed periodically for maintaining its working efficiency. The septic tank is ventilated adequately for controlling the release of odour and noxious gases. Design of a septic tank depends on various factors like water quantity used per capita, the average annual temperature, nature of wastewater, sludge removal frequency. It may be noted that hydraulic retention time of 48 hours is helpful in obtaining moderate treatment.

The basic design criteria for a two-chambered septic tank is shown in Table .5

Table 5: Design criteria for Septic Tank

Design parameters	Recommendations
Hydraulic retention time	> 12 hours at maximum sludge depth and scum accumulation
Sludge accumulation rate	Depending on TSS removal rate and wastewater flow (70 – 100 litres/person/year)
Sludge and scum accumulation volume	Sludge accumulation rate multiplied by sludge accumulation rate
Desludging interval	> 1 year
Volume of first compartment	Two-third of the entire tank volume

5.2.1.2 Compatibility

This technology is highly compatible for the household use. Bigger, multi structured septic tanks can be used for many house groups, public structures etc. using septic tank technology in dense populated areas where onsite infiltration is not possible by which the ground becomes highly saturated (wastewater overflow) and full of contamination, results in health hazards.

To cope up with those situations sometimes the septic tank should be connected to some conveyance technology by which the effluent is directly transferred to a forthcoming treatment or disposal area. Although septic tanks are tightly sealed, it is not suggested to construct it near the areas having high water tables and facing flooding situation repeatedly. Therefore, the selection of the site for septic tank is done in a manner that a vacuum truck will be access easily for the removal of sludge. Generally septic tank is installed for the home purpose under the area of kitchen and washrooms, in this condition it facing difficulty for the sludge removal. The working efficiency of the septic tank shows variation in colder climate due to less removal of pathogens and nutrient from the wastewater.

5.2.1.3 Health Aspects/Acceptance

- During operating conditions, users should not come in contact with the influent or effluent it may be risky for the health. Also, entering in the working septic tank without proper measure may be fatal due to H_2S accumulation in the head space of the tank.
- Effluent, scum and sludge should be maintained with care as it contains high levels of pathogenic organisms and contaminants.
- Appropriate care should be taken during opening of the tank as it contains harmful and inflammable gases.

5.2.1.4 Operation & maintenance

To ensure that the septic tank works efficiently it is needed to prevent the discharge of harsh chemicals into the tank.

- For the proper functioning of the tank it should be ensured time to time that they are properly sealed (water tight), and also scum and sludge levels monitored timely to overcome the flooding situation.

- In general, the sludge removal in the septic tank is done for every 2 to 5 years approx. The best way for desludging is done by using a 'Motorized Emptying and Transport technology' (refers to a vehicle equipped with a motorized pump and a storage tank for emptying and transporting faecal sludge and urine), but Human-Powered Emptying (Human-powered emptying and transport refers to the different ways by which people can manually empty and/or transport sludge and solid products generated in onsite sanitation facilities) can also be an option.

- Septic tanks should be checked from time to time to ensure that they are watertight.

5.2.1.5 Advantages

- Simple and durable technology
- Electrical energy not required
- Less operating costs
- Long service life
- Less land area required (can be built underground)

5.2.1.6 Disadvantages

- Less reduction in pathogens, solids and organics
- Periodic sludge removal required.
- Effluent required further more advance treatment and sludge should be discharge to appropriate landmark.

5.2.2 Anaerobic Baffle Reactor (Improved septic tank)

An anaerobic baffled reactor (ABR) is an enhanced Septic tank technology. In this the baffles (3 to 5) are arranged in series manner over which the wastewater is compelled to flow. High retention time with activated sludge results in high treatment efficiency. The up flow chambers present in the tank helps in degradation and removal of the organic matter. As sludge is amassing, de-sludging is required which should be done for every 2 to 3 years.

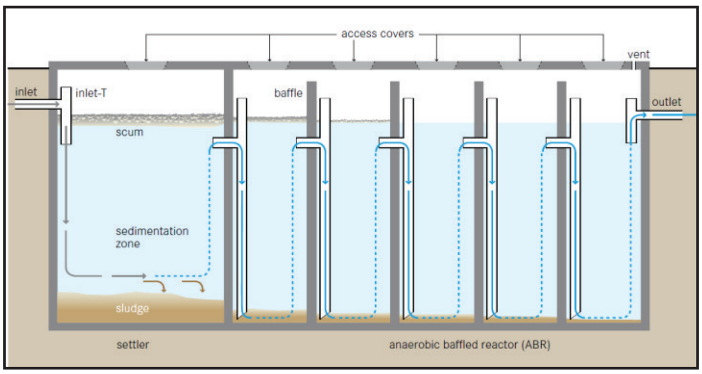


Figure 9: Schematic View of Anaerobic Baffled Reactor (Tilley, *et al.*, 2014)

5.2.2.1 Design Considerations The dominant part of settleable solids is removed out in a sedimentation chamber. Designs without a settling compartment are exceptionally compelling for

(Semi-) Centralized Treatment plants that join the ABR with another innovation for essential settling, or where pre-fabricated modular units are utilized. For this technology the typical inflows ranged from 2 to 200 m^3 per day.

The designing parameters incorporates hydraulic retention time (HRT) which should be 48 to 72 hours, up flow velocity of the wastewater should be less than 0.6 m/h and the number of up-flow chambers should be 3 to 6 (approx.) the linkage between the chamber can be planned either with vertical pipes or baffles. It is necessary to check the working ability of all the chambers for proper maintenance. In this technology, generally biogas formation takes place which is not trapped due to its insufficient amount. The tank ought to be vented for controlled discharge of noxious odor and injurious gases.

The basic design criteria for an anaerobic baffle reactor are shown in Table .6

Table 6: Design criteria for Anaerobic Baffle Reactor

Design parametrs	Recommendations
Hydraulic retention time	> 24 hours at maximum sludge depth and scum accumulation
Sludge accumulation rate	Depending on TSS removal rate and wastewater flow (70 – 100 litres/person/year)
Sludge and scum accumulation volume	Sludge accumulation rate multiplied by sludge accumulation rate
Desludging interval	> 1 year
Number of upflow chambers	> 2
Maximum upflow velocity	1.4 – 2 m/h

5.2.2.2 Compatibility

- The installation of the ABR is not done in those areas having high water table as it affects infiltration rate which results in poor efficiency of the tank. It also pollutes the groundwater. This type of technology is generally designed for the daily inflow of up to 200,000 L/day.
- This technology requires long time period for the start up to working at full capacity. Hence, it cannot be utilized immediately for the wastewater treatment process.
- The de-sludging process done in regular time period with the help of vacuum truck. ABRs can be introduced in each kind of atmosphere despite the fact that the productivity will be influenced in colder atmospheres.

5.2.2.3 Health Aspects/Acceptance

- Although the removal of pathogens isn't high using this technology but cases of wastewater borne diseases are minimum due to less exposure of working staff.
- Effluent and sludge must be handled carefully as they contain elevated amounts of pathogenic life forms.
- To intercept the liberation of potentially harmful gases, the tank ought to be vented properly.

5.2.2.4 Maintenance

- During maintenance process it should be ensured that the ABR tank is watertight and sludge level should be also monitored, to assure proper functioning of the tank.
- The sludge removal of the ABR tank should be done annually using a vacuum truck and it must also observe that no any toxic chemical should enter the tank which can damage it.

5.2.2.5 Operation & Maintenance

- This treatment system requires start-up of several months (typically about 3 months) to reach up to their working capacity, therefore it is necessary to grow anaerobic biomass within the reactor. Sometime to lessen the start-up period the ABR were inoculated with anaerobic bacteria, e.g., by adding digested/fresh cow dung or Septic Tank sludge.
- The anaerobic bacteria multiply and adapt towards the incoming wastewater. The generated sludge is removed out every 1 to 3 years, by using motorized emptying and transport technology is adopted. The sludge removal frequency depends upon the pre-treatment step to be chosen for the wastewater treatment. The possible arrangements for desludging are illustrated in the Figure 10.

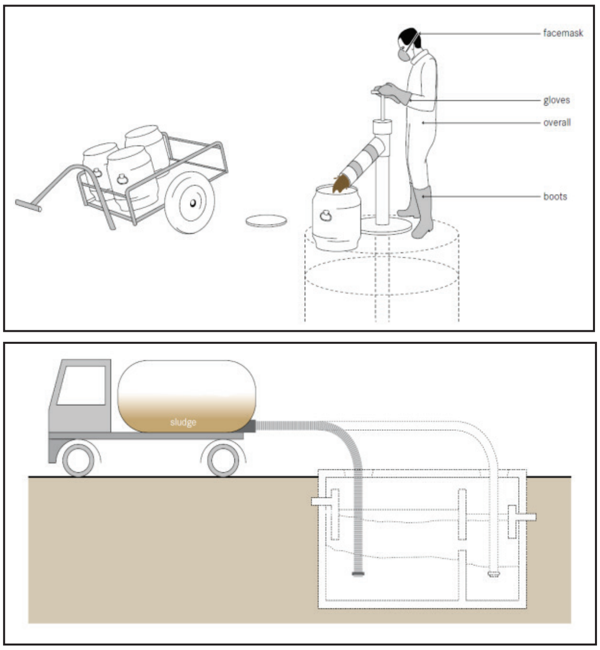
5.2.2.6 Advantages

- Obstructive towards organic and hydraulic shock loads
- Electrical energy not required
- Local available material is used for the construction and repairing work
- Long existence
- Flies and odors do not create problematic situation if technology used appropriately
- High removal of solid particles
- Low capital costs and operation costs

5.2.2.7 Limitations

- Requires continuous water source

- Secondary treatment and/or appropriate discharge required for effluent
- Low pathogen removal.
- Requires expertise for the designing and constructionPre-treatment is expected to check clogging



Human-powered emptying and transport
In this the sludge removal and transportation is done in manual manner and during onsite sanitation facility solid products are produced.

Motorized Emptying and Transport
This consists of a vehicle well equipped with a motorized pump, storage tank for emptying and transporting faecal sludge and urine. The pump is operated by human and sludge is removed mechanically.

Figure 10: Sludge emptying methods during primary treatment of wastewater (Tilley, *et al.,* 2014)

5.2.3 Oxidation ponds

Oxidation (stabilization) pond is a simple and scientifically designed pond (Figure 11) with 2-6 feet depth, where BOD reduction takes place by supporting algal bacterial growth **(Hosetti and Rodgi, 1985)**. These ponds are effective, low-cost and simple technology for the treatment of wastewater before it is discharged to an aquatic ecosystem **(Mahajan *et al.,* 2010)** and are commonly used in warm climates to purify wastewater. The performance of pond depends on climatological conditions like light, temperature, rain, wind and also the wastewater quality. Primarily these are used as tertiary treatment facilities specially to polish the effluents from conventional treatment plants **(Sarner, 1985).**

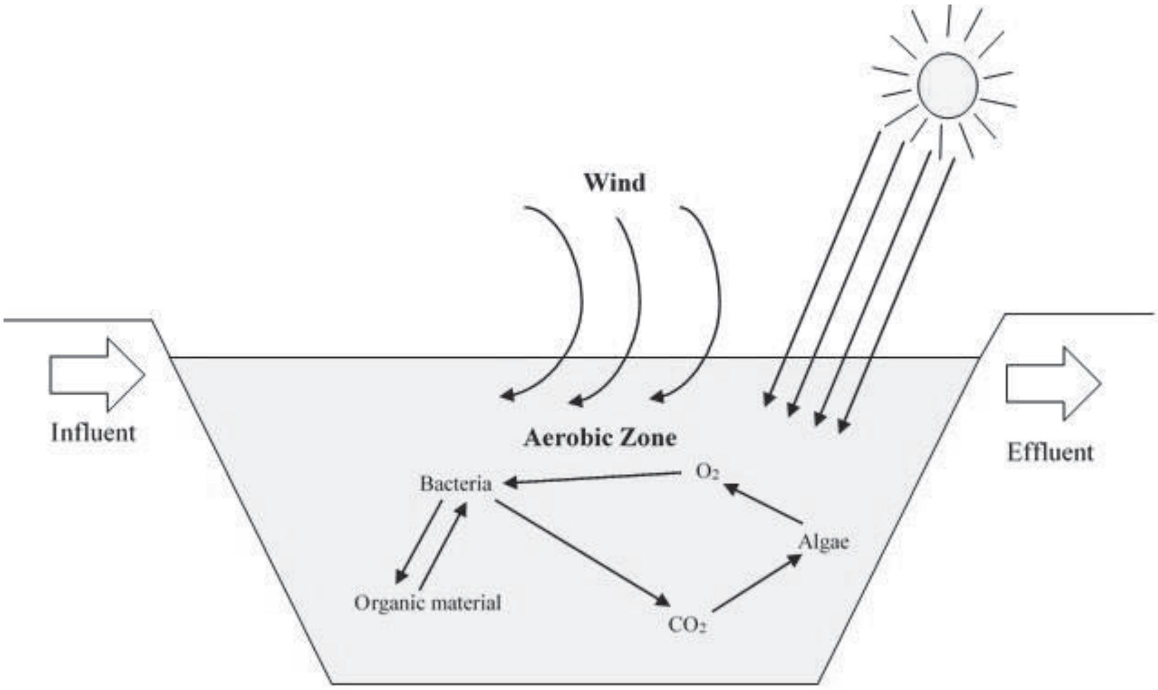


Figure 11 : Flow diagrams of an Oxidation ponds

Working Principle: Microbes present in the pond decompose the biodegradable organic matter and release carbon dioxide, ammonia and nitrates **(Tharavathy and Hosetti, 2003).** These compounds are utilized by the algae, which together with sunlight and photosynthetic process releases oxygen, enabling the bacteria to breakdown more waste and accomplish reduction in BOD levels **(Pearson *et al.,* 1987).**

Advantages: These ponds are also used to treat the raw sewage, settled sewage and industrial effluents **(Abeliovich,1985) .**Oxidation pond typically operate in an extended aeration mode with long detention and solids retention time **(Sperling,2005)** and is a widely adopted technique for the treatment of domestic and trade wastes. It is one of the methods used extensively in the tropical areas of the world for treating the wastewater **(Mara and Pearson,1986).**

Disadvantages: This method would also have disadvantages that it requires extensive land area, potential odour problem, mosquito menace, little control over the effectiveness of the treatment process and the main disadvantage is seepage of effluents into soil which may also lead to ground water pollution. Still, oxidation ponds have proved to be one of the most significant devices of economical waste treatment for small communities and isolated industrial units in Tunisia **(Ghrabi, 1993).**

5.2.4 Flow Equalisation Tank

Fluctuations may occur in the flowrate as well as in the type and concentration of the contaminants. Flow equalisation or balancing of the waste water may therefore be advisable prior to entry to the foul sewer to avoid problems at the treatment plant later. To assess whether this is required, the sanitary authority should obtain background information on the variability of the flow, pollutant levels and temperature. The four basic methods for flow equalisation are:

- Alternating flow diversion, where the total flow from the process is collected in alternate tanks and allowed to equalise. While one tank is filling, another is being discharged;
- Intermittent flow diversion, where significant periodic variations in the discharge are diverted and subsequently allowed to bleed back into the process stream at a controlled rate;
- Completely mixed combined flow systems, where multiple streams are combined in order to reduce their variance. This assumes compatibility between the constituents in each stream;
- Completely mixed flow system, where a completely mixed holding basin is employed and provides a constant discharge to the treatment plant.

The different designs are illustrated in Figure 12.

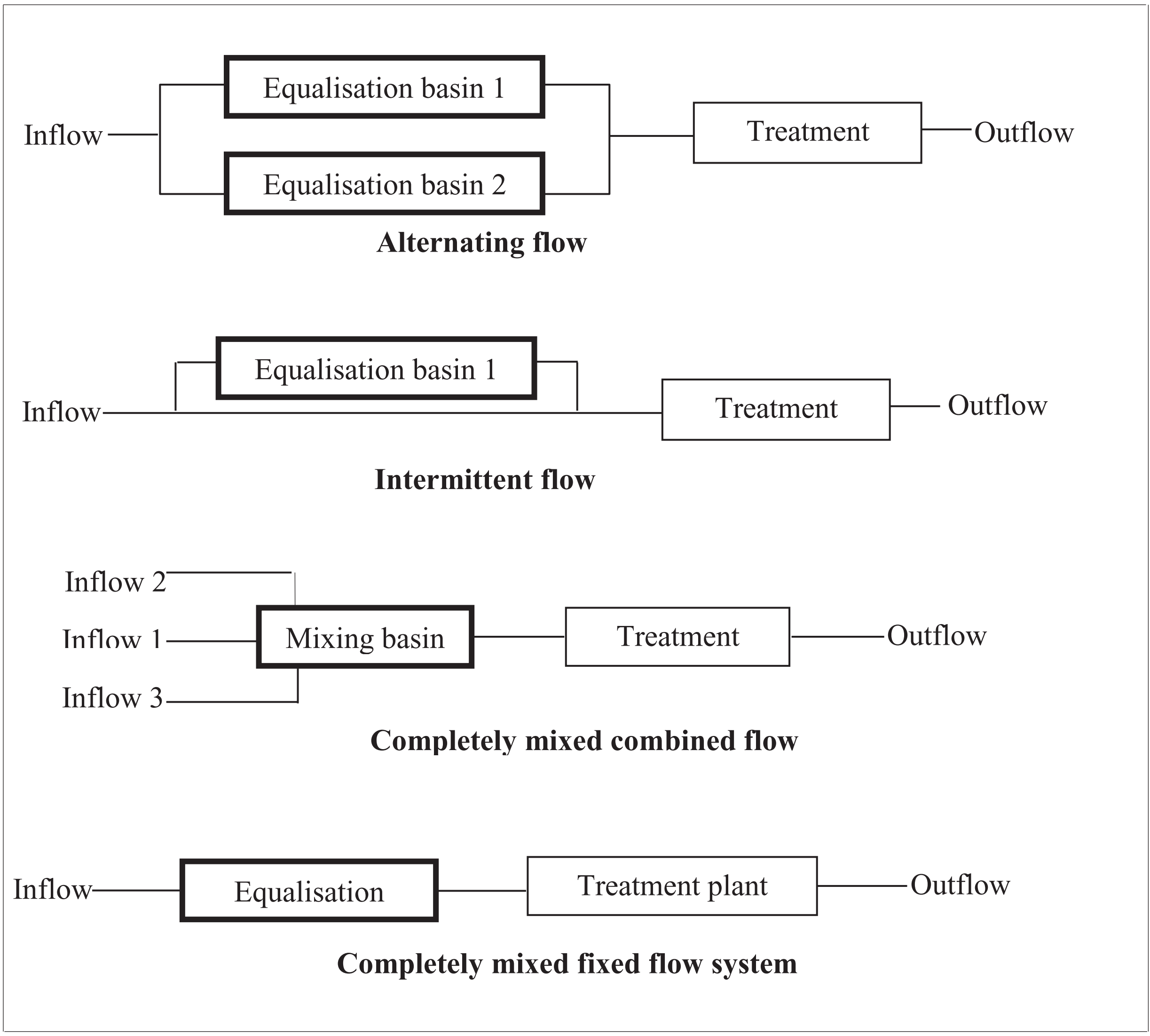


Figure 12: Methods of flow balancing (WEF, 1994)

5.2.5 Flow Arrangement

CW system should be designed and constructed with limited short circuiting of wastewater between inlets and outlets. In the ideal system, wastewater flows evenly across the wetland cell throughout its entire length with no stagnant pools (Crites et al., 2006). An inlet consisting of a gated or slotted pipe across the upstream end helps to ensure initial distribution of flow (Figure 1). As water moves through the plants and detritus, channelization of water may occur as a result of the buildup of islands of roots, rhizomes, and dead vegetation (USDA-NRCS, 2002; WERF, 2006). Long and wide cells results in uneven distribution, which require redistribution of flow. This can be accomplished by using shorter cells in series and discharging the effluent of one into a distribution header pipe or deep trench at the upstream end of a receiving cell. For long cells that have a flat bottom, flow can be redistributed laterally along the flow path by installing deep zones or trenches across the width of the cell at appropriate points. Inlet trenches and redistribution sumps should be at least 3 feet deeper than the constructed bottom of the cell to inhibit growth of rooted vegetation (Kadlec and Knight, 1996; DNR, 2007). As a rule, the length-to-width ratio for the system should be in the range of 1:1 to 4:1. Individual cells within this overall system may have ratios as high as 10:1. In fact, 20:1 length-to-width ratios have been used successfully (Reed et al., 1995). From the standpoint of construction costs, the square (1:1) wetland is most efficient. The cost advantage of the square wetland is offset by the critical need to provide for distribution of flow to prevent short-circuiting.

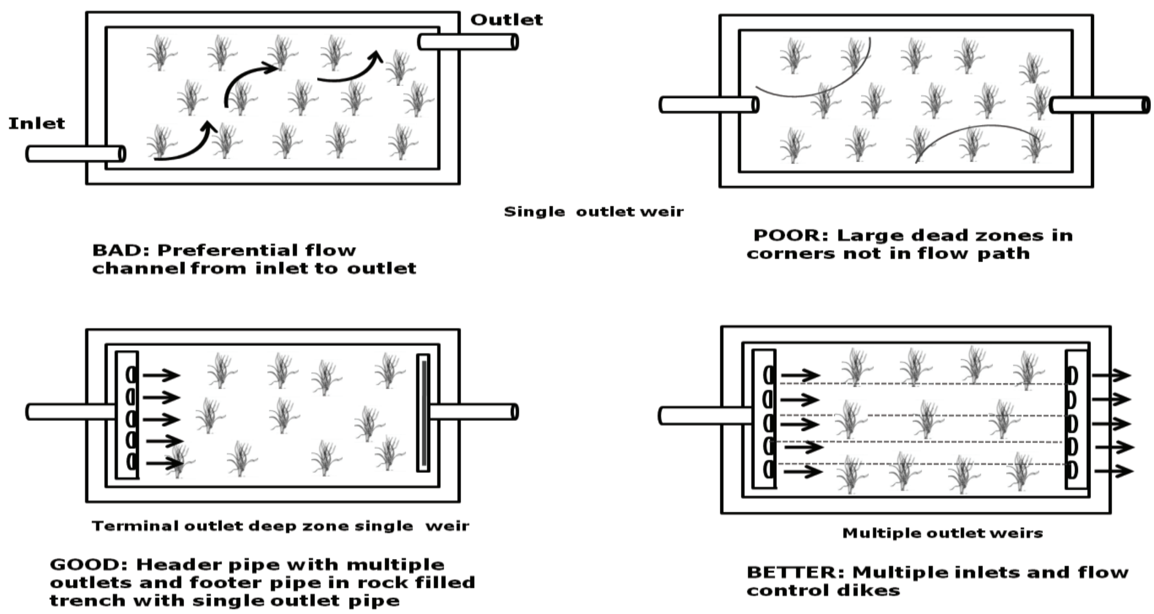


Figure 13: Wetland layout configuration on flow distribution (UN-Habitat, 2008)

5.2.6 Inlet and Outlet Structures

Inlet and Outlet control structures are critical to the overall success of a constructed wetland system.

Inlet zone

Inlet zone has to provide an effective flow distribution across the full width of the wetland entrance, in order to minimise short-circuiting and dead zones and maximise frictional resistance. Inlet structures includes surface and subsurface manifolds, open trenches perpendicular to the direction of flow, and simple single-point weir boxes (Figure 2). Inlets should be simple with an open-end pipe or channel, or gated pipe or ungated gravity flow overflow pipe to the cells of the constructed wetland or pipes with orifice controls, swivel pipes, and valves which releases water into the wetland (USDA-NRCS, 2002; Yeruva et al., 2018a,b). The smaller the length-to-width ratio, the more important equal flow distribution becomes. Accessible and easily adjustable inlets are good for systems with small length-to-width ratios (USDA- NRCS, 2005). Gated pipe that spans the width of the cell can ensure even distribution and eliminate dead zones in the corners. If the incoming water is not well oxygenated and contains a high level of organic nitrogen and ammonia, a zone of the wetland is necessary which allows oxygenation (open water, no vegetation,waves) to enhance nitrification before the macrophyte zone (Bendoricchio et al., 2000). Inlet zones should provide access for sampling and flow monitoring.

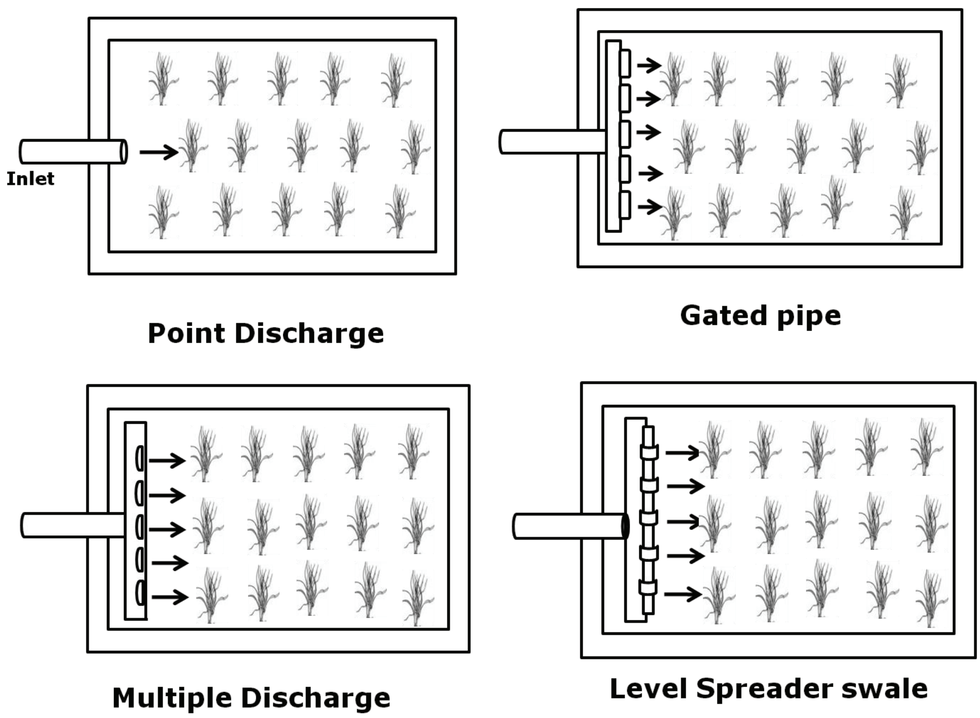


Figure 14: Different types of inlet systems for CWS

A subsurface manifold avoids the buildup of algal slimes and the consequent clogging that can occur next to surface manifolds, but is difficult to adjust and maintain. A surface manifold, with adjustable outlets provides the maximum flexibility for future adjustments and maintenance. A surface manifold also avoids back-pressure problems. The use of coarse rock in the entry zone ensures rapid infiltration and prevents ponding and algal growth (USDA- NRCS, 2005).A flow splitter will be needed for parallel cells. A typical design consists of a pipe, flume, or weir with parallel orifices of equal size at the same elevation. Valves are not practical because they require daily adjustment. Weirs are relatively inexpensive and can be easily replaced or modified. Flumes minimize clogging in applications with high solids but are more expensive than weirs.

The slope of the bottom of the wetland in the inlet zone should be practically zero, thus assuring an equal water distribution. Frictional resistance is higher when water spreads out over a large area, rather than being confined to a channel. When frictional resistance is high, velocity and potential erosion will be lower. Water velocities less than 10 cm/s are recommended for wetland entrance zones if the bottom is not protected (Marble, 1992). High water velocities also effect plant growth. Energy dissipation may be required for the incoming water to provide protection for the wetland inlet. Energy dissipation can be caused by gravity using riser pipe inlet or drip piping or by resistance using rock energy dissipator and in situation of low velocities, by vegetation (Bendoricchio et al., 2000, Yeruva et al, 2018).

Algae growth on distribution system can be controlled by minimizing light contact with the incoming water (e.g. use of riser pipes) and to design openings large enough to avoid obstruction by algae growth. To discourage the growth of algae, open water areas near the outlet should be avoided. Shading with either vegetation or a structure in the summer will probably be necessary.

Outlet Zone

Wetland outlet design is important in avoiding potential dead zones, in controlling water level, for avoiding blocking and for monitoring flow and water quality (Persson et al., 1999). A deep open water zone should be designed to collect and route flows to an outlet weir. Incorrect water levels can lead to wetland failure. The use of an adjustable outlet, which is recommended to maintain an adequate hydraulic gradient in the bed, can also have significant benefits in operating and maintaining the wetland. This terminal deep zone must be kept as small as possible to discourage a long residence time and subsequent algae growth. The final discharge point from the wetland system should be placed high enough above the receiving water that a rise in the water level in the receiving water, for instance after a storm, will not interfere with the flow of water through the wetland (Kadlec and Knight, 1996).

Different types of structures are used to control water level within thewetland depending upon structure to different situations and the objectives of the wetland (Figure 3). The water level is controlled by the outlet structure, which can be a weir, spillway, or adjustable riser pipe. A variable height weir, such as a box with removable stoplogs, allows the water levels to be adjusted easily (Watson and Hobson,1989). Spillways are simple to construct but are not adjustable. Weirs and spillways must be designed to pass the maximum probable flow. Coarse riprap should be used to avoid high flows. Adjustable riser pipes or flexible hoses offer simple water level control. Small diameter (< l2 inch) pipes should be avoided because they clog with litter.

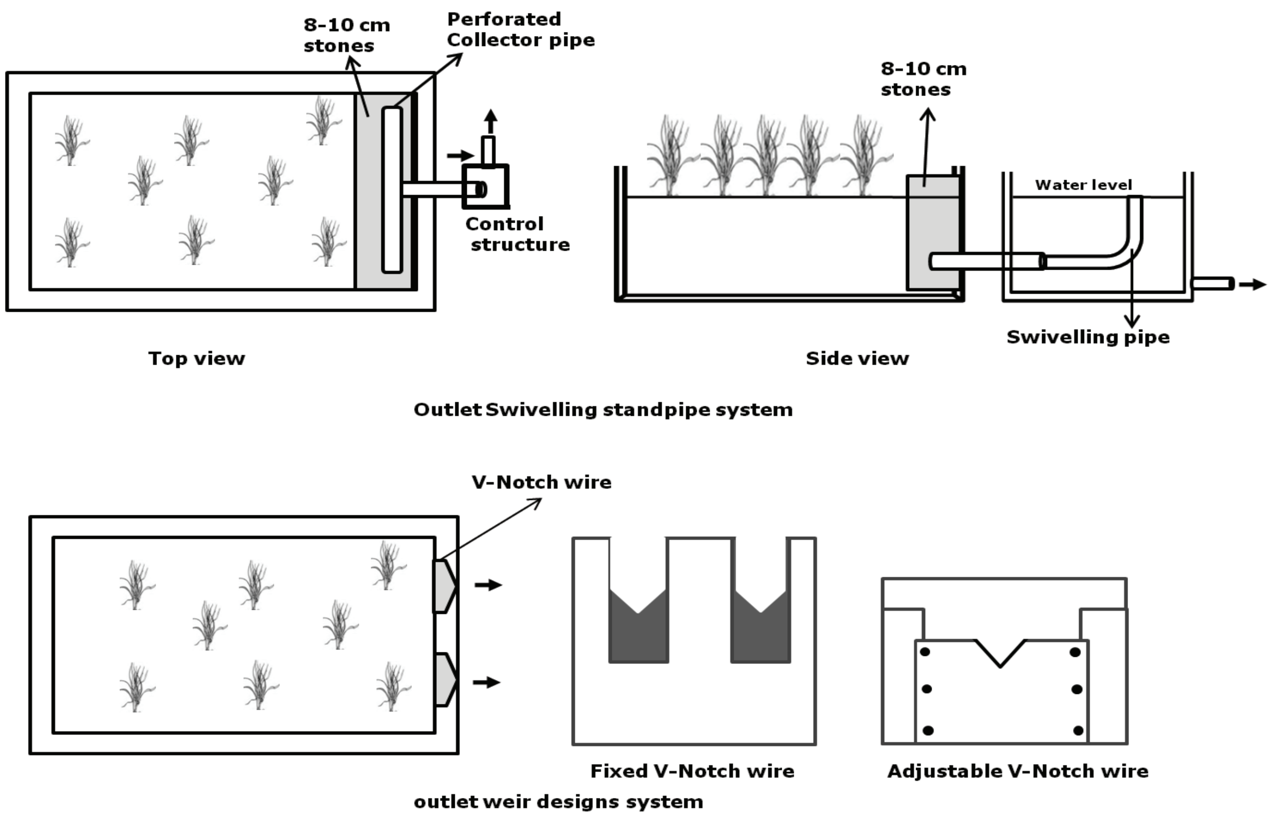


Figure 15: Examples of wetland outlet designs

Outlet structures are sensitive to accumulation of debris. Final filtering of algae biomass in the wetland is desirable to reduce biomass export. System configuration should include final filtration by aquatic plants. Other possibilities are the use of a rock filter or of a large-mesh debris fence placed a meter or two from the outlet structure (UN-Habitat, 2008). The surface of the bed can be flooded to encourage the development of newly planted vegetation and to suppress undesirable weeds, and the water level can be lowered in anticipation of major storms and to provide additional thermal protection against freezing in the winter. The design should allow controlled flooding to 6 inches (15 cm) to foster desirable plant growth and to control weeds. A perforated subsurface manifold connected to an adjustable outlet offers the maximum flexibility and reliability as the outlet device. Since the manifold is buried and inaccessible after construction, careful grading and sub- base compaction are required during construction, and clean-out risers in the line must be provided (UN-Habitat, 2008).

5.3 Free Water Surface Constructed Wetland

5.3.1 Inroduction And Application

This type of constructed wetland is fully flooded with water for this reason it is also as natural wetland (Figure 16). It consists of series of planted flooded beds. In this constructed wetland all the pollutants are flushed out by means of natural processes. The organic matter gets trapped during sedimentation process and eventually accumulates at the bottom of the beds; pathogens are eliminated by means of microbial interactions. Contaminants present in wastewater are reduced by microbial and plant absorption. Free water surface constructed wetland is used in advance treatment followed by secondary and tertiary treatment processes. Usually this technology is reliable for the small communities, small housing population, small scale industries etc. this treatment system is more convenient for the rural and small town societies as per the requirement

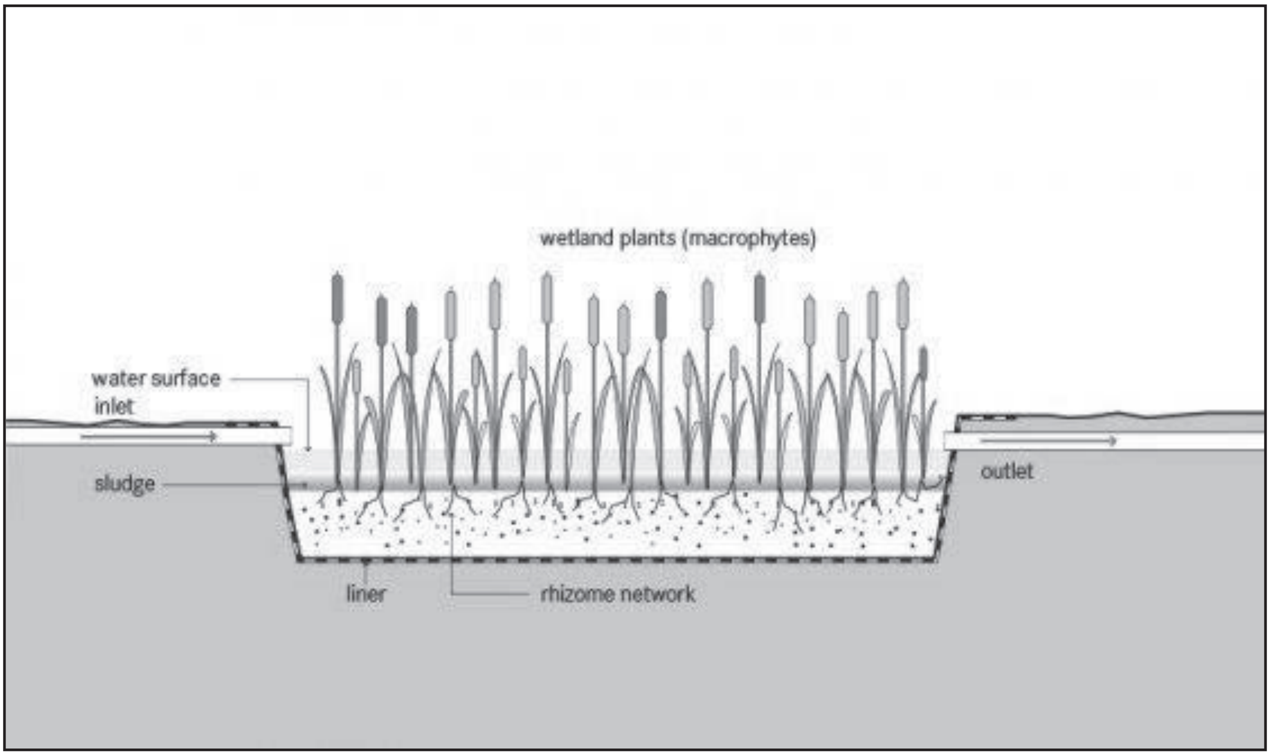


Figure 16: Schematic diagram of free water surface constructed wetland **(Tilley, *et al.,* 2014)**

of land area.

Generally, a FWS constructed wetland consists of:

- Shallow basin,
- Macrophytes
- Submerged soil layer (helps in supporting the growth of emergent macrophytes)
- Appropriate outlet and inlet structures
- Impermeable lined material

5.3.2 Mechanism

In this constructed wetland technology, the most efficient removal of organic matter present in wastewater is taking place majorly through microbial degradation and precipitation of solid particles through filtration and sedimentation processes. In this technique of wastewater treatment layer to layer chemical and physical process occur for contaminants degradation, which results in purifying the water quality.

In the water column nitrification process occurs which removes out the nitrogen present in the wastewater which is the primary cause of pollution for water quality. Nitrification process is followed by denitrification which is taking place in litter layer and after that ammonia volatization occurs when favorable condition of optimum pH values is present by means of algal photosynthesis.

Phosphorus removal in the constructed wetland is very low because of less contact times of water with soil particles which may adsorb or precipitate it. Phosphorus adsorption by means of plant uptake capacity shows less removal percent due to the fact that they are again release to water body after decaying of plant **(Vymazal *et al*., 2008; Kadlec *et al.,* 2008).**

5.3.3 Advantages

- Free water surface constructed wetland provide habitat to many animal species and give aesthetically pleasing environment.
- This technology works efficiently towards the wastewater treatment system. It reduces the use of mechanically operated equipment, strength and the necessity of well-trained operator.
- These systems have low operation and maintenance cost, also construction cost is low in comparison to other conventional treatment methods.
- This treatment system can be built with locally available material.
- This technology doesn't create any problem related to odor, if maintain and operated in proper manner.

- Highly efficient for the removal of BOD, TSS, COD, TN, metals, and organic matters present in municipal wastewaters.

5.3.4 Limitations

- If the target of the treatment system is especially the removal of nitrogen and phosphorus, then the required land area should be large.
- During winter season the removal efficiency is reduced due to the fact that rate of biological reaction slow down which affect the nitrification, denitrification and BOD purification rate.
- It requires long startup time for the initiation of the system working at full competency.
- If the system not managed properly then it may facilitate mosquito breeding.

5.3.5 Designing

Sizing

For the proper sizing criteria of free water surface constructed wetland it is calculated either on volume or area basis. In volume-based methods hydraulic retention time is used to evaluate the pollutant removal while in area-based methods pollutant reduction is evaluated by using the overall wetland area **(Wallace *et al.,* 2006).** Recommended loading rates for attaining target effluent concentration in FWS CWs are provided in Table 7.

Table 7: Recommended loading rates and quality of target effluent for Free Water Surface (FWS) constructed wetland.

S. No	Parameter	Value (mg/L)	Loading Rate (g/m^2 d)	References
1.	BOD_5	30	6	**Wallace *et al.,* 2006 & US EPA Manual (2000)**
		25	3	**Wallace *et al.,* 2006**
		20	4.5	**US EPA Manual 2000**
2.	TSS	30	7	**Wallace *et al.,* 2006**
		30	5	**US EPA Manual (2000)**
		25	3.5	**Wallace *et al.,* 2006**
		20	3	**US EPA Manual (2000)**
3.	TKN	10	1.5	**Wallace *et al.,* 2006**

1. First Order Plug Flow Kinetic

The first-order plug-flow *k-C** approach takes into account influent and effluent concentrations as well as background concentration, but assumes ideal plug-flow hydraulics.

$$A = \frac{Q_i}{k_A} \ln\left(\frac{C_o - C^*}{C_i - C^*}\right) \quad \text{(Eq. 1)}$$

Where,

A = Area, m^2

C_o = outlet concentration, mg/L

C_i = inlet concentration, mg/L

C* = background concentration, mg/L

K_A = modified first-order areal rate coefficient, m/d

Q_i =influent flow rate, m^3 /d

Additionally, the above equation (Eq. 1) can be used to correct the reaction rate coefficient k_A to the anticipated climate conditions for the new wetland design.

Table 8: Background concentrations (C^*) in mg/L for HF, VF, and FWS wetlands (Kadlec and Wallace, 2009)

S. No	Parameter	HF	VF	FWS	
				Lightly Loaded	Heavily Loaded
1	BOD_5	10	2	2	10
2	TN	1	0	1.5	-
3	NH4-N	0	0	0.1	0.1

The values of Table 8 are for wetlands treating primary effluents. For BOD_5 removal, for different influents, **Kadlec and Wallace (2009)** report the following C^* values (50th percentile) for HF wetlands:

- Primary effluent: C_i = 100 to 200 mg/L; C^* = 10 mg/L
- Secondary effluent: C_i = 30 to 100 mg/L; C^* = 5 mg/L
- Tertiary effluent: C_i = 3 to 30 mg/L; C^* = 1 mg/L

It should be noted that C^* concentrations can also vary with temperature (Stein *et al.*, 2007b).

Advantages of the plug-flow k-C* approach:

- It takes into account influent concentration (Ci), background concentration (C^*), HLR (q) and areal reaction rate coefficient (k_A).
- It also considers temperature correction factor (θ).

Disadvantages of the plug-flow k-C* approach:

- It does not account for non-ideal flow, which creates a large risk, especially when low effluent concentrations must be achieved **(Kadlec and Wallace, 2009).**
- There is no guidance as to which kA-value to choose (for example, when a range of reaction rate coefficients are reported).
- The assumption of ideal plug-flow hydraulics has been widely reported in the literature as inaccurate **(Kadlec, 2000),** and thus is no longer recommended for use.

***2*. Pollutant Removal Theory for designing**

Previous studies by **Maria *et al.* (2004)** showed that for the constructed wetland design the pollutant removal efficiency and typical kinetic rate constants theory is useful for treating municipal wastewater.

The following assumptions have been made:

- The water temperature can be assumed approximately equal to the mean ambient temperature. This is a reasonable assumption for relatively warm climates **(Kadlec and Knight, 1996).**
- The removal rates for BOD and nitrogen in FWS constructed wetland systems are typically based on first-order kinetics and on the assumptions of plug flow, which have been used in the design of most constructed wetland systems in the U.S. and Europe **(Chen *et al.*, 1999; Economopoulou and Tsihrintzis, 2003).**

BOD and nitrogen removal rates in FWS constructed wetlands are estimated by the following general removal Equation 2 **(Reed *et al.*, 1995).** Pollutant rate constants used for FWS constructed wetlands are given in Table 9.

$$\frac{C_e}{C_i} = e^{-K_T\, t}$$

(Eq. 2)

Where,

C_e = pollutant effluent concentration [mg L^{-1} of BOD, nitrogen /100 mL]

C_i = pollutant influent concentration [mg L−1 of BOD, nitrogen /100 mL]

K_T = reaction rate parameter [d^{-1}] dependent on the water temperature T [◦C]

Table 9: Pollutant removal equations and rate constants for FWS constructed wetlands by Reed *et al.* (1995)

S. No	Pollutant	Rate constant		Rate constant units
1.	BOD	$K_T = 0.678(1.06)^{T-20}$		[d^{-1}]
2.	Nitrification	$K_T = 0.0389T$	$0 < T < 1$˚C	[d^{-1}]
		$K_T = 0.1367(1.15)^{T-10}$	$1 < T < 10$˚C	[d^{-1}]
		$K_T = 0.2187(1.048)^{T-20}$	$T > 10$ ˚C	[d^{-1}]
3.	Denitrification	$K_T = 0.023T$	$0 < T < 1$˚C	[d^{-1}]
		$K_T = 1.15^{(T-20)}$	$T > 1$ ˚C	[d^{-1}]

In the above table

K_T = reaction rate parameter [d^{-1}] depends on the water temperature T [˚C],

3. Hydraulic Design Theory *(Maria et al., 2004)*

Kadlec (1990) and Kadlec and Knight **(1996)** suggested a general equation for the hydraulic design of FWS constructed wetland systems:

$$Q = a\,W y^{b} S^{c} \qquad \text{(Eq. 3)}$$

Where:

Q = flow rate [$m^3\ d^{-1}$];

W = wetland width [m];

a, b and c are coefficients

Assuming the following values:

a = 107 $d^{-1}m^{-1}$ for dense vegetation,

a = 5× 107 d−1m−1 for sparse vegetation,

b = 3.0 & c = 1.0;

y = depth of flow (m), which usually ranges from 0.1 to 0.6 m **(Reed *et al.*, 1995)**

S = water surface slope [m/m], estimated by the following Equation 4:

$$S = \frac{\gamma\, y}{L} \qquad \text{(Eq. 4)}$$

where γ is the fraction of the depth serving as head differential **(Reed *et al.*, 1995)**;

and L is the wetland length (m).

Hydraulics of Free Water Surface Constructed Wetland

(ERED, 1999, Humboldt State University, Arcata)

Hydraulics is a term implies for the water movement through any system. Its design is one of the important factors that help the system working efficiently. An improper hydraulic design may cause several problems in the system that may slow down the working efficiency of the system. It also causes problem with water conveyance, water quality, odors, etc.

Hydraulic Loading Rate

In FWS wetlands, the wetted area is usually known with good accuracy, because of berms or other confining features, which is defined by Eq. 5.

$$q = Q/A \qquad \text{(Eq. 5)}$$

Where

q= hydraulic loading rate (HLR), m/d

A= Wetland area (wetted land area),m^2

Q = water flow rate m^3 /d

Mean Water Depth

In FWS wetlands, the mean depth calculation (Eq. 6) requires a detailed survey of the wetland bottom topography, combined with a survey of the water surface elevation. The accuracy and precision must be better than normal, because of the small depths usually found in FWS wetlands.

$$h = H - G \qquad \text{(Eq. 6)}$$

where, G = local ground elevation, m; h = water depth, m; H = local water elevation, mSF constructed wetlands must be designed to be compatible with the macrophytes that are contained within the wetland. As such, most emergent type wetland plants cannot tolerate more than 2 feet of submergence when subjected to wastewater loadings **(WERF, 2006).** Therefore, in order to assure that the plants are not subjected to excessive amounts of water depth, the design water depth should be one foot for all emergent vegetation.

Filter media selection

Soils with high humic and sand components are easier for aquatic macrophytes growth. The soil substrate should be loam, well loosened and at least 6 inches deep **(U.S EPA, 2000).**

Inlet Structures

- At SF wetlands are usually simple an open-end pipe, channel, or gated pipe which releases water into the wetland.

- The smaller the length-to-width ratio, the more important equal flow distribution becomes. Accessible and easily adjustable inlets are mandatory for systems with small length-to-width ratios.

Outlet Structuress

- At SF wetlands, the water level is controlled by the outlet structure, which can be a weir, spillway, or adjustable riser pipe. A variable- height weir, such as a box with removable stop logs allows the water levels to be adjusted easily.
- Spillways are simple to construct but are not adjustable; incorrect water levels can lead to wetland failure and correcting spillway height can be difficult. Weirs and spillways must be designed to pass the maximum probable flow.
- Spillways should consist of wide cuts in the dike with side slopes no steeper than 2H:1V and lined with non-biodegradable erosion control fabric. If high flows are expected, coarse riprap should be used.
- Vegetated spillways overlying erosion control fabric provide the most natural-looking and stable spillways. Weirs or spillways should be used for mine drainage wetlands since pipes tend to clog with deposits of iron precipitates. Adjustable riser pipes or flexible hoses offer simple water level control.

5.3.6 Water Quality Targets

FWS wetlands typically target nitrate and/or phosphorus removal but have also been employed to reduce pathogenic organisms and/or suspended solids, specifically algae grown in upstream treatment units. The key design parameter is an appropriate wetland surface area to meet the discharge target or pollutant removal expectation. Some jurisdictions may prescribe a mass loading rate criterion e.g. (kg/ha·yr or $g/m^2 \cdot d$) but the modified first-order rate model is more typically utilized. Both volumetric and areal versions can be employed, but since the range in design depths for FWS wetlands is relatively narrow, the two methods yield similar results. In one case, determination of the appropriate surface area is direct. When the volumetric version is used, the calculated HRT is divided by the water depth in order to determine the required area. In either case, the length of the wetland is determined from the surface area after the width is determined of the cross-sectional area calculated from the hydraulic analysis **(Dotro *et al.,* 2017)**

5.3.7 Operation and Maintenance

For operation and maintenance of the FWS wetlands the guidelines provided by **Dotro *et al.* *(*2017)** are summarized below:

- FWS wetlands need very little maintenance under normal operating conditions. Periodic inspection of inlet and outlet works and plant health is advisable.
- Plants that are subjected to oxygen stress tend to concentrate roots closer to the surface, making them less tolerant of periodic deep-water conditions and more susceptible to lodging, thus complete submergence and death.
- The typical large scale of FWS wetlands makes them susceptible to wave action, which can exacerbate plant lodging and increase the potential of wind-induced bank erosion.

5.3.8 Vegetation

The most commonly used emergent vegetation in constructed FWS wetlands include cattail (*Typha* sp.), bulrush (*Scirpus* sp.), and reeds (*Phragmites* sp.). In systems designed primarily for wastewater treatment, it is common to select only one or two species for planting. The plant canopy formed by the emergent vegetation shades the water surface, preventing growth and persistence of algae, and reduces wind-induced turbulence in the water flowing through the system. Perhaps most important are the submerged portions of the living plants, the standing dead plants, and the litter accumulated from previous growth. These submerged surfaces provide the physical substrate for the periphytic attached growth organisms responsible for much of the biological treatment in the system. The water depth in the vegetated portions of these systems ranges from a few inches to two feet or more.

Free water surface wetlands can be sub-classified according to their dominant type of vegetation as follows:

1. Emergent macrophyte
2. Free floating macrophyte
3. Submerged macrophyte

Emergent Macrophyte Based Wetlands

The common type of free water surface is emergent macrophytes based wetland (Figure 17). It consists of series of channels/basins which are lined with an impermeable material which prevents infiltrations towards the ground water. Emergent macrophytes are planted in an impervious material of soil. It contains 20-30 cm of rooting soil, with a water depth of 20-40 cm.

The most commonly used emergent species for FWS constructed wetlands are:

1. **In Europe**
   - *Phragmites australis* (Common reed),

Scirpus lacustris (Schoenoplectus)

2. **In North America:**
   - *Typh*a spp. (Cattail),

- *Scirpus* spp. (Bulrush),
- *Sagittaria latifolia* (Arrowhead),
- *Phragmitis australis*

3. **In Australia and New Zealand**:
   - *Phragmites australis*,
   - *Typha* spp.,
   - *Bolboschoenus* (Scirpus)
   - *Fluviatilis* (Marsh clubrush),
   - *Eleocharis sphacelata* (Tall spikerush),
   - *Scirpus tubernaemontani* (Scirpus validus, Soft-stem bulrush).

Free Floating Macrophyte Based Wetlands

As the name implies, free floating macrophyte based wetlands make use of floating plants, such as duckweed and water hyacinth, to remove nutrients and control algae in wastewater. A floating barrier grid is used to support the growth of floating macrophytes and to reduce wind effects, which would otherwise cause the plants to drift. It has been found that the free floating plants form a dense cover over the water surface which results in blockage of sunlight and inhibits the photosynthesis process as well as algal growth. **(Lemna Corporation, 1994).** The plant cover and barrier grid reduce turbulence, allowing suspended solids to settle out more readily. It has been suggested that harvesting should be done "periodically", depending on climate, nutrient loading and desired treatment **(Lemna Corporation, 1994)**.

Commonly used free floating species in FWS wetland-

- *Eichhornia crassipes*
- *Pistia stratiotes*

Surface-floating plants with few or no roots

- Duckweed
- Lemna spp.
- Spirodela
- Polyrhiza,

Wolffia spp.

Submerged Macrophyte Based Wetlands

Submerged macrophyte based wetlands are still in the experimental stage. They have been proposed as final polishing steps following primary and secondary treatment **(Brix, 1994).**

The commonly used submerged species were:

- *Hydrocharis morsus-ranae* (Frog΄s bit),

- *Myriophyllum speculum* (European water milfoil),
- *Elodea canadensis* (Common waterweed),
- *Potamogeton pectinatus*
- *Vallisneria americana* (eel-grass)

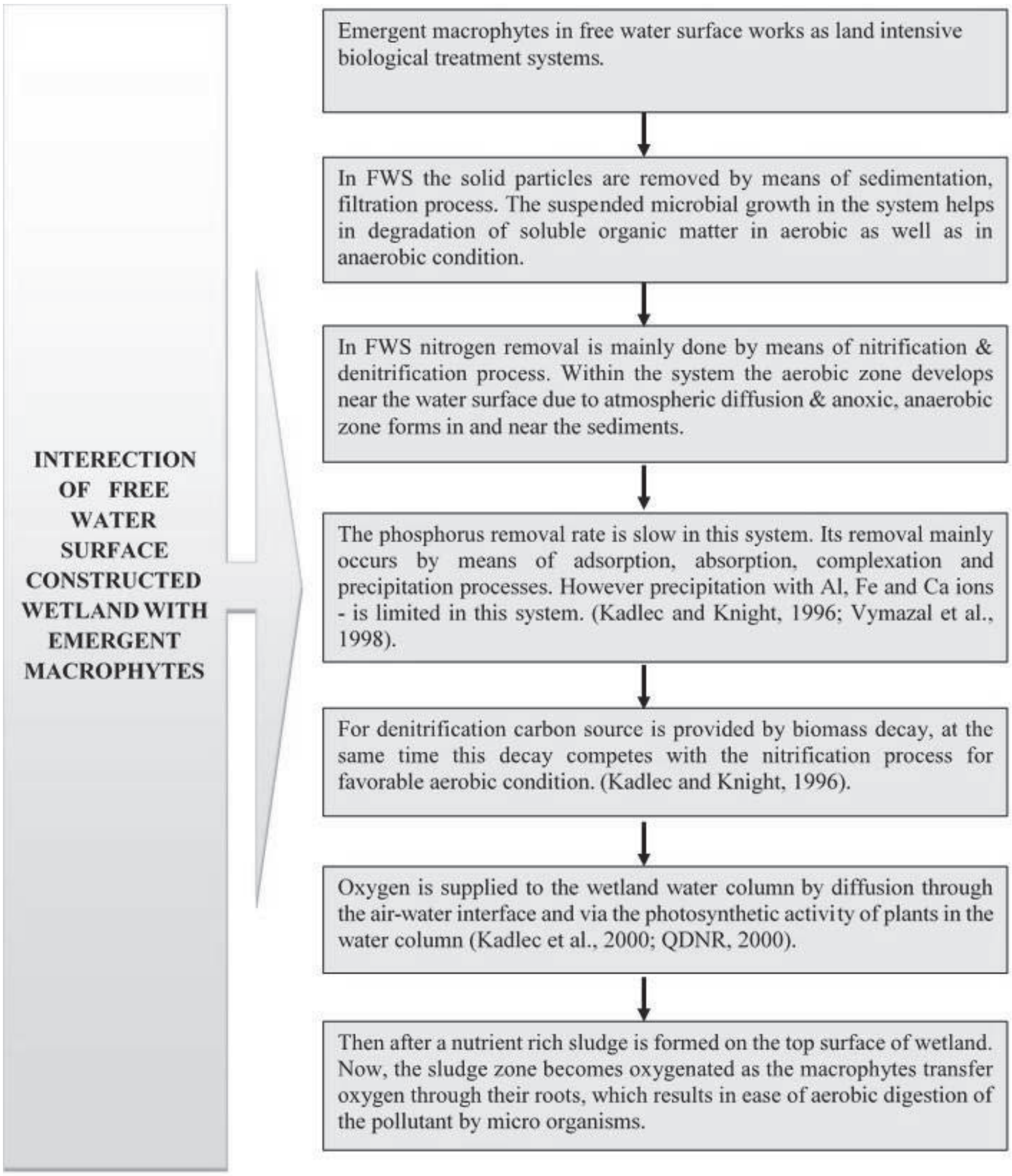


Figure 17: Interaction mechanism of filter media of FWS CWs with emergent macrophyes

5.4 Horizontal Flow Constructed Wetlands

5.4.1 Introduction and Applications

The Horizontal Flow wetland configuration originated from the pioneering work in Germany in the late 1960s. Horizontal subsurface flow (HSSF) constructed wetland (Figure 18) is a large gravel and sand-filled basin that is planted with wetland vegetation. As wastewater flows horizontally through the basin, the filter material filters out particles and microorganisms attached to the plant roots and filter media degrade the organics. The wetland media acts as a filter for removing solids, a fixed surface upon which bacteria can attach, and a base for the vegetation. Although facultative and anaerobic bacteria degrade most organics, the vegetation transfers a small amount of oxygen to the root zone so that aerobic bacteria can colonize the area and degrade organics as well. The plant roots play an important role in maintaining the permeability of the filter.

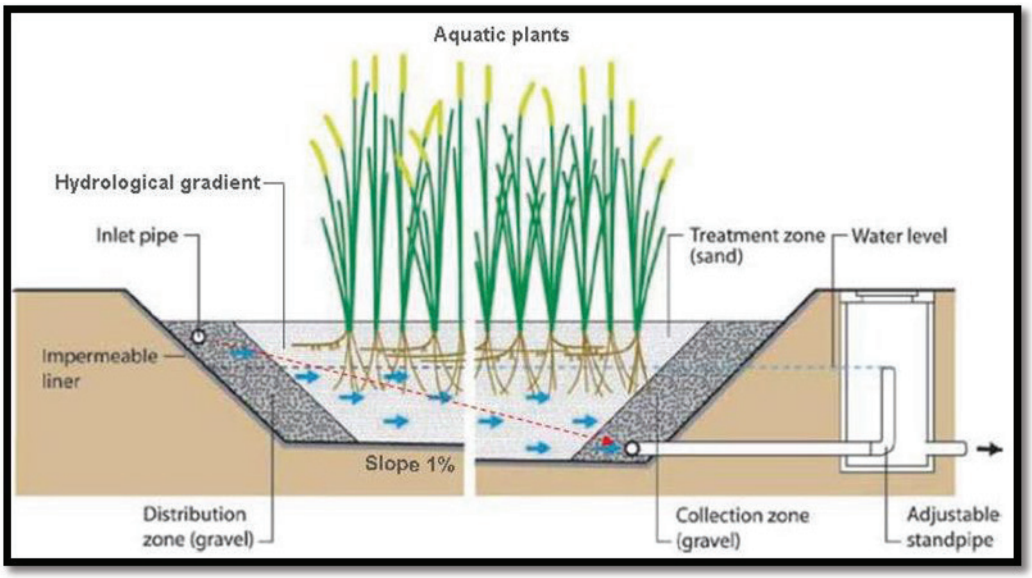


Figure.18: Schematic diagram of Horizontal Flow Subsurface constructed wetland

During the course of treatment, wastewater comes in contact with a network of aerobic, anaerobic and anoxic zones. The aerobic zones occur around roots and rhizomes that release oxygen into the substrate. During the passage of wastewater through the rhizosphere, the wastewater is cleaned by microbiological degradation as well as physical/ chemical reactions **(Vymazal *et al.,* 2007).** Organic compounds are degraded aerobically as well as anaerobically by bacteria associated with the plant's underground parts (roots and rhizomes) and media surface

(Vymazal, 2002). Oxygen required for aerobic degradation of the organic matter is directly supplied from the atmosphere by diffusion or oxygen leakage from the macrophyte roots and rhizomes in the rhizosphere. In a HSSF wetland, anoxic and anaerobic degradation plays very important role in contaminant removal from wastewater.

In a HSSF wetland, nitrogen is removed by biological processes such as nitrification, denitrification, plant uptake, volatilization and adsorption **(Hoffmann *et al.*, 2011)**. The major mechanism involved in nitrogen removal is nitrification and denitrification. Ammonia is oxidized to nitrate by nitrifying bacteria in the aerobic zones and nitrates are converted to gaseous nitrogen by denitrifying bacteria in the anoxic zones. Oxygenation in HSSF wetlands, is limited, and thus incomplete nitrification leads to limited nitrogen removal in these systems **(Vymazal & Kroepfelova, 2008).** Volatilization, adsorption and plant uptake have very less important role in nitrogen removal.

In HSSF wetland, phosphorous removal from wastewater occurs primarily by ligand exchange reactions, where phosphate displaces water or hydroxyls from the surface of Fe and Al hydrous oxides. However, the filter media (e.g. crushed bricks, pea gravels) that are used in horizontal wetlands do not contain sufficient amount of Fe, Al or Ca and therefore, removal of phosphorous is very low in these systems. Settleable and suspended solids (SS) are which are not completely removed by pre-treatment system, are effectively removed by filtration and settlement. Settlement occurs in the quiescent areas of HSSF wetland.

Horizontal flow wetlands are used for secondary and tertiary treatment of domestic wastewater, as well as for a variety of industrial effluents (**Vymazal and Kröpfelová, 2008; Kadlec and Wallace, 2009)**. In HF wetlands, primary treatment is achieved by a septic tank (or Imhoff tank). These types of systems are used widely in Czech Republic, Spain, Portugal and North America **(Vymazal & Kröpfelová, 2008)**. The most commonly found HF systems, in warm climatic regions comprises of HF wetland after septic tanks or anaerobic baffled reactors (ABR), or up-flow anaerobic sludge blanket (UASB) reactors. In the UK, HF wetlands are predominantly used for tertiary treatment, with over 600 HF wetlands in operation **(CWA Database, 2011).**

In this scenario, secondary treatment is often achieved using biological treatment units such as rotating biological contactors or trickling filters, and the HF wetlands are used as a polishing step. Additionally, combinations of HF with other wetland types (VF, FWS, etc.) are presently being used in a variety of hybrid systems. For secondary treatment of domestic wastewater, the gravel depth is generally 0.5 to 0.7 m and the water level is maintained 5 - 10 cm below the surface. In tertiary treatment applications in the UK, the depth of the basin is 1.0 to 1.5 m, of which approximately 0.6 m is filled with gravel. HF systems are generally constructed with a longitudinal sloped base (1%) to facilitate draining of the bed, if needed. The remaining bed volume is used for water storage during high flows or storm events.

5.4.2 Advantages

- High reduction of BOD, suspended solids and pathogens
- Does not have the mosquito problems of the Free-Water Surface Constructed Wetland
- No electrical energy is required
- Low operating costs

5.4.3 Limitations

- Requires a large land area
- Little nutrient removal
- Risk of clogging, depending on pre- and primary treatment
- Long start-up time to work at full capacity
- Requires expert design and construction supervision

5.4.4 Design Considerations

The design of a horizontal subsurface flow constructed wetland depends on the treatment target and the amount and quality of the influent. It includes decisions about the amount of parallel flow paths and compartmentation. In HF systems, the major microbiological pathways are anaerobic. As secondary treatment process, HF systems are capable of removing BOD and TSS to an extent of 20 mg L^{-1} but the performance greatly depends on the concentration of influent and HLRs. Removal of TN in HF systems is somewhat restricted due to limited aerobic conditions for nitrification. HF wetlands can be highly effective in denitrification when there is sufficient nitrate and carbon present in the water column. Phosphorus is not completely removed in HF wetlands over the long term unless reactive media is used.

Design guidance for HF wetlands varies greatly. They can be sized using simple specific surface area requirements (m^2/PE), maximum areal loading rates (for example, g $BOD_5/m^2 \cdot d$), or more sophisticated methods such as loading charts or the *P-k-C** approach. Table 10 summarizes the major design parameters of HF CW system in selected countries.

Table 10: Major design parameters of HF CW system in selected countries

	Czech Republic	**Spain**	**US**	**UK**	**India**
Treatment step	**Secondary**	**Secondary**	**Secondary**	**Tertiary**	**Secondary**
Pre-treatment	Screens + Imhoff tank	Screens + Septic tank	Septic tank	Primary settling + biological treatment	Narrow earthen sewer (45 cm wide x 20 cm deep)
Specific surface area requirement (m^2/PE)	5	10	5-10	0.7	41.8
Maximum areal organic loading rate (g BOD m^{-2} d)	-	6	4-8	2-13	0.07-1.0
Maximum cross sectional organic loading rate (g BOD m^{-2} d)	-	-	250[a]	-	-
Hydraulic loading rate (mm d^{-1})	-	20	20-40	200	-
Gravel size (mm)	<20	5-6	>4	10-12	8
Distribution system	Subsurface pipes	Subsurface pipes	Subsurface pipes	Surface trough	Horizontal PVC pipes

References	**Vymazal, 1996); Vymazal & Kropfelova, 2008**	**Gracia & Corzo, 2008**	**Wallace & Knight, 2006**	**Cooper et al., 1997; Griffith et al., 2008**	**Billore et al., 1999**

***This value has been reduced to 100 g $BOD_5/m^2\cdot d$ in a recent proposal by Wallace (2014).**

Length-to-width ratios for secondary HF wetlands generally fall between 2:1 and 4:1, whereas for tertiary systems, width is typically greater than the length to maximize the cross-sectional area and reduce clogging potential with the higher hydraulic rates applied. According to many design guidelines, maximum loading rate should be specified on the basis of the wetland plan area as it is easy for construction. The underlying assumption is that all the HF beds provide a standard depth of 0.6 m media and this value being assumed as the maximum root depth penetration. The use of a maximum cross-sectional area loading, i.e. the load applied at the inlet width and depth, moves away from this assumption and provides opportunity to modify bed length and depth to allow sustainable treatment of the wastewater. The bed width is limited to a maximum of 25 - 30 m to facilitate even flow distribution into a single wetland cell.

In Europe, HF wetlands are typically planted with common reed (*Phragmites* sp.). The systems can be planted with other types of plants, depending on local regulations and/or climate. For example, in the United States, plants from the *Phragmites* genus are considered an invasive species, so other species such as *Sagittaria latifolia, Schoenoplectus validus, Schoenoplectus acutus* and *Iris pseudacorus* are used **(Wallace and Knight, 2006).** In tropical climates, plants such as *Cyperus, Typha, Helicornia* and *Canna* sp. have been used **(Rani et al., 2011).** In HF system, vegetation is mainly related to the physical processes such as providing increased surface area for attached microbial growth, and thus provides better filtration of TSS. In secondary HF system, the role of plants in treatment of wastewater is very minimum. This process is very minimal in terms of comparison to, oxygen demand exerted by incoming wastewater **(Brix, 1990; Tanner and Kadlec, 2003).**

Design of HF CW based on Rule of thumb

Rule-of-thumb is most commonly adopted design for construction of a CW system. The major design criteria of Rule of thumb includes land requirement per equivalent (m^2/PE). The other parameters used in designing a HF CW are; HRT, BOD loading rate, HLR and areal requirements (Table 11).

Table 11: Rule of thumb design criteria for horizontal SSF constructed treatment wetlands (Rousseau *et al*., 2004).

S.No	Description	Value Range	
		Wood (1995)	Kadlec and Knight (1996)
1.	Hydraulic retention time (days)	2–7	2–4
2.	Max. BOD loading rate (kg BOD ha ^{1} day^{1})	75	n.g (not given)
3.	Hydraulic loading rate (cm day ^{1})	0.2–3.0	8–30
4.	*Areal requirement (ha m ^{3} day)*	*0.001–0.007*	*n.g. (not given)*

Advantages of the rule-of-thumb approach

- It is very simple to use.

Disadvantages of the rule-of-thumb approach

- It does not account for different water usage practices, pre-treatment technologies, influent wastewater concentrations.
- It does not account for non-ideal flow.
- It does not consider the geometry of the wetland cell or specific design approaches to minimize the risk of clogging.

Based on Regression equations

Regression equations have also been used to design CWs. These equations are generated from a large collection of data. Here generally two values are required (inlet concentration or mass load, and possibly HLR) to produce an estimate for expected effluent concentration (Table 12). An extensive list of regression equations for HF wetlands in different areas are described by **Rousseau *et al*. (2004).**

The HF CW wetlands are also designed using regression equations which consider the quality of target effluent in a CW system.

Table 12: Regression equations for HF wetlands

S. No	Parameter	Equation	Input Range	Output Range	R^2
1.	BOD_5	$Mo = (0.13 \times Mi) + 0.27$	$6 < Mi < 76$	$0.32 < Mo < 21.7$	0.85
		$C_o = (0.11 \times Ci) + 1.87$	$1 < Ci < 330$	$1 < Co < 50$	0.74
2.	COD	$Mo = (0.17 \times Mi) + 5.78$	$15 < Mi < 180$	$3 < Mo < 41$	0.79
3.	TSS	$Mo = (0.048 \times Mi) + 4.7$	$3 < Mi < 78$	$0.9 < Mo < 6.3$	0.42
		$C_o = (0.09 \times Ci) + 0.27$	$0 < Ci < 330$	$0 < Co < 60$	0.67
4.	TN	$Mo = (0.67 \times Mi) – 18.75$	$300 < Mi < 2{,}400$	$200 < Mo < 1{,}550$	0.96
5.	TP	$Mo = (0.58 \times Mi) – 4.09$	$25 < Mi < 320$	$20 < Mo < 200$	0.61
		$C_o = (0.65 \times Ci) + 0.71$	$0.5 < Ci < 19$	$0.1 < Co < 14$	0.75

Note: Mi and Mo are mass loads into and out of the system, respectively, in kg/ha.d **(Vymazal, 1998)**. C_i and C_o are concentrations into and out of the system, respectively, in mg/L **(Brix, 1994).**

Advantages of using regression equations:

- They are simple to use.
- They take into account influent water quality (and sometimes HLR).
- They inherently account for background concentration (C^*) because equations were created from actual water quality data from full-scale systems.

Disadvantages of using regression equations:

- They are only applicable if the design of the new wetland falls within the data range from which the regression equations were created.
- Many regression equations were created from very large treatment wetland systems, and may not apply to smaller systems.
- Flow rate is not always considered.

The wetland area cannot be determined from equations that only correlate concentration or mass.

5.4.5 Water Quality Targets

HF CW generally capable of removing BOD_5 and TSS to a reasonable extent (20mg/l in the effluent) but the performance of individual systems depends heavily on influent concentrations and HLRs. In HFCWs limited dissolved oxygen in the filtration beds results in effective degradation of organic compounds mainly by microbial degradation due to anaerobic conditions **(Vymazal and Kröpfelová, 2008).** Suspended solids are retained predominantly by sedimentation and filtration with high removal efficiency. Denitrification is one of the major mechanism for nitrogen removal in HF CWs. Removal of ammonia is limited due to lack of oxygen in the filtration bed as a consequence of permanent waterlogged conditions (**Vymazal, 2007).** Reactive media is essential for removal of Phosphorus in HF CWs. Removal occurs primarily by ligand exchange reactions, where phosphate displaces water or hydroxyls from the surface of iron and aluminum hydrous oxides (**Vymazal, 2007).**

5.4.6 Operation & Maintenance

None of the CW system is maintenance free. The most critical operational issue for HF wetlands is clogging. Clogging is a major problem and occurs when the pore spaces in the media are filled with solids (organic or inorganic), instead of wastewater, thus limiting the contact area and time between the biofilm and the water. Therefore, the influent should be well settled with primary treatment before flowing into the wetland. In a HF system treating domestic wastewater, clogging is mainly the result of excess organic or solid loading onto the gravel beds. This may also be due to improper maintenance of the septic tank (Secondary HF system) or the final settling tanks (Tertiary HF system). Hydraulic and solids loading rates that are at the top end of recommended values have been suggested as the main factors resulting in the reported clogging of HF systems. This can be a result of inadequate design or of a deliberate use of HF beds for solids storage rather than treatment **(Dotro and Chazarenc, 2014).** The filter material at the inlet zone will require replacement every 10 or more years. Maintenance activities should focus on ensuring that primary treatment is effective at reducing the concentration of solids in the wastewater before it enters the wetland. Maintenance should also ensure that trees do not grow in the area as the roots can harm the liner. There are many factors which require routine checkups for proper operation of a HF system:

- **Upstream treatment:** Septic tanks (secondary treatment HF) and final settling tanks (tertiary treatment HF) must be emptied regularly to prevent solids carryover to the HF wetland. The emptying interval depends on the size of the septic tank, but should be conducted at least once per year.
- **Influent distribution system:** Uneven distribution can result in a solids or organic loading over a small portion of the intended influent area, and result in clogging. For surface-loaded systems, it is important to ensure that wastewater is evenly delivered across the width of the wetland bed. For HF wetlands that have subsurface loading, the distribution pipes must be properly designed and should contain inspection ports so that the influent header can be periodically washed out and/or cleaned.
- **Outlet control structure:** The outlet level control structure should be checked on a routine basis. The water level should be maintained 5 - 10 cm below the surface of the gravel.

- **Surface sludge accumulation:** Surface-loaded tertiary treatment systems should be monitored for sludge accumulation. Sludge accumulation at the inlet zone of the bed should be measured once a year.
- **Vegetation:** Wetland vegetation should be monitored to ensure that unwanted plant species (weeds) do not overtake the intended plant community. During the first growing season, it is important to remove weeds that can compete with the planted wetland vegetation.

5.4.7 Vegetations

Vegetation play an important role in physical processes of HFW such as increase surface area for attached microbial growth and providing better filteration of TSS. In HF wetlands, nutrient uptake and oxygen transfer through plants is minimal **(Tanner and Kadlec, 2003).**The system can be planted with different types of plants, depending on local regulations and climate conditions. Native plant species with wide and deep roots that can grow in the wet, nutrient-rich environment is appropriate for these wetlands. One of the commonly used macrophyte is *Phragmites australis* (reed) because it forms horizontal rhizomes that penetrate the entire filter depth. In Europe, HF wetlands are typically planted with common reeds (*Phragmites* sp.). Studies done on HFW systems of United States, found that plants from the *Phragmites* genus are considered an invasive species, so other species such as *Sagittaria latifolia*, *Schoenoplectus acutus* and *Iris pseudacorus* are used **(Wallace and Knight, 2008)**. In tropical climates, plants such as *Cuperus, Typha, Helicornia* and *Canna* sp. have been used.

5.5 Vertical Flow Constructed Wetland

5.5.1 Introduction and Application

The subsurface vertical-flow constructed wetlands (SSVF CW) are designed for the treatment of wastewater coming from primary treatment mechanism. In this system the wastewater enters through the surface and flows in vertical direction slowly through the supporting filter material and the plant roots, until reaching the bottom outlet zone (Figure 19). During this passage all the microbial processes are built up results in the removal of pollutants and contaminants. During the infiltration to the bottom, the water remains able to dissolve oxygen that is present in the pores of the surface layers of the wetland. These systems are built with porous materials such as sand and gravel, which restrict the clogging.

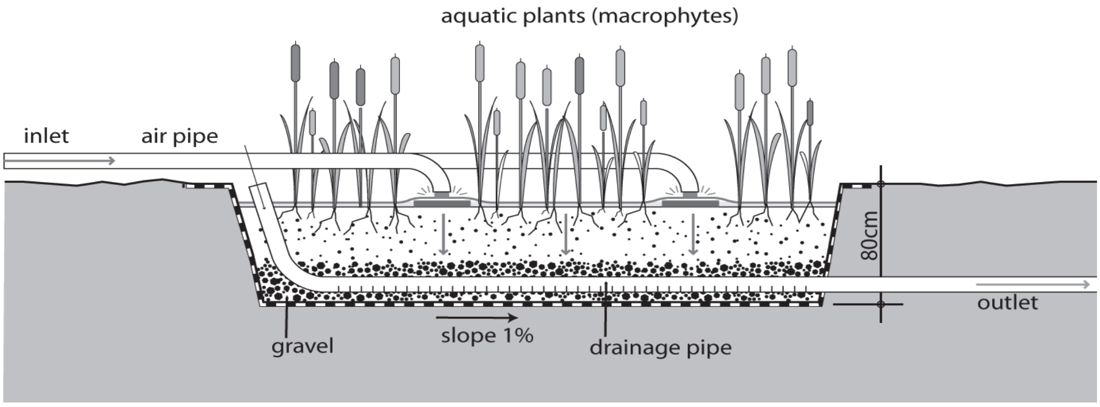


Figure 19: Schematic Diagram for Vertical Flow Subsurface Constructed Wetland (Tilley *et al.,* 2014)

5.5.2 Mechanism

Anaerobically treated wastewater coming from a septic tank or bio digester is intermittently pumped on top of the constructed wetland. By trickling down the wastewater effectively sucks air in the constructed wetland whenever the pump stops, forcing aeration of the rhizosphere. This increases the aeration capacity up to approximately twenty times compare to horizontal subsurface flow constructed wetlands. Mostly, emergent macrophytes are planted in CWs having sand and gravel as filter material. The primary treated wastewater is loaded intermittently to the filter surface. Wastewater percolates through the substrate and get exposed to microbial biofilm and finally collected by the drainage pipes or network. Between intermittent loadings, oxygen re-enters the pore space of the filter material, transporting oxygen into the filter bed in order to sustain aerobic microbial processes. The whole bed is segregated from the surrounding land by means of a plastic liner and a geo textile membrane. In vertical flow wetland intermittent loading creates high aerobic condition for efficient nitrification, removal of Biological Oxygen Demand (BOD) and Chemical Oxygen Demand (COD) **(Langergraber and Haberl, 2001).** VF CWs have high redox potentials to favor aerobic microbial processes **(IWA, 2000).** Significant BOD removal and nitrification occurs but relatively lower denitrification has been observed in VF CWs when compared with SF and HF CWs **(Vymazal, 2007).**

5.5.3 Advantages

- High reduction of BOD, suspended solids and pathogens
- Significant nitrification.
- Does not have the mosquito problem as observed in Free-Water Surface Constructed Wetland
- Less clogging than in a Horizontal Subsurface Flow Constructed Wetland
- Requires less space than a Free-Water Surface or Horizontal Flow Wetland

- Low operating costs
- Construction can provide short-term employment to local laborers (can be an important fact for developing countries)

5.5.4 Limitation

- Requires expert design and construction, particularly, the dosing system
- Requires more frequent maintenance than a Horizontal Subsurface Flow Constructed Wetland
- A constant source of electrical energy may be required
- Long start-up time to work at full capacity
- Not all parts and materials may be locally available

5.5.5 Design consideration

The criteria for VF CW designing include:

- Site selection,
- Appropriate vegetation selection,
- Substrate selection,
- Hydraulic loading rate (HLR),
- Hydraulic retention time (HRT),
- Water depth, operation mode and maintenance procedures **(Akratos *et al.,* 2009; Kadlec and Wallace, 2009).**

Particularly, the factors such as plant selection, substrate selection, water depth, hydraulic loading rate (HLR), hydraulic retention time (HRT), and feeding mode may be most important to establish a feasible CW system and achieve the sustainable treatment performance.

Basic design recommendations for Vertical Flow Wetland treating domestic wastewater

In VF CW wastewater is intermittently pumped onto the surface and then drains vertically down through the filter layer towards a drainage system at the bottom. In VF CW treatment process is characterized by intermittent short-term loading intervals (4 to 12 doses per day) and long resting periods during which the wastewater percolates through the unsaturated substrate and the surface dries out. By means of intermittent loading it provides aerobic condition and facilitates high microbial degradation activities. The top surface of the filter has to be kept levelled and the distribution pipes are often covered with gravel to prevent open water accumulation during the pumping periods. The piping of the system should be design in such manner that they achieve an even distribution of the pre-treated wastewater on the entire constructed wetland bed. This is ensured by selecting the right diameter of the distribution pipes, length of pipes, diameter of holes and spacing between holes in the distribution pipes.

Detailed design of the system provides the distance criteria between drainage pipes but may be around 5 m. The drainage pipe should be covered with gravel to enable better drainage. A bottom slope of 0.5-1% in direction to the outlet is important for large VFBs. The depth of the sand filter beds should be at least 50 cm, with an additional 20 cm of gravel at the base to cover the drainage pipes, 10 cm gravel on the top of the bed and 15 cm freeboard for water accumulation. Generally, the required specific surface area is usually 3-4 m^2/P.E. in cold regions and 1-2 m^2/P.E. in warm regions. However, this may also vary depending on the reuse option and local legislation (**Platzer *et al*., 2007).** For subsurface flow constructed wetland the sizing of system follows the equation as per **Kikuth (1977)** proposed for domestic sewage treatment, i.e.

$$A_h = Q_d (\ln C_{in} - \ln C_{out}) / K_{BOD} \qquad \text{(Eq. 7)}$$

Where,

A_h is the surface flow of bed (m^2),

Q^d is the average flow rate (m^3/d),

C_{in} is the influent BOD_5(mg/L),

C_{out} is the effluent BOD_5 and

K_{BOD} is the rate constant (d^{-1})

$$\boldsymbol{K_{BOD} = KTdn,} \qquad \text{(Eq. 8)}$$

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 generally increases about 10 % per °C. Thus, the reaction rate constant for BOD degradation is expected to be higher during summer than winter. It has also been reported that the K_{BOD} increases with the age of the system.

5.5.5.1 Sizing of vertical flow wetland

Based on Rule-of-thumb

Rule-of-thumb is a prescriptive design approach based on a particular wetland application in a specific climatic or geographical region. Most often, this approach is used for a single wetland technology (most commonly HF or VF) in a local or national guideline **(Brix and Johansen, 2004; DWA, 2017; Önorm, 2009).**

Generally, design advice is given in terms of area requirement per person equivalent (m^2/PE), but can also be given, for example, as a loading rate (g $BOD_5/m^2\cdot d$ or g $COD/m^2\cdot d$). This approach is a practical way of starting a design procedure and can be effective when there is adequate knowledge on the application of the technology in the region under consideration (Table 13).

Table 13: Rule-of-thumb design recommendations for temperate climates

S.No	Country	Technology	Specific surface area (m^2/PE)	Reference
1.	Austria	VF	4	**Önorm, 2505, 2009**
2.	Denmark	HF	5	**Brix and Johansen, 2004**
		VF	3	
3.	Germany	VF	4	**DWA-A 262, 2017**
4.	France	French VF	2	**Iwema et al., 2005**

Based on Specific Area Requirement per population equivalent

For VF systems, the required bed surface area depends on the organic load and is expressed as unit area per population equivalent (m^2/p.e.). The surface area required for each stage of the system depends on the climate, the required level of pollutant removal, and the hydraulic load.

Typical values include:

(a) 1.2 m^2/P.E., divided into three or more identical units for the first stage;

(b) 0.8 m^2/ P.E. divided into two or more identical units for the second stage.

Research in France showed that 2 m^2/ P.E. is a sufficient surface area to achieve satisfactory nitrification, while sizes larger than 2.5m^2/ P.E. do not show remarkable nitrification efficiency improvement **(Molle *et al.,* 2004).**

In France, among CW systems treating municipal wastewater, VF CWs are more widespread. In these systems without any pretreatment the raw sewage directly flows towards VF beds after coarse screening. This makes easier sludge management at the surface of the bed, in comparison to the management of the primary sludge from Imhoff or settling tanks. Such systems are used in France from 20 years and gained much more suitability especially for the treatment of municipal waste water treatment for small population or settlements (**Molle *et al.*, 2004; Paing and Voisin, 2004).**

Table 14: Land requirement of selected wastewater treatment technologies for secondary treatment in warm and temperate climates.

S. No	Treatment Technology	Treatment Area Requirement (m^2/PE)	Reference
1.	HF wetlands	3.0 – 10.0	for warm (Hoffmann *et al.*, 2011) and temperate climates (Kadlec and Wallace, 2009)
2.	VF wetlands	1.2 – 5.0	
3.	French VF wetlands	2.0 – 2.5	for temperate climates (**Molle *et al.*, 2005)**

5.5.5.2 Hydraulic load and Retention Time

Hydrology is one of the crucial factors in controlling wetland functions, and flow rate should also be regulated to achieve efficient treatment performance **(Lee *et al.*, 2009).** The designing should be appropriate for the hydraulic loading rate (HLR) and hydraulic retention time (HRT) as it plays an important role in the removal efficiency of CWs. Generally higher HLR supports fast passage of wastewater through the filter media, thus reducing the optimum contact time. On another side, an appropriate microbial community may be developed in the system and have adequate contact time to remove contaminants at a longer HRT **(Saeed and Sun, 2012; Yan and Xu, 2014)**. **Huang *et al*., (2000)** also reported that the concentration of ammonium and TN in treated effluent decreased with increasing HRT in CWs treating domestic wastewater. A low HRT in CWs results in incomplete denitrification of wastewater, and it is found that the nitrogen removal required higher HRT **(Lee *et al.,* 2009).** Besides it, the effect of HRT may vary between CWs which depends on type of vegetation, temperature etc.

Water Depth

Water depth is one of the crucial factor as it plays important role in knowing about which plant species become suitable for the system. The biochemical reaction occurs within the system also impacted by means of water depth. The appropriate selection of water depth for the system also influent removal rate of contaminants by affecting the redox status and dissolved oxygen level in CWs. (Song et al., 2009). Furthermore, studies of **García *et al.*, (2004)** with 0.5 m deep showed that differences occur in the transformations of pollutants by comparing 0.27 m deep wetland beds within systems of different depths. As per UN Habitat CW manual it is recommended that 0.70 m substrate depth is more suitable, which can provide adequate nitrification as well as the organic pollutants removal.

Influent Dosing Pattern

This is classified into three common distinct categories:

- Continuous,
- Batch,
- Intermittent flow feed.

The feeding mode of influent has been shown to be another important design parameter **(Zhang *et al.,* 2012).** Variations in feeding mode (such as continuous, batch and intermittent) may influence the oxidation–reduction conditions, oxygen transfer and diffusion in wetland systems and, hence, modify the treatment efficiency.

Various study showed variation in feeding mode results in different removal efficiency of the contaminants in the system. Generally, batch feeding mode showed better performance than the continuous operation mode by providing more aerobic conditions. **Zhang *et al.*, (2012)** examine the impact of batch versus continuous flow on the removal efficiencies in tropical SSF CWs. They found that the wetlands with batch flow mode showed higher ammonium removal efficiencies (95.2%) compared with the continuously fed systems (80.4%).

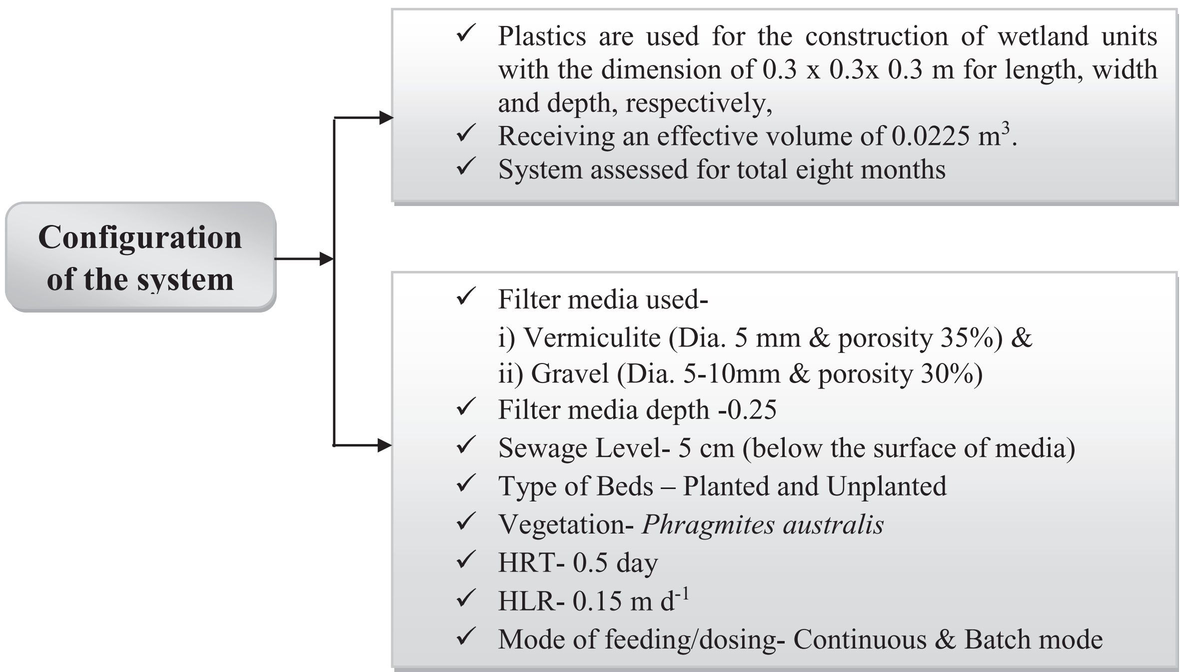


Figure 20: Configuration of a vertical SSF CW system

In CWs for the enhancement of the organics and nitrogen removal, intermittent feeding mode can be considered **(Saeed and Sun, 2012). Caselles-Osorio and García (2007)** assessed the effect of continuous and intermittent feeding modes on contaminant removal efficiency in SSF CWs, and found that by means of intermittent feeding the ammonium removal performances improved in wetland systems compared to continuous feeding. **Abdelhakeem *et al.,* (2016)** evaluated the performance of Vertical SSF CW for sewage treatment under different feeding mode.

Average removal efficiency of COD, BOD, TSS, NH_4 and TP as 75%, 84%, 75%, 32% and 22%, respectively, for the planted beds compared to 29%, 37%, 42%, 26% and 17%, respectively, for the unplanted beds.The efficiency of the system in removing NH_4, TP and dissolved phosphorous (DP) increased by using vermiculite as a filter media in comparison to gravel particularly in planted beds.The mode of feeding also influenced the removal rate of contaminants in the system as the results showed that batch mode was much more effective in removing TSS and NH_4 in comparison to the continuous mode. The effect of feeding mode varied with the filter material used, if vermiculite as filter media operated with batch mode of feeding its shows effective results for the removal of TSS than continuous feeding, while using gravel as a filter media both type of feeding show equal effectiveness.

Filter Media used in Constructed wetland

The selection of filter media is demarcated in terms of the hydraulic permeability and competency of absorbing the contaminants in waste water. Clogging is one of the problem arises during system operation if the hydraulic conductivity is poor. It may also be found that if the adsorption capacity of the filter media gets lowered it affects the long term removal performance of the system **(Wang *et al*., 2010)**. Some studies also suggest that substrates such as sand, gravel, and rock are the poor candidate for long-term phosphorus storage, but by contrast, artificial and industrial products with high hydraulic conductivity and phosphorus sorption capacity could be alternative substrates in CWs (Table 15).

Other studies also provided some information on substrate selection in order to optimize the removal of nitrogen and organics, and the substrates such as alum sludge, peat, maerl, compost and rice husk have been introduced **(Babatunde *et al.,* 2010; Saeed and Sun, 2012).** Besides it, a mixture of substrates (i.e. sand and dolomite) was applied in CWs for removal of phosphates **(Prochaska and Zouboulis, 2006)**, and the mixed (substrate gravel, vermiculite, ceramsite and calcium silicate hydrate) was also used in CWs for treating surface water with low nutrients concentration **(Li *et al.,* 2011a).** The mixed substrates provide high hydraulic conductivity and also exposed reactive surfaces for microbial attachment.

Table 15: Commonly selected Filter media for CW wastewater treatment

S.No	Type of substrates	Source
1	**Natural material**	
i	Sand	Saeed and Sun, 2013
ii	Gravel	Calheiros et al., 2008
iii	Clay	Calheiros et al., 2008
iv	Calcite	Ann et al., 1999
v	Marble	Arias et al., 2001
vi	Vermiculite	Arias et al., 2001
vii	Bentonite	Xu et al., 2006
viii	Dolomite	Ann et al., 1999
ix	Limestone	Tao and Wang, 2009
x	Shell	Seo et al., 2005
xi	Shale	Saeed and Sun, 2012
xii	Peat	Saeed and Sun, 2012
xiii	Wollastonite	Brooks et al., 2000
xiv	Maerl	Saeed and Sun, 2012
xv	Zeolite	Bruch et al., 2011
2	**Industrial by-product**	
i	Slag	Cui et al., 2010
ii	Fly ash	Xu et al., 2006
iii	Coal cinder	Ren et al., 2007
iv	Alum sludge	Babatunde et al., 2010
v	Hollow brick crumbs	Ren et al., 2007
vi	Moleanos limestone	Mateus et al., 2012
vii	Wollastonite tailings	Hill et al., 1997
viii	Oil palm shell	Chong et al., 2013
3	**Artificial products**	
i	Activated carbon	Ren et al., 2007
ii	Light weight aggregates	Saeed and Sun, 2012
iii	Compost	Saeed and Sun, 2012
iv	Calcium silicate hydrate	Li et al., 2011a
v	Ceramsite	Li et al., 2011a

Advantages of artificial substrate

Substrate is the important influencing factor of purification capacity and stable operation in CWs. Traditionally, reed beds had been constructed with local soil as substrate. However, this had caused problems with overland flow and short-circuiting of the wastewater between inlet and outlet because of the low hydraulic conductivity of soils. Therefore, present adopted Therefore, numerous researches around the world have focused on the feasibility of man-made products used as substrate in CWs, such as dolomite **(Prochaska and Zouboulis, 2006),** anthracite **(Wu *et al.*, 2011),** alum sludge **(Babatunde and Zhao, 2009),** steel slag (**Wu *et al.*, 2011),** light expanded clay aggregates **(Brix *et al.*, 2001).** These material are:

- Fine textured with a high surface area.
- Sufficiently permeable to allow water to flow through them without rapid clogging Porous with a particle size of at least 5 mm, and preferably between 10 and 20 mm.
- Sufficiently robust to withstand varying flow conditions
- High organic and nitrogen removal.
- High hydraulic conductivity
- High phosphorus sorption capacity

Sorption capacity of substrate

Substrates are able to remove pollutants from wastewater by means of exchange, adsorption, precipitation and complexation. The adsoption capacity of the used filter media is primarily depends on the content of the filter media, secondary it depends on the hydraulic and pollutant loading **(Lai and Lamb, 2009). Arias *et al*., (2001)**, evaluated 13 Danish CWs filled with sands for determining the phosphorus sorption capacity and found that good phosphorus removal in CWs was due to their Ca-content. **Xu *et al.*,(2006)** studied the phosphorus sorption capacity of nine substrates, and showed that sorption capacity of sands varied between 0.13 and 0.29 g/kg. Similarly, the adsorption capacity of different substrates on ammonium removal also investigated by **Huang *et al*., (2012),** and found that maximum ammonium adsorption of zeolite (11.6 g/kg) was significantly higher than that of volcanic rock (0.21 g/kg). **Ren *et al.*, (2007)** also analyzed the adsorbing capacity of four kinds of substrates (fly ash, hollow brick crumbs, coal cinder and activated carbon pellets) used in CWs for treating domestic wastewater, and the static and dynamic experiments demonstrated that the adsorbing capacity of combined substrates was higher than that of single substrate.

Bed slope

The top surface of the media should be levelled 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 provide a slope from inlet to outlet at the bottom along the direction of flow for easy drainage. 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.

Inlet and outlet structures

Inlet structures at subsurface wetlands include surface and subsurface manifolds such as a perforated pipe, open trenches perpendicular to the direction of the flow etc. A single inlet would not be suitable for a wide wetland cell because it would not be possible to achieve uniform flow across the cell. In general, perforated or slotted manifolds running across the entire wetland width are used typically for the inlets. Sizes of the manifolds, orifice diameters, and spacing are a function of the design flow rate.

Outlet structures help to control uniform flow through the wetland as well as the operating depth. The design of subsurface flow wetlands should allow controlled flooding to 15 cm to foster desirable plant growth and to control weeds. The use of an adjustable outlet, which is recommended to maintain an adequate hydraulic gradient in the bed, can also have significant benefits in operating and maintaining the wetland. A perforated subsurface manifold connected to an adjustable outlet offers the maximum flexibility and reliability as the outlet devices for subsurface flow wetlands. In VF systems, the collection system may consist of a network of drainage pipes surrounded by large stones. The drainage pipe will lead to a collection sump, which will allow the vertical bed to completely drain.

5.5.6 Water Quality

In general, contaminants that are degraded aerobically are easily removed out using VF wetlands with intermittent loading. For the treatment of domestic and municipal wastewater, the organic matter (BOD or COD) and ammonia nitrogen are removed mainly through aerobic microbial processes. Total suspended solids and pathogenic organisms are isolated by physical filtration. The working efficiency of vertical flow wetland is directly related to the filter material used. If the fine filter material is used, the retention time of the wastewater in the filter is high which resulted in higher removal efficiency. However, the hydraulic retention time is moderate, the infiltration rate is low due to fine particles so it increases clogging potential of the bed.

On the other side coarse particles enable higher hydraulic loading rate and less clogging potential, but shows less removal efficiency. This can be partially overcome in some cases by increasing the depth of the main layer. Available design guidelines for VF wetlands are based on empirical rulesof-thumb, such as those using specific surface area requirements **(Brix and Johansen, 2004; DWA, 2017; ÖNORM, 2009).**

The Danish guideline states that, when VF wetlands are designed according to the guideline, they will remove 95% of BOD and 90% of ammonia nitrogen and thus will meet the legal requirements (e.g., effluent concentrations below 10 mg BOD_5/L and 5 mg NH_4-N/L, respectively). In Austrian and German legislation, nitrification is not required in winter, i.e. the effluent standard of 10 mg NH_4-N/L must be met only if the effluent wastewater temperature is above 12°C (valid in Austria for plants smaller than 500 PE and in Germany for plants smaller than 1,000 PE; for larger plants more stringent regulations apply).

Besides the parameters listed in published guideline manuals, all the guidelines require a drainage layer of gravel at the bottom of the bed and an intermediate or transition layer (e.g. 10 cm gravel of 4 – 8 mm in diameter) between main and drainage layer. The intermediate layer prevents grains from the filtration layer from migrating into the drainage layer. The coarse gravel in the drainage layer allows good drainage and together with the drainage pipes, provides oxygen to the deepest layer of the bed. In order to prevent migration of fine gravel to the coarser gravel layers below, the Terzaghi rule of $D15/d85 \leq 4$ is used (*D* corresponds to the transition layer and *d* to the main layer) **(Sherard *et al.*, 1984).**

The design guidelines include a non-compulsory top layer of gravel (e.g. 4 – 8 mm) to prevent erosion during intermittent loading as well as to allow no free water on the surface. Except this, an additional top layer increases thermal insulation and also ensures higher temperatures of the filter in winter (about 1 – 2°C for a 15 cm top layer). However, the top layer reduces oxygen supply to the main layer and fixes the stems of emergent macrophytes so that they cannot move and break up the surface of the main layer in the non-loading periods. Both effects lead to less degradation of particulate organic matter at the surface of the main layer and thus causes higher risk of clogging. If a top layer is used, it should be limited to a depth of 5 – 10 cm (**Langergraber *et al.*, 2009a).**

Mostly *Phragmites australis* (common reed), an emergent macrophytes species, is used for vegetation in VF wetlands. The role of the macrophytes is to remove out the pollutant by means of physical processes. The root structure of plant provides surface area for attached microbial growth, and root growth is known to help maintain the hydraulic properties of the filter. The vegetation cover protects the surface from erosion.

In temperate climates, litter provides an insulation layer on the wetland surface for operation during winter. Comparatively uptake of nutrients plays a minor role in pollutant removal from wastewater then the degradation processes caused by microorganisms. Some plants also release organic compounds, which also aid in denitrification. Compared to the amount of oxygen brought into the system from the atmosphere due to intermittent loading, release of oxygen through roots plays a minor role in VF wetlands **(Brix, 1997).**

5.5.7 Operation and Maintenance

In vertical flow system clogging is the main operational problem due to the insufficient removal of sludge from the primary treatment step (e.g. septic tank). If sludge is not removed periodically, it moves to the filter surface and clog the filter. Several other operational problems can result from poor design and/or problems developed during the construction phase. Problems during design and/or construction that should be avoided include (adapted from **Mitterer-Reichmann, 2012):**

1.Insufficient protection of VF wetland surface from surface water and superficial runoff: Soil substrate from the surrounding area is washed on the filter surface during rain events and causes clogging of the gravel and sand layers. To prevent this, border strips should be established around the filter beds.

1. **Unsuitable filter media**: For economic and sustainability reasons, it is intended to use appropriate sand and gravel to the implementation site. When new providers are used, the grain size of the sand should be tested. The main problem with fine grain size distribution and/or unwashed sand or gravel is that it contains a large portion of fines which can lead to clogging of the filter.
2. **Uneven slope of the filter surface**: Ponding of water in single areas of the filter bed might lead to clogging.
3. **Intermittent Loading System**: Uneven distribution of wastewater causes uneven loading on parts of the VF wetland and can result in ponding (and eventual clogging). Thus, distribution pipes and opening holes must be evenly distributed over the surface of the filter bed and even distribution of wastewater must be ensured. Additionally, it is essential that the pipes drain completely after a loading event. Drilling a downward facing hole in the distribution system can facilitate this.
4. **Primary treatment using a septic tank**: Poor quality concrete tanks can result in corrosion and sludge drift. In some cases, weathering of septic tank walls can occur. In case of less ventilation into the tank, the cover of the septic tank should be perforated or air circulation should be facilitated by other means.

Requirements for regular O&M of VF wetlands include (adapted from **Mitterer- Reichmann, 2012**)

1. **Maintenance logs**: System owners should check nitrification of the VF wetland by measuring effluent ammonia nitrogen using a test kit on a monthly basis. The measurement should be

recorded in a "maintenance book" together with all maintenance work done and operational problems that occur.

2. **Primary treatment**: The sludge should be removed from the primary treatment in order to prevent sludge drifting towards VF beds. The emptying interval depends on the volume of the tank, but sludge should be removed at least once a year. The sludge can be stabilized in a separate sludge treatment wetland onsite, or transported to a centralized wastewater treatment plant for further treatment.
3. **Intermittent Loading**: The intermittent loading can be checked by measuring the height difference in the well before and after a loading event.
4. **Siphons:** After some years, the rubber part of some siphons can get porous, which allows wastewater to seep continuously and thus only one part of the VF filter is loaded. If this is not detected, the filter will become clogged after some time. Additionally, siphon hoses can split. Thus, the loading device should be checked once a month.

5. **Distribution pipes:** In order to prevent freezing of wastewater in the pipes of the distribution system, it is essential that after a loading no water stays in the pipes. This needs to be checked at least in fall and after removing wetland plants.
6. **Wetland plants:** During the first year, weeds should be removed until a mature cover of wetland vegetation is established. Wetland plants should be cut every two to three years either in spring or in fall. If cut in fall, the plant material should be left on the filter surface to provide an insulation layer.

5.5.8 Vegetation

Generally, Macrophytes are used in CW treatments include emergent plants, submerged plants, floating leaved plants and free floating plants. Although more than 150 macrophyte species have been used in CWs globally, only a limited number of these plant species are optimally planted in CWs in reality **(Vymazal, 2013b).**

Commonly used Emergent Species

- *Phragmites spp. (Poaceae),*
- *Typha spp. (Typhaceae),*
- *Scirpus spp. (Cyperaceae),*
- *Iris spp. (Iridaceae),*
- *Juncus spp. (Juncaceae) and*
- *Eleocharis spp. (Spikerush).*

Commonly used Submerged Plants

- *Hydrilla verticillata*
- *Ceratophyllum demersum*
- *Vallisneria natans*
- *Myriophyllum verticillatum*
- *Potamogeton crispus*

Commonly used floating leaved plants

- *Nymphaea tetragona*
- *Nymphoides peltata*
- *Trapa bispinosa*
- *Marsilea quadrifolia*

Commonly used free floating plants

- *Eichhornia crassipes*
- *Hydrocharis dubia*
- *Lemna minor*

Among the all macrophytes, the main vegetation in FWS and SSF CWs designed for wastewater treatments are emergent plants. **Vymazal (2013b)** surveyed emergent plants used in FWS CWs, and revealed that *Phragmites australis* is the most frequent species in Europe and Asia, *Typha latifolia* in North America, *Cyperus papyrus* in Africa, *Phragmites. australis* and *Typha domingensis* in Central/South Americas and *Scirpus validus* in Oceania.

Efficiency of plant in removal of contaminants

Wetland plant has been known to be one of the main influencing factor for water quality in wetlands. As one of the biological component of CWs, plants act as a medium for purification reactions by enhancing a variety of removal processes and directly utilizing nitrogen, phosphorous and other nutrients **(Ong *et al.,* 2010; Liu *et al*., 2011; Ko *et al*., 2011).**

In addition, they can also accumulate toxic elements, such as heavy metals and antibiotics in wastewaters **(Liu *et al*., 2013).** Thus, numerous studies were performed on the uptake capacity of plants in CWs. The capacity of uptake by plants may varies according to the system configurations, retention times, loading rates, wastewater types and climatic conditions **(Saeed**

and Sun, 2012). The plants can remove nitrogen and phosphorus in range of 15–80% N and 24–80% P, respectively **(Greenway and Woolley, 2001).**

5.6 French Vertical Flow Constructed Wetland

5.6.1 Introduction and Application

In 1990s, a unique vertical flow subsurface CW was developed in France for the treatment of raw wastewater which is known as the "French System". In this type of treatment system, the wastewater does not pass primarily through any pretreatment units like septic tank etc., therefore the system prevents the biogas formation and sludge generation, which may cause problem during treatment process. Previous studies showed that French vertical systems have also been executed in the areas of tropical overseas French territories, South America, as well as other countries within the European continent. One of the largest French vertical wetland was built at Moldova and operated for about 20,000 Person equivalent capacity **(Masi *et al.*, 2017a).**

French VF wetlands are consisting of two stage system, first stage constitutes three stacked filters with coarse gravel and the second one consist of two coarse sand filter which are placed in parallel manner **(Molle *et al.,* 2005a).** In both, first and second stages, each unit receives wastewater for 3.5 days with rest period of 7 days, the wastewater directly flows through the simple screen mesh of dia 20 to 40 mm. This screening process by means of mesh helps in fractional removal of organic matter and nitrifies the waste water.

The designing criteria of the French vertical flow system are very simple as it does not require any primary treatment component for treating wastewater (Figure 21). *Phragmites* species are mainly grown in the strands, which removes out the contaminant primarily in first stage system followed by second one. Whole system contain siphon for sequential batch feeding, flow meter for controlling the wastewater pressure, simple bar screen mesh, inlet and outlets structures.

5.6.2 Mechanism

The mechanism of the French vertical flow system is adapted as per **Molle *et al.*, (2005)** publication:

In this system initially the raw wastewater is collected for 3-4 days in the first stage bed, after that rested for 6-8 days. During this whole process the other beds are under working condition. For the control of biomass and maintaining aerobic condition in bed the first stage is operate in alternate manner. This achieves the benefits as illustrated in Figure. 22.

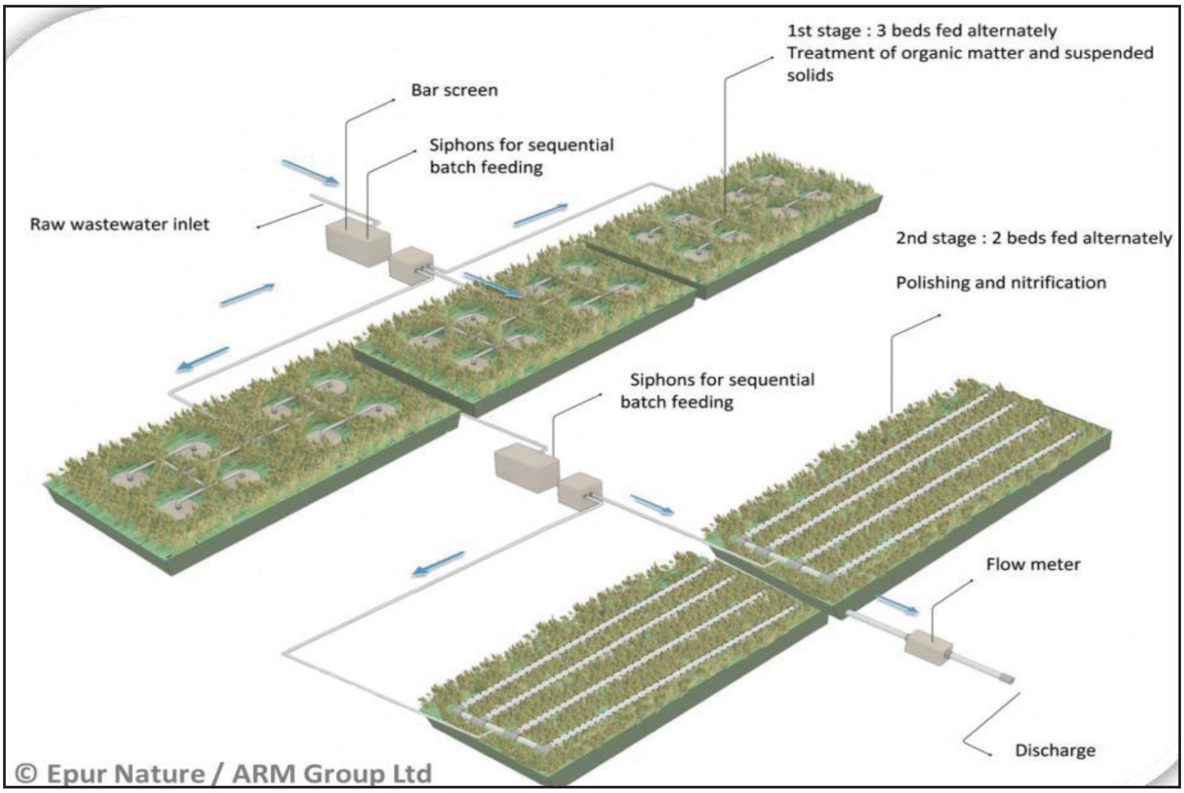


Figure 21: Schematic diagram of the classic French VF design. (Adapted from Epur Nature)

- During treatment process the raw wastewater first passes through a layer of 30 cm fine gravel (2-8 mm particle size), then towards a transition layer of gravel (5-20 mm particle size) and then finally extended towards the drainage gravel layers (20-40 mm particle size or even 30-60 mm particle size) in the base of the filter bed. Solid particles accumulated at the surface of the bed get mineralized.
- In this system the second stage is designed in a way that while one filter bed is in operation another one is in resting period. Both the filter beds are installed parallel to each other. The sand layer used as filter media is of 30 cm thickness which helps in performing further treatment processes. In this stage pollutant reduction occurs by means of several processes like nitrification, COD and TSS removal etc.

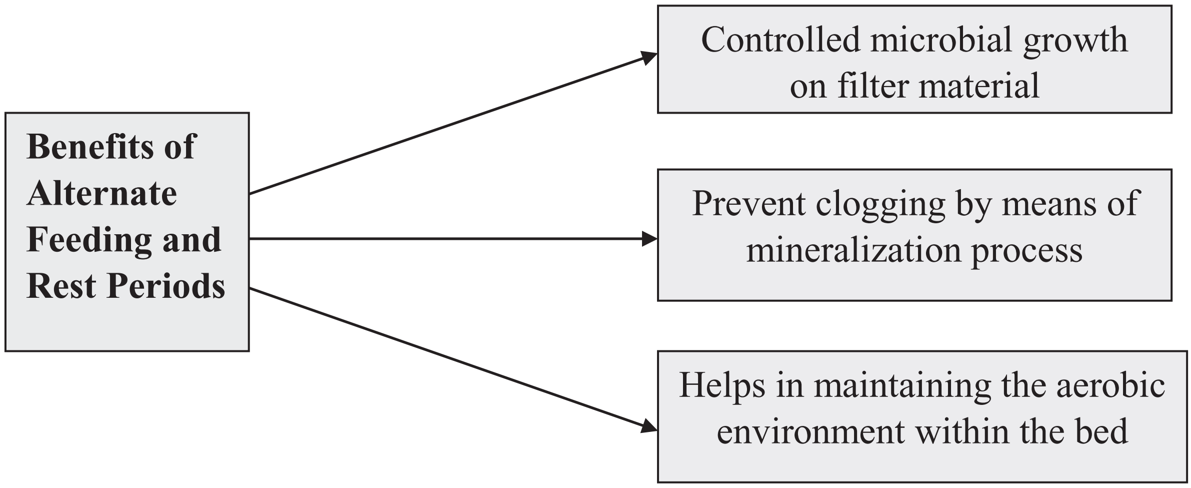


Figure 22: Benefits of alternate feeding and resting period in French systems

Molle *et al*., (2005) reported that if high bulk of gravel is used as filter material in the first stage of the French vertical flow system then it shows efficient removal of 80% COD, 86% TSS, and 50% TKN, this removal rate shows that the treated wastewater can be easily disposed off to the surface water. A solid particle absorbed on the surface of the beds gets accumulated forming sludge that helps in restricting the infiltration rate and ameliorates the distribution of wastewater flow. The sludge layer formed in the first stage is increase up to 1.5 cm per year, in this period the organic matter contained sludge get mineralized into simpler component or inorganic form on the surface of bed and gets eliminated after 10-15 years regularly, when it reaches to 20 cm. In general, the sludge is utilized again in the form of manure for agricultural purpose but, its usage depends on the level of heavy metals present in it.

5.6.3 Advantages

- French reed beds are very productive in eliminating out the suspended solid, dissolved organic particles and microbial pathogens and also having ability to nitrifying the raw waste water during operation phase in the first stage.
- Adoption of saturation bottom layer results in greater denitrification rate and total nitrogen removals within the filter beds. It is also noted that this system doesn't show any problem related to odor because of the oxygenated environment provided by means of cycling feeding system and growing rhizosphere in the accumulated sludge.
- This technology shows remarkable removal of contaminants present in raw sewage as it does not require any pretreatment component like septic and Imhoff tank, it may also be adopted to minimize the capital and operational cost of the system.

5.6.4 Limitation of the French System includes:

- Pumping station for intermittent loading and siphon for maintaining the height between entered wastewater and the bed surface area is required.
- This system is not best suited for working at small level (near the household's colony) due to the reason that the sewage wastewater causes fatal health issues if it is handled openly.
- The efficiency or the performance of system gets affected during winters.

5.6.5 Design consideration

Sizing

For measuring appropriate structures of the French System for the treatment of sewage wastewater, **Molle *et al.*, (2005)** suggest (Figure 23 and 24): ·

- For the 1st phase: 1.2 m^2/person equivalent, (equivalent to an average loading of 100 g COD/(m^2·d); 50 g TSS/(m^2·d); 10 g TKN/(m^2·d) and 120 L/(m^2·d) divided over 03 identical units feeding alternatively.
- For the 2nd stage: 0.8 m^2/person equivalent, divided over two parallel or alternately fed filter beds. This results in a very low average load of 25 g COD/(m^2·d).
- To reduce the operation and maintenance cost and investment per capita only 2 units per stage is suggested **(Boutin *et al.*, 2003).**

Filter Media Selection

Like other designs of CW systems, in this system also gravel and sand are used as a basic filter material in both stages, but are associated with the variations in its dimension and treatment efficiency.

Table 16: Distribution and significance of filter layers in a French CW system

S. No	Layers	Filter media	Significance
1.	Main layer	Gravel (Dia.- 2- 6 mm)	i. Helps in establishing the oxygenated environment in the first stage filter bed. ii. Grain size of the filter media play important role in its functioning ability. If the grain size is smaller clogging problem may be occur and also coarse grain size inhibit the formation of organic matter layer.
2	Transition /Intermediate Layer	Gravel (Dia.- 5-15 mm)	i. This layer helps in preventing fine particles from being washed into the drainage layer by reducing the effective

			porosity of the drainage layer.
3	Drainage layer	Coarse Gravel (Dia.- 20-60 mm)	i. For the collection of treated water placed at the bottom of the bed.
4.	Lining	Filter beds are segregated from surrounding environment by means of plastic liner and a geo textile membrane in combination.	

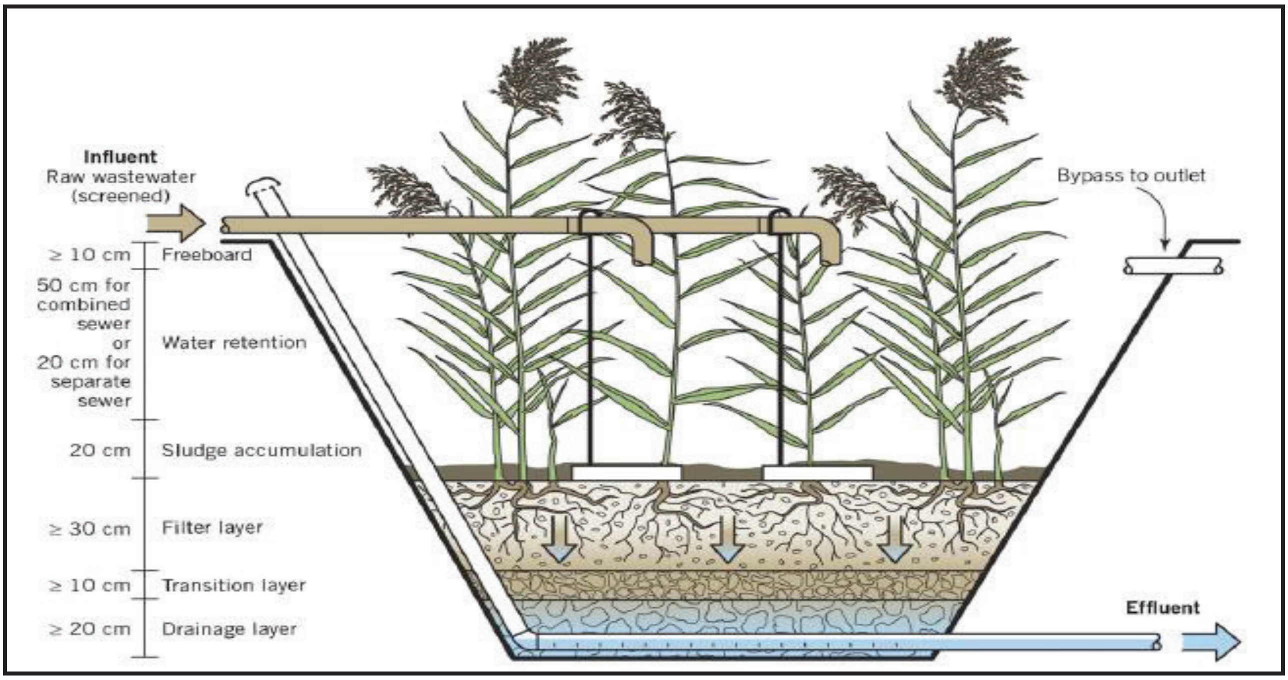


Figure 23: Layout of French VF cells- First Stage (Dotro *et al.*, 2017)

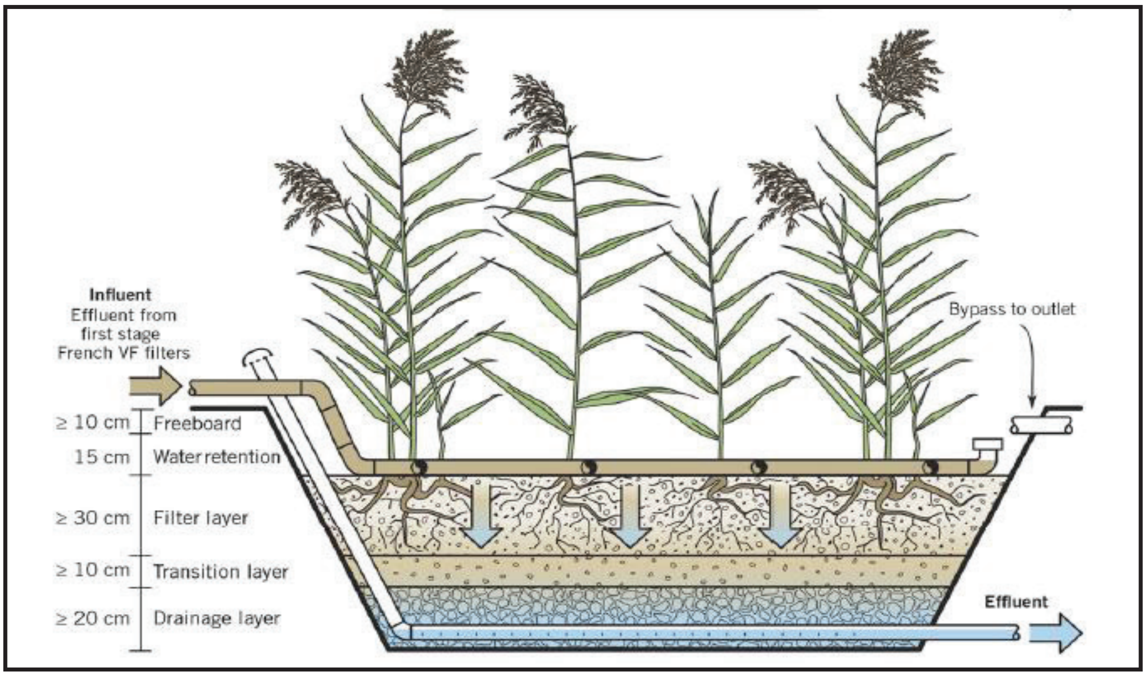


Figure 24: Layout of French VF cells- Second Stage *(Dotro et al.*, 2017)

Liénard *et al.*, 2001, reported that sand is the chief filter material used in the second stage bed on the another hand **Torrens *et al.*, 2009**, said that washed sand may be used in the second stage but it is less efficient. The Terzaghi rule suggested ($D15/d85 \leq 4$) size of sand for as suitable filter media in the transition and drainage layer, and also for the permeability measures. This rule helps in ensuring that the interface between the sand layer and transition layer doesn't produce low permeability by reducing the local porosity.

Table 17: Filter media technical details for a French VF wetland design as per Molle *et al.* (2005)

S.No	Layers	First stage		Second stage	
		Depth	**Material**	**Depth**	**Material**
1	Freeboard	> 30 cm		> 20 cm	
2	Main layer	30 - 80 cm	2 – 6 mm gravel	30 - 80 cm	sand $0.25 < d10 < 0.4$ mm *and* $d60/d10 < 5$ *and* less than 3% fine particles
3	Transition layer	10 - 20 cm	5 – 15 mm gravel	10 - 20 cm	3– 12 mm gravel
4	Drainage layer	20 - 30 cm	20 – 60 mm gravel	20 - 30 cm	20 – 60 mm gravel

Bed Slope and Depth

For the construction of cells generally surface length to width ratio should be one, with an embankment slope of 1:1. The productivity of the system towards the contaminant removal is affected by the depth of main layer. **Millot *et al.*, 2016,** observed that within the uppermost layer of 10-40 cm of an unsaturated filter show high level of carbon and ammonium reduction in French vertical flow system. With strong effluent concentrations must be met, the depth of the main layer can be increased (> 60 cm for COD removal and > 80 cm when full nitrification is required).

Batch and alternate feeding mode

Flowchart for feeding system is described in the Figure 25.

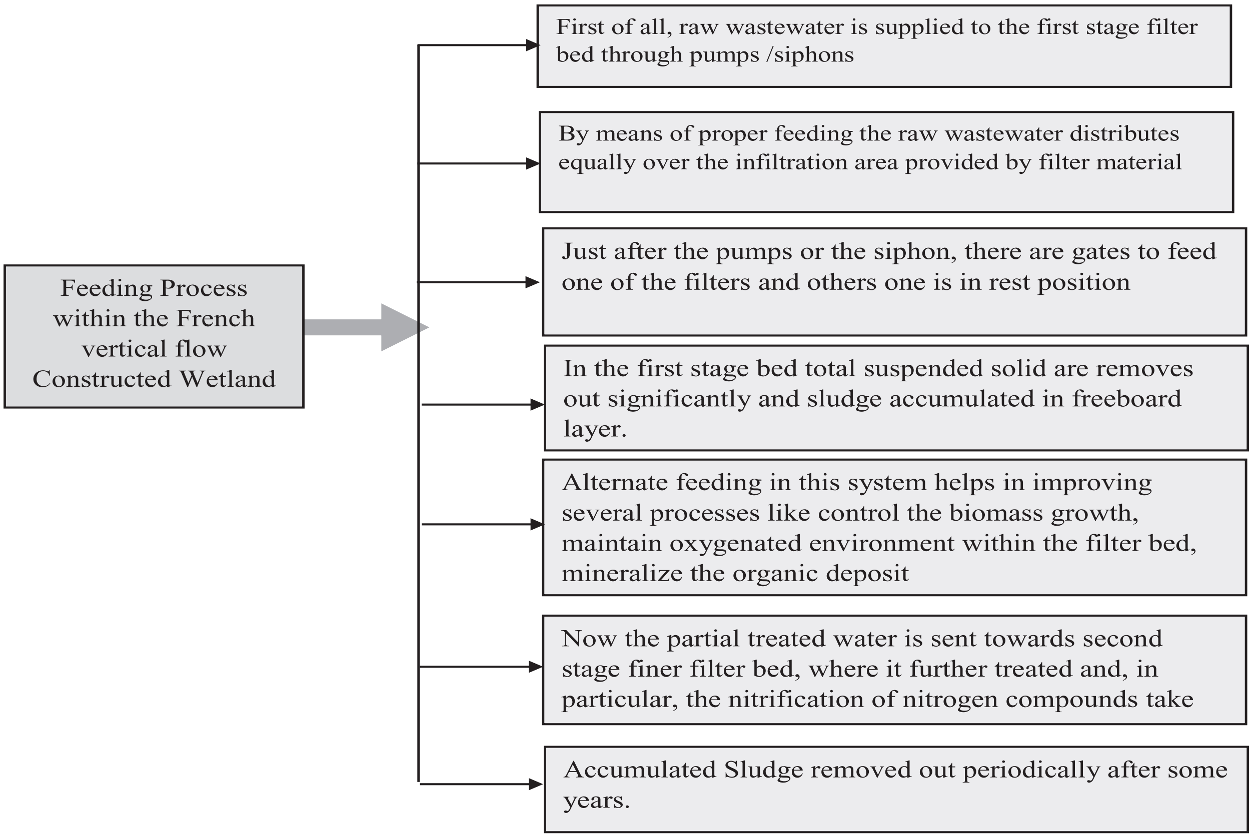


Figure 25: Steps of feeding process in a French CW system

Hydraulic Consideration

In this system the wastewater dosed in an alternate manner, in a way that one filter bed is working while another one is in rest position. Alternation in the feeding system is done especially for the appropriate operation of the system. By means of this type of feeding the microbial growth on the surface of filter beds are regulated, providing oxygenated environment within the bed, also helps in reducing the organic matter accumulated on the surface of first filter beds (Figure 26). For assessing the proper functioning of the system the supervisor must visit the system twice in a week. By installing Programmable Logic Controller (PLC) feeding system the operator visits may be minimized.

Benefits of the alternate feeding method:

- By means of alternate feeding system sufficient oxygen is transferred into the perforated filter media.
- During resting phase, it helps in fixing the deposit layer on top of the filter bed.

- During cold climates it helps in maintaining snow cover for providing high heat insulation. **Prost-Boucle *et al.*, 2015**, reported that wastewater dosing twice in a week results in a shallower ponding depth of raw sewage on the surface of the bed, which inhibit the snow cover from evaporating out.

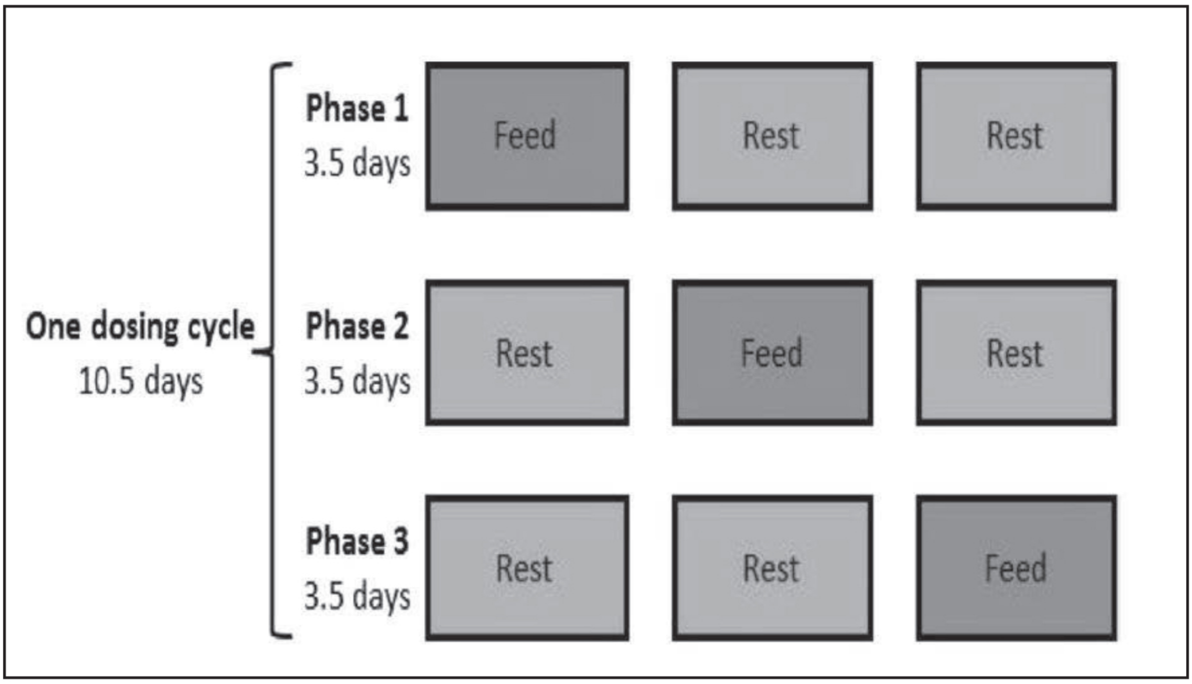


Figure 26: Schematic diagram showing first stage in operational phase (*Dotro, et al., 2017*)

Hydraulic consideration in tropical regions

- The organic degradation process enhances significantly due to the warm temperature in tropical region which eliminate demand of stabilizing it within a week. After that this is mixed with less polluted effluent and dosed in alternate manner, being kept at twice a week, with only two filters on the first stage **(Molle *et al.*, 2015).**
- Batch feeding mode is adopted. Single batch is dosed in a way that it volume up between 2 to 5 cm in the filter bed during operation phase, to make sure that the wastewater distributed equally over the filter bed surface. The maximum limit of 5 cm helps in preventing any short circuiting within the system.
- For maintaining the oxygenated environment within the filters beds it should be mandatory to provide free oxygen at the base of the filter bed. The drainage pipes specifically have minimum diameter of 100 mm, contains slot of the length 1/3 of pipe circumference, width >8 mm for every 10 cm of drainage pipe length.

- The slot in the drainage pipes are set in a way that the air is easily passes from its top whereas the treated wastewater is collected at the base of the drainage pipes.
- In the first stage the raw wastewater is dosed to one point per 50 m^2. For the distribution of raw sewage, the drainage pipes are specifically built with large pipes of dia >110 mm for small scale system, 160-200 mm for larger system.
- In second stage, smaller pipes with drilled holes are used. In which smaller pipes having diameter of (>110 mm) and drilled holes having diameter of (>8 mm). In this stage the pipes are placed directly on the filter surface.
- To prevent the abrading of the topmost filtration layer the care must be taken during first and second stage. To avoid it, in first stage wastewater flow should be 0.5 m3/h·m² minimum per batch to disperse out the wastewater in similar frequency, whereas in second stage the treated water pressure should be greater than or equal to 30 cm at the outermost point.

5.6.6 Operation and Maintenance

The O&M of French VF wetlands is comprised of different phases in which specific tasks must be performed. It incorporates the commissioning period, the routine operation periods during which the removal of accumulated sludge is done.

Commissioning period

During first stage operation, reed growth maintenance is important to retain water infiltration capacity and passive aeration of the filter bed. During the first year, routine maintenance tasks should be performed. Attention must be given to inhibit the intense weed growth in the filter beds. Clearance of overgrowing reed is done manually and in fastidious manner.

For developing favorable condition for the reed formation and its growth in first growing season it is necessary to saturate the filter for one or two weeks. It is suggested that to avoid saturation of first and second stage at the same time as it may hinder the nitrification process.

Troubleshooting might be necessary during commissioning periods. The main issues that occur during commissioning include:

- If the hydraulic load during initiation of the system is low, then the reed growth is affected and it may suffer from water stress problem due to the fact that water percolates near the loading points. This does not affect the treatment plant efficiency in removing contaminant, but it is mandatory to maintain the reed growth to avoid any unexpected problem during operation phase.
- When a system initiated at its nominal design load, the organic matter deposit forms quickly. Due to the reason that the reeds are too small to aid in water infiltration and deposit

mineralization, the deposited organic matter therefore dries quickly, without mineralization, and creates excess ponding. This problem ends once the plant stand becomes established.

- Initially if the deposit layer is not formed and treatment plants receives storm events, then the water can infiltrate very fast in the first stage and surface clogging can occur on the second stage. This process ended when the deposit layers formation start at the first stage. To speed up the process a sludge or compost layer may be applied in the first stage.

Routine maintenance

- The operator should visit the site twice a week to check the proper functioning of the plant and to perform specific short tasks. The screening mesh must be cleaned regularly, and the batch feeding systems have to be checked for proper operation.
- Alternation in the feeding system must be done at every 3.5 days to maintain good oxygen content in the filter. Rest periods that are too long are unfavorable for the microbial community in the wetland.
- Other maintenance tasks can be done less frequently, such as controlling the weeds growth done once in a month or checking the organic deposit height and harvesting the reeds once in a year.
- In tropical climates, the maintenance frequency of the plant stand can be higher due to the warmer climate and thatch accumulation.

Removal of accumulated organic matter

- At the first stage, sludge accumulation occurs at the rate of approximately 2 to 3 cm/yr, if it is run efficiently as the designing load in a temperate climate, if in case only 02 filters are used in parallel manner, the sludge accumulation gets slower.
- The sludge accumulation may hinder the performance of the plants so it showed be removed once it reaches 20 cm (which occur generally in 10-15 years).
- If the accumulated sludge rises to the depth of 20 cm and still not removed periodically then it creates ponding which results in low oxygen transfer in the system.
- Removal of organic matter is done by mechanical machinery and can be spread onto agricultural fields as an organic matter and phosphorous source, depending on local regulations.
- Contrary to sludge treatment wetlands, there is no need to apply a specific rest period before sludge removal. The French VF wetlands can be put back in operation immediately after sludge removal has been completed.

Load variations

In any treatment plant if load is varied then it can affect the treatment efficiency of the filters. High organic matter consumes more oxygen and saturates ammonium adsorption sites faster. This should be avoided, because ammonium adsorption onto organic matter is an important key parameter in nitrification **(Morvannou *et al.*, 2014).** Nevertheless, higher organic loads can be applied in summer because of the higher biological kinetic rates. This means the system does not need to be oversized in order to account for variations in the organic load during the summer season, when population may increase in tourist areas **(Boutin and Prost-Boucle, 2015).**

Hydraulic overloads can induce longer ponding periods that also may affect oxygen transfer into the deposit layer and main filter layer. At the same time, hydraulic overloads decrease the water retention time within the filter **(Molle *et al.*, 2006).** With proper design, storm events can be treated in the filter while maintaining acceptable outlet concentrations **(Arias, 2013).**

5.6.7 Water Quality

FVCW system treats screened domestic wastewater. The first stage filters help in removal of organic matter and TSS whereas the second stage filters have a polishing effect for COD, BOD_5 and TSS. Design and operating conditions in the wetlands guarantees final effluent concentrations of 20 mg BOD_5/L, 90 mg COD/L, 15 mg TSS/L, and 15 mg TKN/L. Organics and suspended solids mostly follow a linear removal trend while TKN removal efficiencies are found to be more complex **(Molle *et al.,* 2005).**

5.6.8 Vegetation

Vegetation is a critical component of the French VF design. Various plants have been successfully used in these systems. *Phragmites australis* is one of the most common macrophyte used but is not always suitable for tropical climates because of its invasive or potentially invasive behaviour. Studies have reported different species from Zingiberales, Heliconiaceae and Cannaceae showing good adaptation to the main stresses generated by VFCWs. They have long vegetative cycles that may require weed growth control after plantation, but low harvesting frequency. *Canna indica* or *Canna glauca* are found to be preferable species. Also, few species of the *Cyperus* genus demonstrated good adaptation to water and anoxic stresses and could be of great interest. Their behavior on full-scale systems has still to be studied for weed competition and even growth. Other effective members may be found in the large Poaceae family. They show a short vegetative cycle, requiring high harvesting frequency to maximize density and control proliferation.

5.7 Tidal Wetlands

5.7.1 Introduction and Application

Tidal flow artificial wetlands (TFAW) are fourth generation wetland systems for wastewater treatment that mimics the processes of natural tidal wetlands. It works by continuous filling and draining the wetland cell with wastewater (Figure. 27). This cycle introduces additional oxygen to the wetland cell. These constructed wetlands have improved aeration and hence contribute an outstanding removal of total nitrogen as compared to traditional wetland systems **(Behrends, 1999)**. Different stages are created in a tidal flow wetland with wetland cells which operated in series. The water filled in the first stage was drained to the next stage and so on **(Sun *et al.*, 2006)**. Leslie L. Behrends introduced a modified form of TFWs for improving wastewater treatment named as "Reciprocating Subsurface-Flow Constructed Wetlands" **(Behrends, 1999)**. This consisted of wetland cell pairs. Here, instead of filling and draining wastewater through the different stages of the wetland system one wetland cell was filled and the water reciprocated between the two cells that together formed a cell pair.

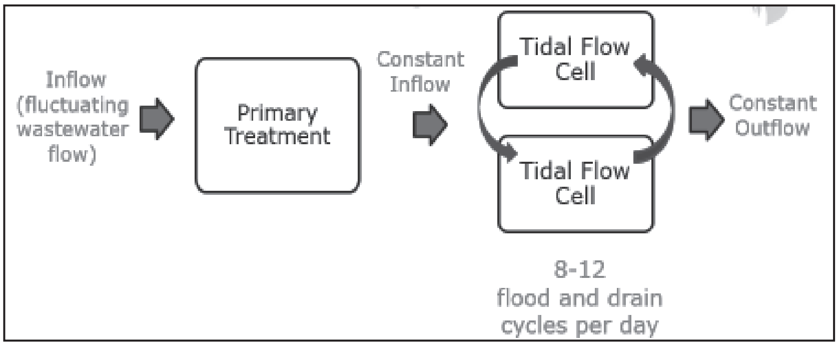


Figure 27: Flow Diagram of Tidal Flow wetland

TFAW is used to treat and reuse wastewater at small communities, public buildings, large offices, universities, schools, campgrounds, resorts, military bases, industrial parks, airports and animal feeding operations **(Behrends & Lohan, 2012)**. They can be designed to be integrated into landscaping or built into a building or greenhouse. This means they can be used where space is limited.

5.7.2 Mechanism

TFAWs consists different stages of water treatment. Firstly primary treatment is done in tanks for coarse-solids and floating material removal. A flow equalisation tank is separate or integrated with the primary treatment tank which buffers periods of high and low flow. Primary treatment is followed by the actual tidal wetland treatment cells. These can provide treatment to tertiary treatment standards.

The tidal flow wetland cells can be set up in stages which means the first pair of treatment cells is followed by a second and so on, depending on wastewater needs. Each pair is connected via pipes and a pumping system. Common are two stages of wetland cells with each stage filled with different type of aggregate, the second stage usually filled with a smaller type aggregate to provide faster treatment. The treatment wetland cells are followed by polishing modules that contain filters and disinfection components (UV and/or chlorine) for removal of pathogens. The last step of the treatment system is the reuse tank and associated pumping components. The whole system is fully automated and uses a remotely sensed control panel which operates all mechanical components.

5.7.3 Advantages

Treatment advantages compared to conventional CWs are-

- It provide anaerobic, anoxic and aerobic environments within and between the cells via reciprocation.
- It provide perfect conditions for nitrification and denitrification which is essential for the process of total nitrogen removal.
- It treats special waste water types with high treatment loads, e.g. agricultural (Pig farm slurry), mixture of landfill leachate and activated sludge, livestock, mixture of dried cheese whey, urea fertilizer and whey water, septic tank effluent, urban stream water with Fe and Cu and domestic waste water.

5.7.4 Design Considerations and operation

The TFW was designed where a pump station was installed in an existing sewer line to harvest sewage for treatment . Wastewater from the sewer-mining pump station entered the primary settling tank to remove most of the settleable and suspended solids plus any floatable waste. Primary treatment also reduced organic waste strength, allowing the main treatment system to be smaller and to function more efficiently. The system consisted of two tidal-flow treatment stages. Both stages used a lightweight, expanded shale aggregate (LESA) with a variation in media sizes between the stages. The water leaving stage 2 was very clean and required minimal final treatment/disinfection for reuse. Wastewater was pumped through a two-stage filtration system followed by two stage UV and chlorine disinfection. The first filter was an automatic, self-cleaning filter to remove any coarse particles, followed by a cartridge filter designed to catch any remaining small particles. Filtering of the effluent was necessary to remove fine particles that would inhibit UV disinfection. Various operating strategies were investigated to improve treatment processes and to prevent clogging of the wetland cells. This included using different types of wetland aggregates **(Liu *et al*., 2014; Vohla *et al*., 2011)**. Trials of varying the number of stages of wetlands cells and the introduction of wetland cell resting periods to prevent clogging of the wetland media were carried out. Cation exchange capacity of the wetland aggregate affected treatment performance significantly **(Austin, 2006)**. A high CEC capacity achieved a higher treatment level due to the high ammonium-ion adsorption capacity of high CEC aggregates. **Liu (2014)** studies confirmed this research. Zhao and coworkers in 2009 and 2011 carried out research with alum sludge-based treatment wetlands. His results were promising, as he achieved good treatment performances for BOD, TSS and nitrogen removal as well as phosphorus.

5.7.5 Water quality and Vegetation

Online turbidity, UV transmissivity and chlorine monitors assured that treatment standards were achieved. The system was planted with a diversity of flowering plant species to uptake residual nutrients and provide aesthetics.

5.8 Hybrid Constructed Wetland

5.8.1 Introduction and Application

Hybrid constructed wetland are those systems in which various types of constructed wetland system are modulated in a way that it results in high removal rate and purification efficiency. In most of the hybrid system vertical and horizontal filter are combined. By combining the two filter systems it gives better removal efficiency.

This type of constructed wetland can be connected in several methods like-

1. VF-VF-HF
2. VF-HF-VF
3. VF-HF

In 1950s and 1960s the vertical- horizontal flow constructed wetland system was fundamentally initiated but its execution was very limited. After that in 1980s this system was used vastly in the areas of France and United Kingdom. Presently, hybrid CWs are operated in numerous countries throughout the world (Table 18). In these systems, Horizontal flow constructed wetland is well approved for the removal of BOD and total suspended solid but has low feasibility for the nitrification process due to limited oxygen transfer capacity. Whereas, vertical flow constructed wetland provides high aerobic condition due to its intermittent loading which increase its oxygen transfer capacity. On the other hand VF wetland has some limitations too, firstly it is not much efficient for the removal of suspended solid and secondly if the filter media is not selected correctly it results in clogging situation. The hybrid systems overcome the problems associated with individual system (HF & VF) by combining both together. Therefore, hybrid constructed wetland are of great interest for the wastewater treatment system.

5.8.2 Advantages

- Employment to local people through the construction work.
- Contaminants removal by means of natural processes.
- Electrical energy only required for the pump operation.
- Highly durable
- Highly efficient for the removal of contaminants present in waste water like total nitrogen, ammonia, nitrate etc.

5.8.3 Limitations

- Requirement of large space area
- Expert advice is necessary for designing and construction
- Less capital and operational cost
- Primary treatment process is requisite to inhibit blockage problem
- Less enduring towards winter season

5.8.4 Design consideration

- The designing of first hybrid constructed wetland was given by Seidel at the Max Planck Institute, Germany. The system consists of a number of vertical beds which are placed in parallel manner and *Phragmites australis* species was used for vegetation purpose. These vertical beds were followed by 2 or 3 nos. of horizontal beds in which Typha or Carex was used as vegetation.
- The pre treated wastewater was loaded for 1-2 days in vertical bed then allowed for 4-8 days to dry out. As a result, thin layer of sludge is formed on the top of the vertical bed which got mineralized during the rest time period **(Vymazal and Kröpfelovà, 2011).**

- After the first hybrid design in 1980s, Johansen and Brix in mid 1990s developed a system which comprised of horizontal- vertical flow bed, known to be as a hybrid system. In this hybrid system denitrification was done in first stage followed by nitrification. If further nitrate removal was required, then the effluent was recycled towards the horizontal bed where denitrification took place in limited aerobic condition **(Vymazal and Kröpfelovà, 2011).**

Generally, hybrid systems have following components:

- A sedimentation tank, comprised of two or three chambers for the removal of large particles and settleable particles.

- A horizontal subsurface bed, with accurate filter material, planted with appropriate species for the removal of TSS and BOD removal and denitrification.

- An intermittent loaded vertical flow bed with proper filter material as well as vegetation for nitrification.

Table 18: Specifications and configurations of Hybrid CW systems built by researchers:

S. No	Location	Design	Size	Media	Load	References				
						BOD	COD	TN	TP	
1	Bangladesh (Tannery)	VF(1)-HF-VF(2) (in series)	VF- 0.65 m^2 (each) HF- 1.33 m^2	VF(1)-organic coco-peat, (size 1.2–2.3 mm) HF-cupola Slag (size ranged 19–20 mm). VF (2)-pea gravel (size ranging 1.2–2.3 mm)	690 g COD m^{-2} d^{-1});	98	98	-	87	Tanveer Saeed et al., 2012
2	Northern Ningbo, China, domestic sewage	HF-FWS-HF	HF- 8m x 6m x 1.0m FWS- 38.5 m^2	HF- the lowest layer of washed gravel (2–6 cm) depth - 20 cm, The middle layer of fine gravel (0.5–2.0 cm) depth - 65 cm, The upper layer of soil (0.1–0.2 cm) depth - 15 cm. The bottom slope was about 1%.	-	-	85	83	64	Fenxia Ye, Ying Li, 2009
3	Southern Spain Combined sewer and storm water	VF-HF-FWS In series	VF- 317 m^2 HF-229 m^2 FWS-240 m^2	VF- top layer of 0.05 m of sand (grain size = 1–2 mm), followed by a 0.6 m layer of gravel (grain size = 4–12 mm) and an underlying 0.15 m stone layer HF- gravel bed of 0.4 m depth (grain size = 4–12 mm), with an inlet and outlet zone of stones of 40–80 mm of diameter.	VF- 9 g BOD5 m^{-2} d^{-1}	94	85	-	-	Cristina Ávila et al., 2013

				FWS- a water depth ranging 10–50 cm. 0.2 m gravel bed (grain size = 4–12 mm).						
4	Spain Municipal sewer	VF-VF-HF-FWS (in series) VF-working alternatively in cycles of 3.5 days, placed parallel	VF- 1.5 m^2 (each) HF- 2 m^2 FWS- 2 m^2	VF- upper 0.1 m layer of sand (1–2 mm) A main layer of fine gravel (3–8 mm). Each VF container has a metal grating 0.1 m above floor level HF- gravel media (4–12 mm), which is 0.3 m deep (water depth = 0.25 m) FWS- 0.1 m of gravel media (4–12 mm)	Actual organic loading rates 37 ± 6, 110 ± 13 and 159 ± 27 g COD m^{-2} d^{-1}	-	HLR = 0.06 m d^{-1} 91 HLR = 0.13 m d^{-1} 89 HLR = 0.18 m d^{-1} 91	-	-	Cristina Ávila at al., 2014
5	Florence, Italy mixed wastewater (grey + black) produced by a Resort Hotel	HF-VF	HF-160 m2 VF-180 m2	HF Depth-0.7 m Media- Gravel (5-10mm) VF Depth-0.9 m Media- sand gravel	HF- 23.5 g COD/m^2/d VF- 2.0 g COD/m^2/d	94	94	60	94	Fabio Masi, Nicola Martinuzzi, 2007
6	Municipal waste water	(Saturated) VF-(Free Drain) VF-HF (in series)	(Saturated) VF-2.5 m^2 (Free Drain) VF-1.5 m^2 HF-6 m^2	crushed rock (4–8 mm sand (0–4 mm) in free drain	-	94.5	84.4	-	65.4	Jan Vymazal and Lenka Kröpfelová, 2011
7	Northern Italy Tertiary treatment of pig slurry effluent	VF1-VF2-VF3- HF VF-in Parallel HF-In series	VF1-VF2-VF3- 21 m^2, Total area HF- 105 m^2	VF1 & VF2- washed gravel: grain size 10–20 mm with porosity of 40%. VF3- 0.10 m deep gravel layer overlying a 0.10 m deep coarse sand (grain size 3–5 mm) Zeolite (grain size 5–10 mm)	-	-	-	95	-	Anna Mietto, et al., 2015

				transition layer 0.30 m deep gravel drainage layer (10–20 mm in size). HF- two strips of coarse-rock material (grain size 50– 100 mm) along two opposite edges of the basin, with washed gravel: grain size 10–20 mm						
8	Spain, Urban waste water	VF-HF	1.22m× 0.55m× 0.52m	crushed stone basaltic gravel & lapilli, a very porous volcanic sediment	-	86	80	-	24	J.A. Herrera Meliá n et al., 2010
9	Japan Milking parlour waste water	VFA-VFB-HF (in series)	160 m^2 (each) in area with a depth of 0.71 m. 336 m^2 in area with a depth of 0.7 m.	VF-Supersol (density of 0.4 g cm-3) Coarse gravel- 5-15 mm Fine gravel – 5-25 mm Clinker ash HF- washed sand (0.25 mm-0.49 mm)	4.9 m^3 day^{-1}	89	88	76.4	76	P. K. Sharma, et al., 2011
10	Northern Italy, Piggery wastewater	VF1-VF2-VF3-HF	VF- 10 m2 each HF- 100 m2	VF1 & VF2- washed gravel: grain size 10–20 mm with porosity of 40%. VF3- 0.10 m deep gravel layer overlying a 0.10 m deep coarse sand (grain size 3–5 mm) Zeolite (grain size 5–10 mm) transition layer 0.30 m deep gravel drainage layer (10–20 mm in size). HF- two strips of coarse-rock material (grain size 50– 100 mm)	5 m3 day^{-1}	-	79	64	61	Maurizio Borin, et al., 2013

				along two opposite edges of the basin, with washed gravel: (dia 10–20 mm)						
11	Uttar Pradesh, India Dairy wastewater	VF1-HF-VF2	VF1-16 m^2 HF-18 m^2 VF2-6 m^2 Total -40 m^2	VF 1 & VF 2- Gravel (dia 15-25 mm & 25-40 mm) HF- Sand (dia-0.25 mm)	2.02 g m^{-2} BOD	87	88	74	76	Proposal MoEF

5.8.5 Operation and maintenance

Operation and maintenance of Hybrid systems is found similar to horizontal flow constructed wetlands or vertical flow constructed wetlands. These wetland systems require maintenance for the entire duration of its life. Some problems faced in their operation is to ensure that the system adjustment and the loading of filters is done correctly which needs expert knowledge and skilled operators.

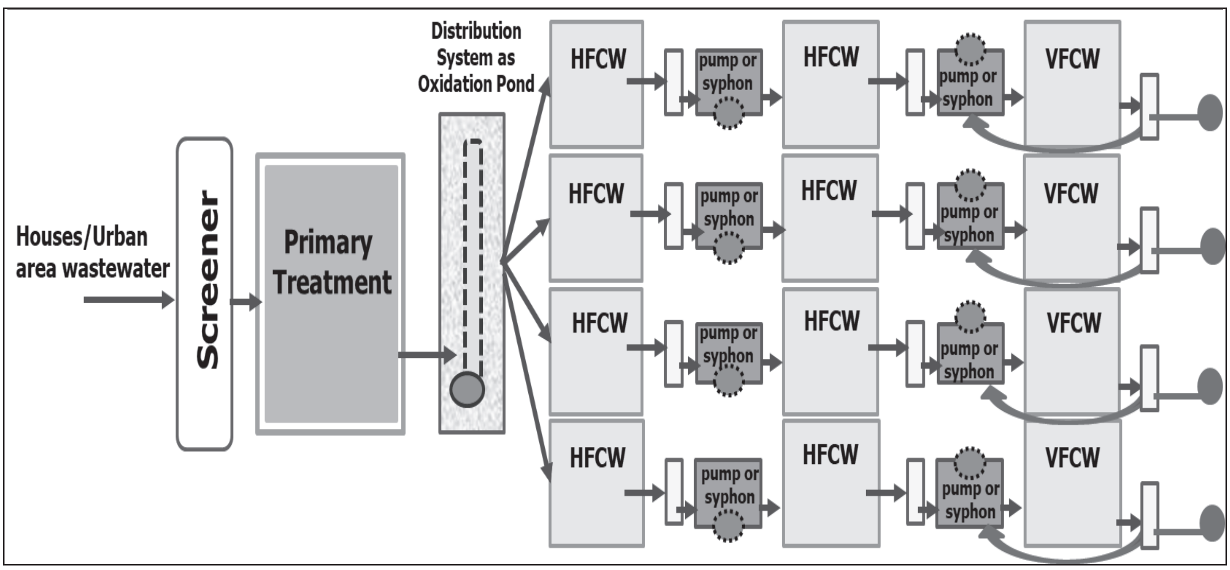
5.8.6 Vegetation

As the name indicates it is a combination of both horizontal subsurface flow and vertical subsurface flow types. The advantages of various systems can be combined to complement each other in hybrid constructed wetlands. Macrophytes like *P. australis* for VF stages and emergent macrophytes such as *Iris*, *Schoenoplectus*, *Sparganium*, *Carex*, *Typha* or *Acorus* etc. for HF stages can be planted in hybrid wetlands.

5.8.7 Design Models

Some of the design models for Hybrid CW treatment systems are present below (Figure 28):

Design Model 1



Design Model 2

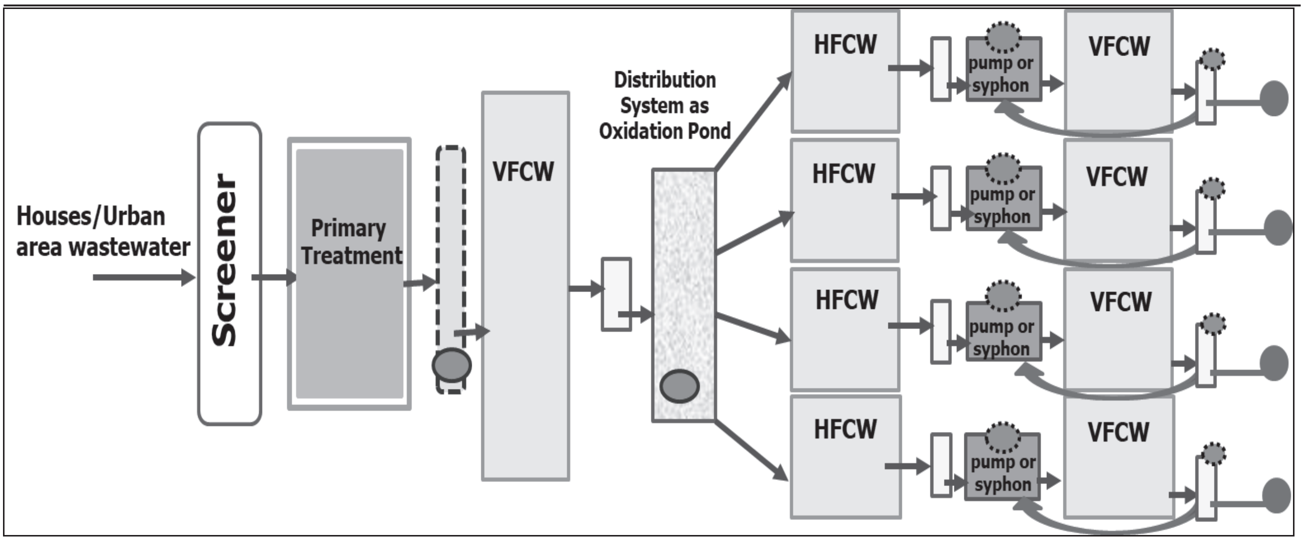


Figure 28: Design models (1&2) for Hybrid CW treatment systems

5.9 Tertiary Treatment

5.9.1 Disinfection technologies

In the developed world the use of water supply disinfection as a public health measure has been responsible for a major reduction in people contracting illness from drinking water. However many of these disinfectant chemicals if overdosed or used inappropriately, as part of a water treatment process, can result in the formation of disinfection b y-products. Disinfection by-products are formed when disinfection chemicals react with organic or inorganic compounds. Research shows that human exposure to these by products may have adverse health effects.

Advantages and limitations of disinfection methods

5.9.1.1 Primary disinfection

Table 19: Advantages/limitations of primary disinfection systems

Process	Advantages	Limitations
Chlorination	Well understood disinfectant capability. Established dosing technology	Chlorination by-products and taste and odour issues can affect acceptability. Ineffective against *Cryptosporidium*
Chloramination	No significant by-product issues. Generally less taste and odour issues than	Considerably less effective than

	chlorine.	compared with chlorine. Not usually practical as a primary disinfectant
Ozone	Strong oxidant and highly effective disinfectant compared with chlorine. Benefits of destruction of organic micropollutants (pesticides, taste and odour compounds).	Bromate by-product and increased assimiable organic carbon (AOC) can impact on re-growth in distribution. Complex, energy intensive and expensive equipment compared with chlorination. Residual insufficiently long lasting for distribution.
Chlorine dioxide	Can be more effective than chlorine at higher pH, and less taste and odour and by-product issues.	Weaker oxidant than ozone or chlorine. Dose limited by consideration of inorganic by products (chlorate and chlorite).
UV	Generally highly effective for protozoa, bacteria and most viruses and particularly for *Cryptosporidium.* No significant by product implications.	Less effective for viruses than chlorine. No residual for distribution.

5.9.1.2 Secondary disinfection

Table 20: Advantages/limitations of secondary disinfection systems

Process	**Advantages**	**Limitations**
Chlorination	Stable residual in clean networks. Potential for using chlorine for both primary disinfection and distribution, makes for straightforward application	By-product formation during distribution. Loss of residual in distribution systems with long residence times.
Chloramination		Needs effective control of process to avoid taste and odour due to either dichloramine or trichloramine. Mixing with

	Stable residual with no significant byproduct issues. Generally lower rate of taste and odour complaints than for chlorine.	non-chloraminated supplies in network can cause taste and odour issues.
Chlorine dioxide		Limited by consideration of inorganic byproduct formation (chlorite and chlorate).

5.10 Comparative Removal Efficiency of Different CWs

Constructed wetlands show variable removal efficiencies for wastewater including municipal, industrial and various runoff waters etc. at different HLR (Table. 21). The optimal design of hydraulic loading rate (HLR) plays an important role in the removal efficiency of CWs. Greater HLR promotes quicker passage of wastewater through the media, thus reducing the optimum contact time.

Table 21: Constructed wetland system removal effciency under different Hydraulic loading rate

System configuration	Type of WW	Area (m^2)	HLR (mm/d)	Pollutant Removal (%)				References
				BOD	COD	TN	TP	
Vertical	Domestic	28.83	450	79	72	-	-	L. C. O. Lana, *et al* 2013
	Domestic sewage	2.0 m^2/PE	340	98	-	91	-	Weedon, 2010
	Dairy waste water	4.0	220	93.3	-	37.1	93.5	Sharma *et al.*, 2018
	Raw sewage effluent	0.09	150	84	75	32	22	Abdalkaheem *et al.,* 2015
	Domestic waste water	1.86	100	96	97.3	92.9	-	V. S. W. Jong and F. E. Tang, 2016
Hybrid	Mixed wastewater (grey + black)	HF-160 VF-180	194	94	94	60	94	Fabio Masi, Nicola Martinuzzi, 2007
	Tannery wastewater	VF- 0.65 HF- 1.33	60	98	98	-	87	Tanveer Saeed et al., 2012
	Milking parlour waste water	VF-160 HF- 336.0	28	89	88	76.4	76	P. K. Sharma et al, 2011
	Combined sewer and storm water	VF- 317 HF-229 FWS-240	0.44	94	85	-	-	Cristina Ávila et al., 2013
FWS	Municipal Wastewater	25	520	68.2	-	-	19	Jinadasa et al., 2006
	Municipal WW/ Secondary	733.5	210	80.78	65.18	58.59	66.5	Katsenovich et al., 2009
	Oil-produced WW	562.5	30	88	80	10.2	18.5	Ji et al., 2007
	Municipal WW/saline condition	4.0	6-150	74.3	-	-	44.9	Klomjek and Nitisoravut, 2005
Horizontal	Industrial WW	4500	4440	70.4	62.2	-	29.6	Song et al., 2009
	Municipal sludge	5.88	7.3	-	60.7	-	-	Kaseva, 2004
	Tannery WW	1.3	60	98	98	-	87	Saeed et al., 2012
	Lake water	30	640	-	39.6	52.1	65.7	Li et al., 2008

5.11 General Design Considerations

Constructed wetland systems monitored have not provided sufficient data for analysis. Performance has varied and the influences of various factors such as location, type of wastewater or runoff, wetland design, climate, weather, disturbance, and daily or seasonal variability, have been difficult to quantify. Basically wetland designs mimic natural wetlands in overall structure. **Mitsch (1992)** suggested the following guidelines for creating successful constructed wetlands

- To keep the design simple as complex approaches may result in failure.
- Minimal maintenance.
- To use natural energies, such as gravity flow.
- Workable under extremes weather and climatic conditions.
- Design according to the natural topography of the site.
- Avoid over-engineering the design and mimic natural systems.
- Give the system time to get functional and wait for the performance to reach optimal levels.

5.11.1 Planning

Setting and prioritizing the objectives of the wetland system is key to the creation of a successful system. The planning phase is very essential and consists of characterizing the quantity and quality of the wastewater to be treated, selecting the site, selecting system type and configuration, determining the discharge standards to be met and specifying the design criteria to be met by the detailed engineering plans. Economic factors include the land area required, vegetation, the type of water containment and control and transport of water through the system. Planning should be oriented toward the creation of a biologically and hydrologically functional system. Plans should include clear goal statements and standards for success. The possible future expansion of the operation should be considered. Plans should include detailed instructions for implementing a contingency plan in case the system does not achieve its expected performance within a specified time. Plans should be reviewed and approved by the appropriate regulatory agencies.

5.11.2 Site Selection- Topography, Land availability, Use and Access

Site selection includes land use and access, land availability and site topography. Selecting an appropriate location can save significant costs site.

A site that is well suited for a constructed wetland is one that-

- Is conveniently located near source of the wastewater.
- Gently sloping, so that water can flow through the system by gravity.

- provide adequate space
- contains soils that can be sufficiently compacted to minimize seepage to groundwater
- Above the water table
- Not in a floodplain
- Doesn't contain threatened or endangered species
- Doesn't contain archaeological or historic resources.

Topography

Landform considerations include shape, size, and orientation to the prevailing winds. Constructed wetland can be built almost anywhere by selecting a site with gradual slopes that can be easily altered to collect and hold water and simplified design and construction with minimum cost. Previously drained wetland areas, including prior converted (PC) agricultural sites, may be well-suited for a constructed wetland since the topography is usually conducive to gravity flow. The appropriate regulatory agencies like Natural Resources Conservation Service (NRCS), the US Fish and Wildlife Service, or state regulatory personnel should be contacted before disturbing any PC site and determine whether or not a site contains jurisdictional wetlands.

Land availability

Land availability should be large enough to accommodate present requirements and any future expansions. The size of constructed wetland is related to the retention time. The effectiveness of a constructed wetland in treating wastewater or stormwater depends on the retention time of the water in the wetland which is directly associated with land availability.

Land use and access

This is an important consideration for constructed wetlands. The site should be accessible to personnel, delivery vehicles, and equipment for construction and maintenance. Wetland should be placed as far from dwellings as possible to keep away the problem of odors or insects, as with some agricultural wastewaters. For agricultural and some domestic wastewaters, the wetland may be installed on private land. The landowner must be carefully chosen. It is essential that the landowner is cooperative and fully understands the limitations and uncertainties associated with a developing technology such as constructed wetland treatment. The current and future use and values of adjoining land will also affect the suitability of a site for a constructed wetland. The opinions of area residents and those of environmental and public interest groups should be considered. A large buffer zone should be placed between the wetland and neighboring property. The wetland should not be placed next to the edge of the property.

5.11.3 Hydrology

The hydrology of a constructed wetland is perhaps the most important factor in its effectiveness. Design of conventional systems is usually based on hydraulic residence time (and therefore water volume), some wetland treatment systems show a more consistent correlation with area and hydraulic loading rate than with hydraulic residence time. Some other hydrologic considerations include climate and weather, hydroperiod, groundwater exchanges (infiltration and exfiltration), losses to the atmosphere (evapotranspiration), and overall water balance.

5.11.3.1 Climate and weather

Wetlands are shallow water bodies open to the atmosphere and are strongly affected by climate and weather. Rainfall, snowmelt, spring runoff, drought, freeze, and temperature all have a major influence on wetland treatment. The high flows caused by heavy rains and rapid snowmelt shorten residence times which further decreases the efficiency of a wetland. High flows may dilute some dissolved pollutants while increasing the amount of suspended material as sediments in the wetland are resuspended and additional sediments are carried into the wetland by runoff. The first flush of runoff from a storm, often carries much higher pollutant concentrations than flows later in the storm. **Taylor and coworkers (1993)** found that intense storms during summer, when conditions were generally dry, often had greater impacts on treatment than storms during other times of the year, when conditions were generally wetter. **Jacobson (1994)** found that runoff during spring may carry more than half the annual nitrate and phosphorus exported during the year and suggests that wetland management should focus on this time of the year. Runoff in excess of maximum design flows should be diverted around the wetland to avoid excessive flows through the wetland. Minimum temperatures limit the ability of wetlands to treat some, but not all, pollutants. Wetlands continue to treat water during cold weather. However, freezing temperatures in winter and early spring can reduce treatment if the wetland either freezes solid or a cover of ice prevents the water from entering the wetland. If under-ice water becomes confined, water velocities may increase, thereby reducing contact times.

5.11.3.2 Hydroperiod

Hydroperiod determines the availability of water throughout the year, the extreme wet and dry conditions that can be expected, the extent of storage and drainage that may be required, and the criteria to be used in designing the water control facilities. It is the seasonal pattern of water level fluctuations and is described by the timing, duration, frequency, and depth of inundation. It results from the balance of inflow, outflow, and storage. The hydroperiod of a wetland is strongly affected by seasonal differences in precipitation and evapotranspiration.

5.11.3.3 Hydraulic load and Hydraulic residence time

Hydraulic loading rate (HLR) refers to the loading on a water volume per unit area basis. **[Loading = (parameter concentration) x (water volume/area)].**

The hydraulic residence time (HRT) of a treatment wetland is the average time that water re-mains in the wetland, expressed as mean volume divided by mean outflow rate. If short-circuiting develops, effective residence time may differ significantly from the calculated residence time.

5.11.3.4 Evapotranspiration

Evapotranspiration is an important factor in wetlands, as the amount of surface area is large relative to the volume of water. Also, many wetland plants do not conserve water during hot and dry weather as most terrestrial plants do and can transfer considerable amounts of water from a wetland to the atmosphere in summer. This indicates that ET is the combined water loss through plant transpiration and evaporation from the water surface. If ET losses exceed water inflows, supplemental water will be required to keep the wetland wet and to avoid concentrating pollutants to toxic levels. Estimates of ET values vary widely. The Water Pollution Control Federation (1990) suggests that, for wetlands that are continuously flooded, ET can generally be estimated as being equal to lake evaporation, or approximately 70% to 80% of pan evaporation values. **Kadlec (1993)** reported the role of dense stands of emergent vegetation in reduction of the total water loss from prairie potholes and concluded that the vegetation removed less water through transpiration than would have evaporated from open surface water.

5.11.3.5 Groundwater Exchange

Constructed wetlands for domestic wastewater, agricultural wastewater, and mine drainage are usually lined to avoid-possible contamination of groundwater. If the wetland is properly sealed, infiltration can be considered negligible. Many stormwater wetlands are sealed so that the water needed to support the wetland will be retained between storms. Other stormwater wet-lands are designed to intercept groundwater to ensure sufficient base flow. In this case, the wet-land will receive groundwater when the water table is high and may discharge to groundwater when the water table is low.

5.11.3.6 Water Balance

The overall water balance for a constructed wetland includes inflow, storage, and outflow of the water.

- Water inflow to the wetland includes surface water (the wastewater or stormwater), groundwater infiltration (in unlined wetlands), and precipitation.
- Storage is the surface water plus water in the pore spaces of the substrate.
- Outflow comprises evaporation from the water surface, transpiration by plants, effluent discharge, and exfiltration to groundwater.

During design and operation, the wetland water balance is important for determining conformance with desired limits for HLR, hydroperiod range, HRT, and mass balances.

A simple water balance equation for a constructed wetland is expressed as:

$$S = Q + R + I - O - ET$$

Where: S = net change in storage,

Q = surface flow, including wastewater or stormwater inflow,

R = contribution from rainfall,

I = net infiltration (infiltration less exfiltration),

O = surface outflow ET= loss due to evapotranspiration.

This equation can be used to calculate water budgets for daily, monthly, or yearly intervals. Detailed water balances can be prepared with site-specific monitoring data collected during pilot- or full-scale operation of the wetland. If large seasonal variation is expected, monthly data are essential.

5.11.4 Structures

5.11.4.1 Flow control structure- Inlet and outlet

These structures play a main role in controlling water levels. Flow control structures should be simple, easy to adjust and flexible so that processes can be optimized initially and adjusted later in response to system changes. They should be able to handle maximum design flows, located for easy access and minimize short circuiting. Boardwalks and piers can be used to make access easy and reduce disturbance of the wetland. PVC pipe is also recommended. Wetland accessible to the public or located in an isolated area should be enclosed in lockable concrete structures or manholes to avoid damage or tampering with water level settings. Structures must be protected against damage by animals. Measures include installing covers or wire mesh over openings, and enclosing controls, gauges and monitoring devices in pipes or boxes.

Inlets

Inlets at SF wetlands are usually simple: an open-end pipe, channel, or gated pipe which releases water into the wetland. The smaller the length-to-width ratio, the more important equal flow distribution becomes. Accessible and easily adjustable inlets are mandatory for systems with small length-to-width ratios. Inlet structures at SSF systems include surface and subsurface manifolds, open trenches perpendicular to the direction of flow, and simple single point weir boxes. A subsurface manifold avoids the buildup of algal slimes and the consequent clogging that can occur next to surface manifolds, but is difficult to adjust and maintain. A surface manifold, with adjustable outlets provides the maximum flexibility for future adjustments and maintenance and avoids back-pressure problems. The distance above the water surface of the wetland is typically 12 - 24 inches. The use of coarse rock (3 - 6 inches, 8 - 16 cm) in the entry zone ensures rapid infiltration and prevents ponding and algal growth. To discourage the growth of algae, open water areas near the outlet should be avoided. Shading with either vegetation or a structure in the summer and some thermal protection in the winter will probably be necessary. A flow splitter will be needed for parallel cells. A typical design consists of a pipe, flume, or weir with parallel orifices of equal size at the same elevation. Valves are impractical because they require daily adjustment. Weirs are relatively inexpensive and can be easily replaced or modified. Flumes minimize clogging in applications with high solids but are more expensive than weirs.

Outlets

At SF wetlands, the water level is controlled by the outlet structure, which can be a weir, spillway, or adjustable riser pipe. A variable- height weir, such as a box with removable stop logs allows the water levels to be adjusted easily. Spillways are simple to construct but are not adjustable; incorrect water levels can lead to wetland failure and correcting spillway height can be difficult. Weirs and spillways must be designed to pass the maximum probable flow. Spillways should consist of wide cuts in the dike with side slopes no steeper than 2H: 1V and lined with non-biodegradable erosion control fabric. If high flows are expected, coarse riprap should be used. Vegetated spillways overlying erosion control fabric provide the most natural-looking and stable spillways. Weirs or spillways should be used for mine drainage wetlands since pipes tend to clog with deposits of iron precipitates. Adjustable riser pipes or flexible hoses offer simple water level control. A PVC elbow attached to a swivel offers easy control of the water level. If pipes are used, small diameter (<l2 inch) pipes should be avoided because they clog with litter. At SSF wetlands, outlets include subsurface manifold, and weir boxes or similar gated structures. The manifold should be located just above the bottom of the bed to provide for complete water level control, including draining. The use of an adjustable outlet, which is recommended to maintain an adequate hydraulic gradient in the bed, can also have significant benefits in operating and maintaining the wetland. The surface of the bed can be flooded to encourage the development of newly planted vegetation and to suppress undesirable weeds, and the water level can be lowered in anticipation of major storms and to provide additional thermal protection against freezing in the

winter. The design of SSF beds should allow controlled flooding to 6 inches (15 cm) to foster desirable plant growth and to control weeds. A perforated subsurface manifold connected to an adjustable outlet offers the maximum flexibility and reliability as the outlet device for SSF systems. Since the manifold is buried and inaccessible after construction, careful grading and subbase compaction are required during construction, and clean-out risers in the line must be provided. The final discharge point from the wetland system should be placed high enough above the receiving water that a rise in the water level in the receiving water, for instance after a storm, will not interfere with the flow of water through the wetland.

5.11.4.2 Cells

Wetlands can be constructed by excavating basins, by building up earth embankments (dikes), or by a combination of the two. Dikes must be constructed of soils with adequate fine-grained material that will compact into a relatively stable and impervious embankment. The dikes should be high enough to contain the expected volume plus ample freeboard to accommodate occasional high flows as well as the buildup of litter and sediment over time. To ensure long-term stability. dikes should be sloped no steeper than 2H:lV and riprapped or protected by erosion control fabric on the slopes. An emergency spillway should be provided. If multiple cells are used, divider dikes can be used to separate cells and to produce the desired length-to-width ratios. On steep sites, they can be used to terrace cells. Dikes can also be used to control flow paths and minimize short-circuiting. Finger dikes are often used to create serpentine flow paths and can be added to operational systems to mitigate short-circuiting. Finger dikes can be constructed of soils, sandbags, straw bales, or treated lumber. Bottom slopes are generally not critical. An exception may be mine drainage wetlands that use subsurface flow through deep beds of compost to induce sulfate reduction; these cells should slope about 1 - 3% upstream. Bottoms should be relatively level from side to side. Muskrats can damage dikes by burrowing into them. Although muskrats generally prefer to start their burrows in water than is more than 3 ft deep, they can be a problem in shallower waters. Musk-rats can be excluded by installing electric fence low to the ground or by burying muskrat-proof wire mats in the dikes during construction.

5.11.4.3 Liners

Constructed wetlands must be sealed to avoid possible contamination of groundwater and also to prevent groundwater from infiltrating into the wetland. Where on-site soils or clay provide an adequate seal, compaction of these materials may be sufficient to line the wetland. Sites underlain by karst, fractured bedrock, or gravelly or sandy soils will have to be sealed by some other method. It may be necessary to have a laboratory analyze the construction material before choosing a sealing method. On-site soils can be used if they can be compacted to permeability of <10^8 ft/sec (<10^{-6} cm/sec). Soils that contain more than 15% clay are generally suitable. Bentonite, as well as other clays, provide adsorption/reaction sites and contribute alkalinity. Synthetic liners include asphalt, synthetic butyl rubber, and plastic membranes (for example, 0.5 to 10.0 mil high density polyethylene). The liner must be strong, thick, and smooth to prevent root attachment or penetration. If the site soils contain angular stones, sand bedding or geotextile cushions should be placed under the liner to prevent punctures. The liner should be covered with 3 - 4 inches of soil to prevent the roots of the vegetation from penetrating the liner. If the wetland is to be used for mine drainage, the reaction of the clay or synthetic liner should be tested before it is used since some clays and synthetics are affected by some acid mine drainages.

As per European Guidelines (**Cooper, 1990)** if the local soil is used for lining then it should have a hydraulic conductivity of 10^{-8} m/s or less then it.

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 groundwater is used for potable supplies)

Sometimes synthetics liners are used:

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

5.11.5 Habitat levels

Constructed wetlands which provide advanced treatment to wastewater also provide some other benefits like habitat to wildlife. Once constructed, wetlands enhance flora and fauna, increase plants diversity, and present favourable habitats for birds, reptiles, fish etc. Vegetation selection needs to support habitat objectives. The use of weedy, invasive, or non-native species should be avoided.

5.11.6 Shade needs

Shade requirement is one of the important factor in Constructed wetlands. One of the risk in CWs is stream warming. If a constructed wetland will discharge to temperature-sensitive water, the designer should consider using the wooded wetland design to shade the water, and any extended detention storage should be released in less than 12 hours. It is recommended that buffer planting areas be over-planted with a small stock of fast growing successional species to achieve quick canopy closure and shade out invasive plant species. The plant canopy formed by the emergent vegetation shades the water surface, preventing growth and persistence of algae, and reduces wind-induced turbulence in the water flowing through the system. Plants requirement also differ for light conditions from full sunlight to dense shade. *Wolffia* does better under darker conditions, *Lemna gibba* does better in sunlight **(Zirschky and Reed, 1988).** Water hyacinth or Duckweed, free-floating macrophytes, can cover completely the surface of the wetlands; algal growth is limited to minimum due to lack of light. This is desirable as in constructed wetlands; phytoplankton growth is not appreciated because of increase of suspended solids in the outflow.

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6. OPERATION MAINTAINANCE AND MONITORING

Operation and maintenance can be categorized as start-up, routine and long term operations. start up process shows the site to site variation. Routine operation is based on the designing details. Proper checkups should be done for the proper functioning of the system. Primary treatment should be monitored properly for the effective functioning of the wetland system.

6.1 Start Up

This period helps to establish out the associated vegetation with the treatment processes. The startup period shows variation which depends on the type of influent wastewater, its characteristics, wastewater volume, season in which monitoring is done and the design of the system. In sub surface flow constructed wetland the start-up period is simple because the performance of the system does not depend upon the vegetation which is generally used for aesthetic purpose only in SSF CWs.During the initial startup period the operator is primarily responsible for adjusting the water level in the wetland. Typically, the wetlands are filled with water to the surface of the substrate at the end of planting. As the plants begin to root, the water level can be gradually lowered to the design operating level.

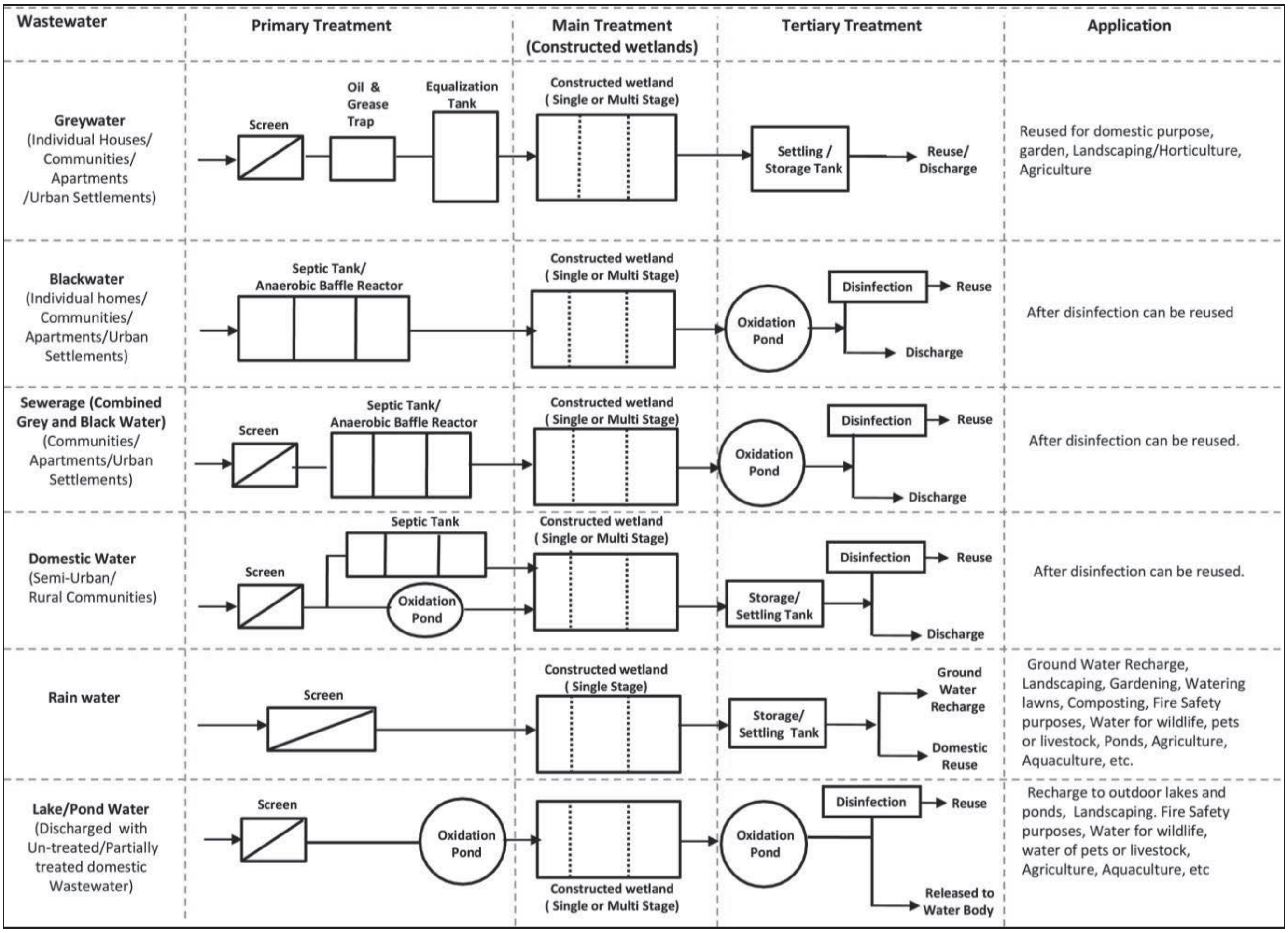

Figure 29 : Unit Operations designed based on specific Wastewater being treated with CWS as main treatment Process (Layout)

6.2 Routine Operation

In routine operation the operators should be attentive towards the problems which are developed within the system. In the constructed wetland this operation is mostly passive and required little operator intervention.

The most important situation in which operator intervention is required:

- Adjustment of water levels
- Maintenance of flow uniformity (inlet and outlet structures)
- Management of vegetation
- Odor control
- Maintenance of berms (walls)
- Clogging of the system substrate

6.2.1 Adjustment of water levels

The most significant thing in the wetland system is its water level and water flow control. It is one of the crucial factors helping in choosing right designing factors that impact the system performance and its removal efficiency. Variation in water levels affects the hydraulic retention time, plant cover and also change the atmospheric oxygen diffusion capability within the system. Any change that occurs in water level should be investigated immediately, as it may be due to storm water drainage, clogged outlet, breach in berm walls, etc.

6.2.2 Maintenance of flow uniformity

For the proper efficient working system it is important to maintain the uniformity between inlet and outlets structures. To prevent any clogging between the inlets and outlets, the debris should be clean regularly and routinely and should be flushed periodically if placed in submerged position. The removal of debris and bacterial slimes from weir and screen surfaces will be necessary. Influent suspended solid gets accumulated near the inlets which results in decreased hydraulic retention time so therefore it is important to use high pressure water spray for the cleaning process. Over a certain time, accumulation of these solids will require removal.

6.2.3 Vegetation management

Plants community used in the wetland system have capability of self-sustain their life cycle; they will grow, die, become litter and re-grow each year. The primary objective in vegetation management is to maintain the desired plant communities within the wetland. This is achieved through changes in the water levels and harvesting undesired plants (like weeds) when and where necessary. Where plant cover is deficient, management activities to improve cover may include water level adjustment, reduced loadings, pesticide application, and replanting. Harvesting and litter removal may be necessary depending on the design of the wetland. A well-designed and well-operated subsurface flow wetland does not require routine harvesting.

6.2.4 Odor control

Odor is one of the main problems in a constructed wetland. Odors are generally produced by means of odorous compound associated with anaerobic conditions, which can be released due to excessive sulphur, organic matter and ammonia content in the wastewater. The occurrence of odor problem is mainly due to uneven flow or distribution of wastewater. If primary treatment size is too big then wastewater may undergo anaerobic condition, which may create odor when such wastewater is feeded into CW. However, such odor is insignificant since wastewater percolates into the bed quickly if there is no clogging. Odor control in constructed wetlands has been virtually undocumented due to the cost and complexity of evaluation. Uniform distribution of water and regular maintenance of plant growth on beds prevent odor formation. Also selection of good design parameters while constructing wetlands may help in odor reduction.

6.2.5 Algae Control (Cyanotoxicity maintenance)

There are a number of technologies that have been proposed for algae control to improve pond effluent quality. Technologies such as centrifugation, micro-straining, coagulation- flocculation, dissolved air flotation, sand filters and rock filters have been discussed extensively in the previous literature **(Hamdan and Mara, 2009)**.. Every method of algae removal from ponds has specific advantages and disadvantages, but the selected method must be specific to the particular treatment situation. It would be desirable if these post-treatment methods could also ensure that the global treatment systems maintain the primordial advantages (easy operation and exploitation, environmental integration) **(Torrens, 2004)**. Also, algae can be harvested for use as a fertilizer, protein rich feed, biofuel or other purposes.

6.2.6 Mosquito habitat control

Mosquitoes are very common in natural wetlands and can be expected in constructed wetlands. In CWs mosquito problems can be avoided through avoiding conditions like open, stagnant water on stands providing excellent mosquito breeding habitat or high nutrient water which promotes larval development. Flowing water along a covered water surface minimizes mosquito development. Various control methods include unblocking flows to eliminate stagnant backwaters, shading the water surface (females avoid shaded water for egg laying) and dispersing floating mats of duckweed or other floating plants. Purple martins, swallows, bats, mosquito fish (Gambusia), green sunfish (*Lepornis cyanellus)* and Insects larvae such as dragon-flies, can be introduced to prey on mosquito. Chemical treatment should be used with caution because it is poorly understood and runs the risk of contaminating both the wetland and the receiving stream.

6.2.7 Pest control

In constructed wetlands the biological components are highly sensitive to toxic chemicals, such as ammonia and pesticides. So, adopting diverse vegetation than a less diverse stand may be more useful to recover from disturbance and resist pests.

6.2.8 Maintenance of Berms (Walls)

Berms (walls) should be properly maintained. Any earthen berm erosion or crack in the walls should be repaired as soon as it is noted. Leaks around berms (walls) should also be repaired by plugging, sealing, etc. as soon as noted.

6.3 Long-term operations

Routine operation is mandatory in managing a wetland. Inflow outflow rates, waste water quality, water flow and its levels should be monitored and evaluated in order to make it more efficient to work. This data may help the operator to solve out the problems and able to select the appropriate corrective actions. The porosity of the system may decrease by means of solid particles accumulation and litter formation; it should be removed time to time to prevent clogging in the wetland system. The rate of solids accumulation depends upon loading.

The performance of the wetland should be checked time to time. Samples should be collected and analyzed to ascertain the treatment efficiencies. Following parameters need to be analyzed:

- Total Suspended Solids (TSS)
- Biochemical Oxygen Demand (BOD_5)
- Chemical Oxygen Demand (COD)
- Ammonia
- Nitrate
- Phosphorus
- Fecal Coliforms

The operation and maintenance requirements are summarized in Table 22, 23 and 24.

Table 22: Fortnightly O & M action list

Berm/Wall	Visual inspection for weeds, erosion and damage
Inlet	Uniform inflow, should be visually inspected and blockages and damages should be identify
Outlet	Visual inspection for blockages and damage, and visual check of water level

	and outflow quality and quantity
Vegetation	Visual inspection for any weed, plant health or pest problems. Take remedial action as necessary

Table 23: Two-monthly O & M action list

Berm/Wall	Visual inspection for weeds, erosion and damage. Take remedial action as necessary.
Outlet	Functioning of discharge system and quality of receiving water should be checked.
Vegetation	Control weeds in wetland by hand weeding, herbicide application, and/or temporary water level increase.
Primary treatment	Visual inspection of upstream primary treatment for structural integrity, quantity and quality of effluent.

Table 24: Yearly O & M action list

Substrate	Clean the substrate and replace if necessary for proper functioning of system. Check clogging of the substrate.
Inlet	Remove end caps from inlet pipe and distribution network and flush out and clean thoroughly to remove slimes and blockages
Outlet	Clean and remove plants around outlet pipe to provide access and guard against blockages.
Vegetation	Harvest vegetation and replant if necessary
Primary treatment	Check sludge levels in primary treatment and de-sludge as necessary to maintain treatment performance and avoid sludge drift into wetland.

6.4 Monitoring

Monitoring is an important operational tool that-

- provides data for improving treatment performance
- identifies problems
- documents the accumulation of potentially toxic substances before they bioaccumulate
- determines compliance with regulatory requirements.

Monitoring helps to measure whether the wetland is meeting the objectives of the wetland system and indicates its biological integrity. Photographs should be taken each time at the same locations and viewing angles for documentation. Detail of the monitoring depends on the size and complexity of the wetland system and may change as the system matures and its performance becomes more well known. Lightly-loaded systems operating satisfactorily need not to be checked every month and after every major storm whereas heavily loaded will require more frequent and detailed monitoring.

6.4.1 Plan

Monitoring plan should include:

- ✓ clearly and precisely stated goals of the project
- ✓ specific objectives of monitoring
- ✓ organizational and technical responsibilities
- ✓ tasks and methods
- ✓ data analysis and quality assurance procedures
- ✓ schedules
- ✓ reporting requirements
- ✓ resource requirements
- ✓ budget

6.4.2 Discharge compliance

Monitoring for compliance with the limitations of the discharge permit represents the minimum of sampling and analysis requirements. A fixed weir at the outlet provides a simple means of measuring flow and collecting water samples. The parameters to be monitored and the frequency of data collection will be set by the terms of the permit.

6.4.3 System performance

Wetland system performance is usually measured by determining-

- hydraulic loading rates
- inflow and outflow volumes
- water quality changes between inflow and outflow
- excursions from normal operating conditions.

The effectiveness of contaminant removal can be determined from the difference between influent loads (inflow volume x contaminant concentration) and effluent loads (discharge volume x contaminant concentration). The parameters of concern may include:

- Domestic wastewater: BOD, nitrogen, phosphorus, total suspended solids, heavy metals, bacteria (total or fecal coliform).
- Agricultural wastewater: BOD, nitrogen, phosphorus, total suspended solids, pesticides, bacteria (total or fecal coliform).
- Mine drainage: pH, iron, manganese, aluminum, total suspended solids, sulfate.
- Storm water: total suspended solids, nitrogen, phosphorus, heavy metals, vehicle emission residues

Surface water sampling stations should be located at accessible points at the inlet and outlet, and, depending on the size and complexity of the system, at points along the flow path within the wetland. Surface water quality stations should be permanently marked. Boardwalks can be installed to avoid disturbing sediment and vegetation while sampling. If the wastewater could contain toxic pollutants, such as pesticides or heavy metals, sediments should be sampled once or twice a year to monitor the potential buildup of contaminants in the wetland sediments. The effluent should be sampled during high storms and high spring runoff flows to assure that sediments are being retained in the wetland. Groundwater should also be monitored once or twice a year to ensure that the wetland is not contaminating groundwater.

Table 25: Comparative summary chart indicating type of flow and organic load under different Constructed wetlands

Type	Hydraulic Load	Organic Load	References
Vertical-flow pilot-scale Constructed wetlands	0.08 or 0.17$m^3 m^{-2}$	0.02 and 0.04 $kgBOD_5 m^{-2}$	**Prochaska *et al.*,2007**
Vertical-flow constructed wetlands	50mm/d (12mm/d five days per week, 150mm/d two days per week	56gBOD/m^2d(=34gBOD/m^3 d)	**Weedon*et al.*, 2010**
Vertical-flow constructed wetlands	18mmd^{-1}(2002) 28mmd^{-1} (2003)	0.9 g BOD m^{-2} d^{-1}in 2002 2.8 gBODm^{-2} d^{-1} in 2003	**Morari and Giardini,2008**
HFCW and VFCW pilot plants	20 m^3/day	2.02 kg BOD/day	**Abou-Elela*et al.*,2013**
Hybrid wetland system	6 cmd^{-1}	690 g COD m^{-2} d^{-1}	**Saeed *et al.*, 2012**
Hybrid treatment system (VF-HF-FWS)	44 mm d^{-1}	9 g BOD_5 m^{-2} d^{-1}	**Ávila *et al.*,2012**
Hybrid wetland system (Saturated vertical-flow (VF) bed- Free-drained VF bed- Horizontal-flow (HF) bed in series)	For individual parts of the system18.1, 29.5 and 3.8 cm/day	180 and 193 gCOD/m^2day	**Vymazal and Kropfelova ,2009**

Hybrid wetland system (HF-VF)	146 ±52 L/m^2.day, 558±213 L/m^2.day	64± 23 g/m^2.day, 82 g/m^2.day	**Melián *et al.*,2018**
French VFCW	0.7m.d^{-1}	600 gCOD.m^{-2}.d^{-1}	**Boucle and Molle, 2013**
Vertical subsurface flow constructed wetland	24.5mmd^{-1}	4 g COD m^{-2} d^{-1}	**Pelissari*et al.*,2016**
Vertical flow constructed wetland	55.0mmm^{-2}	17.8 g BODm^{-2} day^{-1}.	**Sharma*et al.*,2018**
Vertical flow constructed wetland	77 m^{3}day^{-1}	122 kg COD day^{-1}	**Kim *et al.*, 2014**
French VFCW	1 and 1.4m.d^{-1}	250 ± 70g.COD.m^{-2}.d^{-1}	**Molle*et al.*, 2004**
Horizontal subsurface flow system and a saturated vertical downflow system	Three hydraulic loading rates of 80,160 and 320mmd^{-1}	27gm^{-2} d^{-1}	**Dan*et al.*, 2011**
Vertical flow constructed wetland	0.08 or 0.17 m^3 m^{-2}	0.02 kg BOD_5 m^{-2} and 0.04 kg BOD_5 m^{-2}	**Prochaska and Zouboulis, 2009**
VSSF–CW	0.05–0.06 m^{3}m^{-2} day^{-1}	0.01–0.04 kg BOD_5 m^{-2} day^{-1}	**Langergraber*et al.*, 2003**
Hybrid wetland system	0.06, 0.13 and 0.18 m d^{-1}	22, 65 and 93 g BOD5 m^{-2} d^{-1}	**Ávila *et al.*,2013**
Subsurface-horizontal flowconstructed wetlands	0.34 m(m^2 d)$^{-1}$	0.15 kg (m^2 d)$^{-1}$	**Hamouri*et al.*,2007**

6.4.4 Wetland health

The wetland should be checked periodically to observe general site conditions and to detect major adverse changes, such as erosion or growth of undesirable vegetation. Vegetation should be monitored periodically to assess its health and abundance. Large systems and those that are heavily loaded will require more frequent, quantitative monitoring. In general, more frequent monitoring also is required during the first five years after the wetland is installed. Species composition and plant density are easily determined, by inspecting quadrats (square plots, usually 3 ft x 3 ft) within the wetland at selected locations. A lightweight, open frame of wood or PVC pipe is laid on the wetland and the number of stems of each species present within the frame is counted. Changes of concern include an increase in the numbers of aggressive nuisance species, a decrease in the density of the vegetative cover, or signs of disease. The vegetation in constructed wetlands is subject to gradual year-to-year change, just as in natural wetlands. There may be tendency for some species to die out and be replaced by others. Temporary changes, such as the appearance of duckweed or algae, can occur in response to random or seasonal climatic changes. Because vegetative changes are often slow, they may not be obvious in the short-term, and good recordkeeping becomes essential. The buildup of accumulated sediment and litter decreases the available water storage capacity, affecting the depth of the water in the wetland and possibly altering flow paths. Sediment, litter, and water depths should be checked occasionally.

Table 26: Design of reinforced *concrete* water tank (Civil construction guidelines; IS 3370(Part1):2009**)**

Construction Unit Name	**Materials and sizes**
Tank type	Reinforced cement concrete holding tank
Minimum wall thickness	250 mm (RCC M25)
Compressive strength of concrete	M 25 (1:1:2 Cement:sand;metal)
Diameter of bars used	20 mm Reinfoced steel (
Plastering	15mm cement plastering
Platform Base thickness	150-250 mm (PCC 1:4:8)
Water proof lining	Brush bond RFX

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7. STANDARD METHODS (as per CPCB)

7.1 Dissolved Oxygen (Winkler Azide Modification Method)

1. Apparatus
a. BOD bottles, capacity 300mL
b. Sampling device for collection of samples
Reagents

Manganous sulphate solution	Dissolve 480 g $MnSO_4.4H_2O$, 400 g $MnSO_4.2H_2O$ or 364g $MnSO_4.H_2O$ in distilled water, filter and dilute to 1 L.
Alkali-iodide-azide reagent	For saturated or less than saturated samples: Dissolve 500g NaOH (or 700g KOH) and 150g Kl (or 135g Nal) in distilled water and dilute to 1000mL. Add 10g sodium azide, NaN_3 dissolved in 40mL distilled water. This solution should not give color with starch solution when diluted and acidified. For supersaturated samples: Dissolve 10g NaN_3 in 500mL distilled water. Add 480g NaOH and 750g Nal and stir to dissolve the contents. (Cautions: Do not acidify this solution because toxic hydrozoic acid fumes may be produced.)
Sulphuric acid, H_2SO_4conc	One milliliter is equivalent to about 3 mL alkali- iodide-azide reagent.
Starch indicator	Prepare paste or solution of 2.0 g of soluble starch powder and 0.2 g Salicylic acid as preservative in distilled water. Pour this solution in 100mL boiling distilled water. Continue boiling for a few minutes, cool and then use.
Stock sodium thiosulphate,0.1 N	Dissolve 24.82g $Na_2S_2O_3.5H_2O$ in distilled water. Preserve by adding 0.4g solid NaOH or 1.5mL of 6N NaOH and dilute to 1000 mL.
Standard sodium thiosulphate, 0.025N	Dilute 250 mL stock $Na_2S_2O_3$ solution to 1000mL with freshly boiled and cooled distilled water. Add preservative before making up the volume. (This should be standardized with standard dichromate solution for each set of titrations).

Procedure
1. Collect sample in a BOD bottle using Do sampler.
2. Add 1mL MnSO4 followed by 1mL of alkali-iodide-azide reagent to a sample collected in 250 to 300 mL bottle up to the brim. The tip of the pipette should be below the liquid level while adding these reagents. Stopper immediately. Rinse the pipettes before putting them to reagent bottles.
3. Mix well by inverting the bottle 2-3 times and allow the precipitate to settle leaving 150mL clear supernatant. The precipitate is white if the sample is devoid of oxygen, and becomes increasingly brown with rising oxygen content.

4. At this stage, add 1mL conc. H_2SO_4. Replace the stopper and mix well till precipitate goes into solution.
5. Take 201mL of this solution in a conical flask and titrate against standard $Na_2S_2O_3$ solution using starch (2mL) as an indicator. When 1mL $MnSO_4$ followed by 1mL alkali-iodide-azide reagent is added to the samples, 2mL of original sample is lost.

Therefore, 201mL is taken for titration which will correspond to 200mL of original sample.

200 x 300/ (300-1) = 201mL

Calculation

1mL of 0.025N $Na_2S_2O_3$ = 0.2mg of O2

DO in mg/L = (0.2 x 1000) x (0.025N) ml of thiosulphate / 200

Where:

V = mL thiosulphate solution used

M = molarity of thiosulphate titrant

7.2 Biochemical Oxygen Demand (3 Days, 27°C)

Apparatus

a. BOD bottles 300 mL capacity (clean with a detergent, rinse thoroughly and drain before use) with a water seal.

b. Incubator or water-bath to be controlled at 20ºC or at any desired temperature 1ºC. Exclude all light to prevent photosynthetic production of DO.

Reagents

Phosphate buffer solution	Dissolve 8.5 g KH_2PO_4, 21.75 g K_2HPO_4, 33.5 g$Na_2HPO_4.7H_2O$ and 1.7 g NH_4Cl in distilled water and dilute to 1000 mL. The pH should be 7.2 without further adjustment. Discard reagent if there is any sign of biological growth.
Magnesium Sulphate solution	Dissolve 22.5 g $MgSO_4.7H_2O$ in about 700 mL of distilled water and dilute to 1 Litre.
Calcium chloride solution	Dissolve 27.5g anhydrous $CaCl_2$ in about 7000 mL of distilled water and dilute to 1000 mL.
Ferric chloride solution	Dissolve 0.25 g $FeCl_3.6H_2O$ in about 700mL of distilled water and dilute to 1 L.
Sodium Sulphate solution (0.025N)	Dissolve 1.575g Na_2SO_3 in distilled water and dilute to 1000mL. Solution should be prepared daily.
Acid and alkali solution 1N	Prepare 1N H_2SO_4 and 1N NaOH or neutralization of caustic or acidic samples.
Nitrification inhibitor	2-chloro -6 (trichloromethyl) pyridine [Nitrification inhibitor 2570-24 (2.2% TCMP), Hach Co.

	equivalent]
Glucose-glutamic acid solution	Dry reagent grade glucose and reagent grade glutamic acid at 103^0C for 1 h. Add 150 mg glucose and 150 mg glutamic acid to distilled water and dilute to 1000 mL. Prepare fresh immediately before use.

Preparation of dilution water

a. The source of dilution water may be distilled water, tap or receiving-stream water free of biodegradable organics and bio-inhibitory substances such as chlorine or heavy metals.

b. Aerate the required volume of dilution water in a suitable bottle by bubbling clean-filtered compressed air for sufficient time to attain DO saturation at room temperature or at 27ºC. Before use stabilize the water at 27ºC.

c. Add 1mL each of phosphate buffer, magnesium sulphate, calcium chloride and ferric chloride solutions in that order for each Litre of dilution water. Mix well. Quality of dilution water may be checked by incubating a BOD bottle full of dilution water for 5 days at 20ºC for 3 days at 27ºC. DO uptake of dilution water should not be more than 0.2mg/L and preferable not more than 0.1mg/L.

d. For wastes which are not expected to have sufficient microbial population, seed is essential. Preferred seed is effluent from a biological treatment system. Where this is not available, supernatant from domestic wastewater (domestic sewage) settled at room temperature for at least 1h but not longer than 36hours is considered sufficient in the proportion 1-2mL/L of dilution water. Adopted microbial population can be obtained from the receiving water microbial population can be obtained from the receiving water body preferably 3-8 km below the point of discharge. In the absence of such situation, develop an adapted seed in the laboratory.

e. Determine BOD of the seeding material. This is seed control. From the value of seed control determine seed DO uptake. The DO uptake of seeded dilution water should be between 0.6mg/L and 1mg/L.

Sample preparation

a. Neutralise the sample to pH 7, if it is highly acidic or alkaline.

b. The sample should be free from residual chlorine. If it contains residual chlorine remove it by using $Na_2S_2O_3$ solution as described below.

c. Take 50mL of the sample and acidify with addition of 10mL 1 + 1 acetic acid. Add about 1g Kl. Titrate with 0.025 N $Na_2S_2O_3$, using starch indicator. Calculate the volume of $Na_2S_2O_3$ required per Litre of the sample and accordingly add to the sample to be tested for BOD.

d. Certain industrial wastes contain toxic metals, e.g. planting wastes. Such samples often require special study and treatment.

e. Bring samples to 20 ± 1ºC before making dilutions.

f. If nitrification inhibition is desired, add 3mg 2-chloro-6-(trichloromethyl) pyridine (TCMP) to each 300mL bottle before capping or add sufficient amount to the dilution water to make a final concentration of 30mg/L. Note the use of nitrogen inhibition in reporting results.
g. Samples having high DO contents, DO ≥ 9mg/L should be treated to reduce the DO content to saturation at 20ºC. Agitate or aerate with clean, filtered compressed air.

Dilution of sample: Dilutions that result in a residual DO of at least 1mg/L and DO uptake of at least 2mg/L produce reliable results. Make several dilutions of the pre-treated sample so as to obtain about 50% depletion of DO or DO uptake of 2mg/L.

Calculation

a. when dilution water is not seeded :-

$$\text{BOD as } O_2 \text{ mg/L} = \frac{(D1\text{-}D2) \times 100}{\%\ \text{dilution}}$$

b. when dilution water is seeded :-

$$\text{BOD as } O_2 \text{ mg/L} = \frac{(D1\text{-}D2) - (B1\text{-}B2) \times 100}{\%\ \text{dilution}}$$

Where:
D1= DO of diluted sample immediately after preparation, mg/L,
D2= DO of diluted sample after 3 d incubation at 27^0C, mg/L,
B1= DO of seed control before incubation, mg/L,
B2= DO of seed control after incubation mg/L and

7.3 Chemical Oxygen Demand (Open Reflux Method)

Apparatus

a) Friedrich's reflux condenser (12 inch) with standard (24/40) tapered glass joints
b) Electric hot plate or six-unit heating shelf
c) Volumetric pipettes (10, 25, and 50mL capacity)
d) Burette, 50mL with 0.1mL accuracy
e) Burette stand and clamp
f) Analytical balance, accuracy 0.001g
g) Spatula
h) Volumetric flasks (1000mL capacity)
i) Boiling beads, glass
j) Magnetic stirrer and stirring bars.

Reagent:

Standard potassium dichromate solution 0.04167M (0.25N)	Dissolve 12.259g $K_2Cr_2O_7$ dried at 103°C for 24h in distilled water and dilute to 1000mL. Add about 120 mg sulphamic acids to take care of 6 mg/L NO_2 – N.
Sulphuric acid reagent	Add 10 g of $Ag_2SO_4$to 1000 mL conc.H2SO4, and let stand for one to two days for complete dissolution.
Standard ferrous ammonium sulphate (FAS), 0.25M	Dissolve 98g Fe $(NH_4)_2(SO_4)_2.6H_2O$ in about 400mL distilled water, add 20 mL conc. H2SO4, cool and dilute to

	1000 mL.
Ferroin indicator solution	Dissolve 1.485g 1, 10-phenanthroline monohydrate and 695mg $FeSO_4.7H_2O$ in distilled water and dilute to 100 mL.
Mercuric Sulphate, HgSO4, powder	Crystals, analytical grade
Potassium hydrogen phthalate (KHP) standard $HOOCC_6H_4COOK$	Dissolve 425mg lightly crushed dried potassium hydrogen phthalate ($HOOC.C_6H_4.COOK$) in distilled water and dilute to 1000mL. This solution has a theoretical COD of 500µg O_2/mL. This solution is stable when refrigerated, up to 3 months in the absence of visible biological growth.

Standardization:
Dilute 10mL standard $K_2Cr_2O_7$ to about 100 mL, add10 mL conc.H_2SO_4, cool. Add 2 drops of ferroin indicator and titrate with ferrous ammonium sulphate (FAS).

$$\text{Normality of FAS} = \frac{\text{Volume of 0.25N } K_2Cr_2O_7 2 \text{ solution titrated (mL)}}{\text{Volume of FAS used in titration, (mL)}}$$

The deterioration of FAS can be decreased if it is stored in a dark bottle.

Procedure

1. Place 0.4g $HgSO_4$ in a 250mL reflux sample.
2. Add 20mL sample or an aliquot of sample diluted to 20mL with distilled water. Mix well.
3. Add clean pumic stones or glass beads.
4. Add 10mL 0.25N (0.04167M) $K_2Cr_2O_7$solution and mix.
5. Add slowly 30mL concentrated H_2SO_4 containing Ag_2SO_4 mixing thoroughly. This slow addition along with swirling prevents fatty acids to escape due to generation of high temperature. Alternatively attach flask to condenser with water flowing and then add H_2SO_4 slowly through condenser to avoid escape of volatile organic substance due to generation of heat.
6. Mix well. If the color turns green, either take fresh sample with lesser aliquot or add more potassium dichromate and acid.
7. Connect the flask to condenser. Mix the contents before heating. Improper mixing will result in bumping and blow out of flask content.
8. Reflux for a minimum of 2 hours. Cool and then wash down condenser with distilled water.
9. Disconnect reflux condenser and dilute the mixture to about twice its volume with distilled water. Cool to room temperature and titrate excess $K_2Cr_2O_7$ with 0.1M FAS using 2-3 drops of ferroin indicator. The sharp colour change from blue green to reddish brown indicates end-point or completion of the titration. After a small time gap, the blue-green color may reappear. Use the same quantity of ferroin indicator for all titrations.
10. Reflux blank in the same manner using distilled water instead of sample

Calculation

$$COD \text{ as mg } O_2/L = \frac{(A - B) \times N \times 8000}{\text{mL sample}}$$

Where:
A = FAS used for blank, mL
B = FAS used for sample, mL
N = Normality of FAS
8000= milliequivalent weight of O_2 x 1000

7.4 Total Nitrogen (Persulfate Digestion Method)

Apparatus
Spectrophotometer for use at 540 nm with a cell of 1cm or longer light path.

Reagents

Borate solution $Na_2B_4O_7.10H_2O$	Dissolve 38.0 g of $Na_2B_4O_7.10H_2O$ and 3.0 g of NaOH, in approximately 900 mL distilled water, using a magnetic stirring bar in a 1 L of volumetric flask. For the purposed of speedy dissolution gentle heating done. Adjust pH to 9.0 with NaOH or conc. HCL. Dilute to mark and invert it.
Persulfate solution $K_2S_2O_8$	Dissolve 49 g $K_2S_2O_8$ and 975 g distilled water in 1 L tared container. Add a magnetic stirrer bar, dissolve persulfate and dilute to mark. Invert to mix.
Ammonium chloride buffer	Add 500 mL distilled water, 105 mL conc. HCL and 95 mL ammonium hydroxide, NH_4OH in 1 L volumetric flask and dilute to the mark. Invert to mix. Adjust to pH 8.5 with 1N HCL or 1N NaOH solution.
Sulfanilamide color reagent	To a tared, dark, 1 L container add 876 g water, 170 g 85% phosphoric acid, H_3PO_4, 40.0 g sulfanilamide, and 1.0 g N-(1-napthyl) ethyenediamine dihydrochloride (NED). Shake to wet solids and stir for 30 mins to dissolve. Store in a dark bottle and discard when solution turns dark pink.
Cadmium Column	
Stock nitrate standard 1000 mg N/L	In a 1 L volumetric flask dissolve 7.221 g potassium nitrate, KNO_3 (dried at 600 C for 1 h), or 4.93 g sodium nitrite, NaNO2, in about 800 mL distilled water. Dilute to mark and invert to mix. When refrigerate the standard may be stored for up to 3 months.
Standard solution	Prepare nitrate standards in the desired concentration range, using stock nitrate standards and diluting with distilled water.

Procedure:-
Follow method supplied by manufacturer, or laboratory standard operating procedure for this method. Carry both standards and samples through this procedure. If samples have been preserved with sulfuric acid, preserve standard similarly. Samples may be homogenized.

Turbid samples may be filtered, since digestion effectiveness on nitrogen containing particles is unknown; however organic nitrogen may be lost in the filtrations.

Calculation:
Prepare standard curves by plotting absorbance of standards processed through the manifold versus nitrogen concentration. The calibration curve is linear. Verify digestion efficiency by determine urea, glutamic acid, or nicotinic acid standards at regular interval. In the concentration range of the method, the recovery of these compound should be >95%.

7.5 Ammonia (Phenate Spectrophotometric)

Apparatus
Spectrophotometer for use at 640nm with a cell of 1cm or longer light path.

Reagents

Phenol solution	Mix 11.1 mL liquified phenol (>89%) with 95% V/V ethyl alcohol to a final volume of 100 mL. Prepare weekly.
Sodium nitroprusside 0.5% (w/v)	Dissolve 0.5g sodium nitroprusside in 100 mL de-ionisedwater, store in amber bottle, discard after a month
Alkaline citrate	Dissolve 200 g trisodium citrate and 10g sodium hydroxide in de-ionised water, dilute to 1000 mL.
Sodium hypochlorite commercial solution, 5%	This solution slowly decomposes once the seal on the bottle cap is broken. Replace about every 2 months.
Oxidizing solution	Mix 100 mL alkaline citrate solution with 25 mL sodiumhypochlorite. prepare fresh daily
Stock ammonium solution	Weigh 3.819 g anhydrous, NH_4Cl, earlier dried at 100ºC and cooled in desiccator, in ammonia free water and dilute to 1L. 1 mL = 1mgN = 1.22 mgNH_3
Standard ammonium solution	Use stock ammonium solution and water to prepare a calibration curve in a range appropriate for the concentration of the samples.

Procedure

a. Take 25 mL sample in a 50 mL conical flask, and add with mixing, 1 mL phenol solution, 1 mL sodium nitroprusside solution, and 2.5 mL oxidising solution. Avoid light exposure by suitably covering the flasks at room temperature.

b. Prepare a blank and 2 other ammonia standards in the range, treating in the same way as sample, measure absorbance after 1h at 640nm.

Calculation
Prepare calibration curve by plotting absorbance readings against ammonia concentration of standards, compute sample concentration from the standard curve.

7.6 Nitrate (Spectrophotometer)

Apparatus

Spectrophotometer- for use at 220 nm and 275 nm with matched silica cells of 1cm or longer light path.

Reagents

Nitrate free water	Use redistilled or distilled deionized water of highest purity to prepare all solutions and dilutions.
Stock Nitrate Solution	Dry potassium nitrate (KNO_3) in an oven at 105^0C for 24 hr. Dissolve 0.7218 g in water and dilute to 1000mL; 1.0ml = 100µg NO_3-N. Preserve with 2 mL $CHCl_3$/L. This solution is stable for atleast 6 months.
Intermediate Nitrate Solution	Dilute 100 mL stock nitrate solution to 1000 mL with water; 1.0 mL=10µg NO_3-N. Preserve with 2 mL $CHCl_3$/L. This solution is stable for 6 months.
Hydrochloric acid, HCl, 1 N	

Procedure

a. **Treatment of sample:** To 50 mL clear sample, filtered if necessary , add 1 mL HCL solution and mix thoroughly.

b. **Preparation of standard curve:** Prepare NO_3^- calibration standards in the range 0 to 7 mg NO_3^- N/L by diluting to 50 mL the following volumes of intermediate nitrate solution: 0, 1.0, 2.0, 4.0, 7.0……35.0 mL. Treat $NO3^-$ standards in same manner as samples.

c. **Spectrophotometric measurement:** read absorbance or transmittance against redistilled water set at zero absorbance or 100% transmittance. Use a wavelength of 220 nm to obtain NO3- reading and a wavelength of 275 nm to determine interference due to dissolved organic matter.

Calculation: Obtain a standard curve by plotting absorbance at standards against nitrate nitrogen concentration, compute sample concentration directly from standard curve report as milligrams of oxidized nitrogen per liter (sum of nitrate nitrogen plus nitrite nitrogen) unless the concentration of nitrite nitrogen is separately determined and subtracted.

7.7 Total Phosphorus (Stannous Chloride Method)

Apparatus

a. Colorimeter for use at 690nm and 880nm providing 0.5cm light path.

b. Nessler tubes, 100mL.

Reagents

Stock phosphate solution	Dissolve 219.5mg anhydrous KH_2PO_4 in distilled water and dilute to 1000mL. 1mL = 50mg PO_4^{3}-P.
Phosphate working solution	Dilute 50 mL stock solution to 1000 mL with distilled water; 1 mL = 2.5µg P.
Ammonium molybdate solution	Dissolve 25g in about 175 mL distilled water. Add carefully 280 mL conc H_2SO_4 to 400mL distilled water. Cool and add molybdate

	solution and dilute to 1000mL.
Sulphuric acid , H_2SO_4 10 N	Add 300 mL conc $H_2SO_4$to approximately to 600 mL distilled water. Add 4mL conc. HNO_3, cool, dilute to 1000mL.
Sodium hydroxide 6N	Dissolve 24g NaOH and dilute to 100mL.
Phenolphthalein indicator	Dissolve 0.5g in 500mL 95% ethyl alcohol. Add 500mL distilled water. Add drop-wise 0.02 N NaOH till faint pink color appears (pH 8.3)
Stannous chloride reagent I:	Dissolve 2.5gm fresh $SnCl_2.H_2O$ in 100mL glycerol. Heat on water bath to ensure complete dissolution.
Dilute stannous chloride reagent II	Mix 8 mL stannous chloride reagent I with 50 mL glycerol and mix thoroughly.
Potassium antimonyl tartrate solution	Dissolve 2.7g in 800mL distilled water and dilute to 1000mL.
Ascorbic acid	Dissolve 1.76g ascorbic acid in 100mL distilled water. The solution is stable for a week at 4°C
Combined reagents	Mix 250mL, 5N sulphuric acid, 75mL ammonium molybdate solution and 150mL ascorbic acid solution. Add 25mL potassium antimonyl tartrate solution and mix well. The solution must be prepared daily.

Calibration

a. Into a series of 100mL Nessler tubes pipette appropriate amounts of phosphate working solution to cover the range of 5-30 mg/L or 0.3-2 mg/L P when $SnCl_2$/Ascorbic acid reagent is used as a reducing agent.

b. Add 4mL ammonium molybdate followed by 0.5mL stannous chloride or 8mL combined reagent and dilute to 100mL with distilled water and mix well. Allow to stand for 10 minutes.

c. Prepare blank using distilled water in the same way.

d. Measure the intensity of blur colored complex at 690nm or 880nm between 10 and 12 minutes after the development of the color.

e. Plot absorbance vs. phosphate concentration to give a straight line passing through the origin.

Digestion Procedure

- Take 100mL well mixed sample in 150mL conical flask. Add one drop of phenolphthalein indicator. If red color develops, add sulphuric acid solution dropwise to just discharge the color.
- Then add 1mL sulphuric acid solution in excess. Boil gently for at least 90 minutes, adding distilled water to keep the volume between 25 and 50mL. Cool, add one drop

phenolphthalein indicator and neutralize to a faint pink color with hydroxide solution. Filter if necessary and restore the volume to 100mL to 50mL.

Calculation
The concentration is calculated from the standard calibration curve.

7.8 Total Suspended Solids

Apparatus and equipment
a. Electrically heated temperature controlled oven
b. Evaporating dish (200mL)
d. Pipettes
e. Measuring cylinder (100mL)

Procedure
a. Take a known volume of a well-mixed sample in a tarred dish ignited to constant weight (W_1)
b. Evaporate the sample to dryness at 103-105°C for 24hrs.
c. Cool in desiccator, weigh and record the reading (W_2)
d. Ignite the dish for 15-20 minutes in a muffle furnace maintained at 550±50°C.
e. Cool the dish partially in air until most of heat has been dissipated, and then transfer to a desiccator for final cooling in a dry atmosphere and record final weight (W_3).
f. The concentration is to be calculated in percent by weight.

Calculation
The total and the volatiles solids are expressed as:
Total solids, mg/L = $(W_2 - W_1) \times 1000$ / mL of sample
and

$$(W_2 – W_3) \times 1000 / \text{mL of sample}$$

Where W_1, W_2 and W_3 are recorded in mg.

7.9 Microbiological Analysis

7.9.1 Multiple tube fermentation technique for coliform bacteria (MPN test):
In the multiple-tube method, a series of tubes containing a suitable selective broth culture medium (lactose-containing broth, such as MacConkey broth) is inoculated with test portions of a water sample. After a specified incubation time at a given temperature, each tube showing gas formation is regarded as "presumptive positive" since the gas indicates the possible presence of coliforms. However, gas may also be produced by other organisms, and so a subsequent confirmatory test is essential. The two tests are known respectively as the presumptive test and the confirmatory test.
For the confirmatory test, a more selective culture medium (brilliant green bile broth) is inoculated with material taken from the positive tubes. After an appropriate incubation time, the tubes are examined for gas formation as before. The most probable number (MPN) of bacteria present can then be estimated from the number of tubes inoculated and the number of

positive tubes obtained in the confirmatory test. Using specially devised statistical tables. This technique is known as the MPN method.

7.9.2 Membrane filtration method for total coliform and thermotolerant (faecal) coliforms

The method is based on the filtration of a known volume of water through a membrane filter consisting of a cellulose compound with a uniform pore diameter of 0.45 or 0.2 µm; the bacteria are retained on the surface of the membrane filter. When the membrane containing the bacteria is incubated in a sterile container at an appropriate temperature with a selective differential culture medium, characteristic colonies of coliforms/ thermotolerant coliforms develop, which can be counted directly. In contrast to the multiple-tube method, the membrane-filtration method gives as a direct count of total coliforms and thermotolerant coliforms present in a given sample of water.

7.9.3 EC-MUG Test for confirmation of *E. coli*

This is a simple test for confirmation of presence of *E. coli* in water samples and may be knitted into the Multiple Tube Fermentation (MTF) procedure, as a confirmatory test. If the lab chooses to use EC-MUG test, it would replace using BGLB and tryptone broth (indole test) at 44.5ºC. MUG (4-methlumbelliferyl-β-D-glucoronide) is the substrate for the enzyme β-glucoronidase. This enzyme is primarily found only in *E. coli.*

8. CASE STUDIES OF CONSTRUCTED WETLAND SYSTEMS

In-situ remediation

In developing countries, water pollution is a key problem, with high levels of contaminates being reported in many rivers **(Nasr and Ismail, 2015)**. Different pollution control and water treatment technologies methods can be applied to resolve this issue (**Yudianto and Yuebo, 2011).** Water treatment technologies can be classified as physical, chemical, or biological treatment techniques. They can also be classified as in-situ or ex-situ technologies. Insitu remediation techniques involve treatment at the site, while ex-situ involves the removal of contaminants at a remote location. Understanding in-situ treatment systems is essential to maintaining and controlling hydraulic conditions in open streams **(Wang *et al*., 2012).** Insitu bioremediation has many advantages when compared to other techniques, such as low costs, less adverse impacts on the environment, and no secondary production of pollutants **(Mingjun *et al*., 2009).** Indeed, many in-situ remediation processes, such as ecological floating bed techniques and constructed wetlands, have been developed for the bioremediation of polluted water and have produced "satisfactory" results (**Cao *et al*., 2012).** This manual provides a holistic review of the latest surface water remediation technologies applied in-situ.

CASE STUDY # 1

VERTICAL FLOW SUBSURFACE SYSTEMS OPERATED FOR TREATING SEWAGE WASTEWATER IN EGYPT

This case study used eight months of monitoring program for assessing the sewage treatment under different operational condition. The raw sewage was collected from the Zenien wastewater treatment plant in Giza, Egypt. Within the vertical flow constructed wetland system the sewage was treated by allowing it in different ways of operation which includes presence or absence of vegetation on the bed, variations in filter material and mode of sewage feeding. Within the system *Phragmites australis* (common reed) was used for the vegetation, gravel or vermiculite were used as filter material and continuous and batch processes were selected for the influent feeding in the verticals beds.

Configuration of the Vertical Subsurface Flow CW

- Plastics were used for the construction of wetland units with the dimension of 0.3 x 0.3x 0.3 m for length, width and depth, respectively.

- Influent volume (day^{-1}): 0.0225 m^3.
- Hydraulic Retention Time (HRT) : 0.5 day
- Hydraulic Loading HLR: 0.15 m d^{-1}
- Filter media used-
  - Gravel (Dia. 5-10 mm & porosity 30%) &
  - Vermiculite (Dia. 5 mm & porosity 35%)
- Filter media depth : 0.25 m
- Sewage Level- 5 cm (below the surface of media)
- Type of Beds – Planted and Unplanted
- Vegetation- *Phragmites australis*
- Mode of feeding/dosing- Continuous & Batch mode

Operational details of system:

Common reed plants collected from the Nile bank at Gezerit El Warak, Cairo, Egypt were planted @ 6 plants m^{-2} on the wetland beds. After plantation, the beds were fed with the diluted waste water which contained 50% tap water and 50% primary treated sewage for time one month. Subsequently, the beds were fed with only raw sewage effluent for one month. In this manner the system was initiated which resulted in providing favorable conditions for the plants growth and establishment.

Analysis Method Used

Table 27: Water parameters and methods of analysis

S. No	Parameters	Method
1.	Total Suspended Solids (TSS)	Paper Filtration Method
2.	Chemical Oxygen Demand (COD)	Open Reflux Method
3.	Biological Oxygen Demand (BOD)	Winkler method
4.	Ammonium nitrogen (N-NH+4)	Nesslerization method
5.	Nitrate nitrogen (N-NO–3)	Ultraviolet spectrophotometric screening method
6.	Soluble phosphate P (P-PO_3 4)	Vanadomolybdophosphoric acid colorimetric method
7.	Total phosphorus (TP)	digestion method with nitric and sulfuric acids

The researchers also evaluated the efficiency of the constructed wetland system under different operations on the basis of percent removal, mass removal rate, areal removal rate constant and volumetric removal rate constant.

Calculations for treatment efficiency of wetland units:

1. Percent Removal (removal efficiency)

Removal efficiency (%) = $(C_{in} – C_{out})/ C_{in} \times 100$

Where C_{in} and C_{out} = inflow and outflow concentrations, respectively (mg L^{-1}).

2. The Mass Removal Rate (r, in gm $^{-2}$ d $^{-1}$)

$r = q (C_{in} - C_{out})$

r = mass removal rate (g m^{-2} d^{-1}).

q = hydraulic loading rate (m d^{-1}).

Removal Rate Constants: A first-order degradation approach was used to predict the removal performance of COD, BOD, TSS, N and P in the constructed wetlands. The rate constants for this model can be defined on either an areal (kA) or a volumetric (kV) basis.

The areal removal rate constant (kA)

$\ln(C_{out} - C_{in}) = -k_A/q$

where

q = hydraulic loading rate (m day^{-1}) = Q/A,

Q = flow rate through the wetland (m3 d $^{-1}$),

A= area of the wetland (m2), and

kA =areal removal rate constant (m d $^{-1}$).

The volumetric removal rate constant (kV)

$\ln (C_{out} - C_{in}) = - k_v t$

where

k_v = volumetric removal rate constant (d $^{-1}$),

t = hydraulic retention time in the wetland (d) = VƐ/Q,

V= volume of the wetland (m^3), and

Ɛ = wetland porosity.

Results and Discussion

COD, BOD, and TSS removal

Influent wastewater showed fluctuations i.e. COD: 400 - 700 mg L^{-1}, BOD: 150 -300 mg L^{-1} and TSS: 100 -350 mg L^{-1} during the study period. As per the results recorded it was found that

BOD/COD ratio in the influent ranged from 0.36 to 0.54, which showed that the quality of raw sewage is fairly biodegradable and can be treated biologically.

Table 28: Concentrations of various wastewater parameters and removal efficiency of CW system

Beds Details	Filter Media	Feeding Mode	COD			BOD			TSS		
			Average Influent Concentration (mg L^{-1})	Average effluent Concentration (mg L^{-1})	Removal Efficiency (%)	Average Influent Concentration (mg L^{-1})	Average effluent Concentration (mg L^{-1})	Removal Efficiency (%)	Average Influent Concentration (mg L^{-1})	Average effluent Concentration (mg L^{-1})	Removal Efficiency (%)
VFCW (with plantation)	Gravel	Continuous	624	187	**70**	226	38	**83**	202	78	**61**
		Batch	465	110	**76**	253	38	**85**	227	45	**80**
	Vermiculite	Continuous	624	149	**76**	226	37	**83**	202	44	**78**
		Batch	465	101	**78**	253	32	**87**	227	42	**81**
VFCW (without plantation)	Gravel	Continuous	475	325	**32**	181	102	**43**	180	119	**34**
		Batch	383	260	**33**	186	124	**33**	281	144	**48**
	Vermiculite	Continuous	475	362	**24**	181	114	**37**	180	116	**35**
		Batch	383	286	**25**	186	125	**33**	281	136	**51**

The removal rates of COD, BOD and TSS were highest in the vertical bed with the plantation in comparison to unplanted vertical beds. Lower concentrations of pollutants were measured in the planted beds, only the levels of BOD and TSS in the effluent were lower than the recommended guidelines, whereas the COD level was much greater than the recommended guideline. It was also noted that the unplanted vertical are not capable for the efficient removal of pollutant in raw sewage. The data obtained from the study highlighted that the removal efficiency was maximum when the influent was dosed by means of batch process due to the reason that it promotes greater aerobic conditions for the degradation of organic matter.

The effect of the feeding mode on the removal of TSS was explained by its effect on the sedimentation rate of the suspended particles. In the batch mode of feeding the wetland system was filled with wastewater for a determined period of time and subsequently drained completely before the next batch of effluent is applied, whereas in the continuous mode the wastewater flowed into the media continuously thus keeping it moist all the time. The batch feeding mode allowed more solids to be trapped in the pore spaces of the media compared to the continuous mode, resulting in higher values of TSS removal efficiency.

Nutrient Removal Rate

1. NH_4-N and NO_3-N

The wastewater was collected periodically and analysed for NH_4-N and NO_3-N at inlet and outlet points to assess the effect of wetland processes on concentration of Nitrogen components in the wastewater.

Table 29: The effect of different operational conditions of constructed wetlands on the concentration & removal Rates of NH_4-N and NO_3-N

Beds Details	Filter Media	Feeding Mode	NH_4 - N			NO_3- N		
			Average Influent Concentration (mg L^{-1})	Average effluent Concentration (mg L^{-1})	Removal Efficiency (%)	Average Influent Concentration (mg L^{-1})	Average effluent Concentration (mg L^{-1})	Removal Efficiency (%)
VSSFCW (with plantation)	Gravel	Continuous	42	34	**19**	6.1	7.2	**-18**
		Batch	33	21	**36**	5.8	7.1	**-22**
	Vermiculite	Continuous	42	31	**26**	6.1	7.7	**-27**
		Batch	33	17	**48**	5.8	7.6	**-31**
VSSFCW (without plantation)	Gravel	Continuous	30	23	**22**	6.7	6.7	**0**
		Batch	35	27	**23**	5.2	4.4	**15**
	Vermiculite	Continuous	30	23	**22**	6.7	5.9	**12**
		Batch	35	22	**37**	5.2	4.2	**19**

The results showed that the NH_4 concentration of the influent was approximately five times greater than that of the NO_3. The initial concentration of NH_4 ranged 30–42 mg L^{-1} and decreases after treatment. Generally the removal rate of NH_4 under all condition was low and followed the pattern- planted beds (32%)> unplanted beds (26%), the vermiculite media (33%)> gravel media (25%) and the batch feeding (36%)> continuous feeding (22%). By means of ANOVA, statistical analysis data showed that the average concentration of NH_4 –N was not considerably differ in condition of planted and unplanted beds showing average value of 26 and 24 mg L^{-1}, respectively. The removal efficiency of NH_4 was found to be influenced by filter media. Vermiculite showed higher removal due to its higher cation removal capacity.

3 On the another hand the above table showed that the concentration of NO_3 in the influent was relatively low at approximately 5–6 mg/l. whereas the NO_3-N concentration in the effluent of planted beds are high by 16% over the influent concentration while the unplanted bed show decrease in effluent concentration. The data show the negative removal rate which suggests the unfavorable condition for nitrate removal**TP (Total phosphorus) and DP (Dissolve phosphorus)**

Phosphorus removal in a CW system occurs by interaction of dissolved and suspended P of the wastewater with wetland media. Furthermore, surface vegetation also eliminates the P content from wastewater by absorbing it at root-zone.

Table 30: The effect of different operational conditions of constructed wetlands on the concentration & removal Rates of TP and DP

Beds Details	Filter Media	Feeding Mode	Total-P (TP)			Dissolved-P (DP)		
			Average Influent Concentration (mg L^{-1})	Average effluent Concentration (mg L^{-1})	Removal Efficiency (%)	Average Influent Concentration (mg L^{-1})	Average effluent Concentration (mg L^{-1})	Removal Efficiency (%)
VSSFCW (with plantation)	Gravel	Continuous	2.6	2.1	**19**	1.5	1.2	**20**
		Batch	2.5	2.1	**16**	1.4	1.1	**21**
	Vermiculite	Continuous	2.6	1.8	**31**	1.5	1.1	**26**

		Batch	2.5	1.9	**24**	1.4	1.0	**28**
VSSFCW (without plantation)	Gravel	Continuous	2.9	2.7	**7**	1.9	1.7	**10**
		Batch	2.6	2.2	**15**	1.5	1.2	**20**
	Vermiculite	Continuous	2.9	2.3	**20**	1.9	1.3	**31**
		Batch	2.6	1.9	**27**	1.5	0.8	**47**

The study data showed the low values for the initial TP concentration (2.6–2.9 mg L^{-1}) and the removal rate (7–27%). The observed result showed that the feeding mode and vegetation was insignificant for the removal rate. However, the vermiculite media removed significantly ($P < 0.05$) higher amounts of TP (25.5%) compared to the gravel (14.2%), which could be caused by the adsorption of P on vermiculite surfaces.

On the another hand the concentration of the DP in the raw sewage ranged from 1.4 to 1.9 mg L^{-1} and on average represented approximately 60% of the TP. The wetland removed an average of 25% of the DP. Statistical analysis showed that only the type of media exerted a significant effect ($P< 0.05$) on the DP removal. The removal efficiency of the DP for the vermiculite media was approximately 2 times greater than for gravel.

Conclusion

The case study showed the most affecting factor for the removal efficiency of COD, BOD, TSS and NH4 in vertical subsurface flow system was vegetation. The filter media selected in the study also acted as one of the crucial factor for the removal of NH_4, TP and DP. The organic matter was removed in the large extent in batch type feeding. This study also showed that the system efficiently worked for the removal of organic and inorganic matter as well as suspended solid, NH4-N from the raw sewage .

CASE STUDY # 2

PHYTORID TECHNOLOGY FOR SEWAGE WASTEWATER TREATMENT IN INDIA

Phytorid Technology was developed by NEERI, India. It has been extensively used in treating wastewater at different locations in India. PHYTORID system works on the principle of subsurface flow constructed wetland technology in which wetland beds filled with filter media are connected in series /parallel manner. Crushed bricks, gravel and stones are used as a porous filter material to enhance the purification processes naturally. This technology was patented by **Kumar *et al.*, 2004.** The design parameter includes: minimum requirement of about 35.0 m^2 of land area for treating a wastewater load of 20 m^3/day (Figure 30).

Components of the treatment system

- Sewage Collection Tank
- Settler/Screening Chamber
- Phytorid Bed
- Treated water Storage Tank

Phytorid technology has been used in treating variety of wastewaters such as:

- Domestic wastewater
- Open Drainage
- Cleaning of nallah water
- Agriculture wastewater
- Dairy wastewater
- Municipal landfill leachate
- Pre treated industrial wastewater

Table 31: Commonly used plants species in Phytorid systems

S.No	**Name of Species**
1.	Reeds (*Phragmites Spp*)
2.	Elephant grass (*Pennisetum purpurem*)
3.	Cattails (Typha Spp.)
4.	Cana Spp
Ornamental Plant Species used for aesthetic purpose	
1.	Golden dhuranda
2.	bamboo
3.	Nerium
4.	Colosia

Major benefits of adopting Phytorid technology for Sewage treatment

- Cost effective
- Operation of Phytorid is based on gravity rule, so less electricity required.
- Operation and maintainance expenses are low/negligible.
- The treated water is reused in various operation facilitating Zero liquid dischage.
- Able to endure the situation of variation in temperature, pH and flow rate of the sewage treated.

Pollutant Removal processes occur during treatment process: -

- Sedimentation
- Filtration
- Adsorption
- Precipitation
- Decomposition
- Microbial degradation
- Nutrient uptake

Table 32: Removal efficiency of Phytorid System

Water Parameters	**Removal rate (%)**
Biochemical oxygen demand (BOD)	80-95
Chemical oxygen demand (COD)	85-95
Total nitrogen	60-70
Phosphate	30-40
Total suspended solids	75-95
Faecal Coliform	90-95

Figure 30: Photographs of Phytorid systems developed by NEERI, India

Table 33 : Technical details of treatment plants based on Phytorid Technology at different locations

S. No	Location of Plant	Type of Wastewater treat	Capacity of Treatment Plant & Design	Operation details (Starting year)	Utilization of treated water
1.	Mumbai University Campus (Kalina-Mumbai)	Sewage and laboratory in mixed form	50 CMD ➢ Primary chamber ➢ Second advance system ➢ Phytorid system	June 2006	Reuse in garden and in lake within the campus premises.
2.	Premier Auto Ltd. (Pimpri Chincwad)	Sewage	150 CMD(m^3/d) ➢ Primary treatment system ➢ Phytorid system	Jan 2007	Reuse for gardens and lawn.
3.	Mahindra & Mahindra Ltd. (Igatpuri, Dist. Nashik)	Sewage	60 CMD (2 STP's) ➢ Primary Treatment System ➢ Phytorid system	July 2007	Reuse for gardens.
4.	Siemens Factory (Kalwa, Thana)	Sewage	500 CMD	Aug 2007	Reuse for gardens and lawns.
5.	Ajay Metachem Pvt. Ltd. (Wadki, Pune)	sewage	2 CMD ➢ Primary treatment ➢ Tertiary treatment ➢ Phytorid system	Jan 2008	Reuse for garden.
6.	Warana Industries Ltd (Warananagar,	Sewage	10 CMD ➢ Primary treatment	Oct 2008	reuse for gardens and floor washing

	Dist: Kolhapur		system ➢ Phytorid system		
7.	Kolimb Agricultural College (Titwala -Thane Dist.)	Grey wastewater	5 CMD ➢ Septic chamber ➢ Phytorid system	June 2009	Reuse for garden purpose and in vermin composting plant.
8.	Bharat Forge Limited (Baramati)	Sewage	100 CMD ➢ Septic chamber ➢ Phytorid system	July 2009	Reuse for gardens and lawns
9.	Matheran Hill Station (Anand Ridtzs -Alibaug Dist.)	Sewage	20 CMD ➢ Septic chamber ➢ Phytorid system	Oct 2010	Reuse for gardens and lawns

CASE STUDY# 3

VERTICAL SUB-SURFACE CONSTRUCTED WETLAND UNITS FOR TREATMENT OF DAIRY WASTE WATER

This case study involves use of nine pilot scale vertical flow constructed wetlands units for the treatment of dairy waste water located near Graphic Era deemed to be University, Dehradun, Uttrakhand . Each CW unit consisted of a primary tank and two vertical sub surface beds connected in series (Figure 31, 32a, 32b, 32c). The systems were operated for 03 years investigating the treatment efficiency of CW units as well as to assess the effect of filter material, seasonal variations, surface vegetation for pollutant removal from wastewater.

Figure 31: Pictures showing construction of CW units and growth of surface vegetation on CW

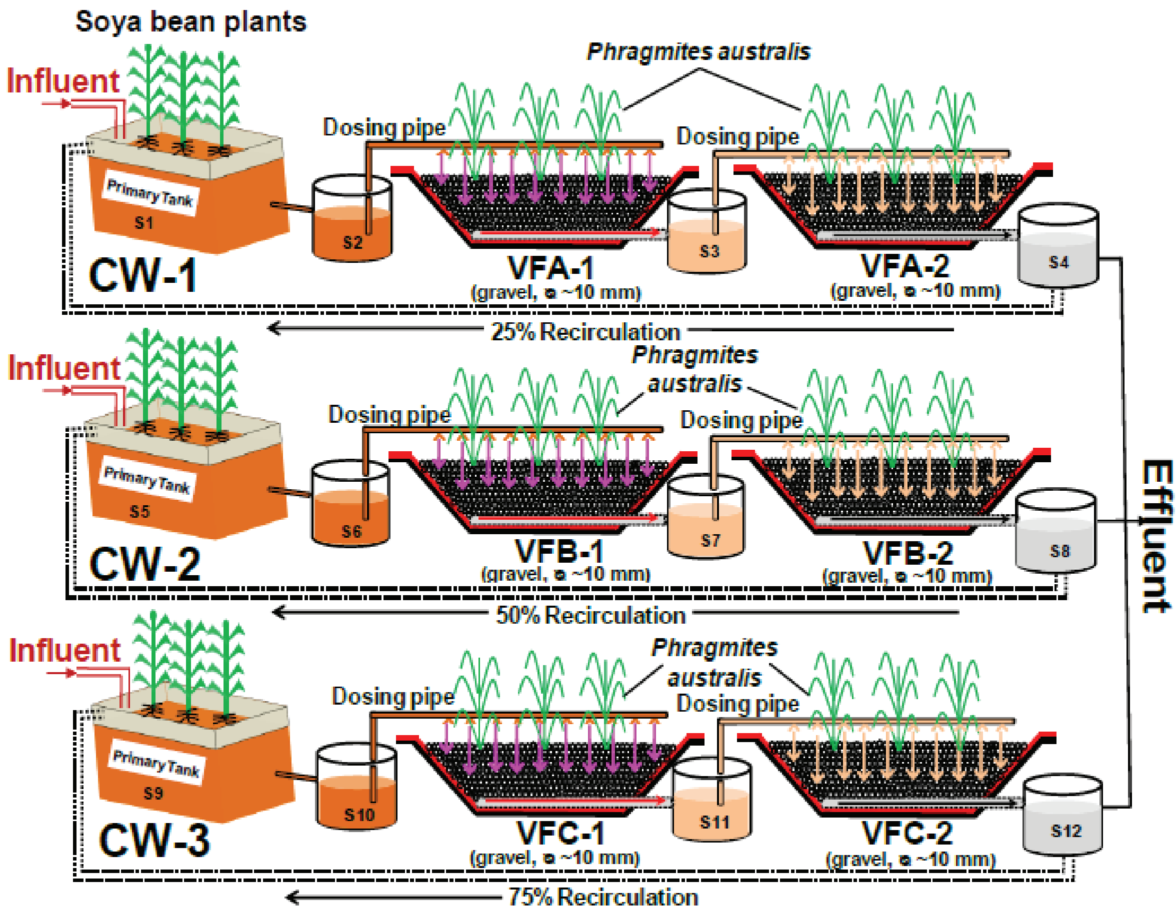


Figure 32a: Schematic layout of CW units

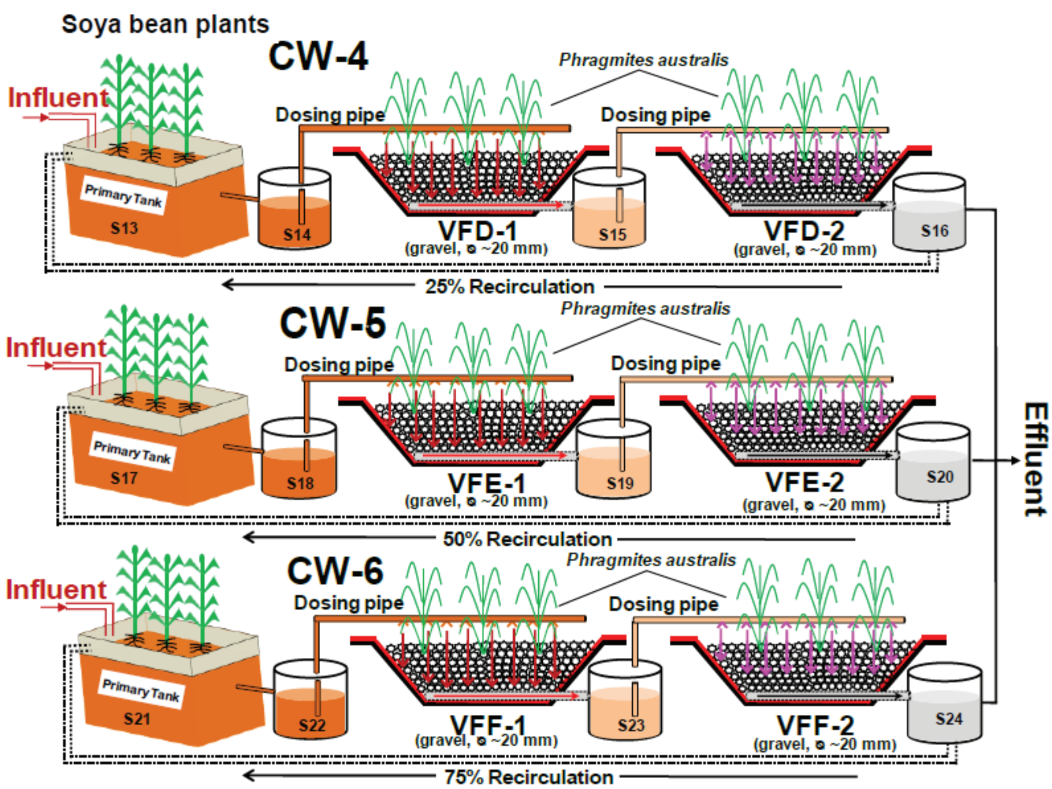


Figure 32b: Schematic layout of CW units

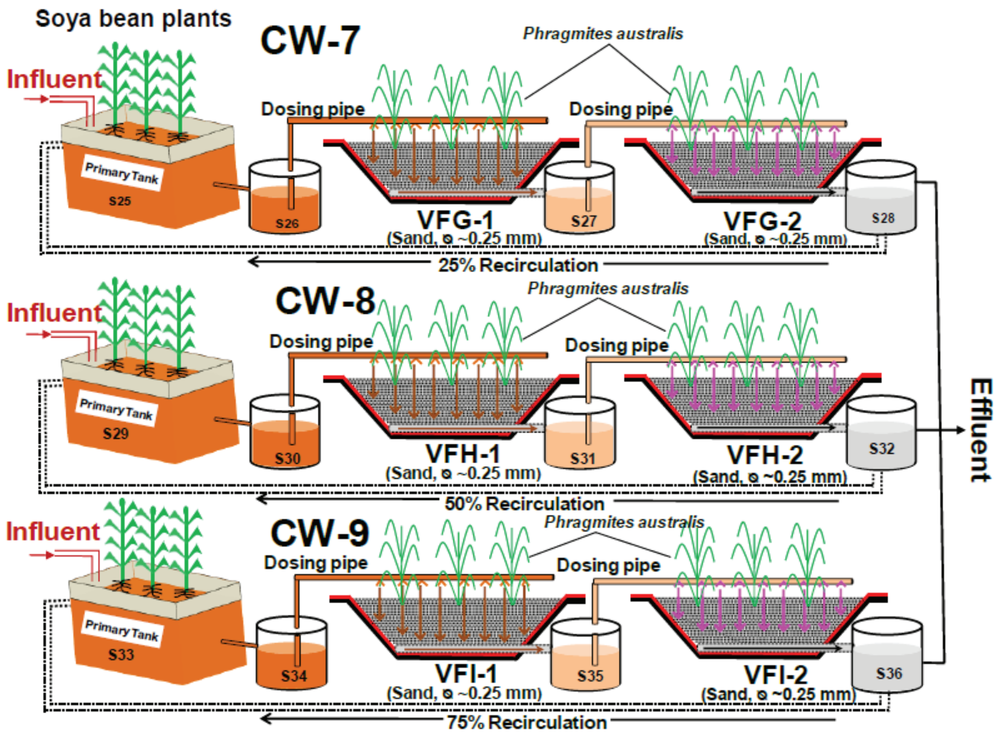


Figure 32c: Schematic layout of Vertical CW units

Table 34: Designing Details of Nine Pilot Scale CWs

Items	**Details with Specifications**	
Primary tank	Fitted with soybean planted floating bed	-
CW 1 to CW 3	Contain 10 mm sized gravel as a filter material & planted with *Phragmites australis*. Bed depth : 0.70 m.	Recirculation rate maintained at final outlet tank to inlet tank, was CW1-25 % CW2-50% CW3-75%
CW 4 to CW 6	Contain 20 mm sized gravel as a filter material & planted with *Phragmites australis*. Bed depth : 0.70 m.	Recirculation rate maintained at final outlet tank to inlet tank, was CW4-25 % CW5-50% CW6-75%
CW 7 to CW 9	Contain 0.25 mm dia sand as a filter material & planted with *Phragmites*	Recirculation rate maintained at final outlet tank to inlet tank,

	australis. Bed depth: 0.70 m.	was CW7-25 % CW8-50% CW9-75%
Bottom slope of all the units	1 % from inlet to oulet	
Lining	Thick concrete was used at the bottom and circumference to avoid seepage	
Dosing pipe	Perforated pipes was used	
Feeding mode	Intermittent type	
Total nos. of water sample collected	36 nos.	

Primary Tank

This tank receives the raw dairy waste water, the waste water contains animal urine, floor washing and cow dung. This tank consisted of hollow bamboo stem piled over each other and placed in such an order that it looks like a rectangular shaped floating beds.

Results

A volume of 220 litres of waste water was dosed to each CW units every day. HRT of waste water was fixed as 24 hrs in all CW units. Samples were taken at the outlet tank of each CW unit. Untreated and treated waste water samples were analysed for pH, EC, ORP, DO, temperature, TDS, BOD, COD, TN, NH_4-N, NO_3-N, TP and PO_4-P. The efficiency of each CW unit in decreasing pollution load from wastewater was assessed as follows.

Purification Rate (%) = (Ci – Co)*100/Ci

Ci = Inlet concentration (mgL-1); Co = Outlet concentration (mgL^{-1})

Removal Rate (%) = (Inlet Load – Outlet Load)*100/Inlet Load

Load($g\ m^{-2}\ day^{-1}$)= [waste water volume dosed(litre) x conc.($mg\ L^{-1}$))/1000]/area of CW unit(m^2)

Table 35: Filter material effect on purification rate of dairy waste water pollutants

Parameters	Purification Rate (%)			
	10 mm Gravel Filled Units	20 mm Gravel Filled Units	Sand Filled Units	Average PR in all CW units
TSS	78.1 to 97.3%	82.0 to 97.7%	92.2 to 95.5%	91.4 to 97.7%
BOD	83.4±4.8%,	83.2±6.2%	94.9±2.9%	83.2 to 94.9%
TP	21.3 to 82.0%	32.0 to 84.5%	77.0 to 99.0%	55.1 to 91.8%
NH_4^+	30.7 to 76.7%	41.9 to 73.6%	23.5 to 63.3%.	44.6%
TN	35.9±4.4%,	59.3±9.0%	35.9±7.5%	-

Table 36: Nutrient uptake capacity of *Phragmites australis*:-

Parameters	Observed Results of *Phragmites australis*
Total Chlorophyll Content	1.9 to 17.9 mg g^{-1} fresh wt.
Total Dry Biomass Content	0.13 to 0.47 g g^{-1} fresh wt.
TN	
TP	5.5 to 13.6 mg g^{-1}

Summary and Conclusions

This case study showed that all the units worked efficiently in removing the contaminants from dairy wastewater during entire time period. Average concentrations of BOD, TN, NH_4-N and TP in the influent was recorded as 323, 115, 69, and 38.0 mg L-1 respectively whereas, lower concentrations of all these parameters were observed at outlet point of all CW units and were ranged as BOD (2-194 mg L -1), TN (11-101 mg L -1), NH_4-N (5-57 mg L -1) TP (0.6-16.4 mg L -1) after recirculation.

Efficiency of CW units was also assessed with different filter material and recirculation rates during study period. Recirculation of treated water promotes denitrification process and helps in achieving higher removals of Nitrogen. In this study, recirculation increased removal rates of TN (10-19%), NH_4-N (10-21%), TP (4-27%) and BOD (3 -13%) in all CW beds. Maximum removal of TSS and BOD (99%), TP (93.5%) was achieved by sand filled CW unit with 75% of recirculation of treated water (CW9). However Highest removal efficiencies of TN (65%) and NH_4-N (64.9%) were recorded in CW6 (20 mm size gravel filled +75% recirculation rate).

In this case study the observed results showed that all the beds were capable of removing contaminants from wastewater. Gravel filter material resulted into good nitrification (2.9 to 15.0 mg L^{-1}) of wastewater and increased DO levels (2.3-7.6 mg L^{-1}) at the outlets during treatment period. Temperature variation showed no significant difference in treatment efficiencies of CW units.

CASE STUDY# 4

NEELA-HAUZ BIODIVERSITY PARK

Neela Hauz Lake (covering around 2.5 hectares) is a symbol of environmental rejuvenation of a dead lake at the Neela Hauz Biodiversity Park. This rejuvenation model has proved so successful that officials have submitted the concept to the Delhi Jal Board for implementation to rejuvenate other water bodies across Delhi.About a decade ago the lake was completely filled with debris during the construction of a flyover over it. Revival process started immediately after petition was filed in Delhi High Court by local residents. Delhi Development Authority (DDA) in collaboration with Centre for Environmental Management of Degraded Ecosystems (University of Delhi) took responsibility to revive dead lake through constructed wetlands(CWS). The problem of low water level in the lake was also solved by storing the treated raw sewage water after passing it through constructed wetland system.

Design layout of the CW unit

The CW unit operating at NeelaHauz represents continuous, horizontal, free surface flow system developed on site (Figure 33, 34).

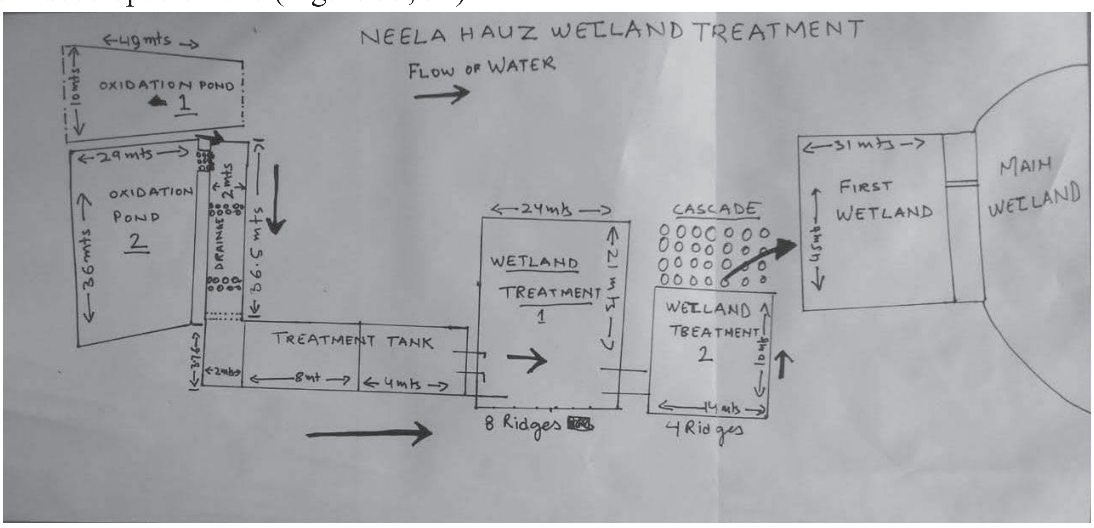


Figure 33: Design layout of Neela Hauz, Biodiversity Park

CONSTRUCTED WETLANDS

Biological processes

Oxidation step I

Sewage stored and retained for 7 hours in large surface area.

- **Breakdown of organic material naturally by atmospheric oxygen.**

Oxidation step II

Storage of water for 7 hours in a pond where free floating aquatic plants like *Lemna* and *Alternanthera* are found.

- **Sharp reduction in nitrates, phosphates and BOD levels.**

Physical processes

Physical Treatment

Water is passed through physical treatment channels with large sized river bed pebbles. After this water is passed again through three tanks-

Tank I and II has smaller pebbles

Tank III has the smallest pebbles

- **These tanks remove particulate organic matter of all sizes and also get degraded by biofilms attached to filters.**

↓

Water is again passed through Ridges with gravels and Furrows with 20 different aquatic species.

- **Removal of biotoxins, heavy metals, nutrients, sludges and fine particulates biodegradation of pollutants**

↓

Enters into another pond with floating aquatic plants

- **Removal of left out fine particulate organic matter by biodegradation and sedimentation.**

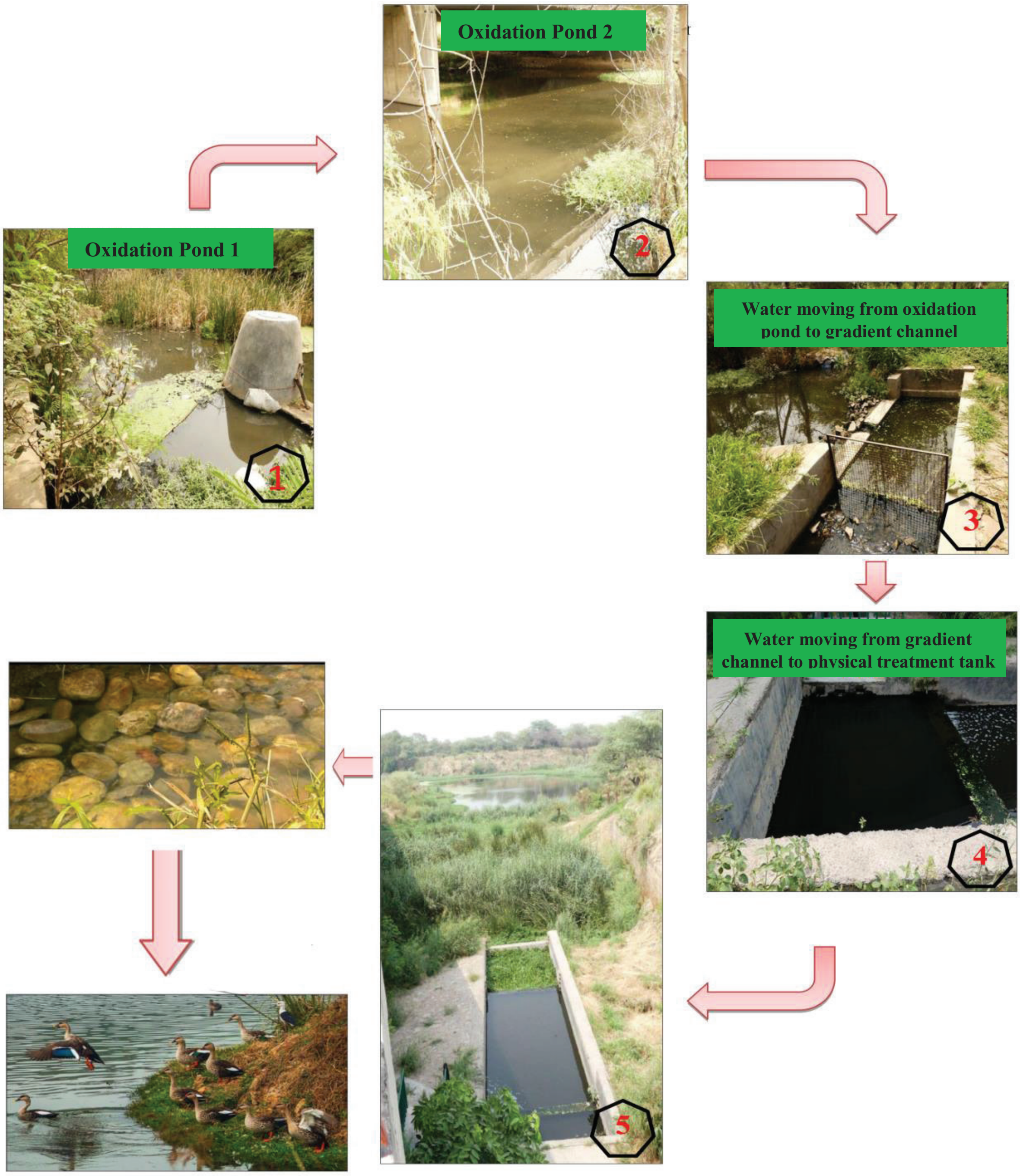


Figure 34: Wastewater treament Mechanism

Dosing load (g m^{-2} d^{-1})

- 1 MLD of raw sewage + STP treated water with BOD of more than 40 mg L^{-1}.

Feeding Mode

- Continuous type

Table 37: Water quality data of lake before and after the treatment at Neela Hauz

Samples	Water Analysis								
	pH	Conductivity ($\mu S\ cm^{-1}$)	Chlorides ($mg\ L^{-1}$)	BOD ($mg\ L^{-1}$)	COD ($mg\ L^{-1}$)	Sulphates ($mg\ L^{-1}$)	Dissolved Oxygen ($mg\ L^{-1}$)	Phosphates ($mg\ L^{-1}$)	Total Dissolved Solids ($mg\ L^{-1}$)
Before Treatment	7.8	1254	163	40	80	355	0	103	600
After Treatment	6.7	606	118	4.0	0.7	78	3.4	14	298

Advantages-

- No energy is being consumed in the process, as only physical materials like river bed pebbles, gravel and aquatic plants are used to clean the water and the water flow is across the gradient.
- Quality of the treated water reaches a good level which is same as that of river water by all natural processes.
- The CW unit at Neela Hauz now treats close to a million litres of water everyday through natural processes. More than 15,000 saplings of native trees and shrubs belonging to several biological communities have been planted in the surroundings of the CW and rejuvenated lake to make the area aesthetic and it has now become recreation centre for the public. The constructed wetland has the following plant species: *Ipomoea, Typha*, *Phragmites*, *Alternanthera*, *Scripus*, *Cyperus*, *Eleocharis*, Polygonum and Lemna; these species together with their rhizospheric communities have been playing an important role in removal of pollutants.

CASE STUDY ## 5

2 MLD CONSTRUCTED WETLAND FOR SEWAGE TREATMENT AT INDIAN AGRICULTURAL RESEARCH INSTITUTE (DELHI CAMPUS)

The Indian Agricultural Research Institute (IARI) is constructing a wetland in its Delhi campus. Covering over an area of 1.42 hectares, it is capable of holding and treating two million litres of sewage in a day. The source of raw sewage is from the Krishi Kunj Colony adjoining IARI's campus. The treated wastewater is used for the agricultural purpose. The one time construction cost incurred was Rs 1.4 crore, the wetland consists of three treatment tanks/ cells and one treated-water holding tank.

Wastewater Treatment Process:-
Raw sewage collected from the Krishi Kunj Colony enters into one sump where all the coarse particles are settle down. The wastewater is then pumped into the second sump for additional sedimentation process. For overcome the clogging problems all the sumps were cleaned periodically. After that all the wastewater enters towards grit chamber which have broken pieces of bricks to eliminate any floating matter, finally it goes to the wetland beds. The wastewaters in the CW beds are retained for 2.2 days. Each bed is covered with 60 cm thick layer of stones, on which plant species such as *Phragmites, Typha* and *Acorus* are planted. The final treated water is collected in the holding tank, and distributed through a riser pipe to IARI's fields.

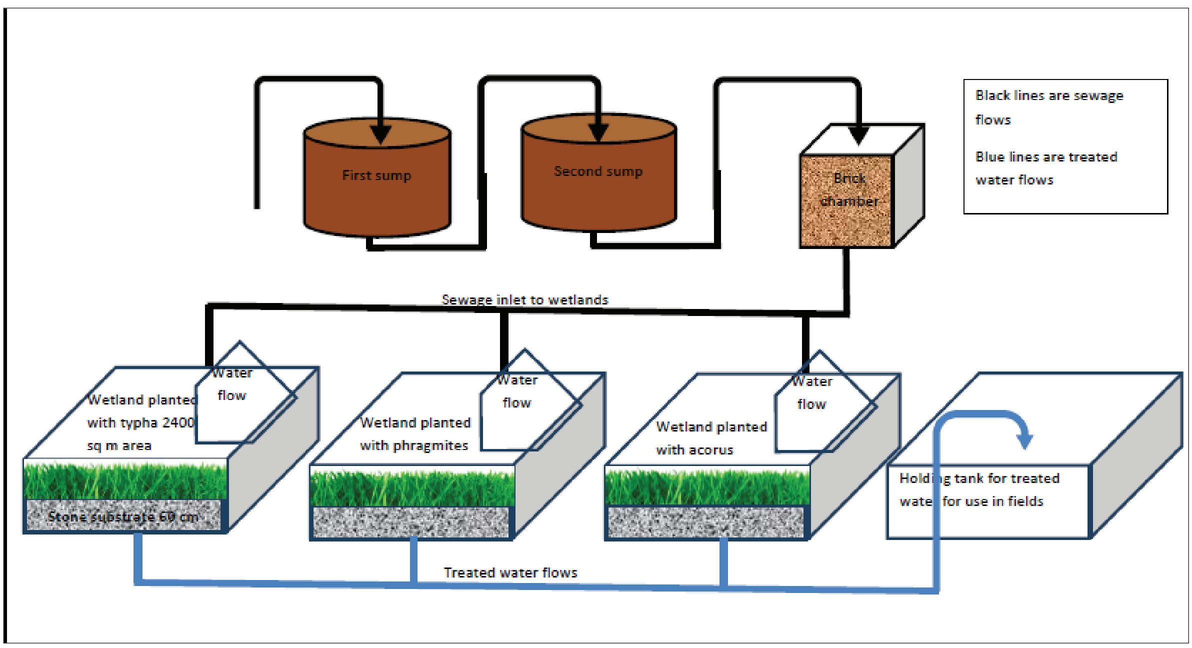


Figure 35: Layout Plan of 2 MLD Constructed Wetland

CW system Performance

The analysis results showed that the plants works efficiently and gives high quality treated water which is reused for the agricultural purpose within the premises. It is noted that CW system is highly effective in reducing TSS and BOD .

BOD 460 -100 mg L^{-1}; TSS 220 -2.2 mg L^{-1}; NO_3-N 86-50 mg L^{-1} ; PO_4-P 69-26 mg L^{-1} at the inlet and outlet zones respectively. The unplanted tanks work as a control system. The plants not only remove pollutants but also aid in oxygenation through their roots

CASE STUDY ## 6

CONSTRUCTED WETLAND SYSTEM TO TREAT WASTEWATER AT INDIAN INSTITUTE OF TECHNOLOGY, POWAI, MUMBAI

The Horizontal Subsurface flow Constructed wetland system is located next to Lake Powai in an area of 400 m^2. The CW system is operated within the campus of the IIT Powai, Mumbai, about 1.25 km away from CESE building. It has a designed capacity of 25 KLD, implemented by Indian Institute of technology, Mumbai & Centre for Environment Science and Engineering (CESE). Starts functioning since November 2013. During construction phase the one time capital cost incurred was 10 Lakhs (INR) and the operation and maintenance cost about 1.2 Lakhs. The main objective of the project is to define the effectiveness of the constructed wetland technology for the treatment of sewage.

Design Configuration of the CW system

Primarily the raw sewage is discharge into primary settling tank for the purpose of primary treatment followed by planted horizontal flow filter bed (area-400 m^2). The horizontal bed is rectangular in shape where gravel is used as filter media/substrate filled up to the depth of 0.8 m. the inlet and outlets structures are filled through 50-100 mm dia. gravels for the proper drainage of the wastewater. Before the final outlet tank there is provision of water regulation chamber. After collecting the wastewater samples from various monitoring ports its water quality were analyzed.

Conclusion

Analysis results showed positive effects of CW system and it can be grouped efficiently with the tertiary treatment facilities to produce high quality treated water results in recycling for various kind of water operation within the premises. The resulting treated wastewater is discharged into the Powai Lake.

CASE STUDY ## 7

PILOT RURAL HOUSEHOLD SEWAGE WATER TREATMENT SYSTEM AT PANDIT DEEN DAYAL UPADHYAY VILLAGE- FARAH, MATHURA (BY IARI)

Design configuration:-

Capacity: 1500 LPD (4 Households with 4 members)

Design: Batch fed Vertical Sub-surface Flow

HRT: 14.41 hrs (< 1 day)

Land area: 2 sq. meter/ KL

Figure 36:Layout of Pilot Rural Household Sewage Water Treatment System

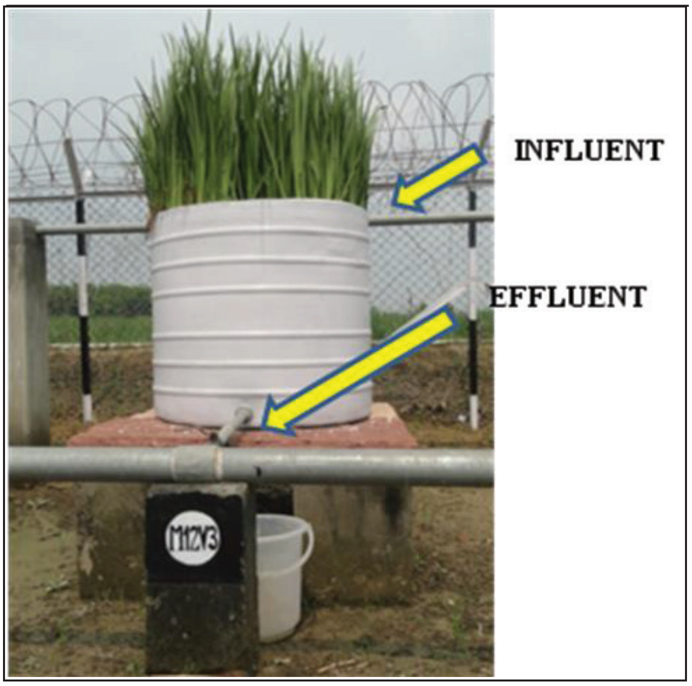
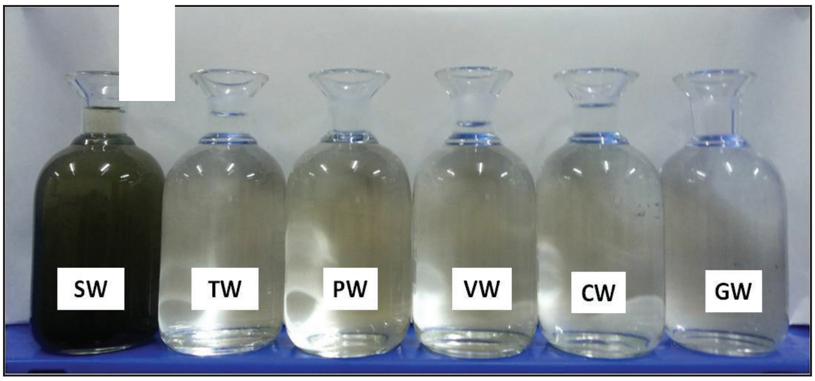


Figure 37 : Showing grown vegetation (*Arundo donax* and *Typha latifolia*) and inlet outlet points across the system



SW: Sewage Water
CW: Unplanted System treated Water
PW: Phragmites treated Water
TW: Typha treated Water
VW: Acorous treated Water
GW: Ground Water

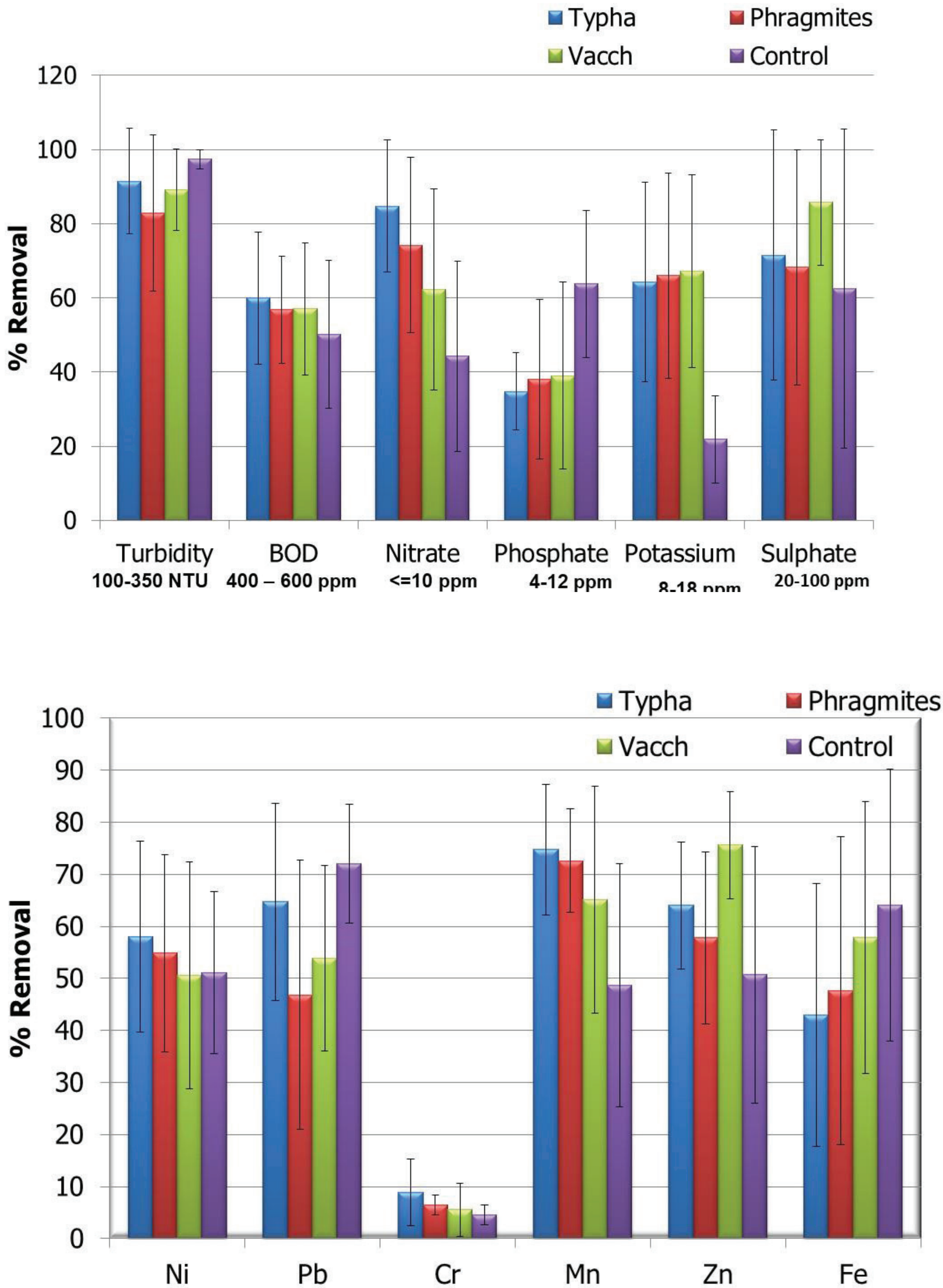
Figure 38: Quality of treated waste water

Results: -

Table 38: Water Quality of Treated Sewage Water a) Microbial count (b) Other wastewater parameters

Samples	Bacterial counts on EMD plates (cfu/100ml)	Faecal Coliforms (cfu/100 ml)	% Pathogen (of total population on EMD agar)
Untreated (Inlet sample)	1.37×10^5	4.6×10^4	33.6%
Treated (Outlet sample)	1.6×10^3	ND	ND

Samples	EC (ds/m)	pH	ORP (mV)	BOD (PPM)	Turbidity (NTU)	NO3 (PPM)	PO4 (PPM)	SO4 (PPM)
Untreated (Inlet sample)	11.8 (12.4)	8.05 (8.37)	-232.3 (-284)	199	274 (458)	10.49 (14.6)	8.55 (13.25)	1222 (1660)
Treated (Outlet sample)	10.7 (9.9) (9% to 20%)	8.03 (7.76)	146.4 (197)	36.7 (82%)	0.00 (100%)	7.07 (5.13) (32-64%)	4.02 (5.13) (53-61%)	1043 (1135) (15-32%)



Key Contaminants:

Turbidity, Organic Load & Pb, Ni, Fe, Zn, Mn

Figure 39: Long Term (2009-2019) Pollutant Reduction Range of (a) Different wastewater parameters (b) Heavy metals for Various Rural Household Models

Scalability

Since the 1950s, CWs have been used effectively to treat different wastewaters with different configurations, scales and designs throughout the world. Existing systems of this type range from those serving single-family dwellings to large-scale municipal systems. Nowadays, constructed wetlands are common alternative treatment systems in Europe in rural areas and over 95% of these wetlands are subsurface flow wetlands. In the following years, the number of these systems is expected to be over 10,000 only in Europe (**Platzer, 2000).** Even though the potential for application of wetland technology in the developing world is enormous, the rate of adoption of wetlands technology for wastewater treatment in those countries has been slow. It has been identified that the current limitations to widespread adoption of CW technology for wastewater treatment in developing countries is due to the fact that they have limited knowledge and experience with CW design and management. Constructed wetlands do not exhibit economies of scale to the same degree that high-rate aerobic treatment plants do. For small plants of up to 500 p.e., constructed wetlands are usually cheaper to build than high-rate aerobic plants but for larger plants, they are usually more expensive in terms of capital costs. Constructed wetlands have significantly lower operation and maintenance costs compared to high-rate aerobic processes for energy use and operator time. For large scale treatment plants of more than 10 000 person equivalents (p.e.) in areas where land is available cheaply, ponds have lower capital costs than constructed wetlands. But there is a range of other aspects which have to be taken into account when making the decision between the two different treatment processes.

Livelihood

Constructed wetlands are essential for humans to live and prosper. They are some of the most important biodiverse areas in the world. More than one billion people depend on wetlands for their living. The use of CWs for wastewater treatment provides many benefits.

- Environmental benefits including adapting to specific site conditions and targeting specific pollutant loads **(California State Water Resources,2002),** provide natural sponges against river flooding, store carbon dioxide to regulate climate change, protecting vital ecosystems such as rivers and lakes, providing wildlife habitat, creating green areas, and eliminating use of chemical products.

- Social benefits include integration in the design of buildings and landscape, leading to society interaction with waste water treatment, increasing awareness and education about water problems, providing great public spaces at low costs, such as outdoor lunch time areas, making them favorably viewed by the general public and regulatory agencies.

- Economic benefits include less construction, operating and maintenance costs. Construction costs are 1/3 the costs of a conventional wastewater treatment plant while maintenance costs are ¼ +/_ of WWTP. They are most durable as they have no or few moving parts resulting in longer life cycles of about 15 years minimum **(Nelson,2014)**

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9. DESIGN EXAMPLES (Dotro *et al.*, 2017)

1# For Horizontal Constructed Wetland

HF constructed wetland for a single-family home (5 PE) in a temperate climate. BOD_5 effluent target is 30 mg/L.

Pre treatment facility:-

- ✓ A septic tank for pre-treatment, and that the septic tank removes 1/3 of the BOD_5 load.
- ✓ An average per capita wastewater generation of 150 L/d and a per capita BOD_5 load of 60 g per person and day **(DWA, 2017).**

Methods adopted for the designing consideration:-

- ➢ Rule-of-thumb
- ➢ Regression equation
- ➢ Plug-flow *k-C**
- ➢ Mass loading charts

Calculation

Inflow, Q_1= 5 PE x 150 L/PE. d x 1 m^3 /1000 L = 0.75 m^3 d^{-1}

Mass Load Influent, M_1= 5 PE x 60 g BOD /PE. d x 2/3 = 200 g BOD/day

Concentration Influent, C_1= M_1/Q_1 = 200 g BOD/ 0.75 m^3 d^{-1} = 266 g BOD/m^3/day = 266 mg BOD/L

Rule-of-thumb

Choose a rule-of-thumb guideline. For example, according to the Danish guideline **(Brix and Johansen, 2004)** HF wetlands are sized at 5 m^2/PE.

$A = 5 \text{ PE} \times 5 \text{ m}^2/\text{PE} = 25 \text{ m}^2$

According to the Danish guideline, HF wetlands sized at 5 m^2/PE are expected to achieve 90% reduction in BOD_5, which should result in an effluent concentration close to 25 mg/L (0.1 × 266 mg/L = 27 mg/L). Note that any further increase in the influent water quality (e.g., septic tank effluent) would result in an increase in expected effluent BOD_5 concentrations.

A length-to-width ratio between 2:1 and 4:1 is common for HF wetlands. Choosing a length-to-width ratio of three yields the following calculation:

$$A = L \times W$$

$$\frac{L}{W} = 3$$

Solve for w:

$$w = \sqrt{\frac{A}{3}} = \sqrt{\frac{25}{3}} = 2.9 \text{ m}$$

Choosing a length-to-width ratio of three results in a wetland that is 2.9 m wide by 8.7 m long (total area of 25.2 m^2).

These dimensions, although exact, are not practical to use in the field. Engineering designs must take into consideration the constructability of the system. Small treatment wetland systems, especially those built for individual homes, are often constructed by homeowners themselves or small contractors. Choosing wetland dimensions that are easy to measure and implement in the field is an important aspect of the design process. Choosing a wetland of 3.0 m wide by 8.5 m long (total area of 25.5 m^2) results in a length-to-width ratio of 2:8, and system dimensions that are much easier to measure and implement during construction. When adjusting the width of the wetland bed, it is generally better to increase the width rather than to decrease it. Decreasing the width will increase the overall cross-sectional organic loading rate and increase chances of clogging. Typical saturated depth for a HF wetland treating septic tank effluent is 0.5 m.

Regression equations

An example regression equation for BOD_5 removal in HF wetlands is:

$C_o = (0.11 \times C_i) + 1.87$ (with the constraints $1 < C_i < 330$ and $1 < C_o < 50$). Expected BOD_5 effluent concentration is then:

$(0.11 \times 266 \text{ mg/L}) + 1.87 = 31 \text{ mg/L}$

Such a system, in principle, should produce an effluent BOD_5 concentration slightly higher than 30 mg/L, but the calculation does not produce a recommended area for the wetland.

Plug-flow k-C*

Step 1. Select k-rate

Locate the appropriate values for k_A:

$k_A = 25$ m/yr

Step 2. Check input parameters and unit conversions. Calculate minimum required area

As with any engineering equation, it is extremely important to check that the unit labels are consistent. Failing to convert Q_i (which is often given in L/d) and k_A (which is often given in m/yr) into compatible units will yield incorrect calculations.

The following values are converted to correct units where necessary –

Inflow, Q1= 5 PE x 150 L/PE.d x 1m^3/1000L = 0.75 m3 d-1 x 365 d/ 1 yr = 273.75 m^3 yr^{-1}

Concentration In, C1 = M_1/Q_1 = (200 g BOD/d) / 0.75 m^3 d^{-1} = 266 mg BOD L^{-1}

Background concentration, C*= 10 mg L^{-1}

First order areal rate coefficient, K_A= 25 m yr^{-1}

$$A = -\frac{Q_i}{k_A}\ln\left(\frac{C_o - C^*}{C_i - C^*}\right) = -\frac{273.75\,\frac{m^3}{yr}}{25\,\frac{m}{yr}}\ln\left(\frac{30\,\frac{mg}{L} - 10\,\frac{mg}{L}}{266\,\frac{mg}{L} - 10\,\frac{mg}{L}}\right) = 27.9\ m^2$$

Step 3. Choose wetland dimensions

A length-to-width ratio between 2:1 and 4:1 is common for HF wetlands. Choosing a length-to-width ratio of three yields the following calculation:

A= L x W

$$\frac{L}{W} = 3$$

Solve for w:

$$w = \sqrt{\frac{A}{3}} = \sqrt{\frac{27.9}{3}} = 3.0\ m$$

Choosing a length-to-width ratio of three results in a wetland that is 3 m wide by 9.3 m long (total area of 27.9 m^2). These dimensions, although exact, are not practical to use in the field. Choosing a wetland of 3.0 m wide by 10.0 m long (total area of 30 m^2) results in a length-to-width ratio of 3.3, and system dimensions that are much easier to measure and implement during construction. Typical saturated depth for a HF wetland treating septic tank effluent is 0.5 m.

Step 4. Check cross-sectional organic loading rate

Clogging is a commonly cited problem in HF wetlands, and can occur when large length-to-width ratios are chosen. Wallace and Knight (2006) recommend a maximum cross-sectional organic loading rate of 250 g $BOD_5/m^2 \cdot d$.

The cross-sectional area of the wetland is:

3 m x 0.5 m = 1.5 m^2

The influent BOD_5 loading to the wetland is 200 g/d (calculated earlier). The cross sectional organic loading is therefore:

200g BOD d^{-1} / 1.5 m^2 = 133 g BOD / m^2.d

This is well below the recommended maximum of 250 $g/m^2 \cdot d$, so the wetland is not likely to clog on a medium term.

Mass loading charts

Loading charts can give an indication for effluent concentration based on influent mass loading.

Step 1. Choose desired confidence interval

Choose desired confidence interval on chart (50%, 75% or 90%). A full collection of charts is provided in **Wallace and Knight (2006).** Locate corresponding effluent concentration and corresponding influent mass loading rate.

With mass loading charts, choosing a confidence interval of 50% indicates that five of every ten effluent samples will have an effluent concentration below the desired outlet concentration, as long as the wetland being sized has similar wastewater characteristics and is located in similar (temperate) climate conditions. New designs with particularly strong or weak wastewater, or those located in extreme climates, should not be made using the mass loading chart approach.

In this example, assuming similar wastewater and climate conditions, the 50% bound line crosses 30 mg/L effluent concentration at an influent loading of approximately 90 kg/ha·d

Step 2. Calculate required wetland area
Areal mass loading rate (from mass loading chart)

90 kg/ha.d x 1000 g/1 kg x 1 Ha /10,000 m^2 = 9g/m^2.d

Mass BOD_5 load into the wetland (from assumptions) = 200 g BOD_5/d

Total daily BOD_5 load divided by the mass load of BOD_5 into wetland equals the wetland area:

A= (200 g BOD d^{-1})/ 9g m^{-2}. d^{-1} = 22.2 m^2

Note that the determination of wetland area is highly dependent on the desired effluent concentration. If an effluent concentration of 20 mg/L BOD_5 is desired, the required area (based on the information in the provided chart) would be approximately 80 m^2.

Note that HF wetlands treating septic tank effluent generally do not produce very low effluent concentrations, which is why the confidence intervals of 75% and 90% in this example either result in a very large calculated area or cannot be used for design purposes.

Step 3. Choose wetland dimensions
A length-to-width ratio between 2:1 and 4:1 is common for HF wetlands. Choosing a length-to-width ratio of three yields the following calculation:
Knowing:
A= L x W

$$\frac{L}{W} = 3$$

Solve for W:

$$w = \sqrt{\frac{A}{3}} = \sqrt{\frac{22.2}{3}} = 2.7 \text{ m}$$

Choosing a length-to-width ratio of three results in a wetland that is 2.7 m wide by 8.1 m long (total area of 21.9 m^2).

Choosing a wetland of 3.0 m wide by 8.0 m long (total area of 24 m^2) results in a length-to-width ratio of 2.7, and system dimensions that are much easier to measure and implement during construction. Typical saturated depth for a HF wetland treating septic tank effluent is 0.5 m.

Step 4. Check cross-sectional organic loading rate

Clogging is a commonly cited problem in HF wetlands, and can occur when large length-to-width ratios are chosen. **Wallace and Knight (2006)** recommend a maximum cross-sectional organic loading rate of 250 g $BOD_5/m^2\cdot d$

The cross-sectional area of the wetland is:

$3.0\ m \times 0.5\ m = 1.5\ m^2$

The influent BOD_5 loading to the wetland is 200 g/d (calculated earlier). The cross-sectional organic loading is therefore:

$200\ g\ BOD\ d^{-1} / 1.5\ m^2 = 133\ g\ BOD/\ m^2.d$

This is well below the recommended maximum of 250 g $BOD_5/m^2\cdot d$, so the wetland is not likely to clog on the medium term.

Summary

Each design approach provides a different result for the HF wetland area listed below:

Table 39 : Summary of calculated HF wetland area for a single-family home (5 PE) in a temperate climate

Method	Will the wetland produce an effluent concentration of 30 mg/L?	Minimum calculated wetland area (m^2)	Minimum practical wetland area (m^2)
Rule-of-thumb	Yes	25.0	25.5
Regression equation	No	–	–
Plug-flow *k-C**	Yes	27.9	30.0
Mass loading chart	Yes	22.2	24.0

Note that the use of regression equations cannot always provide enough information for wetland sizing. The rule-of-thumb approach is arguably the easiest to use, but care must be taken that the new design falls within the assumptions that were used to create the sizing recommendation. The plug-flow *k-C** approach, which is often reported in the literature, is no longer recommended for use in design.

In this example, the Mass Loading Chart provides the least conservative result, which is half the area from the *P-k-C** approach. For small-scale systems, especially at the household level, a slightly oversized system will be able to better cope with fluctuations in influent flow and load. However, as the number of homes increases, the fluctuations in flow and load will decrease, and over sizing a system can inflate construction costs to the point where a treatment wetland is no longer a cost- effective treatment option.

In this example, the only target pollutant was BOD_5 and is thus the simplest scenario for design. In practice, most treatment systems have multiple water quality targets (e.g., BOD_5, TSS, TN). In such cases, the calculations must be repeated for each pollutant. The limiting factor will result in the largest system footprint, and this value should be selected for design to ensure the treatment system meets all water quality targets.

2# Horizontal Constructed Wetland for Small Community (100 PE)

Pre treatment facility:-

- BOD_5 effluent target is 30 mg/L.
- An UASB reactor is used for pre-treatment, and the UASB reactor removes two-thirds of the BOD_5 load (~ 67%, typical removal efficiency of UASB reactors (von Sperling, 2007a).
- Because the UASB reactor provides a biological treatment (even though not a very efficient one), the wetland will receive an influent from a secondary treatment.
- Assume an average per capita wastewater generation of 120 L/d and a per capita BOD_5 load of 50 g per person and day.

Perform the design according to the *P-k-C** method, which is currently the preferred procedure. Summary of wastewater generated (influent to UASB reactor):

Inflow, Q1= 100 PE x 120 L/PE.d x $1m^3$/1000 L = 12 m^3 d-1
Mass Load In, M_1 = 100 PE x 50 g BOD/PE.d = 5000 g BOD L^{-1}
Concentration In, C1 = M_1/Q_1 = (5000 g BOD/d) / 12 m^3 d^{-1} = 417 g BOD m^{-3} = 417 mg BOD L^{-1}

Summary of inputs to the HF wetland (effluent from UASB reactor):

Inflow, Q_1=12 m^3 d^{-1}

Mass Load In, M_1 =5000 g BOD/d x (1- 2/3) = 1667 g BOD d^{-1}

Concentration In, $C_1 = M_1/Q_1$ = (1667 g BOD d^{-1}) / 12 m^3 d^{-1}= 139 g BOD/ m^3 =139 mg BOD L^{-1}

Step 1. Select k-rate

Locate the appropriate values for k_A:

k_A value for treatment of primary effluents is 25 m/yr and for secondary effluents is 37 m/yr . Because the treatment provided by the UASB reactor is secondary, but not very efficient, an intermediate value of k_A = 32 m/yr (20ºC) will be adopted in this design.

Step 2. Check input parameters and unit conversions. Calculate minimum required area

As with any engineering equation, it is extremely important to check that the unit labels are consistent. Failing to convert Q (which is often given in L/d) and k_A (which is often given in m/yr) into compatible units will yield incorrect calculations. The following values are converted to correct units (where necessary) and inserted into Equation followed.

C1=139 mg L^{-1} (calculated earlier)

$C0 = 30$ mg L^{-1} (given)

$C^* = 7$ mg L^{-1} (values in between 5mg L-1 [treatment of secondary effluent] and 10 mg L-1 [treatment of primary effluent]

$P = 3$

$Q_1 = 12\ m^3\ d^{-1} \times 365\ d\ yr^{-1} = 4380\ m^3\ yr^{-3}$

$K_A = 32\ m\ yr^{-1}$

$$A = \frac{PQ_i}{k_A}\left(\left(\frac{C_i - C^*}{C_o - C^*}\right)^{\frac{1}{P}} - 1\right) = \frac{3 \times 4380\ \frac{m^3}{yr}}{32\ \frac{m}{yr}}\left(\left(\frac{139\frac{mg}{L} - 7\frac{mg}{L}}{30\frac{mg}{L} - 7\frac{mg}{L}}\right)^{\frac{1}{3}} - 1\right) = 325\ m^2$$

Step 3. Choose wetland dimensions

In order to give operational flexibility, two wetlands in parallel will be adopted (n=2). Therefore, the area of each unit will be:

$$A_1 = A_2 = \frac{A_{Total}}{2} = \frac{325\ m^2}{2} = 162\ m^2$$

A length-to-width ratio between 2:1 and 4:1 is common for HF wetlands. Choosing a length-to-width ratio of l/w=3 yields the following calculation:

Knowing:

$$A = l \times w$$

$$\frac{l}{w} = 3$$

Solve for w:

$$w = \sqrt{\frac{A}{3}} = \sqrt{\frac{162}{3}} = 7.3\ m$$

Therefore, the length is $l = 3 \times w = 3 \times 7.3\ m = 21.9\ m$.

Therefore, the length is l =3 * w = 3 *7.3 m =21.9 m.

Adopting round values of length l=22.0 m and width w=8.0 m will lead to an area of 176 m^2 per unit, and a total area of 2x176 m^2 = 352 m^2.

This value of 352 m^2, for a population of 100 PE, corresponds to a net per capita land requirement of 352/100 = 3.5 m^2/PE.

The depth for the liquid will be adopted as h=0.5 m, which is a typical saturated depth for a HF wetland. With these dimensions, the saturated volume (media and liquid) will be:

Each unit: $V1 = V2 = l \times w \times h = 22\ m \times 8\ m \times 0.5\ m = 88\ m^3$

Total: $VTotal = V1 + V2 = 2 \times 88\ m^3 = 176\ m^3$

The total media bed volume is comprised by the saturated volume plus the height above the liquid level. Adopting an additional unsaturated media depth of 0.10 m will lead to a total bed height of 0.5+0.1=0.6 m. The total media bed volume of both units will be 2 * (22 m * 8 m * 0.6 m) = 211 m³.

Step 4. Check HRT and surface loading rates

Assuming a porosity of $\varepsilon = 0.35$, the theoretical HRT will be :

$$\tau = \frac{V \times \varepsilon}{12\ \mathrm{m^3}/d} = \frac{176\ \mathrm{m^3} \times 0.35}{12\ \mathrm{m^3}/d} = 5.1\ \mathrm{d}$$

The resulting surface HLR *q* will be :

$$q = \frac{Q_i}{A} = \frac{12\ \mathrm{m^3/d}}{352\ \mathrm{m^2}} = 0.034 \frac{\mathrm{m^3}}{\mathrm{m^2 \cdot d}} = 34\ \frac{\mathrm{mm}}{\mathrm{d}}$$

The surface organic loading rate will be:

$$\frac{M_i}{A} = \frac{1667\ \mathrm{g\ BOD/d}}{352\ \mathrm{m^2}} = 4.7 \frac{\mathrm{g\ BOD}}{\mathrm{m^2 \cdot d}}$$

All the loading values are within reasonable values, according to the literature. However, it is known that in several warm-climate locations, HF wetlands perform well with higher loading rates compared with temperate climates, that is, with smaller volumes and areas. The designer may consider that these calculations with the *P-k-C** method have been too conservative for the climatic conditions under study, since most experience with its use lies in temperate climates.

To gain more insight and verify the resulting surface area, the design based on the mass loading charts may be used, as it was shown to be the least conservative of the approaches. For an effluent BOD_5 of 30 mg/L, the recommended organic loading rate for a 50th percentile is 90 kg BOD_5/(ha·d) or 9.0 g $BOD_5/(m^2 \cdot d)$. This is almost double the loading rate that resulted from the *P-k-C** method (4.7 g $BOD_5/(m^2 \cdot d)$), implying that the surface area could be halved. On the other hand, if the 75th percentile is considered in the design, the loading rate would be substantially smaller than the one calculated from the *P-k-C** model at 1.5 g $BOD_5/(m^2 \cdot d)$. Coming back to the 50th percentile, the loading rate calculated from the *P-k-C** model of 4.7 g $BOD_5/(m^2 \cdot d)$ corresponds to an effluent BOD_5 concentration of 25 mg/L. Small differences in the desired effluent quality may have a considerable impact on the required surface area.

This uncertainty is typical in design. The designer must reflect on these implications and decide on the adoption of an approach that delivers the right balance of safety and feasibility. This is also an incentive to the development of design guidelines that cater for the specific conditions of warm climates. For the sake of this example, the dimensions calculated with the *P-k-C** method will be used.

Step 5. Check cross-sectional organic loading rate

Clogging is a commonly cited problem in HF wetlands, and can occur when length-to-width ratios that are too large are chosen. Wallace and Knight (2006) recommend a maximum cross-sectional organic loading rate of 250 g $BOD_5/(m^2 \cdot d)$.

The cross-sectional area of each wetland unit is:

8 m □ 0.5 m = 4 m^2

The influent BOD_5 loading to the wetland system is 1667 g BOD_5/d (calculated earlier), or, for each unit, M_i/n = 1.667/2 = 834 g BOD_5/d per wetland.

The cross-sectional organic loading is therefore:

$$834\ \frac{\text{g BOD}}{\text{d}} \div 4\ \text{m}^2 = 209\ \frac{\text{g BOD}}{\text{m}^2 \cdot \text{d}}$$

This is below the recommended maximum of 250 g BOD_5 $(m^2 \cdot d)$, so the wetland is not likely to clog in the medium term.

Step 6. Specify other dimensions and details in the wetland units

In the inlet and outlet zones, a buffer zone with larger stones to allow better distribution of the influent and collection of the effluent will be provided. Usual values are between 0.5 and 1.0 m of length. In the present design, a value of 0.7 m will be adopted. The size of the stones in these inlet and outlet zones may be between 10 and 20 cm.

The additional bed volume associated with these zones is:

Inlet zone: $V = l \times w \times h = 0.7\ \text{m} \times 8\ \text{m} \times 0.6\ \text{m} = 3.4\ \text{m}^3$

Outlet zone: $V = l \times w \times h = 0.7\ \text{m} \times 8\ \text{m} \times 0.6\ \text{m} = 3.4\ \text{m}^3$

The grain size in the filter bed varies; according to different design criteri. In the present case, in order to further reduce risks of clogging, a diameter in the upper bound of the values presented in Table 32 will be adopted: effective diameter d_{10} = 16 mm.

The dimensions of the basin must be such as to accommodate the bed and a freeboard above the top surface of the bed. In this example, a value of 0.2 m is adopted. Therefore, the total height of the basin is 0.8 m, of which 0.6 m is for the bed (being 0.5 m saturated and 0.1 m non-saturated) and 0.2 m is for the freeboard.

The dimensions calculated are for rectangular longitudinal and cross sections. The wetland cells may be built with sloped banks with compacted soil of good quality, to facilitate construction. In the case of units with sloped banks, the dimensions provided before are for the bottom of the saturated bed. Note that some designers prefer to use the top of the gravel bed for the length specification, as this is what will be visible after the wetland is built. However, this will mean the treatment area and treatment volume for the system will be smaller than the design specifications, as the bottom of the bed will effectively be shorter than the calculated value. For this reason, some designers (and what is recommended in this volume) apply the calculated length for the treatment area at the bottom of the cell, resulting in a longer bed when looking at the plan area once the system is built.

A longitudinal slope of the bottom level, between 0.5 and 1.0%, towards the outlet end may be adopted. This can be used to facilitate emptying of the bed, but requires additional work. In this example, no slope of the bottom was included. The wetland would be planted with a species well-adapted to the climatic conditions of the region. This can be checked in various literature sources from academic journals or books (e.g**., Kadlec and Wallace, 2009).** For simplicity, *Typha sp.* is selected here as it is widespread in the warm climates of South America.

Step 7. Make schematic drawings of the system

The schematic arrangement of the system in plan view is presented in Figure 37, and a schematic longitudinal section for one unit is presented in Figure 38. Both drawings are not to scale. The dimensions length *l*=22 m and width *w*=8 m are measured at the bottom of the wetlands (conservative approach). With the side-slope this then gives 23.6 m × 9.6 m as measured on the top.

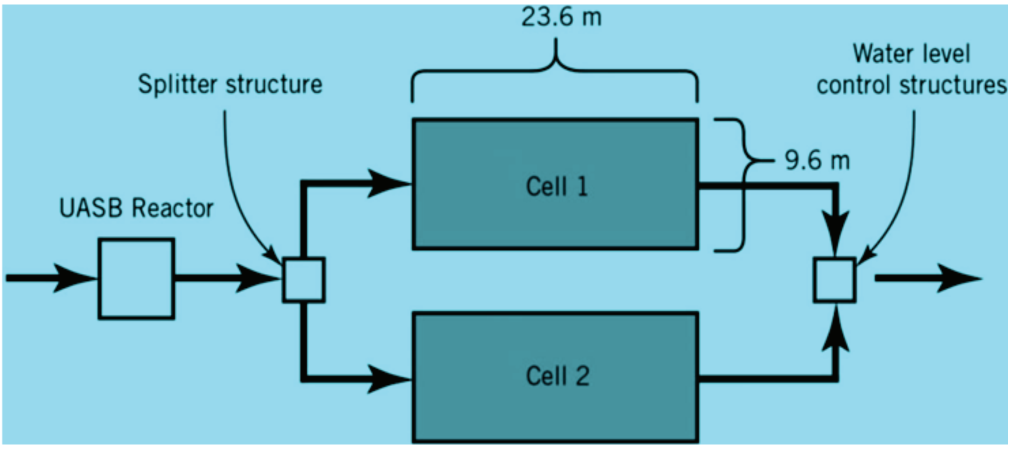

Figure. 40: Schematic arrangement of the system (not to scale).

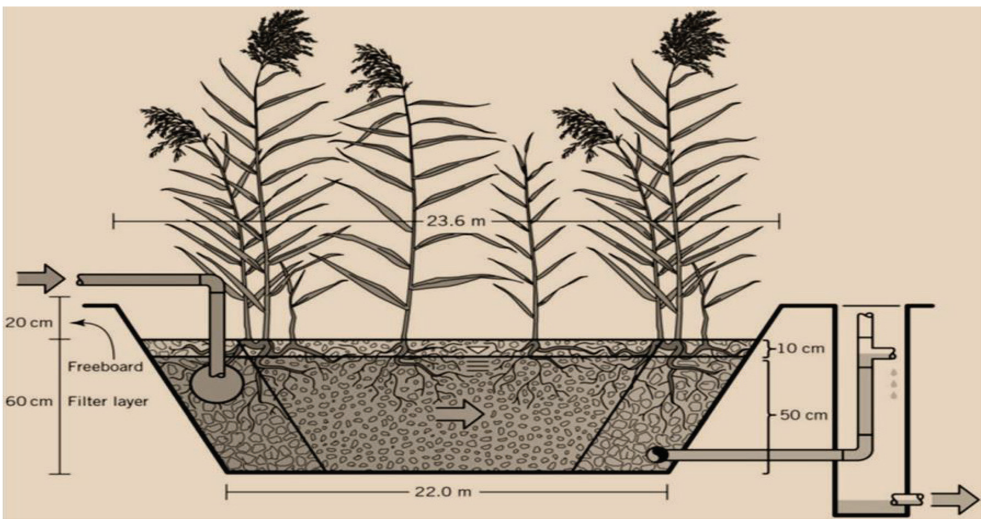

Figure. 41: Longitudinal section of one unit (not to scale).

3# Vertical Constructed Wetland for Small Community (50 PE)

The following simple example shows the design of a VF wetland in a temperate climate. It is estimated that the VF wetland shall treat household wastewater of a small settlement with 50 PE, the average flow is 150 L/PE·d. Pollutant per capita generation rates of 60 g BOD_5, 120 g COD and 11 g TKN per capita and day are assumed **(DWA, 2017; ÖNORM, 2009).**

Step 1. Define influent flow and pollutant concentrations

$$\text{Inflow, } Q_i = 50\ \text{PE} \times 150 \frac{\text{L}}{\text{PE}\cdot\text{d}} \times \frac{1\ \text{m}^3}{1000\ \text{L}} = 7.5\ \frac{\text{m}^3}{\text{d}}$$

$$\text{COD Concentration (raw wastewater)} = 120\ \frac{\text{g COD}}{\text{PE}\cdot\text{d}} \div 150\ \frac{\text{L}}{\text{PE}\cdot\text{d}} \times \frac{1\ \text{mg}}{1000\ \text{g}} = 800\ \frac{\text{mg COD}}{\text{L}}$$

$$\text{TKN Concentration (raw wastewater)} = 11\ \frac{\text{g TKN}}{\text{PE}\cdot\text{d}} \div 150\ \frac{\text{L}}{\text{PE}\cdot\text{d}} \times \frac{1\ \text{mg}}{1000\ \text{g}} = 73.3\ \frac{\text{mg TKN}}{\text{L}}$$

Step 2. Design the three-chamber septic tank

According to ÖNORM B 2505 (2009) for populations greater than 50 PE, septic tanks are sized at 0.25 m^3/PE, with a minimum per capita tank surface area of 0.06 m^3/PE. The first chamber of the tank should comprise of 50% of the septic tank volume, whereas the second and third chambers should each be comprised of 25% of the total tank volume. The third chamber of the septic tank functions as the dosing tank for the wetland. It is assumed that one-third of the COD is removed in the septic tank (DWA, 2017).

$$\text{Calculate minimum tank volume: } 50\ \text{PE} \times 0.25\ \frac{\text{m}^3}{\text{PE}} = 12.5\ \text{m}^3$$

$$\text{Selected septic tank volume} = 13\ \text{m}^3$$

$$\text{Calculate minimum surface area of septic tank: } 50\ \text{PE} \times 0.06\ \frac{\text{m}^2}{\text{PE}} = 3\ \text{m}^2$$

$$\text{Selected surface area of septic tank} = 3.5\ \text{m}^2$$

$$\text{Calculate depth of septic tank: } \frac{13\ \text{m}^3}{3.5\ \text{m}^2} = 3.7\ \text{m}$$

$$\text{Hydraulic retention time in first and second septic tank chamber: } \frac{13\ \text{m}^3 \times 0.75}{7.5 \frac{\text{m}^3}{\text{d}}} = 1.3\ \text{d}$$

$$\text{COD Concentration (post-septic tank)} = 800\ \frac{\text{mg COD}}{\text{L}} \times \frac{2}{3} = 533\ \frac{\text{mg COD}}{\text{L}}$$

Step 3. Design the VF wetland

Two different design approaches are shown. The first uses sand with a grain size of – 4 mm (d_{10} = 0.3 mm; according to ÖNORM, 2009). The second approach uses coarse sand with grain size 2 – 3 mm (such as the first stage according to **Langergraber *et al.*, 2011**). The key parameters of the two designs are shown in Table 44.

Summary

In general, the coarser the filter media used for the main layer of the VF bed:

- The higher the acceptable hydraulic and organic loads.

- The smaller the required surface area of the VF bed.
- The smaller the single loading of the VF bed.
- The more opening holes are required to achieve good distribution of the wastewater on the surface.
- However, less pollutant removal (TSS, BOD_5, COD and NH_4-N) can be expected.

Table 40: Key design parameters and expected effluent concentrations of two different VF wetlands.

Main Layer	Sand (0.06- 4.0 mm)	Coarse Sand (2-3 mm)
Surface Area		
Maximum areal organic loading rate (g COD/m^2.d)	20	80
Organic Load (g COD/d) [a]	4000	4000
Required surface area (m^2) [b]	200	50
Wetland cell configuration (m)	10 x 20	5 x 10
Intermittent loading		
Loading intervals (hours)	6	2
Volume of single dose (m^3) [c]	1.875	0.625
Surface area of intermittent loading tank (m^2) [d]	0.875	0.875
Height difference in intermittent loading tank (m) [e]	2.2	0.70
Distribution pipes		
Minimum one opening per	2 m^2	1 m^2
Expected effluent concentration ($T \geq 10^0C$) [f]		
BOD_5 (mg/L)	<3	30-40
COD (mg/L)	<20	80-100
TSS (mg/L)	<5	10-20
NH4-N (mg/L)	<1	10-20

[a] Organic load: Q_i. COD effluent conscentration from septic tank

[b] Required surface area : Organic load/Maximum organic loading rate

[c] Amount of a single load: Q_i/(24 hours/Loading interval)

[d] Surface area of intermittent loading tank: Q_i/(24 hours/Loading interval)

[e] Height difference in intermittent loading tank: Volume of a single dose/Surface area of dosing chamber

[f] **Langergraber *et al.*, (2007)** for main layer of sand with gravel size 0.06 – 4.0 mm and **Langergraber *et al.*, (2008)** for main layer of coarse sand with grain size 2-3 mm, respectively.

References:

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10. EFFLUENT DISCHARGE STANDARDS IN INDIA

(A). In India, Central Pollution Control Board (CPCB) sets standards for discharge of wastewater to the surrounding area including land and water bodies. Thus a constructed wetland system should be designed with proper care so that it could produce the effluent that meets all the discharge standards. The discharge standards of CPCB are as follows:

Table 41: General standards for discharge of environmental pollutants in India

S. No	Parameters	Standards		
		Inland Surface Water	Public Sewers	Land For Irrigation
1.	Suspended solids mg/l, Max	100	600	200
2.	pH Value	5.5 to 9.0	5.5 to 9.0	5.5 to 9.0
3.	Temperature	shall not exceed 5°C above the receiving water temperature	-	-
4.	Ammonical nitrogen (as N), mg/l Max	50	50	-
5.	Total Kjeldahl Nitrogen (as NH3) mg/l, Max.	100	-	-
6.	Free Ammonia (as NH3) mg/l, Max.	5.0	-	-
7.	Biochemical Oxygen demand 1[3 days at 27oC] mg/l max.	10*	350	100
8.	Chemical Oxygen Demand, mg/l, max.	250	-	-
9.	Dissolved Phosphates (as P), mg/l Max	5.0	-	-
10.	Nitrate – nitrogen	10		

*Revised value for BOD discharge

(C) Recycling and reuse of sewage (as per CPHEEO)

With 80 countries and 40% of the world's population facing chronic water problems and with the demand for water doubling every two decades, recycling and reuse of sewage is important. The largest source of reuse resides in agriculture and the equally largest misplaced resource is sewage in the habitations. In the "Handbook on Service Level Benchmarking" by MoUD, reuse and recycling of sewage is defined as the percentage of sewage recycled or reused after appropriate treatment in gardens and parks, irrigation, etc. and, is to be at least 20% to begin with. The objective of this chapter is to bring out guiding principles for practice in India. In India treated sewage is being used for a variety of applications such as (a) Farm Forestry, (b) Horticulture, (c) Toilet flushing, (d) Industrial use as in non-human contact cooling towers,(e) Fish culture and (f) Indirect and incidental uses.

Overview of Current Practices in the World

The use of treated sewage elsewhere in the world is listed herein –

a) **Agriculture**: It is used for irrigation in certain places in Africa, Israel, Mexico and Kuwait.

b) **Farm Forestry**: Treated sewage is used for watering urban forests, public gardens, trees, shrubs and grassed areas along roadways in certain places in Egypt, Abu Dhabi, Woodburn in Oregon USA. It is also used for timber plantation in Widebay Water Corporation in Queensland, Australia. It is used for alfalfa plantation in Albirch Palestine.

c) **Horticulture:** Certain places in Elpaso in Texas, Durbin Creek in Western California in USA.

d) **Toilet flushing**: Certain locations in Chiba Prefecture, Kobe City, and Fukuoka City and Tokyo Metropolitan in Japan.

e) **Industrial and commercial**: essentially used for cooling purposes in Sakaihama Treated Wastewater Supply Project, Japan, Bethlehem Steel mills, USA. Sewage reclaimed as high quality water is supplied to Mondi Paper Mill and SAPREF Refinery in Durban, South Africa. Landscape and golf course irrigation in Hawai,

f) **Fish culture**: It is used in fish hatcheries / fish ponds in Vietnam and in Bangladesh

g) **Groundwater recharge**: Orlando and Orange County Florida, Orange County California, Phoenix (Arizona), Santa Rosa (California) Recharge Project all in USA.

h) **Indirect recharge of impoundments**: Restoration of Meguro River in Japan, NEWater project in Singapore, Windhoek in Namibia, Berlin in Germany

i) **Other uses**: Coach cleaning, subway washing and water for building construction is being practised in Jungnang, Nanji, Tancheon, Seonam in Seoul and treated sewage sprinkled on the water retentive pavement that can store water inside paving material at Shiodome Land Readjustment District (Shio Site) in Tokyo and this reduces the surface temperature.

Standard of Treated Sewage and its Uses

In addition to the guiding principles mentioned earlier the recommended treated sewage quality as in **Table** 42 is proposed to be achieved for the stated uses. Hence, in order to achieve the desired water quality, excess chlorination, granular activated carbon adsorption / ozonation and/or various kind of filtration including membrane are recommended. For recreational impoundments for non-human contact, residual chlorine is not required so as to protect aquatic species of flora and fauna.

Table 42.: Recommended norms of treated sewage quality for specified activities at point of usage

S. No	Parameter	Toilet Flushing	Fire Protection	Vehicle exterior washing	Non-contact impoundments	Landscaping, agriculture and horticulture			
						Horticulture Golf Course	Non Edible Crops	Crops which are eaten	
								Raw	Cooked
1	Turbidity (NTU)	<2	<2	<2	<2	<2	AA	<2	AA
2	Suspended Solids	Nil	Nil	Nil	Nil	Nil	30		30
3	TDS	2100							
4	pH	6.5 to 8.3							
5	Temperature °C	Ambient							
6	Oil and Grease	10	Nil	Nil	Nil	10	10	Nil	Nil
7	Minimum Residual Chlorine	1	1	1	0.5	1	Nil	Nil	Nil
8	Total Kjeldahl Nitrogen as N	10	10	10	10	10	10	10	10
9	BOD	10	10	10	10	10	20	10	20
10	COD	AA	AA	AA	AA	AA	30	AA	30
11	Dissolved Phosphorus as P	1	1	1	1	2	5	2	5
12	Nitrate Nitrogen as N	10	10	10	5	10	10	10	10
13	Faecal Coliform per 100	Nil	Nil	Nil	Nil	Nil	230	Nil	230
14	Helminthic Eggs/Litre	AA	AA	AA	AA	AA	<1	<1	<1
15	Odour	Aseptic which means not septic and no foul odour							

NOTE:-All units in mg/l unless Specified

AA-as arising when other parameters are satisfied;
A tolerance of plus 5% is allowable when yearly average values are considered.

11. SUMMARY

- Water stress has become a perennial concern in most Indian cities and towns. It is often insufficient to meet the growing demand for water by all economic sectors. With a growing population, the per capita availability of water has dropped from 1,816 cubic meters in 2001 to 1,545 cubic meters in 2011 (Central Pollution Control Board (2009) The latest census reported that only 70% of urban households have access to piped water supply. The average per capita supply to these households is well below the recommended 135 liters per day in many cities. With 80 countries and 40% of the world's population facing chronic water problems and with the demand for water doubling every two decades, has made recycling and reuse of sewage important. In India treated sewage is being used for a variety of applications such as Farm Forestry, Horticulture, Toilet flushing, Industrial use, Fish culture and Indirect and incidental uses. CPHEEO has proposed guiding principles for the treated sewage quality to be achieved and recommended for the stated uses.

- Constructed wetlands (CWs) serve as alternatives to conventional treatment options to eliminate/reduce contaminant and nutrient concentration in wastewaters. They are the artificially created man made systems in which waste water treatment take place by utilizing natural processes by involving soil, vegetation, and microbial communities. They resemble to the natural wetlands in treatment processes but processes are carried out in a controlled environment.Since 1990s the constructed wetlands have been extensively built and operated for treatment of all kind of wastewater such as dairy farm **(Sharma *et al*., 2013, Kato *et al*., 2013)**, landfill leachate, runoff, food processing, industrial, agricultural farms, mine drainage and sludge dewatering **(Farooqi *et al* .,2008)**.

- In constructed wetland technology, the most efficient removal of pollutants present in wastewater is taking place majorly through processes such as Sedimentation, Absorption, Adsorption, Ammonification, Nitrification, Denitrification, Microbial Degradation & Plant uptake.

- Constructed wetlands are categorized as surface/free water surface flow and subsurface flow systems. Free Water Surface (FWS) wetlands/ surface flow wetlands are heavily planted systems in which water flow is above the media bed. Subsurface flow treatment wetlands are categorized into Vertical Flow (VF), Horizontal Flow (HF) and Hybrid wetlands on the basis of the direction of water flow. In the past years, modified VF wetlands termed as 'French Systems' and Tidal wetlands have also been introduced as well as adopted for treatment of screened raw wastewater. Some of the Advanced Versions of Constructed Wetland Systems include Baffled Subsurface-flow constructed wetland, Aerated Constructed Wetlands and Multi-tropic Ecological Engineered Wetlands.

- Pre-treatment of wastewater is essentially required before this wastewater is applied to the wetland beds because the sludge constituents such as oil, grease, and various solids (e.g., sand, fibers and trash) present in wastewater may clog the filter media of the wetland beds and subsequently interrupt the treatment processes. Therefore, the prevention and removal of these substances at initial stage is crucial for the long life of a CW treatment system. Some of the methods involved in pretreatment of wastewater are Grease Trap chambers, Screening and Grit Chambers.

- Primary treatment separates the suspended matter by physical operations mainly sedimentation. The septic tank is the most common primary treatment used in small-scale constructed wetland worldwide. It comprises of water tight chamber made up of concrete, fiber glass, PVC or plastic. In recent years, anaerobic baffle reactor (improved septic tank) designs have been developed to enhance removal efficiencies of solids and organic pollutants. It consists of baffles (3 to 5) are arranged in series manner over which the wastewater is compelled to flow. Fluctuations may occur in the flow rate as well as in the type and concentration of the contaminants. Flow equalisation or balancing of the waste water may therefore be advisable prior to entry to the foul sewer to avoid problems at the treatment plant later.

- Free water surface constructed wetland is fully flooded with water and used as advance treatment followed by secondary and tertiary treatment processes. Usually this technology is reliable for the small communities, small housing population, small scale industries etc. For the proper sizing of free water surface constructed wetland equations adopted are First Order Plug Flow Kinetic **(Kadlec and Wallace, 2009)**, Pollutant Removal Theory **(Reed *et al.*,1995)**and Hydraulic Design Theory **(Maria *et al*., 2004).**

- Horizontal subsurface flow (HSSF) constructed wetland is large gravel and sand-filled basin that is planted with wetland vegetation. As wastewater flows horizontally through the basin, the filter material filters out particles and microorganisms attached to the plant roots and filter media degrade the organics. They can be sized using methods such as *P-k-C** approach, rule of thumb **(Rousseau *et al*., 2004)** and regression equations **(Rousseau *et al*., 2004).**

- The subsurface vertical-flow constructed wetlands (SSVF CW) are designed for the treatment of wastewater coming from primary treatment mechanism. In this system the wastewater enters through the surface and flows in vertical direction slowly through the supporting filter material and the plant roots, until reaching the bottom outlet zone. VF wetlands can be sized by Equation as per **Kikuth (1977)** for treating domestic waste water, Rule of thumb (**Rousseau *et al*., 2004)** and Based on Specific Area Requirement per population equivalent (1.2 – 5.0 (m^2/PE)-For warm **(Hoffmann *et al.*, 2011)** and temperate climates **(Kadlec and Wallace, 2009).**

- A unique vertical flow subsurface CW was developed in France for the treatment of raw wastewater which is known as the "French System". In this type of system, Primary treatment is not required for treating wastewater. For measuring appropriate structures of the French System, **Molle *et al.*, (2005)** suggested: For the 1st phase: 1.2 m^2/person equivalent, with average loading of 100 g COD/(m^2/d), 50 g TSS/(m^2/d), 10 g TKN/(m^2/d), 120 L/(m^2/d) divided over 03 identical units feeding alternatively and For the 2nd phase: 0.8 m^2/person equivalent, with average load of 25 g COD/(m^2/d), divided over two parallel or alternately fed filter beds.

- Tidal flow artificial wetlands (TFAW) are fourth generation wetland systems for wastewater treatment that mimics the processes of natural tidal wetlands.. It works by continuous filling and draining the wetland cell with wastewater.

- Hybrid constructed wetland are those systems in which various types of constructed wetland system are modulated in a way that it results in high removal rate and purification efficiency. Several combinations of Vertical flow and Horizontal flow constructed wetland systems are VF-VF-HF, VF-HF-VF, VF-HF and HF-VF.

- Tertiary Treatment includes various disinfection methods used as a public health measure and responsible for a major reduction in people contracting illness from drinking water. However many of these disinfectant chemicals if overdosed or used inappropriately, as part of a water treatment process, can result in the formation of disinfection by-products.

- Constructed wetland systems performance is influenced by various factors and is difficult to quantify. Basically wetland designs mimic natural wetlands in overall structure but the general design considerations include : Planning (Selecting site,System type and configuration, Determining discharge standards),Site selection (Topography, Land availability, Use and Access),Hydrology (Climate and weather, Hydroperiod, Hydraulic load, Hydraulic residence time, Evapotranspiration, Groundwater Exchange and Water Balance),Structures (Flow control structure, Cells, Liners) and Habitat & shade needs.

- Operation and maintenance of CWs can be categorized as Start-up (Establishment of vegetation), Routine (Adjustment of water levels, Maintenance of flow uniformity, Management of vegetation, Odor control, Algae Control, Mosquito habitat control, Pest control, Maintenance of berms, Clogging of the system)and long term operations (Parameters analyzed: Total Suspended Solids (TSS), Biochemical Oxygen Demand (BOD_5), Chemical Oxygen Demand (COD), Ammonia, Nitrate, Phosphorus, Fecal Coliforms). Monitoring of CWs helps to measure whether the wetland is meeting the objectives of the wetland system and indicates its biological integrity.

- Various standard methods for detection of different pollutants as per CPCB include: DO(Winkler azide method), BOD(3 DAYS, 27°C), COD(Open reflux method), TN (Persulfate digestion method), Ammonia (Phenate spectrophotometric), Nitrate(Spectrophotometer), TSS(Colorimeter), TP (Stannous chloride method) and Microbiological Analysis (MPN test).

- In-situ remediation processes, such as constructed wetlands, have produced "satisfactory" results **(Cao *et al*., 2012).** This manual provides holistic review of few case studies i.e.: Vertical flow subsurface systems (Egypt), Phytorid technology in india developed by NEERI (India), Vertical sub-surface constructed wetland units for treatment of dairy waste water (Dehradun , Uttrakhand), Neela-hauz biodiversity park (New Delhi), 2 MLD Constructed Wetland for sewage Treatment at Indian Agricultural Research Institute (Delhi campus), Constructed wetland system to treat wastewater at Indian Institute of Technology (Powai, Mumbai) and Pilot rural household sewage water treatment system at Mathura by IARI.

- Constructed wetlands serve from single-family dwellings to large-scale municipal systems. Also they are essential for humans to live and prosper. More than one billion people depend on wetlands for their living. The use of CWs for wastewater treatment provides many environmental, social and economic benefits.

- In India, Central Pollution Control Board (CPCB) and MoEF, New Delhi has set standards for discharge of wastewater to the surrounding area including land and water bodies. Thus a constructed wetland system should be designed with proper care so that it could produce the effluent that meets all the discharge standards.

सत्यमेव जयते

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