Adapting Constructed Wetlands Treatment of Domestic Wastewater for New Reuse Applications

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ABSTRACT

Vaishnavi Komaravolu: Adapting Constructed Wetlands Treatment of Domestic Wastewater for New Reuse Applications
(Under the Direction of Howard Weinberg)

Wetlands, whether constructed or manmade, have been widely used in wastewater treatment methods as they are efficient water purification systems and nutrient sinks. A constructed wetland is a sustainable and environmental friendly option for the treatment of domestic wastewater because it is affordable, reliable, easy to operate and offers control over design and operating conditions at the point of wastewater generation. It can be designed to remove total suspended solids, pathogens, heavy metals, organic pollutants and reduce oxygen demand of the treated water and has been demonstrated to remove pharmaceuticals and personal care products with comparable efficiencies to that of conventional wastewater treatment plants. However, the land requirements and high water retention times often make the treatment process slow. This report suggests engineering modifications to an existing system at Jordan Lake Business Park that would potentially improve the effectiveness of the constructed wetland in removal of traditional pollutants and pharmaceutical compounds with the purpose of directly using the treated effluent for agricultural land applications.

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List of Abbreviations

BOD: Biological Oxygen Demand

C_u: Uniformity Co-efficient

COD: Chemical Oxygen Demand

CW: Constructed Wetland

DO: Dissolved Oxygen

D_{60}: Equivalent Diameter

EPA: Environmental Protection Agency

FSF: Free Surface Flow

HFCW: Horizontal Flow Constructed Wetland

HLR: Hydraulic Loading Rate

HRT: Hydraulic Retention Time

HSF: Horizontal Surface Flow

HSSF: Horizontal Subsurface Flow

HUSB: Hydrolytic Upflow Sludge Blanket

NW: Natural Wetland

OM: Organic Matter

SF: Surface Flow

SPE: Solid Phase Extraction

TOC: Total Organic Carbon

TP: Total Phosphorus

TSS: Total Suspended Solids

VFCW: Vertical Flow Constructed Wetland

WWTP: Wastewater Treatment Plants

Some Specialized Terms Used in the Report

- Population Equivalent (P.E): A term used to express wastewater in terms of biological oxygen demand (BOD) of domestic wastewater produced per person. Wastewater characterized as 100 P.E refers to wastewater having BOD equivalent to that of Domestic wastewater produced by 100 people per day[20]. It is expressed in units of P.E.
- Specific Surface Area (SSA): Refers to the top view surface area of the wetland. (Length x Width). Units of m^2.
- Water Depth: As measured from the bottom of the wetland basin for sub-surface flow wetlands and measured from the top for surface flow wetlands
- Aspect ratio: the ratio of width to height of the wetland.
- Hydraulic Retention Time (HRT): It is simply given by $\frac{Volume\ of\ wetland}{influent\ flow\ rate}$. The volume used will be the effective wetland volume. Units of HRT is in days.
- Effective volume: Determined by adding a known mass of tracer to the wetland and measuring its concentration at the outlet. The tracer concentration C is equal to the mass of tracer per unit volume of water in the wetland and thus the effective volume can be measured. The effective volume is the actual volume of the wetland available for various chemical, biological and physical transformation of the incoming wastewater

1. INTRODUCTION

A wetland is defined as an area of soil or land that is completely covered with water or near a water source such that it can support an ecosystem of aquatic as well as terrestrial species. Hydric soils and hydrophytes are one of the major features of wetlands, which are highly seasonal and regional in nature. This is due to the differences in climate, topography, soil composition, water chemistry and most probable human disturbances of the concerned wetland region [1]. Natural wetlands (NW) are areas where water and soil co-exist in varying quantities throughout the year or for varying periods of time during the year in such a manner that a particular ecosystem specific to the wetland conditions is developed. A constructed wetland (CW), on the other hand, is an artificial ecosystem that mimics a natural wetland but is modified so as to suit human needs. CWs and NWs have been widely used in wastewater treatment methods, as they are found to act as efficient water purification systems and nutrient sinks [2]. CWs have been used extensively for treatment of municipal and industrial wastewater and some experimental work has used them for removal of heavy metal residues that had been contaminating groundwater [2]. Natural wetlands are highly effective water treatment systems but are unpredictable as environmental and natural factors influence their performance. Climatic changes and accumulation of toxic substances are some of the factors that can disrupt the treatment process of a natural wetland thus making its operation unpredictable. A CW is a sustainable and environmental friendly alternative to NW and has gained popularity in the treatment of domestic wastewater because it is affordable, reliable, and easy to operate [3]. A constructed wetland offers control over the design and operating conditions of the wetland commonly used for the treatment of domestic wastewater, agricultural run-off, and run-off from industries such as paper mills [2]. Wetlands are designed to remove pathogens, heavy metals and organic pollutants. Constructed wetlands are engineered so as to achieve maximum pollutant removal depending on the wastewater to be treated.

This report presents a case study of the Jordan Lake Business Park wetland system and its operation. Modifications to this existing system are proposed based on the discussions presented in chapters 1 and 2 so as to improve the performance efficiency of the system for the removal of organic micro-pollutants, with a possibility of effluent reuse for crop irrigation. The main aim of proposing modifications to the system is to arrive at treated effluent having quality parameters as close as possible to conventional water used for irrigation of crops. Chapter 1 gives a detailed description of wetland designs and Chapter 2 reviews various papers published on constructed wetlands and their working to aid arriving at a modification proposal.

1.1. Ecology of Constructed Wetlands

The ecology of a wetland strongly influences how its various components interact with each other and how these interactions can lead to treatment of wastewater and degradation of pollutants. Constructed wetlands in general have three major constituent components which are, vegetation, micro-organisms and media.

1.1.1 Vegetation

Plants utilized in wetlands are terrestrial or aquatic [4]. The root systems of wetland vegetation play a pivotal role in transferring oxygen to the bulk of a CW (which consists of the wetland media, wastewater and macrophyte root system) so as to support microbial growth and perform biological treatment. The vegetation of the wetlands is referred to as macrophytes, they are aquatic plants that are responsible for important functions in CWs, such as removal of pollutants from wastewater by accumulating them in the plant biomass and filtering the suspended solids that are present in the wastewater flowing through the wetland [5]. Phytoremediation, which detoxifies the wastewater and polluted soil (wetland soil may adsorb some of the incoming contaminants [6]) using green plants, is one of the most important roles of the wetland vegetation. The most commonly planted macrophytes in constructed wetlands are submerged (Pondweed and Fanwort), emergent (Cattails, Bulrushes and Common Reed) or free floating (Duckweed and Aquatic Fern). The *Phragmites* sp., an extensively used wetland macrophyte, has an extensive root system that provides surface area for microbial activities resulting in transformation of pollutants in the wastewater. Macrophytes encompass a large number of processes some of which are crucial to the wetland treatment system and include phytosequestration (removal of bioavailable contaminants by storing them in the root vacuoles), phytoextraction (uptake of substances from the environment into the plant biomass) and phytotransformation (chemical modification of environmental substances as a result of plant metabolism). However, plant uptake efficiency is influenced by environmental factors, design considerations and the nature and the amount of pollutants present in wastewater.

1.1.2 Micro-organisms

Microbes play an extremely important role in the remediation of wastewater by CWs. They are generally present either as a suspension or a biofilm [5] and have diverse metabolic pathways which are important in the disintegration and transformation of minerals. The biodegradation of organic substances is governed by facultative or obligate aerobic/anaerobic bacteria but for a wetland, aerobic systems are more efficient in removing organic pollutants [7]. There is, however, a limitation to the amount of pollutants that can be taken up or consumed by the microorganisms because when the microbes reach a steady state of biomass after the growth stage there is no further net removal of nutrients /pollutants from the system. The major nutrients that are required for biomass growth and are found in domestic wastewater are nitrogen and phosphorus. The processes that are responsible for the elimination of nitrogen from wastewater are ammonification, nitrification and denitrification. Phosphorus removal is poor compared to nitrogen removal. In a constructed wetland, efficient removal of phosphorus can occur only by including a highly sorbing matrix into the design of the wetland [8].

1.1.3 Media

The basic underlying principle of a CW is to pass wastewater to be treated through it, during which the water will undergo various physical, chemical and biological processes eventually decontaminating the water which can then be put to other uses. The media influences how the wastewater interacts with the vegetation and microbes present. It is, therefore, really important to optimize effective contact between the wastewater and the media, which could include soil, sand and gravel providing a large surface area for the microbes to attach to the vegetation biomass and also which act as filters and adsorption media for the contaminants [9]. Soil with low permeability is more suited for wetland constructions as it allows for higher contact time of the contaminated water with the wetland microbes and vegetation, which in turn improves remediation. It also ensures that the wastewater does not percolate to the bottom of the engineered system immediately [10]. The chemical parameters such as soil composition and physical parameters such as pore-size distribution, homogeneity of the soil and permeability influence the treatment performance of a constructed wetland. The most effective compounds for ammonia removal are zeolites as they are readily available, can be easily incorporated into the soil matrix and are cost effective [11].

1.2 Design of Wetland Systems

Wetlands can be classified as free surface flow or subsurface flow based on water flow regimes. These flow regimes refer to the quality, timing and quantity of water flow in a constructed wetland so that the wetland ecosystem thrives and survives. The surface flow wetlands generally utilize free-floating[a], floating leaved[b], emergent and submerged macrophytes whereas the subsurface flow wetlands are restricted to use of emergent macrophytes [5]. Constructed wetlands with free surface flow are not widely used even though they had the earliest origins [12]. In subsurface systems, horizontal flow is most widely used for wastewater treatment but vertical subsurface systems are gaining popularity [13].Both horizontal and vertical flow systems have different advantages and to combine these, hybrid systems (combination of horizontal and vertical wetlands) are becoming popular. Constructed wetlands have been mostly used for the treatment of domestic or municipal sewage but modern times demand for a greater use of this sustainable technology and thus hybrid wetland systems are being designed in order to treat water from a wide range of sources such as industrial waste and agricultural run-off. Suspended solids present in the influent wastewater can hinder the treatment processing by clogging the pipe systems and minimizing contact between the wastewater and the media in a CW and so pretreatment is important before discharging the domestic wastewater into the CW. This can include simple primary wastewater treatment or a septic tank in series with the CW [14]. A septic tank is a watertight compartment which receives and stores the domestic wastewater discharged from households or small communities for a long period of time such that the suspended solids settle and a layer of partially clarified water is left behind [15].

[a] Similar to terrestrial plants

[b] The stomata are located on the top since upper surface is exposed to the atmosphere

1.2.1 Horizontal Subsurface Flow Constructed Wetlands (HFCW)

Design of a HFCW depends on the amount and quality of influent and effluent target [16]. It is basically a large sand and gravel filled basin that is planted with vegetation. Pre-treated wastewater flows in a horizontal path in the subsurface layer through porous sand and gravel filled media until it reaches the outlet. During this passage, the wastewater comes in contact with filter materials and micro-organisms which effectively treat the wastewater. Pre- treatment of the wastewater is necessary to ensure there is no clogging of the channel [16]. The wetland bed is lined with an impermeable liner to prevent leaching [16]. The basin itself should be wide and shallow to allow maximum and effective contact with the vegetation roots. A wide inlet would allow for even distribution of the influent wastewater and prevent short circuiting [16]. Oxygen supply is an important part of the treatment process, so the horizontal flow wetlands are designed with a large surface area to increase oxygen transfer with the external atmosphere. The inlet and outlet zones are constructed with gravel as opposed to sand or fine grain materials so as to prevent clogging [16]. Horizontal flow systems do not require energy and can be operated by gravity flow if the topography allows as depicted in Figure 1.

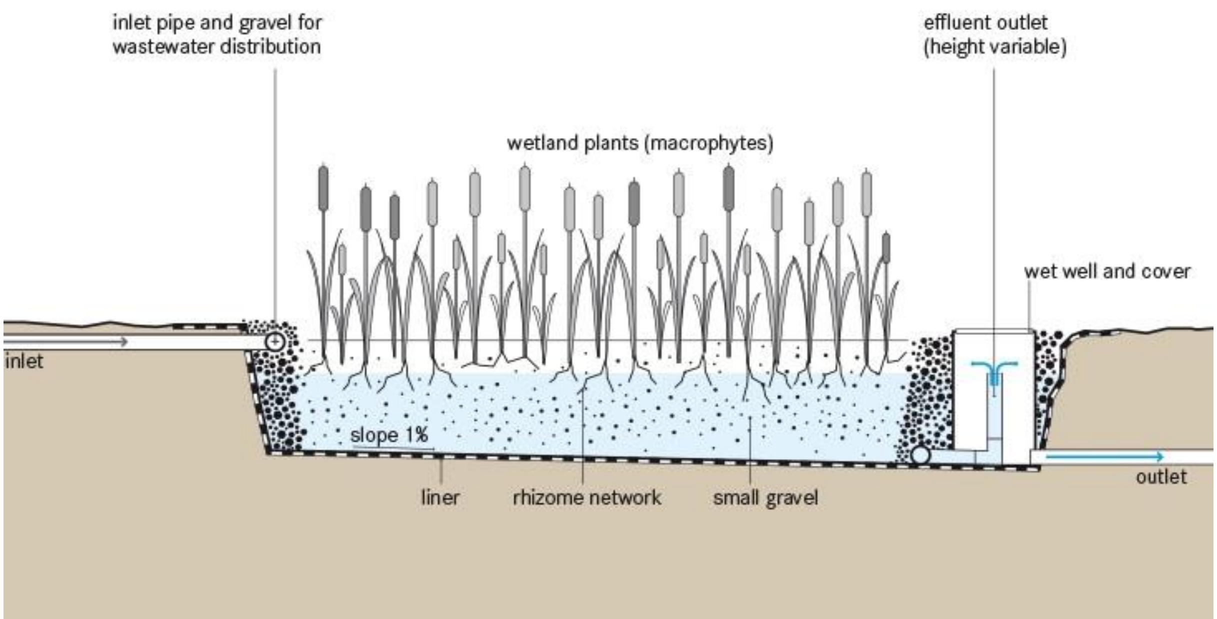


Figure 1: Horizontal Flow Constructed Wetland (HFCW)
Source: *Tilley et al. 2014* [16]

1.2.2 Vertical Subsurface Flow Constructed Wetlands (VFCW)

In a VFCW the wastewater is sprayed onto the surface of the wetland from above using mechanical systems [17]. The influent wastewater flows vertically down through the wetland where it is then collected by a drainage pipe. A CW can be designed as an above the ground construction or as a shallow excavation, an example of which is depicted in Figure 2. Like horizontal subsurface flow wetlands, VFCWs be lined with an impermeable liner. Sometimes these systems include a ventilation pipe so as to maintain aerobic conditions in the subsurface region [17]. The vertical wetland is intermittently dosed with wastewater and thus goes through the stages of being saturated and unsaturated. Wastewater percolates down through the unsaturated bed during the dosing period and as it drains through the wetland, air is drawn into it and oxygen has time to diffuse through the porous media. An area of 1.2 m^2 per person equivalent of wetland area is required for effective domestic wastewater treatment [18].

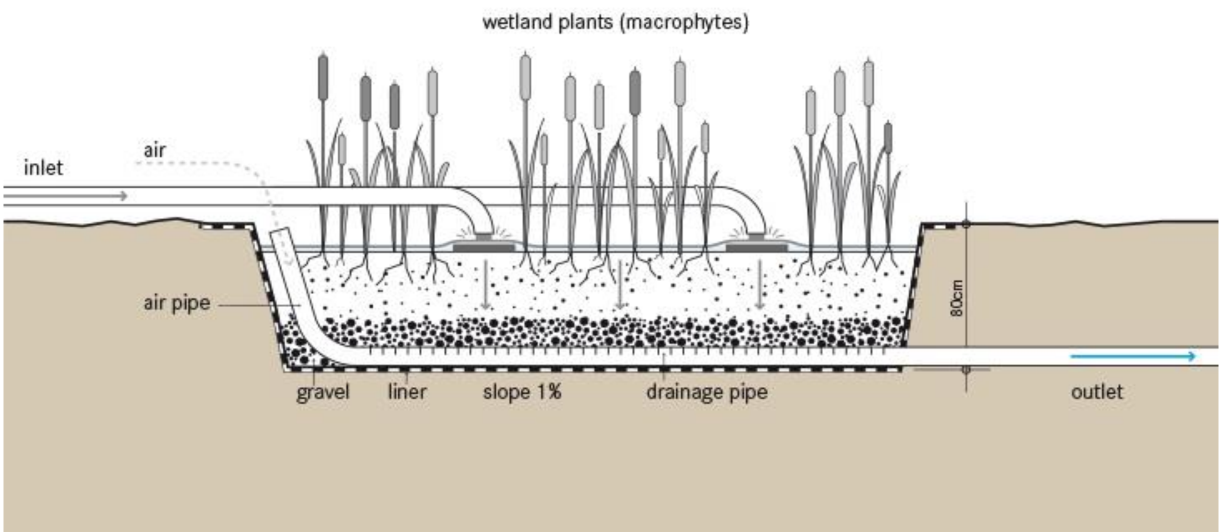


Figure 2: Vertical Flow Constructed Wetland (VFCW)

Source: *Tilley et al. 2014* [17]

1.2.3 Hybrid Systems

To achieve higher treatment efficiency and particularly for nitrogen removal, various types of constructed wetlands are combined in series providing for a hybrid system [19]. In polluted water nitrogen is present as organic nitrogen and ammonia. Various chemical and biological processes first convert this organic nitrogen to ammonia which is then converted into nitrates and nitrites. Wastewater which contains high amounts of nitrates and low levels of organic nitrogen, is said to be fully nitrified [20]. This conversion process occurs under aerobic conditions. Hence, fully nitrified effluents are not achieved in a horizontal flow system because of their limited oxygen transfer capacity, whereas this is possible in a vertical flow system. A hybrid system is of interest as it would combine the advantages of both these systems [13]. An effluent with low Biological Oxygen Demand (BOD), which is fully nitrified (organic nitrogen is converted to ammonia by microbes which on oxidation is converted to nitrites and nitrates) and then denitrified either partially from nitrate to nitrite or fully to nitrogen gas) can be achieved by using the two systems to complement each other [21].

1.3 Wetland Performance

CWs primarily deal with removal of heavy metals, organics, suspended solids and nutrient pollutants. Their performance depends on many factors including environmental conditions, degree of vegetative completeness (whether the macrophytes are fully grown or not) within a wetland unit, types of plant, operational strategy taken, bacterial population and oxygen concentration [5]. The most common vegetation found on CW surfaces are emergent Phragmites *sp.* and free floating water hyacinth as they have been found to have excellent phytoremediation properties for wastewater treatments. This can be attributed to their higher growth rate and extensive root systems which are in turn responsible for greater microbial mass contribution, nutrient cycling, oxygen transfer efficiency, filter bed stabilization, and water quality improvement [5]. Another important factor which affects the performance of a constructed wetland is the hydraulic retention time. A very short hydraulic retention time would lead to inefficient treatment whereas a high retention time would contribute to clogging of the filter material and would not be economically feasible [5]. Wastewater flows through CWs by gravity and HRT can be modified by changing the wetland media. A high retention time can be achieved by employing media with low permeability and this would then lead to its clogging.

1.4 Constituents of Domestic Wastewater

Domestic wastewater is composed of the effluents from residences, institutions and commercial buildings. It is generated from kitchens, bathrooms, laundries, and any other domestic sources. The major pollutants of wastewater are suspended solids, organic matter, pathogens and nutrients as detailed in Table 1.

Table 1: Contaminant concentrations in domestic wastewater (*Source: Metcalf and Eddy, 2004*)[10]

Contaminants	**Concentrations Range (mg/L)**
Solids, total	350-1200
Dissolved solids, total	250-850
Fixed	145-525
Volatile	105-325
Suspended solids, total	100-350
Fixed	20-75
Volatile	80-275
BOD, 5-day at 20 ^{0}C	110-400
TOC (Total Organic Carbon)	80-290
COD (Chemical Oxygen Demand)	250-1000
Nitrogen (Total as N)	20-85
Organic	8-35
Free Ammonia	12-50
Nitrites	0
Nitrates	0
Phosphorus (Total as P)	4-15
Organic	1-5
Inorganic	3-10
Chlorides	30-100
Alkalinity (as $CaCO_3$)	50-200
Oil and Grease	50-150

1.5 Composition of Effluent of a Constructed Wetland

Table 2 compares the characteristics of domestic wastewater treated by CWs in three different countries.

Table 2: Comparison of removal efficiencies of various CWs

Source: Valipour and Ahn 2015 [5]

CW type	WT	Wastewater characteristics							HRT (day)	Flow rate (m^3/day)	HLR (m^3/m^2/day)	Vegetation	Reduction (%)					Study period (Months)	Country
		Temp. (°C)	pH	COD (mg/L)	BOD_5 (mg/L)	TSS (mg/L)	NH_4-N (mg/L)	TP (mg/L)					COD	BOD_5	TSS	NH_4-N	TP		
SF[a]	R	26	7.7	309	155	–	–	–	1.5	–	–	*Eichhornia* sp.	48	50	–	–	–	3	India
SF[a]	R	26	7.7	309	155	–	–	–	1.5	–	–	*Salvinia* sp.	37	38	–	–	–		India
SF[a]	R	26	7.7	309	155	–	–	–	1.5	–	–	*Eichhornia* sp. and *Salvinia* sp.	48	51	–	–	–		India
FSF	R	24–27	7.4	363	212	144	30	–	1.8	0.03	0.27	*Eichhornia* sp.	76	87	67	69	–	22	India
HSF	R	28–30	7.2	445	235	152	33	–	1	0.026	0.23	*Phragmites* sp.	80	90	69	73	–		India
HSF	R	19–42[b]	6.5	477	167	159	–	20	2	0.0125	0.014	*Phragmites* sp.	69	95	90	–	96	6	India
HSF	R	–	7.69	–	105	33	16.6	5.03	1.5	0.198	0.34	*Typha* sp.	–	80	87	59	53	3	Thailand
HSF	R	–	7.69	–	105	33	16.6	5.03	1.5	0.198	0.34	*Canna* sp.	–	77	84	56	58		Thailand
HSF	R	–	7.69	–	105	33	16.6	5.03	1.5	0.198	0.34	*Typha* sp. and *Canna* sp.	–	79	86	63	64		Thailand
HSF	R	–	7.69	–	105	33	16.6	5.03	3	0.099	0.17	*Typha* sp.	–	86	90	69	77		Thailand
HSF	R	–	7.69	–	105	33	16.6	5.03	3	0.099	0.17	*Canna* sp.	–	84	91	68	79		Thailand
HSF	R	–	7.69	–	105	33	16.6	5.03	3	0.099	0.17	*Typha* sp. and *Canna* sp.	–	87	87	72	82		Thailand
HSF	R	–	7.69	–	105	33	16.6	5.03	6	0.0495	0.086	*Typha* sp.	–	90	92	86	86		Thailand
HSF	R	–	7.69	–	105	33	16.6	5.03	6	0.0495	0.086	*Canna* sp.	–	92	93	84	86		Thailand
HSF	R	–	7.69	–	105	33	16.6	5.03	6	0.0495	0.086	*Typha* sp. and *Canna* sp.	–	91	90	88	90		Thailand
HSF	R	5–22[b]	–	536	340	272	36	23	4.7	2	0.05	*Typha* sp.	79	97	92	20	36	24	Spain
HSF	R	5–22[b]	–	744	485	359	43	29	4.7	2	0.05	*Typha* sp.	81	97	92	36	12		Spain

SF surface flow; *HSF* horizontal subsurface flow; *WT* means wastewater type, including raw sewage (*R*)

[a] Operated under batch mode

[b] Air temperature

HLR –Hydraulic Retention Time

HRT- Hydraulic Loading Rate

The rows that are highlighted in Table 2 show a high percentage reduction in the COD, BOD, Total Suspended Solids (TSS), ammonia and total phosphorus. HRT (Hydraulic Retention Time) refers to the average time the wastewater remains in contact with the CW media and HLR (Hydraulic Loading Rate) means the volume of wastewater sprayed over a surface area per day. It is also seen from Table 2 that the HRTs for the first and second highlighted rows are 2 and 6 days, respectively, show comparable percentage reduction in all the above mentioned parameters. A slope of 1% from the horizontal is maintained so as to promote gravity flow of the batch loaded wastewater through the CW. Batch loading, also known as drain-fill operation for wetlands, is when the wetland is completely saturated or filled with wastewater and the wastewater is allowed to remain in the wetland for a period of time during which no new influent of wastewater into the system occurs for a specified period of time also known as batch time. After this time, the wetland system is completely drained and new influent wastewater saturates the system once again. During the batch time the pollutants in the wastewater undergo various physical, chemical and biological changes which results in treated water at the end of the cycle. The batch operation is considered to be more advantageous to a continuous system (continuous flow of wastewater in and out of the system) as the draining and filling cycle helps aerate the wetland media, resulting in greater oxygen transfer. This increased oxygen availability allows for better pollutant removal as compared to the continuous flow systems which maintain anaerobic conditions throughout the operation period. Batch operation would however require additional storage for the incoming wastewater as it is not continuously pumped into the system. A closer look at the Table 2 shows that the CWs planted with *Typha* sp*.*, *Phragmites* sp. and *Canna* sp. had a higher removal efficiency as compared to the *Eichhornia* sp. *and Salvinia* sp. As seen in the sections 2.1 and 2.3, most of the wetlands were planted with *Phragmites* sp*.*, also known as common reed, since it has an extensive root system which allows better oxygen diffusion into the bed of the wetland and also allows greater microbial activity. The HRT is another important factor that determines the removal efficiency of the wetland. A long contact time of the wastewater with the wetland media ensures that sufficient time is available for all the physiochemical transformations to take place. As seen in Table 2, the wetlands with the longest retention time of 6 days show the highest percentage reductions in the conventional wastewater parameters. CWs are a sustainable alternative to conventional WWTP as they provide almost comparable removal efficiencies of the pollutants from domestic wastewater with the operating time being a major disadvantage. At present these reuse applications are limited to mostly landscape irrigation and toilet flushing operations. However, reuse of this treated water for agricultural irrigation might benefit communities with limited potable water resources. Further research into the uptake of the various micro-pollutants present in the treated water by the food crops would be necessary before direct reuse of treated wastewater could be considered. This would include a study of the conditions of CW operations that would provide for maximum removal of pathogens and micropollutants. The United Nations has established a set of standards that are to be met by water for agricultural reuse and these are further described in section 1.6.

1.6 Required Water Quality Standard for Agricultural Irrigation

It can be seen from Tables 2 and 3 that further modification of constructed wetlands is required so as to make the treated effluent fit for agricultural use. Slight modifications in the engineering design of the constructed wetland would make this possible. The current use of treated CW water is restricted to growing local and aesthetic plants, direct release into groundwater and minimal treatment of domestic wastewater [10]. The engineering of the CW has to be further improved and modified if the treated wastewater has to conform to potable water or be directly used for irrigation of crops. If the water parameter is in the lower range of the given values then there is no restriction on the use of water for crop irrigation, however if it tends towards the higher extreme values then there are severe restrictions on the use of water for irrigation. The World Health Organization (WHO) together with the Food and Agricultural Organization of the United Nations has provided certain guidelines for treatment processes required for wastewater reuse for crop irrigation which are described in Table 4. If these guidelines are met and the limits of the various parameters in water remain within limits then the treated wastewater can be used for irrigational purposes.

Table 3: Concentration of various parameters in irrigation water.
Source: *http://www.fao.org/DOCReP/003/T0234e/T0234E01.htm*

Water Parameter	Symbol	Range in irrigation water	Units
Total Dissolved Solids	TDS	0-2000	mg/L
Calcium	Ca^{2+}	0-20	me/L
Magnesium	Mg^{2+}	0-5	me/L
Sodium	Na^{+}	0-40	me/L
Carbonate	CO_3^{2-}	0-1	me/L
Bicarbonate	HCO_3^{-}	0-10	me/L
Chloride	Cl^{-}	0-30	me/L
Sulphate	SO_4^{2-}	0-20	me/L
Nitrate-Nitrogen	NO_3^{-}-N	0-10	mg/L
Ammonium-Nitrogen	NH_4^{+}-N	0-5	mg/L
Phosphate-Phosphorous	PO_4^{3-}-P	0-2	mg/L
Acid/Basicity	pH	6-8.5	—

mg/L-(milligrams per litre) or parts per million-(ppm)
me/L-milliequivalent per litre (mg/L +equivalent weight)

A look at Table 4 shows that there are different regulations for the different irrigational purposes, with the highest treatment required for crops that are to be eaten raw and which use treated wastewater for direct irrigation application.

Table 4: Treatment processes suggested by WHO for wastewater reuse.
Source: http://www.fao.org/DOCReP/003/T0234e/T0234E08.htm#ch7

	IRRIGATION			RECREATION	
	Crops not for direct human consumption	Crops eaten cooked; fish culture	Crops eaten raw	No Contact	Contact
Health criteria (see below for explanation of symbols)	1 + 4	2 + 4 or 3 + 4	3 + 4	2	3 + 5
Primary treatment	X X X	X X X	X X X	X X X	X X X
Secondary treatment		X X X	X X X	X X X	X X X
Sand filtration or equivalent polishing methods		X	X		X X X
Disinfection		X	X X X	X	X X X

Health criteria
1) Freedom from gross solids; significant removal of parasite eggs
2) As 1, plus significant removal of bacteria
3) Not more than 100 coliform organisms per 100 mL in 80% of the samples
4) No chemicals that lead to undesirable residues in crops or fish
5) No chemicals that lead to irrigaion of mucous membranesand skin
In order to meet the given health criteria, processes marked XXX will be essential. In addition, one or more processes marked XX will also be essential, and further processes marked X may be required

1.7 Fertigation

Remediated wastewater is being considered for irrigation to reduce dependence on increasingly scarce freshwater. Some wastewaters contain valuable nutrients in the form of nitrogen and phosphorus which are the basic components of any fertilizer. Thus arises the concept of fertigation which involves using partially treated wastewater rich in nutrients for agricultural irrigation purposes. Effluents from the constructed wetlands can be considered as a source for fertigation provided that they are free of pathogens. The combined use of water and the nutrients contained in wastewater is a promising option to increase sustainability in agricultural water use [22].

1.8 Economic Feasibility of Constructed Wetlands

The capital costs of wetlands are highly dependent on the cost of sand and gravel that is used for filling the wetland bed and the cost of the land on which the wetland is to be constructed [16]. Compared to other intensive aerobic treatment options, CWs are natural systems and work extensively which means that the treatment may require more land and time but requires no electrical power and skilled labor to operate [16]. There is also no need for sophisticated equipment, expensive spare parts or chemicals. They are cheaper to build compared to high rate aerobic treatment facilities but for larger plants they are usually more expensive in terms of capital costs, incurred in terms of land acquisition but not operating costs [16]. Only the design and construction of a subsurface flow wetland requires skilled staff which could be expensive, but it has very low operating costs [16].

2. COMPARISON OF DIFFERENT WETLAND SYSTEMS

The following chapter includes reviews of simple constructed wetland systems and provides a comparison between them based on conventional wastewater quality parameters. It also reviews hybrid wetland systems and their efficiencies in removing pharmaceutical compounds present in domestic wastewater.

2.1 Review of Wetland Systems

This section compares and evaluates the basic designs of 5 different wetland systems in terms of their impacts on the reduction of various wastewater characteristics which include BOD, COD, TSS and nutrients. They include both simple and hybrid wetland systems described since 2005. A description of the wetland system numbering used for comparison of the graphs in section is given in the appendix.

a) Cova da Beira, Portugal wetland system (two parallel HSSF CWs) [23]:

The design consisted of a bar rack, which is a form of preliminary water treatment used to remove large floating objects. It was followed by a sand channel which led into an Imhoff tank followed by two parallel HSSF CWs. This system was designed for 800 people equivalent. The HSSF bed had dimensions of 50×15.5×1m, length × width × depth respectively. 733 m^2 of the wetland surface area was colonized by *Phragmites australis.* The wetlands were monitored for a period of 9 months from March to December 2009. Each was filled to 0.95 m with gravel and the water depth was maintained at 0.65m from the bottom of the wetland basin during the monitoring period. An influent flow rate of 35±4 m^3/ day and effluent flow rate of 21±2 m^3/day was maintained. The influent pH and temperature were 6.4 – 7 and 19±2 ^{0}C respectively, while the effluent pH and temperature were 7 – 7.4 and 20±2 ^{0}C [22], respectively.

b) Pilot plant system to treat municipal wastewater in Barcelona, Spain (HSSF) [24]*:*

This system was used to study treatment of urban wastewater by constructed wetlands generated by a housing development municipality located in Barcelona, Spain. The system treated only a part of the wastewater generated to study the CWs. The primary clarification consisted of screens and an Imhoff tank. The effluent from the Imhoff tank was equally divided and fed into 8 parallel HSSF constructed wetlands having a specific surface area of 54 – 56 m^2. The complete system was fitted with pumps, flow meters and valves to allow for monitoring and controlling of the influent streams. The subsurface wetlands require macrophytes with extensive root systems which have root lengths greater than 0.60m as this is the minimum water depth in such systems, hence they were planted with *Phragmites australis.* The 8 HSSF beds were further categorized into 4 pairs, namely A, B, C and D, respectively. Each pair had different size specifications. The aspect ratios were 1:1, 1.5:1, 2:1, 2.5:1 for pair A, pair B, pair C, and pair D. Pairs A, B and C had an average water depth of 0.50m whereas pair D had an average water depth of 0.27m. The size of granular media within each pair was different: each pair consisted of one bed with coarse granitic gravel (D_{60} = 10mm and C_u= 1.6) and the other bed with fine granitic gravel (D_{60} = 3.5mm and C_u= 1.7), where D_{60} is the diameter of the sieve through which 60% of the particles pass through in a sieve analysis and C_u refers to the uniformity coefficient. In addition, the wetlands had two perforated tubes (diameter = 0.1m) inserted into their middle so as to facilitate intermediate sample collection[23].

c) Two pilot plant systems in Northern Giza, Egypt [25]:

The pilot plant units were fed with settled wastewater from an existing municipal wastewater treatment plant. The settling refers to primary treatment in which all heavy solids were allowed to settle out and the supernatant was fed into the system of constructed wetlands. The system consisted of two CWs, one Horizontal Flow Constructed Wetland (HFCW) and the other a Vertical Flow Constructed Wetland (VFCW). The specifications of the HCFW were 37.87 × 17.3 m (length × width) and with a depth of 0.85m and a 0.7% slope along the basin. The entire HFCW basin was filled with gravel of diameter 20mm except for the first and last 1m which was filled with 40-80 mm diameter gravel to prevent clogging. Wastewater was fed into the HFCW basin through PVC pipe with 10 holes at the beginning. The VFCW had specifications of 21.95 × 20.85m (length × width), the influent wastewater was distributed through a PVC network. Both the basins had a bottom covered with a PVC liner to prevent the seepage into groundwater. Both wetlands were run at same operating conditions and loading rates [25]. A schematic of the system described is shown in Figure 3.

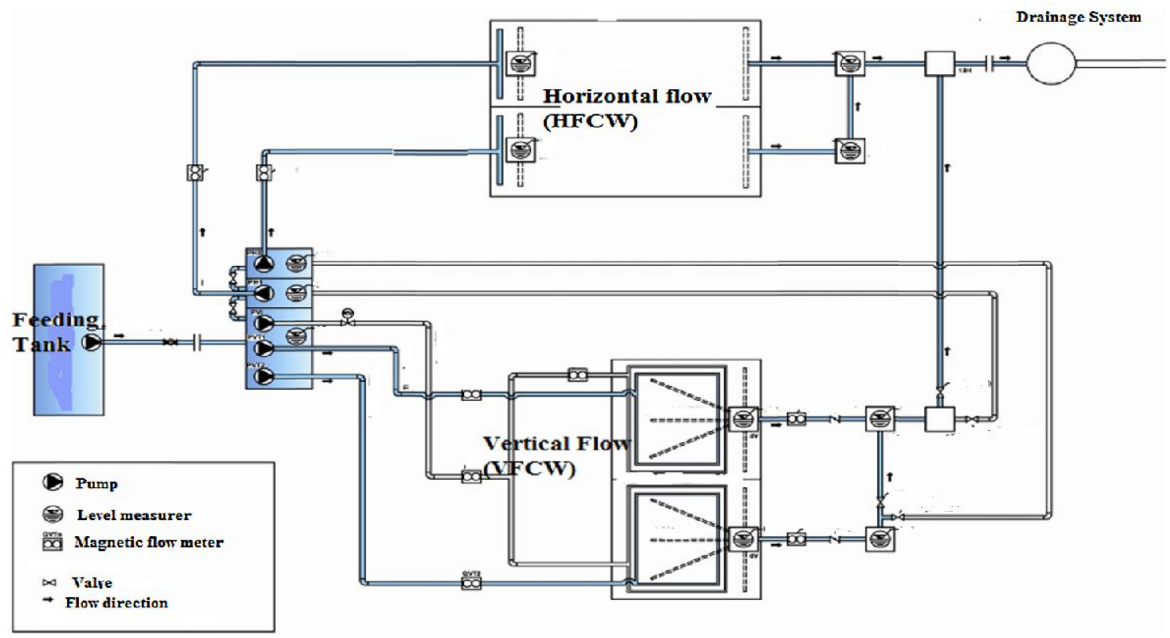


Figure 3 : Schematic of pilot plant systems in Northern Giza, Egypt
Source: Abou-Elela etal. 2013. [25]

d) Vertical flow CW systems in Northeastern Italy [26]*:*

The system consisted of 4 lysimeter [c] units which were modified to function as two VFCWs. One of the wetland system was planted with *Typha latifolia* and the other with *Phragmites australis*. The wetlands were pilot scale systems and used for experimental studies. Each wetland system had a surface area of $1m^2$ and was 1.5m deep. They were filled with sand (D_{60} = 0.16mm and C_u= 2.2) in the first 16 cm, followed by two 22cm layers of gravel with a diameter of 4-8mm and 8-12mm and a 90cm layer of gravel 30-50mm in diameter as shown in Figure 4 . The level of influent wastewater which received only primary sedimentation treatment in each VFCW was controlled by an underground pipe connected to a piezometer [26].

[c] A measuring device used to measure evapotranspiration losses.

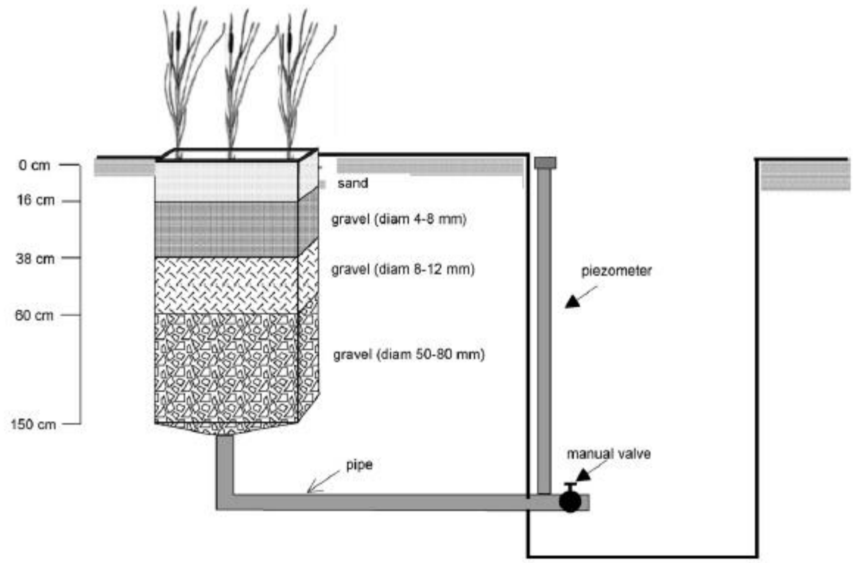


Figure 4: Design of vertical flow wetland in Northeastern Italy
Source: Morari and Giardini 2009 [26]

e) Subsurface wetland system in Southern China [27]*:*

The main treatment units were two stages of subsurface flow CWs. It is essentially a hybrid CW system. A block diagram of the system is shown in Figure 5. Primary treatment included screens, primary settling basins and a facultative pond. The first stage wetland was designed as a horizontal flow wetland consisting of two series of wetlands in parallel. It had a total area of 4800 m^2, with dimensions of each series of wetland 80m×30m×1.5m (length × width × height), bed depth of 1m and a hydraulic retention time (HRT) of 11.5 h. The second stage was designed as a vertical flow wetland with a total of 4 series of CWs in parallel. The whole vertical flow system had a total surface area of 4640 m^2 with dimensions of each series of CW being 58 m × 20m × 1.65m (length × width × height) , bed depth of 0.75m and HRT of 8 h .

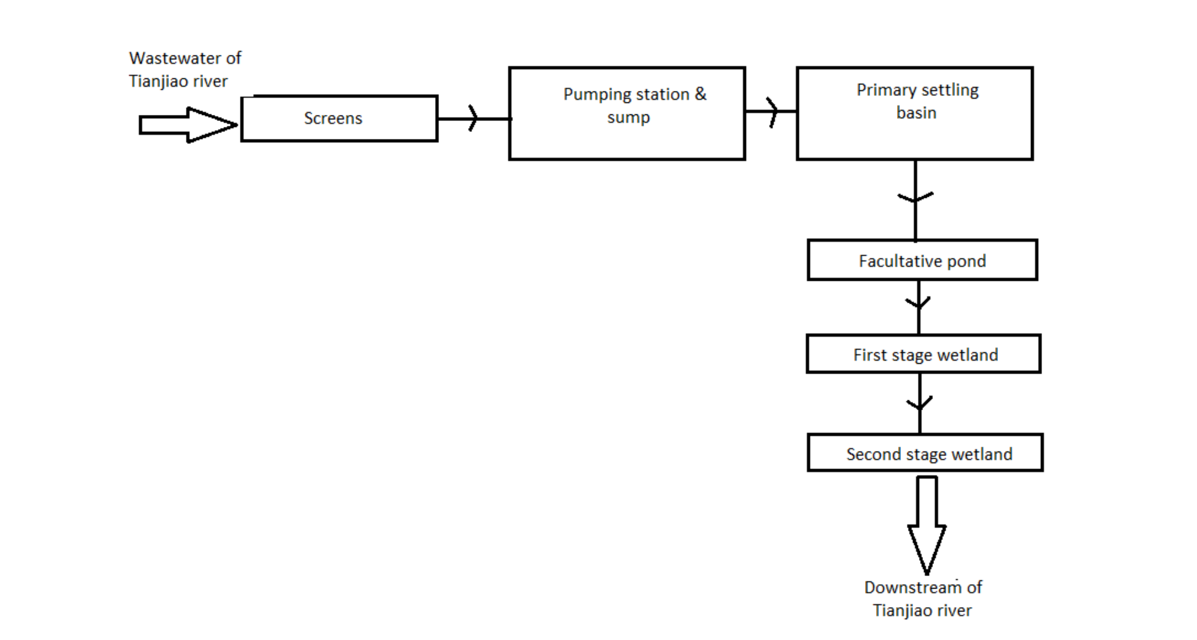


Figure 5: Flow diagram of wetland system in Southern China [27]

Table 5 summarizes all the systems that are being compared in this section. The following sections will compare the removal efficiency of various wastewater contaminant parameters by each wetland to assess which design might provide maximum treatment effectiveness.

Table 5: Summary of wetlands described in section 2.1
(Description of wetland system numbering is given in the appendix on page 71)

Wetland system	Pretreatment method	Dimensions (Length (m) × width (m))	Water Depth (m)	Vegetation	Hydraulic Loading Rate HLR (mm/day)	pH	Media size	Surface area colonized (m^2)
a	Imhoff tank	50×15	0.95	*Phragmites australis*	48	Influent: 6.8-7 Effluent: 7-7.4		733
b Pair A Pair B Pair C Pair D	Imhoff Tank	1×1 1.5×1 2×1 2.5×1	0.5 0.5 0.5 0.27	*Phragmites australis*	36		D_{60} = 10mm and Cu= 1.6 or D60 = 3.5mm and Cu= 1.7	54 - 56
c HFCW VFCW	Sedimentation	37.87 × 17.3 21.95 × 20.85	0.85 0.85	Canna *Phragmites australis* Cyperus papyrus	31 44	6.5-7.9	40-80 mm 10-20mm	654.5 457.6
d VFCW(1) VFCW(2)	Primary Sedimentation	1×1	1.5 1.5	*Typha latifolia* *Phragmites australis*	18-28		First 16 cm (0.16mm) next 22cm (4-8mm) next 22cm (8-12mm) last 90cm (30-50mm)	1
e First Stage CW Second Stage CW	preliminary screens and primary settling basin	80×30 58×20	1 0.75	Canna,Reed, Sweetcaneflower, Great Bulrush,Thalia	41-208 43-216		weathering stone 30-50mm	4800 4640

2.1.1 Evaluation of CW Treatment Processes in Terms of their Remediative Effects

Constructed wetlands are effective in the removal of a variety of pollutants present in wastewater, namely, suspended solids, pathogens, nitrogen, phosphorus, BOD, COD, organic compounds and trace elements such as heavy metals. This section looks into the removal efficiencies of organic matter, nitrogen, phosphorus, suspended solids and pathogens by the systems considered on the previous pages.

2.1.1.1 Organic matter (OM)

The concentration of organic matter in domestic wastewater can be represented by BOD and COD and can be subdivided into particulate OM which is removed by filtration/ settling and dissolved/colloidal OM, removed by either aerobic or anaerobic decomposition [28]. The particulate OM is removed in the pretreatment stages whereas the dissolved OM undergoes aerobic degradation performed by chemoautotrophic and chemoheterotrophic microorganisms often added to the system for supplementing the existing microbes in the septic or Imhoff tank. Figure 6 provides the process flow diagram for decomposition of organic matter in a wetland that would mirror any reduction in BOD and COD.

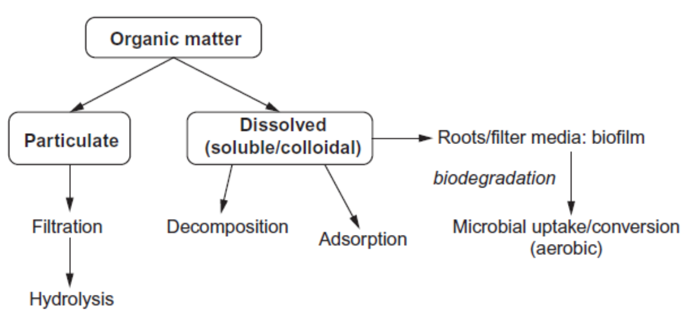


Figure 6: Processes of OM removal in a CW

Source: Stefanakis et al. 2014. [29]

VFCWs have higher rates of aerobic OM degradation as compared to HFCWs because the feeding regime of discontinuous loadings creates a flood on the wetland bed and subsequent gravitational flow of the wastewater provides higher rates of oxygen availability [29]. OM is decomposed in the biofilm that is attached to the roots, stems and surface of the wetland media. Anaerobic degradation is more dominant in subsurface HFCWs where the contact of wastewater with the atmosphere is minimal resulting in low dissolved oxygen (DO) [23]. This degradation is carried by acid- or methane- forming bacteria and is much slower than aerobic degradation [30]. It should be noted that the OM decomposition depends on the OM composition of the influent wastewater and the HRT applied as municipal and industrial wastewater have completely different characteristics that may respond differently to operational conditions. Table 5 provides a summary of the OM characteristics of influent wastewater into the different wetland systems together with their effect on OM removal.

Table 6: Removal efficiencies of OM in the wetland systems
(Description of wetland system numbering is given in the appendix on page 71)

Wetland			BOD			COD		
Systems	HRT (days)	HLR (mm/day)	Influent	Effluent	% removal	Influent	Effluent	% removal
a	4.5-9	70-150	286±16	15±4	95	344±10	110±15	71
b								
Pairs (A-C)	3-5.6	36	140±54	56	60	170±55	68	60
Pair D				28	80		42.5	75
c								
HFCW	7	n/a	121.7±45.2	11.94	93	246.2±78.4	29	92
VFCW				11.24	94		29	93
d year 2002								
VFCW_P	7	18-28	145	59	59	481	165	66
VFCW_T			144	56	61	443	165	63
d year 2003								
VFCW_P	7	18-28	595	37	94	1628	94	94
VFCW_T			571	40	93	1418	106	93
e			56	8	86	146	34	77
First Stage	11.5 h							
Second stage	8h							

2.1.1.2 Suspended solids

Physical processes are solely responsible for the removal of suspended solids in CWs [29]. The main removal mechanism involves sedimentation and filtration [31]. Suspended solids are trapped in the pores of the wetland media by mechanical hindrance or by adhesion [29]. The gradual accumulation of these suspended solids is one of the most important parameters affecting clogging. In VFCWs most of the substrate clogging occurs at the top of the wetland bed whereas for HFCWs the clogging occurs at the entry of the pipes into the wetland bed. One advantage of the VFCWs is that they have intermittent loading through a number of supply lines which prevents clogging. In the HFCW, the influent wastewater is distributed over the whole surface of the wetland, and with good aeration of the bed oxidation of the accumulated organic solids occurs and preventing bed clogging. . Thus to avoid solids buildup and to allow time for transformation of the OM an organic loading rate of 6 mg/L of BOD_5/m^2.day is recommended by the US Environmental Protection Agency [10]. Table 7 shows the removal efficiencies of suspended solids by the various wetland systems described in this chapter.

Table 7: Removal efficiencies of suspended solids in wetland systems (all values in mg/L except removal efficiency)
(Description of wetland system numbering is given in the appendix on page 71)

Wetland Systems	TSS Inflow	TSS Outflow	removal %
a	116±20	34±10	71
c			
HFCW	98.6±40.9	7.5	92
VFCW		5.9	94
d			
VFCW_P_2002	513	261	49
VFCW_T_2002	270	304	55
VFCW_P_2003	1201	393	67
VFCW_T_2003	998	340	66
e	59.88	7.92	87

2.1.1.3 Nitrogen

The levels of ammonia and organic nitrogen in the influent wastewater impact the effectiveness of DO for the aerobic transformation processes of nitrogen. They can also lead to the phenomenon of eutrophication or over-enrichment of water by nitrogen which can produce harmful algal blooms and oxygen depletion due to utilization of the DO by these blooms eventually causing hypoxia. The common forms of nitrogen in wastewater are [29]:

- Organics: Urea [$CO(NH_2)_2$], amino acids ($-NH_2$ and –COOH), uric acid ($C_5H_4N_4O_3$) and purine ($C_5H_4N_4$)
- Inorganics: ions like ammonium (NH_4^+), nitrate (NO_3^-), nitrite (NO_2^-) and gases like nitrous oxide (N_2O) and free ammonia (NH_3)

Various biological and physiochemical processes are responsible for the reduction/ transformation of nitrogen [32] in CWs as depicted in Figure 7. However, its removal relies primarily on the effectiveness of the microbial processes of nitrification, denitrification and ammonification effected by bacteria present in the domestic wastewater from human waste sources.

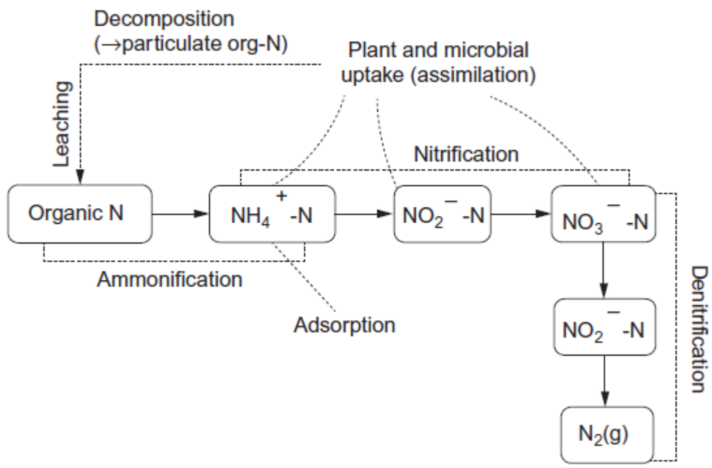


Figure 7 : Nitrogen removal mechanism in wastewater
Source: Stefanakis et al. 2014. [29]

Figure 7 shows a pathway by which the organic nitrogen present in the influent wastewater is converted into ammonia. Most of the transformation takes place due to microbial processes and while this occurs in both aerobic and anaerobic layers of the CW it is rapid in the oxygen rich layers, which is why the ammonification rate is higher in VFCWs as compared to other CWs [29]. The next step in nitrogen transformation is nitrification. Ammonia-N is first oxidized to nitrite under aerobic conditions and the presence of ammonium-oxidizing bacteria and to nitrate by nitrite-oxidizing bacteria [30]. The final step involves the reduction of the produced nitrite and nitrate to nitrogen gas by denitrifying bacteria such as *Pseudomonas* and *Bacillus* [29]. Denitrification takes place in conditions with limited oxygen such as in HFCWs [28]. Wetland vegetation contributes directly (macrophytes using the nitrogen as a nutrient for their growth) or indirectly (root systems providing oxygen for the nitrogen transformation process) to the removal of nitrogen from the influent wastewater. Plants adsorb and utilize the nutrients present for their growth [29]. Various parameters like loading rate, bed configuration, plant type and environmental conditions affect the plant uptake of nitrogen [30]. A look at Table 7 shows the various removal efficiencies of nitrogen by the systems in section 2.1.

Table 8: Nitrogen Removal Efficiencies (all values in mg/L, except removal efficiencies). n/a- not available
(Description of wetland system numbering is given in the appendix on page 71)

Wetland system	Ammonia-N			Nitrate-N			Total Nitrogen		
	Influent	Effluent	removal%	Influent	Effluent	removal%	Influent	Effluent	removal%
a	33±3	7±3	78.8	7.5±0.6	0.7+0.1	90.7	38±5	9±3	76
b									
Pairs (A-C)		26.6	30						
Pair D	36.8±11	18.4	50	n/a	n/a	n/a	n/a	n/a	n/a
c									
HFCW_3		8.8	57.1				16	6.5	60
VFCW_3	17.2±4.7	6.5	62.7	n/a	n/a	n/a	42.6	16	63
d									
VFCW_P_2002							27.5	26.4	4
VFCW_T_2002							32.9	21.4	35
VFCW_P_2003							119.3	9.9	92
VFCW_T_2003	n/a	n/a	n/a	n/a	n/a	n/a	94	9.5	85
e							16.53	9.11	45

2.1.1.4 Phosphorus

Phosphorus both in organic and inorganic forms is a macronutrient and along with nitrogen in wastewater it can lead to eutrophication and depletion of oxygen, which in turn affects aquatic life [29]. The most common form in wastewater is free orthophosphate (PO_4^{-3}-P) but other inorganic forms include polyphosphates, while organic phosphates consist of phospholipids and nucleic acids [31]. For biological consumption, all organic and inorganic phosphorus has to be converted into a soluble inorganic form [29]. Wetland vegetation takes up soluble reactive phosphorus and utilizes it as a nutrient although some is adsorbed onto the wetland media [33]. The main transformation processes for phosphorus include adsorption, precipitation, plant/microbial uptake and mineralization [29] which is depicted in Figure 8 where pore water refers to the water trapped between the media in the wetland.

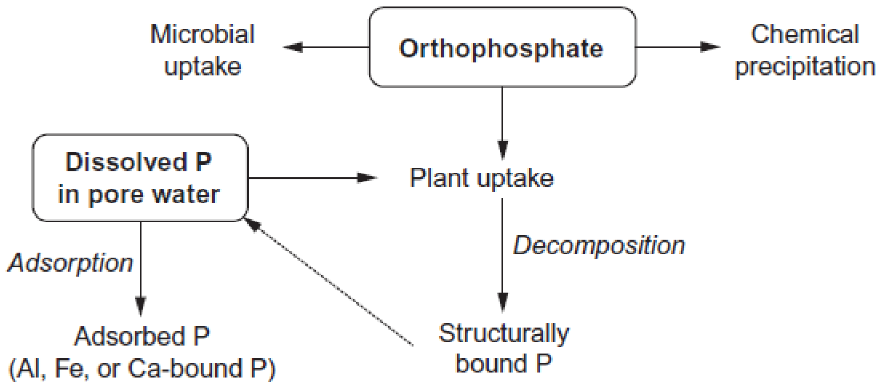


Figure 8: Phosphorus removal mechanisms in wastewater

Source: Stefanakis et al. 2014. [29]

Table 9 shows a summary of phosphorus removal efficiencies by the wetlands described in section 2.1. For CWs being utilized for crop irrigation, most of the phosphorus is taken up by the crops which are harvested, this results in the net removal of P from the system as a whole. Some of the P however remains in the system as a sediment.

Table 9: Phosphorus removal by different systems (All values in mg/L except removal efficiencies)

(Description of wetland system numbering is given in the appendix on page 71)

Wetland system	Total Phosphorous		
	Influent	Effluent	removal%
a	7±1	3±1	57
b			
Pairs (A-C)	5.6±1.9	5.6±1	0
Pair D		5.04	10
c			
HFCW_3	3.2±1.1	1.11	63
VFCW_3		1.02	68
d			
VFCW_P_2002	9.6	3.1	51
VFCW_T_2002	10	2.3	55
VFCW_P_2003	20.5	5	75
VFCW_T_2003	17.8	5.3	70
e	3.07	0.56	81

2.1.1.5 Pathogen removal

Although CWs are designed for removal of OM, SS and nutrients they are capable of removing microbes. Pathogens present in the wastewater present a potential environmental risk if they are not removed from the treated wastewater, especially when it is reused. Some of the most important pathogenic bacteria include *Salmonella sp., Shigella sp., Vibrio cholera, Yersinia enterocolitica, Escherichia coli and Pseudomonas* [26], pathogenic enteroviruses and coliphages as well as parasites such as roundworms and are removed through various chemical, physical and biological mechanisms and processes which include [29]:

- Physical : filtration, sedimentation,
- Chemical: oxidation, UV radiation by sunlight, exposure to plant biocides,
- Biological: antimicrobial activity of roots exudates, predation by nematodes and protozoa, retention in biofilms and natural die-off.

2.1.2 Comparison of Performances of Wetland Systems

Figure 9: Graphical representation of removal efficiencies of wetland systems reviewed in section 2.1(Description of wetland system numbering is given in the appendix on page 71)

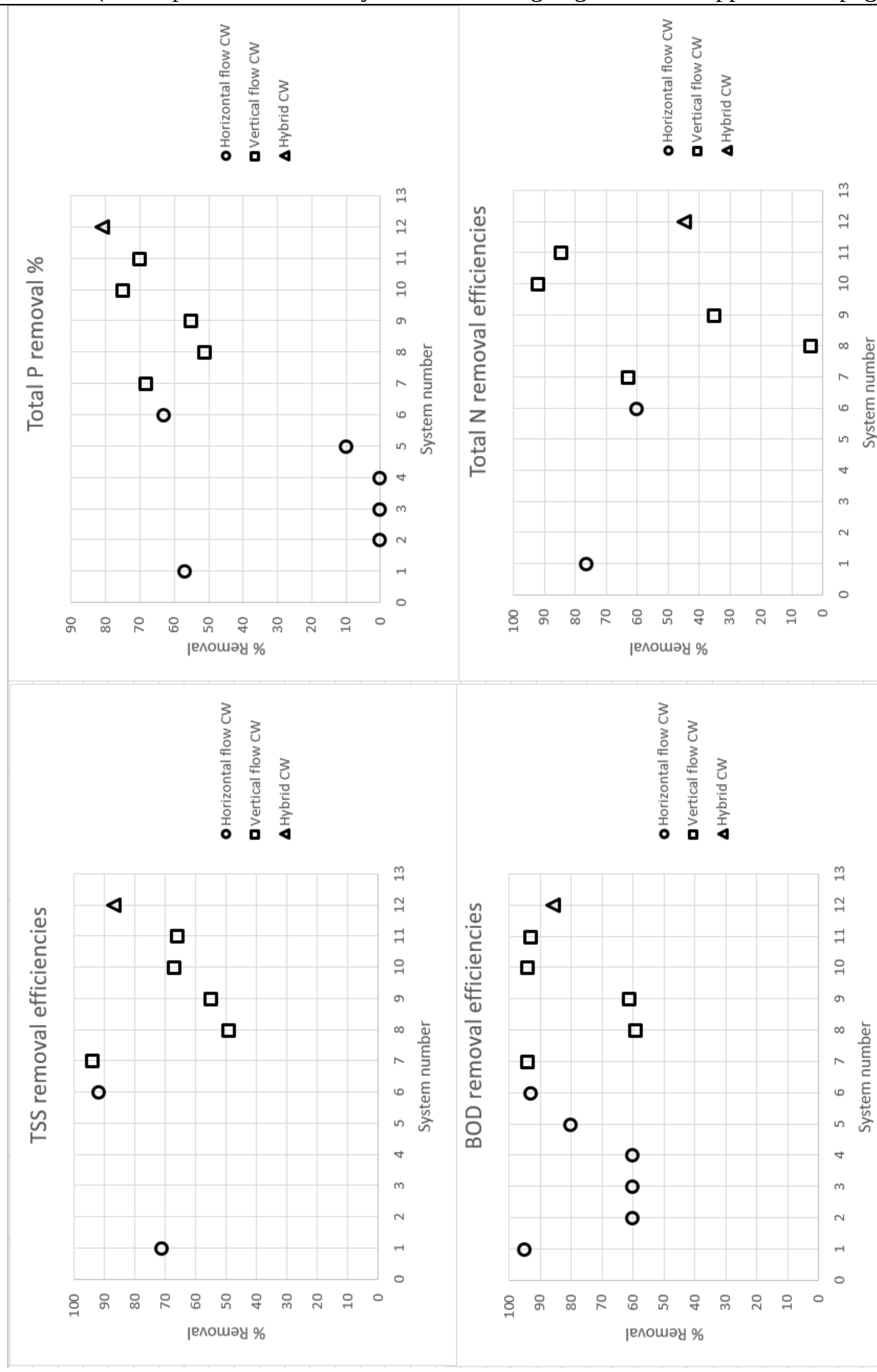
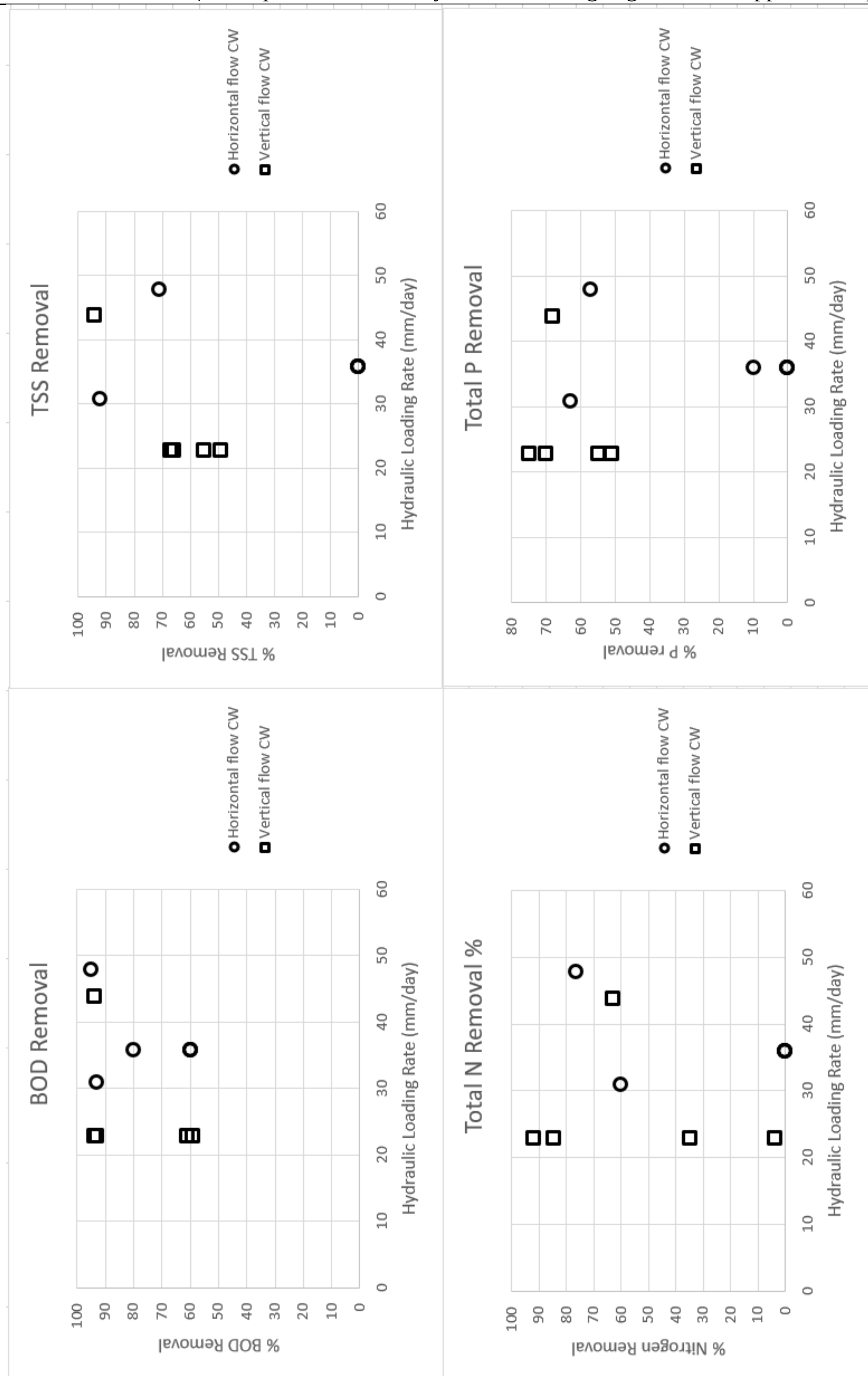


Figure 10: Graphical comparison of hydraulic loading rate and efficiencies of wetland systems reviewed in section 2.1(Description of wetland system numbering is given in the appendix on page 71)



It can be seen from Figure 9 that the removal efficiencies of vertical flow systems is the highest. This can be attributed to the fact that the VFCW have more oxygen transfer from the atmosphere and hence there is a wider range of micro-environments present i.e. the surface has aerobic conditions and the wetland media saturated with wastewater has anaerobic conditions which helps in the better transformation of the pollutants present in wastewater.

Figure 10 shows a high removal efficiency of BOD or TSS for different hydraulic loading rates across both VFCW and HFCW systems. Table 10 indicates the HLR values which are almost the same for the various systems reviewed and, thus, any difference in the removal efficiency of nitrogen and phosphorus in Figure 10 is due to the difference in system operation (VFCW or HFCW). VFCW shows greater removal efficiency as compared to the HFCW.

Table 10: Hydraulic Loading Rate of various systems described in section 2.1
(Description of wetland system numbering is given in the appendix on page 71)

System	HLR (mm/day)	System pattern
1	48	HFCW
2	36	HFCW
3	36	HFCW
4	36	HFCW
5	36	HFCW
6	31	HFCW
7	44	VFCW
8	23	VFCW
9	23	VFCW
10	23	VFCW
11	23	VFCW

2.2 Pharmaceutical Compounds.

Pharmaceutical compounds are natural or synthetic chemicals that are found in therapeutic drugs and prescription medicines [34]. There has been a continuous release of these compounds into the environment due to their widespread use in human and veterinary medical practices. They undergo natural attenuation by adsorption, dilution or degradation in the environment, depending on their biodegradability and hydrophobicity [35]. Water bodies thus often contain variable concentrations of these compounds depending on the extent of attenuation from metabolism or removal through natural or water treatment processes [35]. Wastewater treatment processes are not specifically designed to remove the trace pharmaceutical compounds [23]. However, various studies in developed countries have shown that the conventional water treatment processes have demonstrated varying removal rates of pharmaceutical compounds of up to about 90% [35]. Advanced treatment processes such as reverse osmosis, ozonation and oxidation technologies are shown to achieve higher removal efficiencies as compared to conventional activated sludge treatment [34]. As described in the earlier sections of this report, constructed wetlands have the ability to remove conventional pollutants such as nutrients, pathogens, organic compounds, COD and BOD. Recent studies have shown that CWs can remove emerging contaminants and pharmaceutical compounds somewhat effectively. Some of the most common pharmaceutical compounds that have been studied include Carbamazepine (antiepileptic), Diclofenac (anti-inflammatory), Ibuprofen (analgesic), and Naproxen (anti-inflammatory) [35]. The section 2.3 looks into how various wetland designs affect the removal of these pharmaceutical compounds from influent wastewater.

2.3 Review of Hybrid Wetland Systems

The following cases are compared to assist the selection of an optimum design for a wetland in Chapter 3 so as to achieve maximum treatment of pharmaceuticals and personal care products that are present in domestic wastewater. The wetland systems reviewed in section 2.1 were simple systems and presented treatment efficiencies of wetlands based on conventional wastewater parameters. The systems reviewed in section 2.3 are hybrid systems which were monitored for reduction in pharmaceutical compounds. A description of the wetland system notations is given in the Appendix. A comparison of traditional wastewater parameter removal efficiencies of each system mentioned in section 2.3 is given in Table 10 section 2.4.

f) Grand Marais wetland system, Canada [36]*:*

The Grand Marais, Canada treatment wetland receives rural wastewater trucked in after pretreatment by septic tanks and deposited into a lagoon from which the wastewater flows via a 0.7 km long channel into the wetland system. The five receiving channels in the CW are designed in such a manner that the water enters them at a single point but exits only once it has passed through all the rows (snaking configuration). It is a hybrid system (made up of two different wetland types) consisting of a secondary step lagoon followed by a surface CW (40-60 cm water depth throughout the year, total volume of 23,200 m^3) planted with *Typha* sp. [36]. The water flows through the wetland by gravity. The treated water is released into the Marais creek. The water was sampled for levels of pharmaceutical compounds at the inlet, mid-channel, west wetland, east wetland and outlet twice during the experiment period. Figure 11 shows the schematic of the wetland. The wetland channel was a ditch lined with macrophytes. Wastewater, once released from the lagoon flowed by gravity through the entire channel. The water samples were analyzed for the presence of carbamazepine using Polar Organic Chemical Integrative

Sampler (POCIS) and Solid Phase Extraction (SPE). The results of this study, as seen in Figure 12, showed that treatment wetlands operating in a manner similar to the Grand Marais wetland may not be optimal for the removal of pharmaceutical compounds. This could be because of the low retention time of the wastewater in the wetland system which did not allow complete degradation of the pollutants.

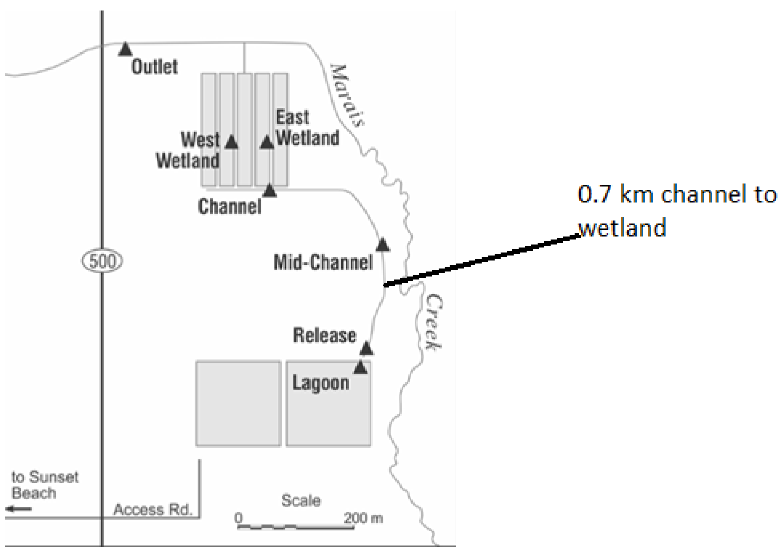


Figure 11: Grand Marais wetland system

Source: Anderson et al. 2013.[36]

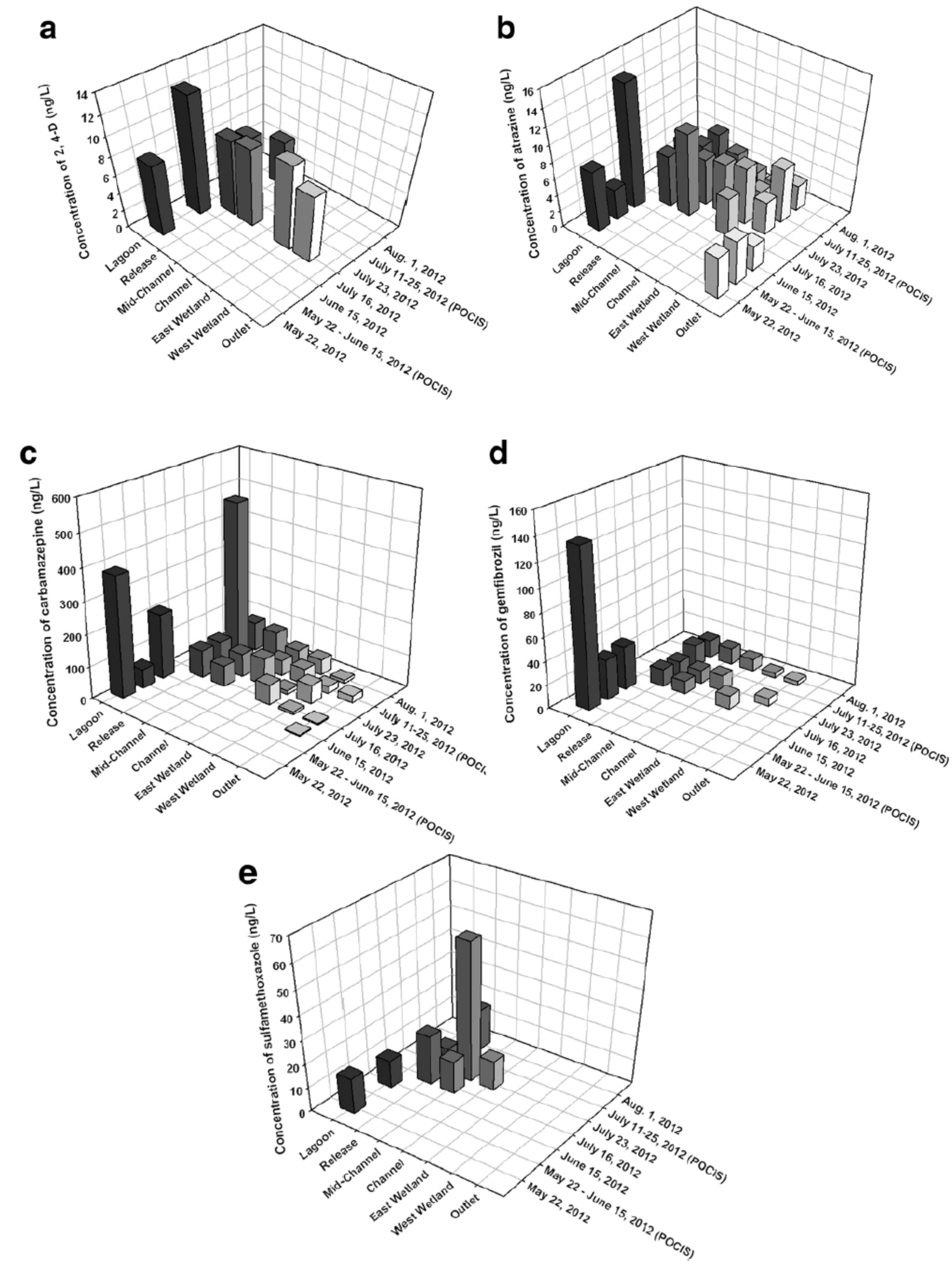


Figure 12: Mean concentrations of a) 2,4-D, b) atrazine, c) carbamazepine, and d) gemfibrozil and e) sulfamethoxazole measured at different locations in the Grand Marais system. *Source: Anderson et al. 2013.* [36]

g) System located at Technical university of Catalonia- Barcelona, Spain [37]:

The treatment system consists of a hydrolytic upflow sludge bed reactor-HUSB (acts as a sedimentation tank and also hydrolyzes suspended solids) as primary treatment. It was then followed by two HSSF wetlands (B1 and B2) (surface area of 0.65m^2) connected in parallel to another HSSF wetland-B3 (1.65m^2 surface area) working overall in series. The system received wastewater from a local municipal sewer and was first screened before it was sent into the HUSB. The wetlands consisted of a 30cm gravel layer (D_{60}=5mm, porosity of 40%). Water depth was maintained at 25cm and vegetation planted was *Phragmites australis*. The hydraulic loading rate was 0.028 m/ day and HRT was 3.5 d [37]. Figure 13 shows a representation of the system. The tracer, potassium bromide (KBr), was introduced to monitor steady state conditions, and sampling for various pharmaceutical compounds was done after these conditions were met. 12-hour composite samples were collected from each of the wetlands and were analyzed for naproxen, diclofenac, tonalide and ibuprofen by gas chromatography. The samples were analyzed to see the effect of wetlands on the removal of some of the most common pharmaceutical compounds present in municipal wastewater. Results as seen in Figure 14 showed that different compounds showed different removal efficiencies due to their different rates of adsorption and degradation characteristics. HSSF CWs are successful in removing considerable amount of pollutants but a combination of aerobic and anaerobic micro-environments can further improve their removal, as opposed to the purely anaerobic conditions in a horizontal flow constructed wetland. The results obtained in this study further support this, as most of the emerging pollutant removal took place in the first stage of the system where conditions were still fairly anaerobic as compared to the final stage of the system where the conditions were completely aerobic.

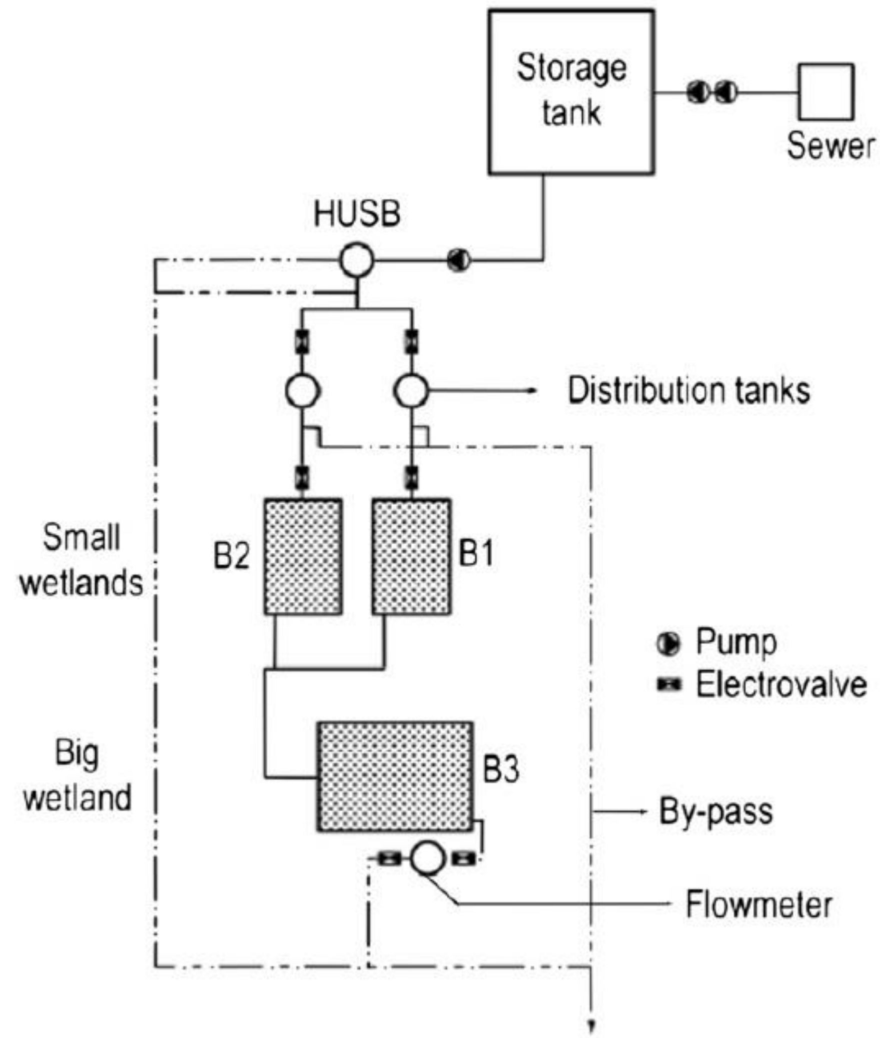


Figure 13: Barcelona wetland treatment system

Source: Ávila et al. 2010 [37]

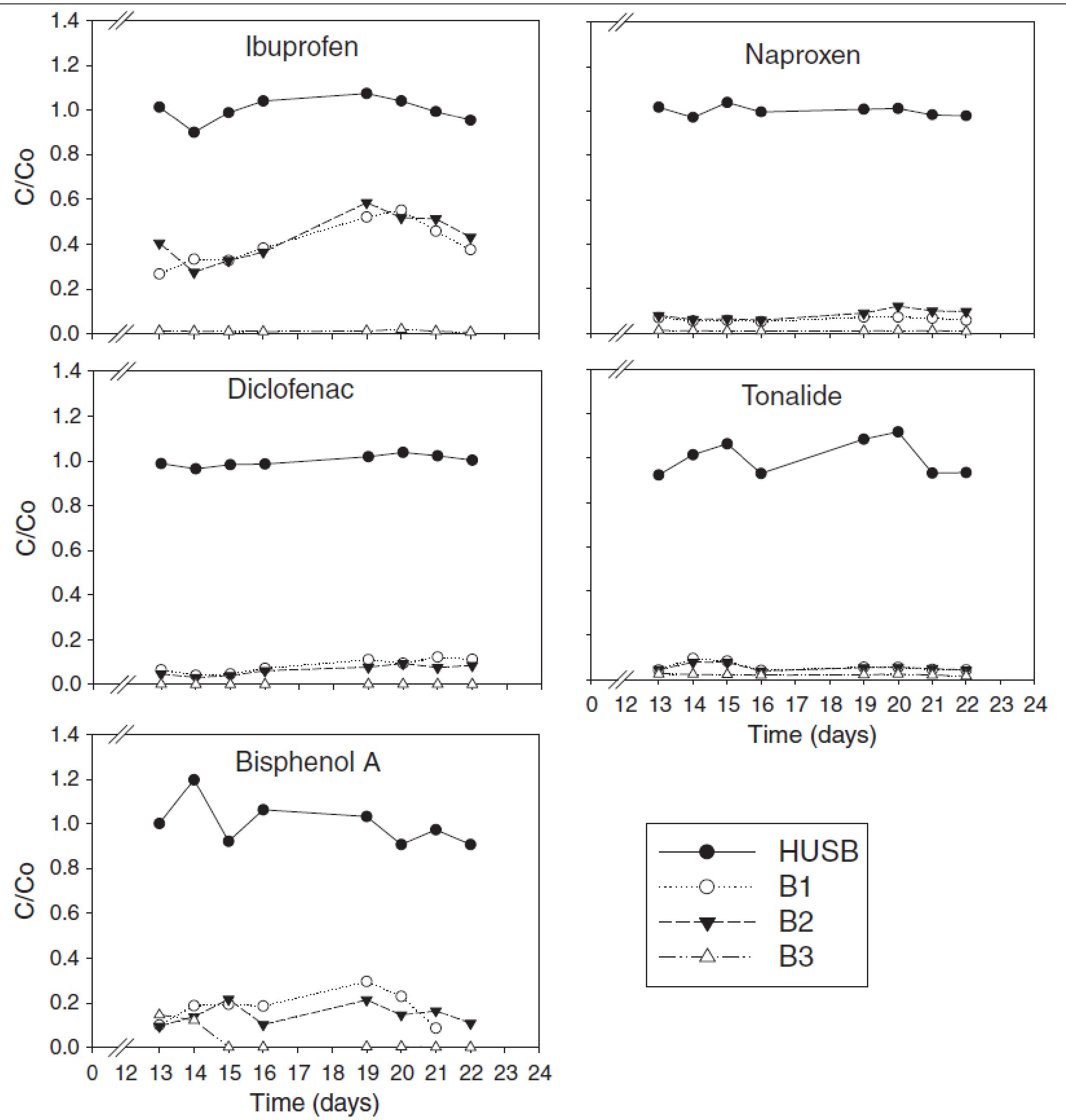


Figure 14: Results obtained from gas chromatography analysis for system at Barcelona, Spain wwhere C is the effluent concentration and C_o is the influent concentration.
Source: Ávila et. al. 2010 [37]

h) HSSF systems located at Universitat Politécnica de Catalunya- Barcelona, Spain [38]:

Wastewater from a nearby municipal sewer was the source of influent for this system, which was divided into 3 units named batch, control, and anaerobic. The layout of each unit was the same and consisted of two HSSF CWs (surface area 0.65 m^2) in parallel connected overall in series with another HSSF CW (1.65 m^2 surface area). Each of the wetlands received a flow of 84 L/d and had a HLR of 28.5 mm/day with a HRT of 3.5 per day. The wetland surfaces were colonized with common reed [38]. The three lines, shown in Figure 15 differed only in their primary treatment methods, which are as follows:

- BATCH: settler followed by saturated/unsaturated phases, as the wastewater was batch loaded the line mimicked a tidal marsh which led to saturated and unsaturated conditions

- CONTROL: settler followed by saturated phases, continuous operation ensured that the wetland was always saturated with wastewater.

- ANAEROBIC: Hydrolytic upflow sludge blanket followed by wetland permanently saturated with wastewater as in the case of control line as this unit was operated continuously as well.

The investigators wanted to review the influence of primary treatment methods on the removal efficiencies of various pharmaceutical compounds. Samples of water were collected at each stage of the system after primary treatment units and at the end of each CW. Two sampling days per week for three consecutive weeks was ensured. The samples were analyzed for the pharmaceutical compounds using gas chromatography. The results (Figure 16) obtained showed that the use of HUSB as compared to conventional settlers did not enhance the removal efficiencies of these pharmaceutical compounds. The batch mode of operation ensured sufficient aerobic and anaerobic conditions existed due to saturation and unsaturation of the wetland beds with the wastewater and hence provided for a better removal efficiency for two of the six chemicals as compared to the continuously operated wetland units.

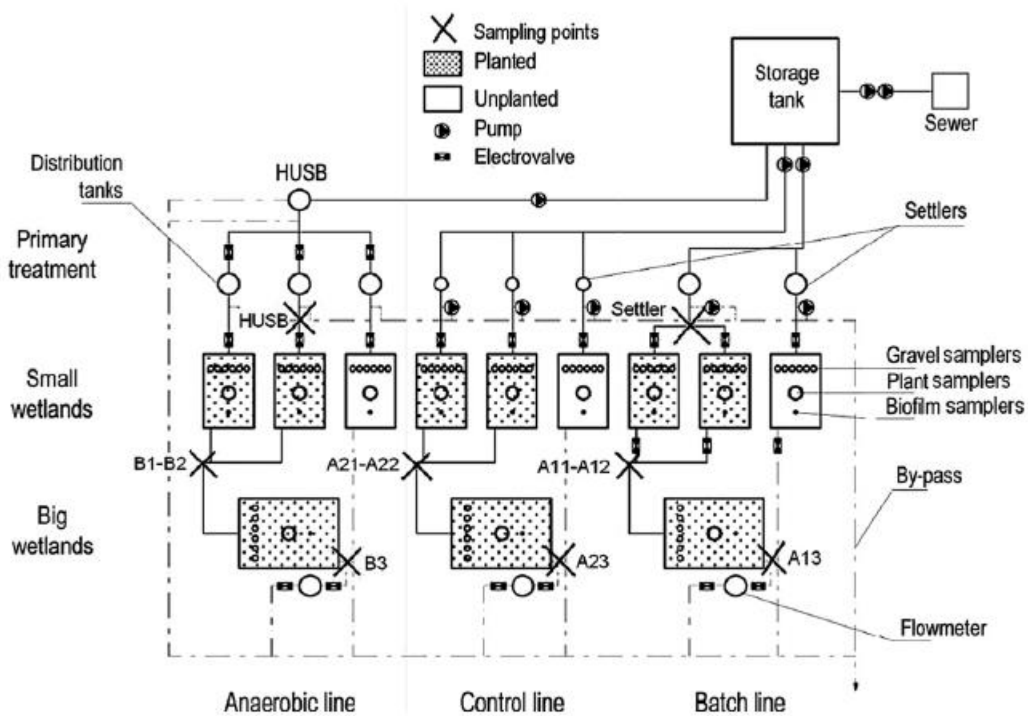


Figure 15: Schematic of wetland treatment system at University of Catalonia, Spain
Source: Ávila et al. 2013 [38]

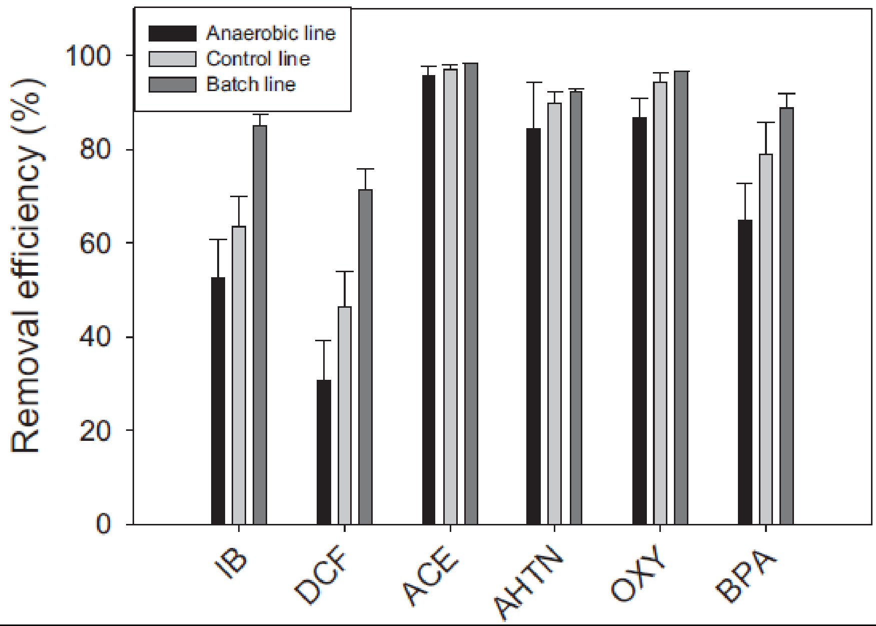


Figure 16: Removal efficiencies of various pharmaceutical compounds in the wetland system considered in Figure 16. (IB-Ibuprofen, DCF-Diclofenac, ACE-Acetaminophen, AHTHN-Tonalide, OXY-Oxybenzone and BPA-Bisphenol A)
Source: Ávila et al. 2013 [38]

i) Constructed wetland systems used for tertiary treatment Stockholm, Sweden [39]*:*

This treatment system consisted of 4 different CWs which were used for tertiary treatment of mechanical, chemical and biological processed water at a sewage treatment plant. The first two wetlands, Eskiilstuna and Nyñashamn, had a sequencing batch reactor treatment, whereas the next two, Oxelösound and Trosa, had activated sludge treatment which received wastewater intermittently and allowed for sedimentation, as compared to the sequencing batch reactor. The specifications of the 4 wetlands in the order mentioned above are as follows [39]:

- Eskiilstuna: Covers an area of 28 hectares and receives a flow of around 48,000 m^3/d. The wetland depth is 1m and has a HRT of 6-7 days. The wetland is covered by a variety of vegetation which include emergent plants like weed mangrass, bulrushes and lakeshore bulrush. The submerged vegetation includes hornwort, waterweeds and Eurasian watermilfoil. Waterlilies were also commonly observed.

- Nyn¨ashamn: Covers an area of 28 hectares and receives a flow of 5500 m^3/d. The HRT is 10-15 days. The emergent plants include bulrushes, variegated marginated sedge (*Carex riparia*), wood clubrush and sedges. The submergent vegetation includes waterweeds, rigid hornwort, and pondweeds

- Oxel¨osund: Has a total surface area of 24 hectares and receives a flow of 4000 m^3/ d. It has a HRT of 6 days. This wetland is mainly dominated by bulrushes, common weed and sedges. The submerged vegetation includes waterweeds and pondweed.

- Trosa: This wetland covers an area of 6 hectares and receives 1620 m^3/d of inflows and has a HRT of 8 days. The basin is dominated by bulrushes and common reed, but various submerged species may be present.

Sampling for 65 pharmaceutical compounds was done at the inlet and outlet of each wetland system to analyze the removal efficiency of the system, out of which only carbamazepine, diclofenac, ibuprofen and naproxen were considered for comparison between various systems in section 2.6. The samples were analyzed via SPE and mass spectrometry. It was observed under the cold Scandinavian conditions present, the average removal of the various compounds by the four wetland systems was comparable to conventional wastewater treatment plants and can be concluded that wetlands can provide a complementary wastewater treatment option but require additional advanced treatment technologies to fully remove all contaminants from the wastewater [39]. The results obtained are shown in Table 11. The negative removal efficiency indicates that the effluent water had a greater concentration of the compound as compared to influent wastewater, this could be partly due to analytical variations or daily concentration fluctuations caused during the different times of sampling.

Table 11: Removal efficiencies (%) of the 4 different systems described in case i.
E_{RE} – Eskiilstuna removal efficiency, N_{RE}- Nyn¨ashamn removal efficiency ,O_{RE} –Oxelsound removal efficiency,T_{RE} –Trosa removal efficiency.
Source: Brieholtz et al. 2012 [39]

Compound	$E_{RE\ \%}$	$N_{RE\ \%}$	$O_{RE\ \%}$	$T_{RE\ \%}$
Carbamazepine	12	11	21	-19
Diclofenac	31	24	36	30
Ibuprofen	38	80	88	5
Naproxen	34	46	75	50

j) Three HSSF wetland systems at Leon, Spain [40]*:*

The study took place at 3 different locations which are as follows:

- Fresno de laga Vega pond system: Primary treatment consisted of metallic bar screens, followed by two anaerobic ponds (3.75 m depth, 335 m^2 surface area, HRT of 0.4 day) in parallel, connected to a facultative pond (2m depth, 8481 m^2 surface area and HRT of 4.1 days) and finally a maturation pond (1.5m depth, 3169 m^2 surface are and HRT of 1 day). The wetland continuously received raw domestic wastewater which had a mean inflow rate of 3200 m^3/ d.

- Cubillas de los Oteros pond constructed wetlands: Primary treatment includes bar screens and a septic tank. This was followed by a facultative pond (1.6m depth, 1073 m^2 and HRT of 75.9 d) which was planted with *Lemna minor*, which was connected to a surface flow constructed wetland (30cm layer of 6-8 mm gravel, 40 cm depth of water, 44 m^2 surface area and a HRT of 1.2 days) colonized with *Typha latifolia* followed by a subsurface flow CW planted with *Salix atrocinerea* (55cm of 6-8 mm gravel, 585 m^2 and HRT of 5.7 days). The wetland continuously received domestic wastewater with a flow rate of 20m^3/d.

- Bustillo de Cea pond constructed wetlands: Pretreatment consisted of a bar screen and a coarse solid tank following which the wastewater flowed into a primary pond (1.5-2 m depth, 230 m^2 surface area had a HRT of 4.21 days). This was then connected to a surface flow CW (theoretical HRT 3.53 days and a surface area of 210 m^2) colonized with *Typha latifolia* which finally flowed into a subsurface flow CW planted with *Salix atrocinerea* (theoretical HRT of 362.5 m^2 and surface area of 3.16 days). The wetland received raw domestic wastewater which had a flow of 56.3 m^3/ d

All three systems received raw wastewater from a WWTP at Leon, Spain. A flow diagram of the systems described is shown in Figure 17. Sampling for various personal care products and pharmaceutical compounds was done at the end of F1, F2, F3, F4, C1, C2, C3, C4, B1, B2, B3 and B4. Results obtained after sampling are shown in Figure 18. It was concluded that most of the pharmaceutical compound removal occurred in the first stage (F1, C1 and B1) of the system irrespective of the design and this phenomenon was said to be dependent on the influent pollution concentration. The presence of various microenvironments in the CWs ensured that they had removal efficiencies comparable to those of the conventional WWTP. The presence of wetland macrophytes promoted greater removal of certain pollutants, however further experimentation is required to attest their preference for the pharmaceutical compounds.

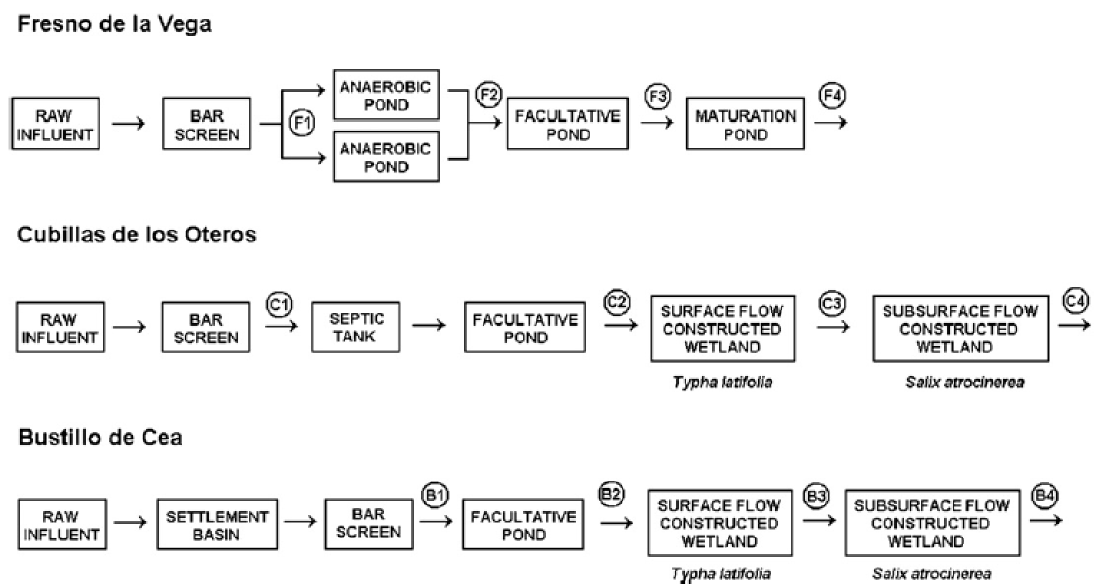


Figure 17: Schematic of system at Leon WWTP

Source:Hijosa-Valsero et al. 2009 [40]

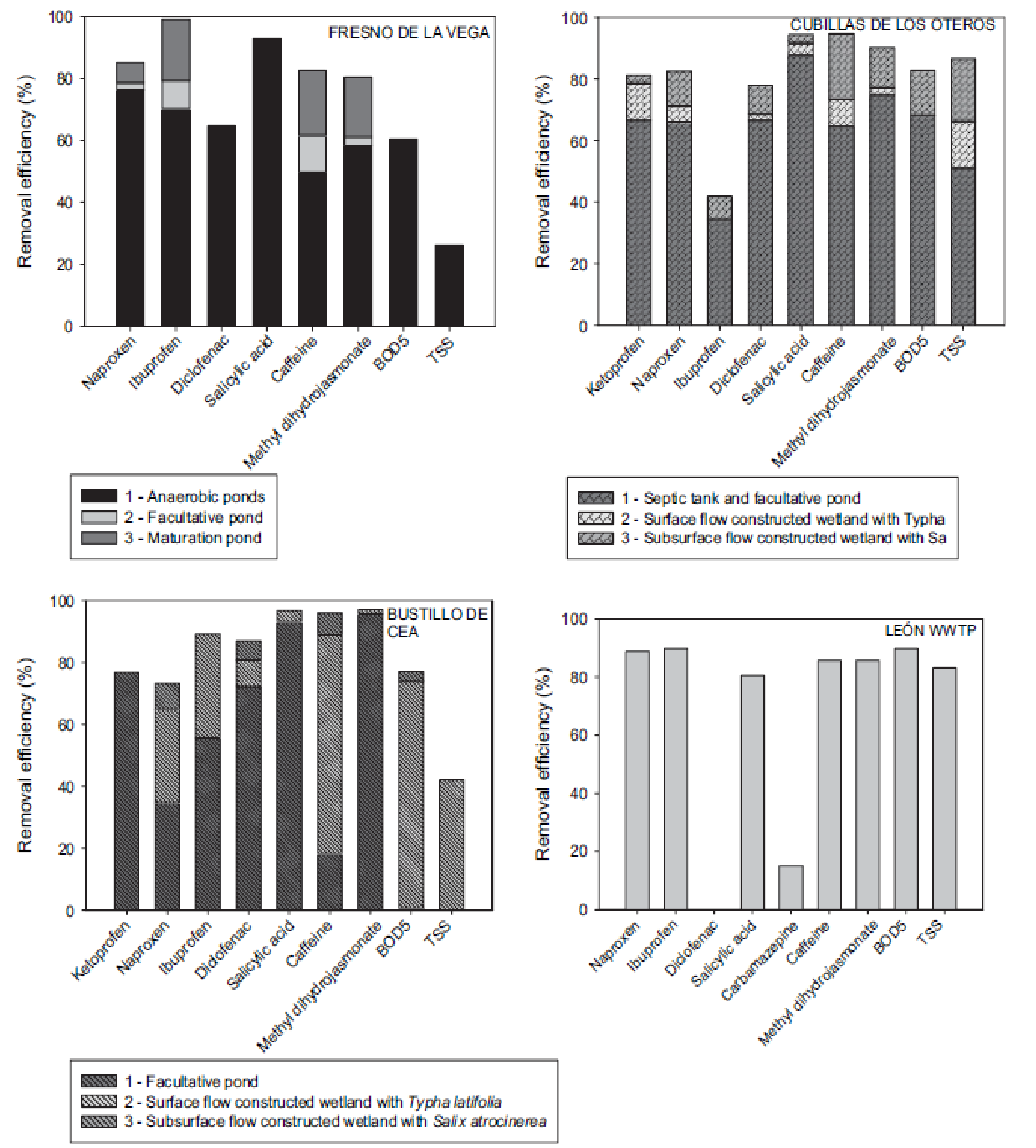


Figure 18: Removal efficiencies of wetland systems in Leon, Spain.

Source:Hijosa-Valsero et al. 2009 [40] *k) Case study of two CW systems Leon, Spain [41]:*

The description of the treatment systems are as follows:

- Case study 1: 7 different mesocosm CWs were present and set up inside a wastewater treatment plant at Leon. This study was conducted to observe the importance of plants on CW systems. Each CW had a surface area of 1 m^2. All CWs were in a fiberglass container of the dimensions 80 cm wide × 130 cm long × 50 cm high. However the wetlands had certain differences. The systems CW1 and CW5 had no gravel bed (soilless systems) with floating macrophytes and surface flow. CW2, CW3 and CW4 had 25 cm of siliceous gravel (d_{10}= 4 mm) and had a 25 cm layer of free water. CW6 and CW7 were the conventional horizontal subsurface systems. CW1, CW2 and CW3 were planted with *T. angustifolia*, CW5 and CW6 were planted with *P. australis*. CW4 and CW& were left without vegetation so as to use them as controls. The theoretical HRT of the tanks CW1, CW2, CW3, CW4, CW5, CW6 and CW7 were 2.1, 3.3, 5.1, 6.1, 2.9, 2.5 and 2.6 days respectively. A primary clarifier was used as pretreatment. Figure 19 shows the set-up of the 7 different wetlands.
- Case 2: This system consisted of 3 different mesocosm-scale treatment CWs, each with an approximate surface area of 2.4 m^2. All wetlands were operated as horizontal subsurface flow systems. The wetlands were different in their primary treatment methods which consisted of a sedimentation tank or hydrolysis upflow sludge reactor. A detailed description of the design of the wetlands is shown in Figure 20.

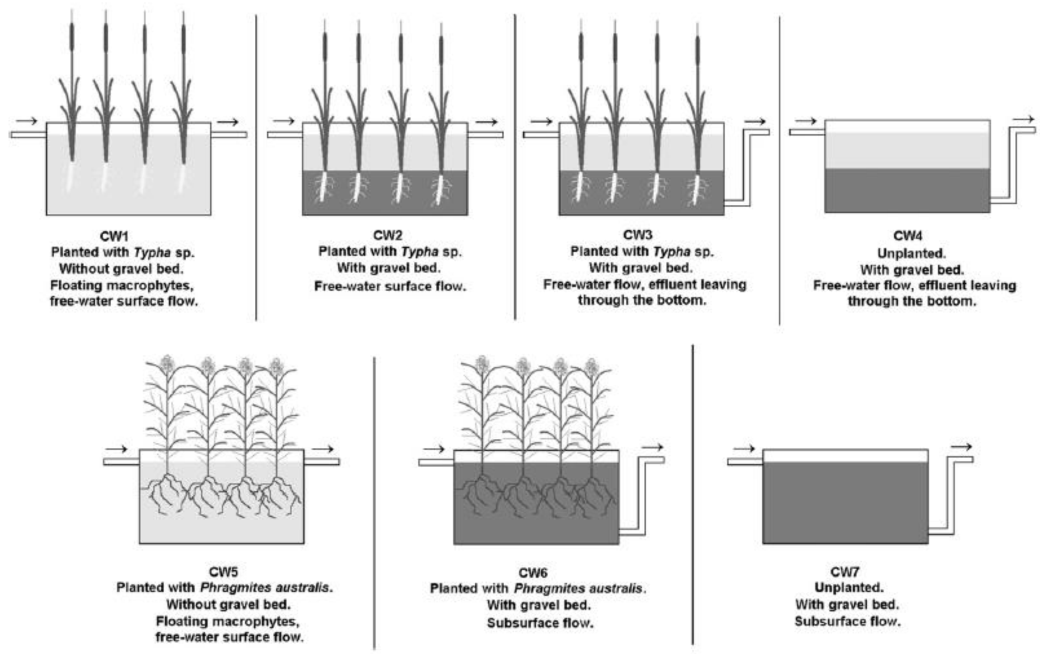


Figure 19: Case 1 of system set inside WWTP at Leon.

source: Hijosa-Valsero.et al 2011 [41]

The main aim of the study was to determine the effect of macrophyte vegetation and operating conditions of the wetland systems on the removal of various pharmaceutical compounds. In addition, pharmaceutical compound removal efficiencies were measured for summer and winter to determine the seasonal effects.

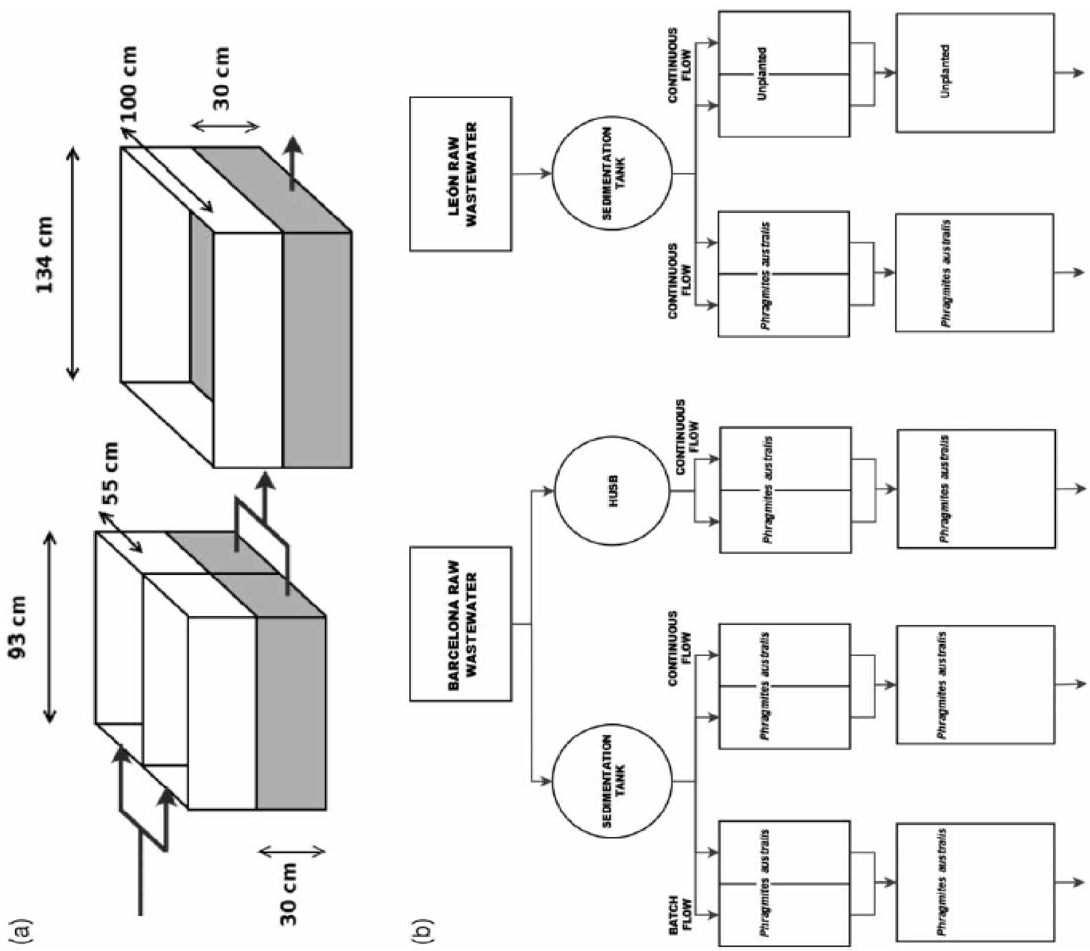


Figure 20: Case 2 of system at Leon WWTP

Source: Hijosa-Valsero et al. 2011 [41]

The pharmaceutical compounds present were analyzed using a Gas Chromatography- Mass Spectrometry method. Results for the studies conducted are shown in Table 12. It was concluded that the presence of plants favored removal of naproxen, ibuprofen and diclofenac and this beneficial influence was noticed more in the summer as compared to winter, it could however not be established which species had a greater removal efficiency. The design configuration and flow type also effected removal efficiencies, with surface flow wetlands removing greater amounts of ibuprofen and carbamazepine as compared to subsurface flow wetland which removed caffeine and ketoprofen more efficiently. All wetlands had a pretreatment stage and operated as a secondary or tertiary treatment step. In Table 12 the non-bracketed values represent the influent concentrations of the pharmaceutical compounds in both summer/winter months, while the bracketed values represent the removal efficiencies of these compounds by the respective CWs in summer/winter seasons.

Table 12: Mean influent concentrations and removal efficiencies of various pharmaceutical compounds by the different wetland systems described in subsection k. (The highlighted compounds are the common compounds compared for all the wetland systems in section 2.3) FM- Floating Macrophyte, SF- Surface Flow, FW- Free Water, SSF- Subsurface Flow, ST- Sedimentation Tank, HUSB- Hydrolytic Upflow Sludge Blanket, cont- continuous, IBU- Ibuprofen, DIC- Diclofenac, CAR- carbamazepine, NAP- Naproxen KET-ketoprofen and SAL-Salicylic Acid

	KET (a)	NAP	IBU	DIC	SAL	CAR
	Concentration in winter/ concentration in summer (%removal in winter/%removal in summer)					
Experiment 1 (mesocosm-scale, 1 m^2)						
Typha-FM-SF (b)	1.8/n.d. (40/n.d.)	3.5/1.4 (40/70)	24/8.4 (55/85)	0.8/0.4 (25/0)	9.9/10 (55/85)	1.4/1.5 (35/50)
Typha-FW-SF	1.8/n.d. (45/n.d.)	3.5/1.4 (45/25)	24/8.4 (50/65)	0.8/0.4 (25/0)	9.9/10 (65/85)	1.4/1.5 (15/30)
Typha-FW-SSF	1.8/n.d. (50/n.d.)	3.5/1.4 (65/55)	24/8.4 (75/60)	0.8/0.4 (40/0)	9.9/10 (85/85)	1.4/1.5 (25/25)
Unplanted-FW-SSF	1.8/n.d. (45/n.d.)	3.5/1.4 (60/70)	24/8.4 (45/55)	0.8/0.4 (25/35)	9.9/10 (75/90)	1.4/1.5 (0/10)
Phragmites-FM-SF	1.8/n.d. (35/n.d.)	3.5/1.4 (40/75)	24/8.4 (50/95)	0.8/0.4 (20/50)	9.9/10 (35/85)	1.4/1.5 (25/50)
Phragmites-SSF	1.8/n.d. (20/n.d.)	3.5/1.4 (45/85)	24/8.4 (40/55)	0.8/0.4 (15/35)	9.9/10 (60/85)	1.4/1.5 (25/40)
Unplanted-SSF	1.8/n.d. (10/n.d.)	3.5/1.4 (25/55)	24/8.4 (25/5)	0.8/0.4 (10/0)	9.9/10 (50/85)	1.4/1.5 (20/0)
Experiment 2 (mesocosm-scale, 2.4 m^2)						
B-ST-batch-SSF	0.6/0.5 (20/0)	3.8/5.4 (10/95)	18/25.1 (30/99)	0.6/0.8 (0/65)	34/7.3 (95/45)	4.3/2.0 (0/40)
B-ST-cont-SSF	0.6/0.5 (5/35)	3.8/5.4 (0/95)	18/25.1 (0/99)	0.6/0.8 (0/70)	34/7.3 (95/40)	4.3/2.0 (0/60)
B-HUSB-cont-SSF	0.7/0.5 (25/0)	5.8/5.7 (35/90)	24/26.0 (20/95)	0.8/0.8 (20/70)	32/22 (90/90)	7.4/2.5 (10/55)
L-ST-cont-SSF	1.8/n.d. (30/n.d.)	3.5/1.4 (45/60)	24/8.4 (50/35)	0.8/0.4 (10/0)	9.9/10 (0/80)	1.4/1.5 (5/0)
L-unplanted-ST-cont-SSF	1.8/n.d. (15/n.d.)	3.5/1.4 (25/40)	24/8.4 (25/0)	0.8/0.4 (0/0)	9.9/10 (0/0)	1.4/1.5 (10/0)

Table 13 summarizes the operation of all the hybrid wetland systems reviewed in Section 2.3

Table 13: Summary of hybrid wetland systems considered in section 2.3

(Description of wetland system numbering is given in the appendix on page)

	Pretreatment method	Type of wetland	water depth	Wetland Vegetation	Flow
f) Grand Marais	Septic Tank	Surface Flow	40-60 cm	*Typha sp.*	1700 cu. m/day
g) Barcelona	anaerobic reactor	Horizontal subsurface flow	25 cm	*Phragmites australis*	84 L/day
h					
3.1	Settler				
3.2	settler	Horizontal subsurface flow	30 cm	*Phragmites australis*	84 L/day
3.3	HUSB				
i					
4.1	Sequencing batch reactor		1 m	Mangrass, bulrushes & waterlilies	48000 cu. m/ day
4.2	Sequencing batch reactor	Surface flow		Bulrushes,wood culbrush & waterweeds	5500 cu. m/day
4.3	Active sludge treatment			Bulrushes,wood culbrush& waterweeds	4000 cu. m/day
4.4	Active sludge treatment			Bulrushes,wood culbrush & waterweeds	1620 cu. m /day
j		Hybrid of			
5.1	Metallic br screens	horizontal Flow			3200 cu. m/ day
5.2	Bar screen & Septic tank	&	2m	*Lemna minor and Typha latifolia*	20 cu. m/ day
5.3	Bar screen & solids tank	Surface Flow		*Typha latifolia and Salix atrocinerea*	56.3 cu. m/ day
k		Surface and Horizontal			
Case study 1	Primary clarifier	Subsurface flow	25 cm	*T. angustifolia and P. australis*	50 L/day
Case study 2	Sedimentation Tank or HUSB	Horizontal subsurface flow		*P. australis*	84L/day

2.4 Conventional Wastewater Parameters Concentrations at each Stage of The Systems Described in 2.3

Table 14 summarizes the concentrations of conventional wastewater parameters present at different stages of the various wetland systems described in section 2.3. These parameters include organic matter, suspended solids, total nitrogen and total phosphorus.

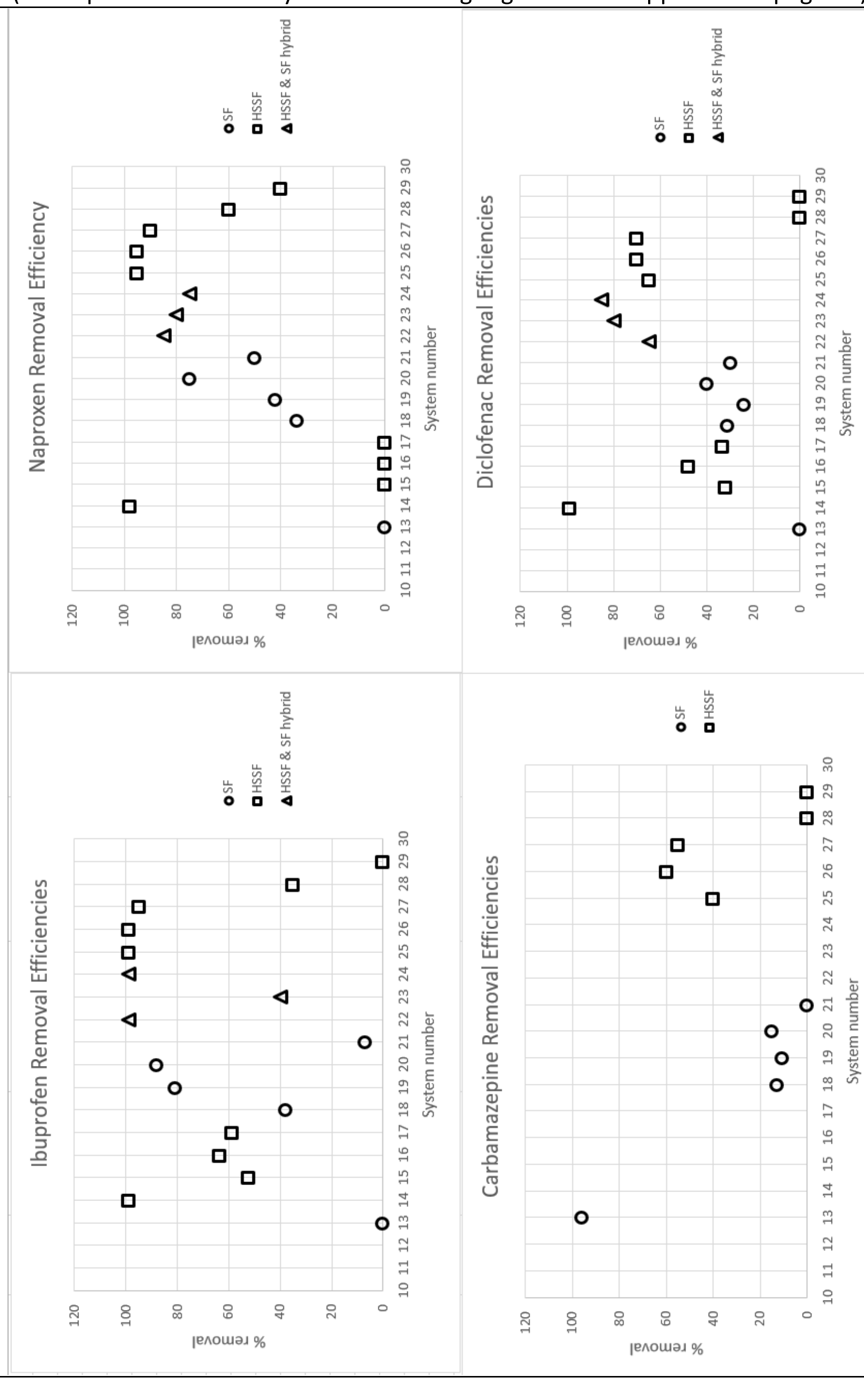
Table 14: Conventional wastewater parameter concentrations of systems in 2.3
(Description of wetland system numbering is given in the appendix on page 71)

Wetland System	DO (BOD or COD)		TSS		Nitrogen		Phosphorous	
f Grand Marais West Wetland East Wetland Outlet	BOD 130 µg/L 120 µg/L 5.3±0.5µg/L		15±5 mg/L 5.3±0.5 mg/L 4.2±1 mg/L		Below Detection limit		0.040±0.01 mg/L 0.10±0.04 mg/L below 0.01 mg/L	
g Barcelona HUSB B1 B2 B3	COD 255±42 mg/L 90±23 mg/L 98±14 mg/L 47±7 mg/L		48±5 mg/L 3±1 mg/L 4±1 mg/L 3±1 mg/L		Amonnium 27±4 mg N /L 9±3 mg N /L 9±4 mg N /L 0.02±0.01 mg N/ L		–	
	Influent	Effluent	Influent	Effluent	Influent	Effluent	Influent	Effluent
h (Anaerobic line) (Control line) (Batch line)	COD 150±20 mg/L 108±15 mg/L 89±12 mg/L	COD 82±9 mg/L 68±9mg/L 59±9 mg/L	8±3 mg/L 9±6 mg/L 11±3 mg/L	24±8 mg/L 21±7 mg/L 9±3 mg/L	17.3±3.1 mg/L 15.9±1.3 mg/L 13±0.2 mg/L	2.1±0.1 mg/L 0.8±0.6 mg/L 0.1±0.2 mg/L	–	–
	Influent	Effluent	Influent	Effluent	Influent	Effluent	Influent	Effluent
i (Eskiilstuna) (Nynashamn) (Oxelosund) (Trosa)	BOD 4 mg/L 7.9 mg/L 3.3 mg/L 18 mg/L	BOD 3 mg/L 3 mg/L 3 mg/L 3.8 mg/L	–	–	23.4 mg/L 29.3 mg/L 17.3 mg/L 24 mg/L	22.3 mg/L 18.8 mg/L 10.5 mg/L 26 mg/L	0.2 mg/L 0.2 mg/L 0.2 mg/L 0.3 mg/L	0.2 mg/L 0.1 mg/L 0.1 mg/L 0.5 mg/L
j Fresno de laga Cubillas de los oteros Bustillo de Cea	Effluent concentration 10 mg O_2/ L 19 mg O_2/ L 15 mg O_2/ L		Effluent Concentration 18 mg/L 9 mg/L 27 mg/L		–		–	
k (Case study 1) Typha-FM-SF Typha-FW-SF Typha-FW-SSF Unplanted-FW-SSF Phragmites-FM-SF Phragmites-SSF Unplanted-SSF	Effluent concentration (COD) 24±4 4 mg/L 29±6 mg/L 17±7 mg/L 50±18 mg/L 44±11 mg/L 48±2 mg/L		Effluent Concentration 9±5 mg/L 18±7 mg/L 22±3 mg/L 28±12 mg/L 12±3 mg/L 27±14 mg/L 9±3 mg/L		–		–	

2.5 Comparison of Removal Efficiencies of Pharmaceutical Compounds by Hybrid Systems

Figure 21 shows a comparison of removal efficiency of pharmaceutical compounds by the different wetland systems described in section 2.3.

Figure 21: Removal efficiencies of the hybrid wetland systems reviewed
(Description of wetland system numbering is given in the appendix on page 71)



On comparing the results in Table 14 with the results mentioned in section 2.1 for BOD, TSS, Nitrogen and Phosphorus removal efficiencies, it is seen that CWs are efficient in removing pharmaceutical compounds as well as reducing the conventional wastewater parameters. Also as seen from Figure 21, comparison of the various hybrid wetland systems, it can be said that CWs have the potential to remove some of the common pharmaceutical compounds present in domestic wastewater. The ability of CWs to remove pharmaceutical compounds can be attributed to the existence of anoxic-aerobic-anaerobic microenvironments within the wetlands, as well as different mechanisms such as biodegradation, plant uptake, sorption and photodegradation [37]. This environment is best provided by a system consisting a VFCW system. CWs, however, receive wastewater from small communities and hence have lower mass concentrations of drugs in the effluents as compared to conventional wastewater treatment plants [37]. Studies have shown that even though conventional wastewater treatment plants are efficient in meeting standard water effluent regulations, no system is effective in completely eliminating pharmaceutical compounds present in wastewater [38]. High variations in the effluent concentrations of pharmaceutical compounds are observed as their degradation depends on wastewater constituents, treatment operations and conditions [38]. Chronic toxicity effects of the various compounds are yet to be studied and thus their risk to the environment cannot be fully assessed.

2.6 Existing regulations

CWs are used to treat a variety of wastewater including those from municipal and industrial sources as well as agricultural and urban run-off but some degree of pretreatment is required so that the treated wastewater can be directly discharged into a stream or be reused. The U.S. EPA has set standards [42] for CWs so as to achieve standard effluent water qualities, which are given in Table 15 and Table 16.

Table 15: Guidelines for surface flow wetlands	
Parameter	**Design Criteria**
Effluent quality	BOD & TSS effluent: 20 & 30 mg/L
Pretreatment	Oxidation ponds (lagoons)
Design Flows	Maximum monthly flow Average flow
Max BOD loading (to entire system)	45 kg/ha-d for 20 mg/L effluent 60 kg/ha-d for 30 mg/L effluent
Max TSS loading (to entire system)	30 kg/ha-d for 20 mg/L effluent 50 kg/ha-d for 20 mg/L effluent
Water Depth	0.6-0.9 m for fully vegetated zone, 1.2-1.5 m for open water zone, 1 m for inlet settling
Minimum HRT (at maximum Flow rate)	2 days (for fully vegetated zone)
Maximum HRT (at average flow rate)	2-3 days (open water)
Minimum number of cells	3
Basin Geometry (Aspect Ratio)	Optimum : 3:1 to 5:1
Inlet settlings	Where pretreatment fails to retain settleable solids
Inlet structures	Uniform distribution across cell inlet
Outlet structures	Uniform across cell outlet
Outlet weir loading	< 200 m^3/m-d
Vegetation – emergent	*Typha* or *Scirpus* (native species preferred)
Vegetation- submerged	*Potamogeton* , *Elodea* etc.
Design porosities	0.65 for dense emergent species in fully vegetated areas, 0.75 for less dense stand of emergent species, 1 for open water areas
Total Kjeldahl Nitrogen	< 10 mg/L for 5 kg/ha.d
Total Phosphorus	<1.5 mg/L for 1.5kg/ha.d

Table 16: Guidelines for subsurface flow wetlands	
Parameter	**Criteria**
Pretreatment	Recommended primary treatment – sedimentation (e.g., septic tank, imhoff tank, primary clarifier); SSF not recommended for use after ponds because of problems with algae (clogging)
Surface area	Based on desired effluent quality and areal loading rate as follows
BOD	1.6 g/m^2-d for 20 mg/L effluent 6 g/m^2-d for 30 mg/L effluent
TSS	20 g/m^2-d for 30 mg/L effluent
TKN (Total Kjeldahl Nitrogen)	Use another process in conjunction with wetlands
TP	Not recommended for phosphorus removal
Depth Media Water	 0.5-0.6 m 0.4-0.5 m
Length	As calculated; minimum 15m
Width	As calculated; minimum 61m
Bottom slope	0.5%-1%
Top slope	Level or nearly level
Hydraulic conductivity, First 30% of length Last 70% of length	 Use 1% of clean conductivity for design calculations Use 10% of clean conductivity for design calculations
Media Inlet – 1st 2 meters Treatment Outlet – last 1m Planting media- top 10 cm	 40-80 mm 20-30 mm 40-80 mm 5-20 mm

2.7 Theoretical Wetland Design for achieving Optimal Organic Removal Efficiencies

Influent wastewater should undergo some form of pretreatment, as this step can help regulate the incoming organic load and surface loading rate into the CW and also prevents unnecessary clogging of the inlets [22] which in turn averts flooding of the wetland basin. For small domestic systems which would have almost constant wastewater discharge throughout the year, pretreatment can include either a septic or an Imhoff tank. As seen from the above case studies presented in this report, both VFCWs and HFCWs have comparable percent reductions in BOD, COD and TSS. VFCWs have enhanced oxygen transfer from the atmosphere to the beds as compared to the HFCW due to intermittent loading in vertical flow systems resulting in increased removal efficiencies of nutrients and pharmaceutical compounds. The nitrification process is faster under aerobic conditions and thus VFCW is more effective in nitrogen removal than HFCW [23, 24]. High temperatures lead to enhanced biodegradation and can govern the removal efficiencies of pharmaceutical compounds [37, 38]. Emerging contaminants have different behaviors in CWs as each compound has dissimilar sorption properties and biodegradation characteristics [37, 38]. Pharmaceutical Compounds are among the most widely studied group of emerging contaminants [39] and a key factor in their removal in CWs is the presence of various co-existing microenvironments, which result in different physicochemical conditions that allow both aerobic and anaerobic metabolic pathways [37, 38]. A hybrid CW system will thus be most beneficial for achieving high pharmaceutical compound removal. Choice of wetland plants is also highly important as there can be water losses due to evapotranspiration [39]. *Phragmites australis* a type of grass having narrow leaves is the most common macrophyte used and shows high removal efficiencies of conventional wastewater parameters. Media size and water depth are two key design factors which control the efficiency of a subsurface flow wetland for wastewater treatment [22]. Small granular media should be used to improve effectiveness of microbial removal attributed to the fact that there is a larger surface area for wastewater to be in contact with [22]. This reduction in microbial concentration occurs at the inlet of the CW and occurs due to a combination of biological and physical mechanisms (sedimentation and filtration) [22, 23].

Currently, all reuse applications of effluent from CWs are restricted to landscape irrigation and reuse for toilet flushing. Another possible reuse application is using the treated water for crop irrigation. The presence of small quantities of nitrogen and phosphorus in the effluent of the CW can act as a nutrient source for the crops. Use of effluent for crop irrigation is a possibility in the near future. However, regulations require the effluents from all wastewater treatment sites to be disinfected.

3. DESIGN PROPOSALS AND MODIFICATION FOR AN EXISTING SYSTEM

Based on the detailed working and case studies reviewed in Chapters 1and 2, Chapter 3 proposes a modification for the Jordan Lake Business Park CW system and justifications for said proposal.

3.1 Existing System to be Modified

The Jordan Lake Business Park in Apex, North Carolina has a constructed wetland system that has been active for the past 15 years and produces reclaimed wastewater that is used for toilet flush and landscape irrigation. This system design contains three major components, namely

1. A hill/marsh wetland that mimics a set of sand dunes around a marsh,
2. A wetland designed to flood and drain like a tidal marsh,
3. A set of greenhouse planters filled with tropical plants.

1200 gallons of wastewater per day from the buildings of the Business Park flow into a septic tank which has a capacity of 2000 gallons. Wastewater from the septic tank is automatically released into the wetland system once every 6-8 hours, essentially creating a batch loading system. The system has three discontinuous vegetated sand filter systems in a parallel arrangement which are placed over a large HSSF wetland. The water flows by gravity vertically through the sand filters and enters the wetland from which it flows into a pumping station. The water from this pumping station is then sent into the last set of vegetated sand filters in a greenhouse for final pollutant removal. Water leaving the greenhouse is disinfected with chlorine and sent back to the building for reuse purposes. The flooding and draining cycles of the wetland are controlled to influence nitrogen and phosphorus flow from the system. Figure 22 is a schematic of the Jordan Lake Business Park System.

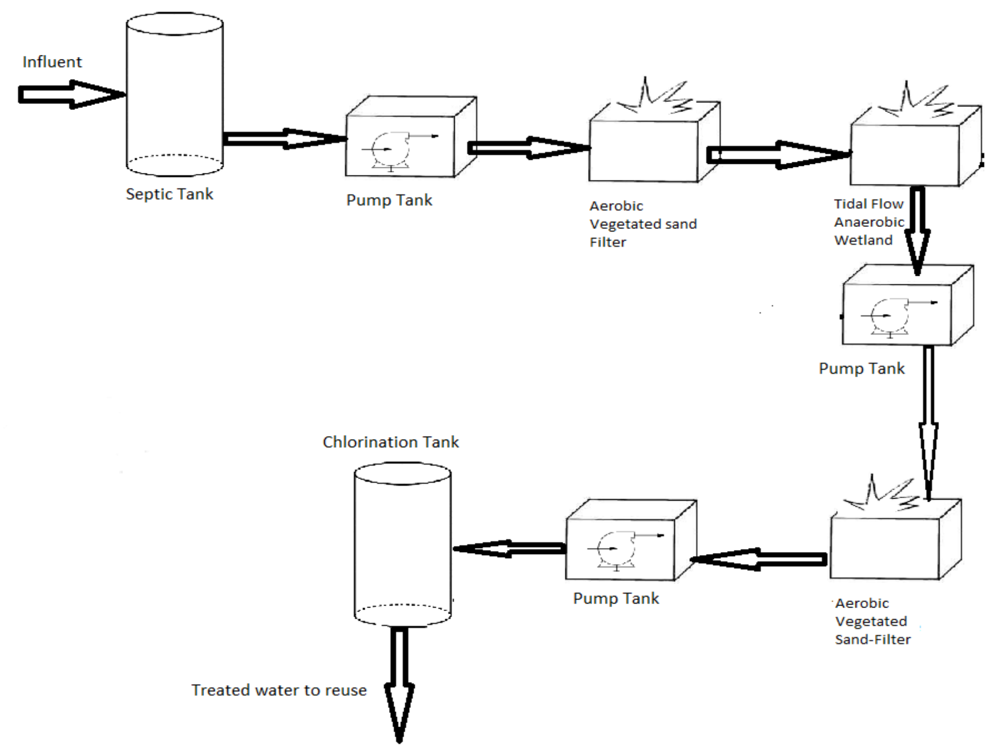


Figure 22: Jordan Lake Business Park Constructed Wetland System

3.2 Proposal of Design Modification for the Existing System

As mentioned previously, the aim of the report is to propose modifications to the existing system at Jordan Lake Business Park, which uses a constructed wetland system to treat the domestic waste generated on site. Certain modifications are proposed to the existing system in order to use the treated effluent for crop irrigation instead of its current reuse applications which include landscape irrigation and toilet flushing. These changes are proposed in order to achieve maximum removal of not only conventional wastewater pollutants but also pharmaceutical compounds. The final goal is to generate effluent which can be directly used for agricultural irrigation with the crops being edible.

The current Jordan Lake Business Park system providing reclaimed water already consists of a septic tank and thus would require no additional pretreatment. The system is designed to treat 1200 gallons/day. No structural changes are required for the existing system. The proposed modifications address the gravel and soil used for the media, the wetland vegetation (currently planted with tropical plants) and the flow regime of the system modified to improve oxygen transfer between the wetland and atmosphere, all of which would result in greater removal efficiencies of the pollutants. As seen from the wetland systems reviewed in Chapter 2, it can be concluded that the VFCW leads to greater oxidation of the wetland, resulting in better transformation of the influent pollutants. Also, wetland plants play an important role in the uptake of various pollutants as well as providing surface area for microbial degradations of contaminants to take place. *Phragmites australis*, which belongs to the family of common weeds presented the highest removal efficiencies as compared to other macrophytes, but the North Carolina Department of Agriculture and Consumer Services lists it as a noxious weed and prohibits its sale, use or culture. Thus the next best macrophyte, *Scirpus* species, can be used. Media of the wetland should be heterogeneous, with the entry and exit of the wetland bed having gravel or larger media sizes as compared to the center of the bed, as this would prevent bed clogging by providing unobstructed flow into/from the CW. After treatment in the septic tank, liquid phase could be pumped into two of the existing vegetated sand filters connected to a horizontal sub-surface flow wetland. The last portion of the HSSF wetland together with the third vegetated sand filter could be sectioned off so that the effluent from the first section could be pumped vertically from above into the last section, essentially creating a vertical flow wetland. The inflow to the wetland should be regulated such that the system is fully saturated with the influent wastewater from the septic tank so as to maintain anaerobic conditions. As the wastewater progresses through the wetland it will encounter aerobic conditions that exist in the horizontal flow system but to maintain alternating anaerobic-aerobic conditions we must maintain saturated conditions at the inlet. The loading rate should be maintained at 6 g/m^2.day of BOD. The final section can be planted with any native *Scirpus* species, which is an emergent macrophyte belonging to the family of grasses. As the grasses have small surface areas, evapotranspiration losses can be avoided.

Another modification that can be brought about to the system is by changing the wetland media to include various media in the wetland bed as described in Chapter 2. The removal mechanism of phosphorus largely depends on its adsorption to wetland media. A look into the systems reviewed show us that the weathering stone and gravel media show the greatest P removal and hence can be considered as suitable substrates for the wetland. The irregular shape of the gravel and stones will provide a straining action and also act as an efficient filter. Effluent from this wetland section can then flow into the existing soil filter boxes within the greenhouse, which would provide further nutrient uptake. This treated wastewater (which has been disinfected by chlorination) can then be reused for agricultural applications as it would be pathogen-free. A high retention time and exposure to adequate sunlight is known to destroy cryptosporidium oocysts which are not eliminated by chlorination disinfection and the proposed modification ensures sufficient retention time to provide for both mechanisms. Figure 23 shows a schematic of the proposed modified wetland system. The numbers 1, 2 and 3 represent the disjointed vegetated sand filters which are placed on a HSSF wetland. The sectioning would separate the third sand filter along with a part of the wetland, and convert it into a VFCW. As can be seen on comparing Figure 22 and Figure 23 the proposed design modification occurs at the third vegetated sand filter. In the existing design, the wastewater influent directly flows through the vegetated sand filters into the HSSF CW, whereas in the proposed design the effluent is taken out of the system at the end of the second sand filter and pumped again into the system to create a vertical flow system in the last section of the existing CW.

The effluent wastewater from the vegetated sand filters of the wetland system is sent into a greenhouse where tropical crops are planted. The uptake of chemicals by these crops would need to be measured by testing their edible portion. To check if the proposed design modification brings about changes to the quality of effluent treated wastewater, removal efficiencies achieved by the system before and after system modification can be compared. Analyzing the edible portion of the crops for the presence of any pharmaceutical compound or major pollutant can be used to justify the success of the proposed modification. The presence of pharmaceutical compounds in CW-treated wastewater is generally below detection limit and, hence, for evaluating potential uptake the wastewater could be spiked with a cross-section of chemicals. Table 17 shows the concentrations of pharmaceutical compounds in effluent of conventional sewage treatment plants. The modifications would need to take into account the ability of the soil to remove any residual chemicals from CW treatment (well below those concentrations listed in the table) and thus make any crops grown from this wastewater indistinguishable from those conventionally grown.

Table 17: Average range of concentration of some pharmaceutical compounds in the effluent of 50 sewage treatment plants

Pharmaceutical Compound	Effluent Range (ng/L)
Carbamazepine	300-1200
Diclofenac	250-5450
Ibuprofen	20-1820
Naproxen	290-5220

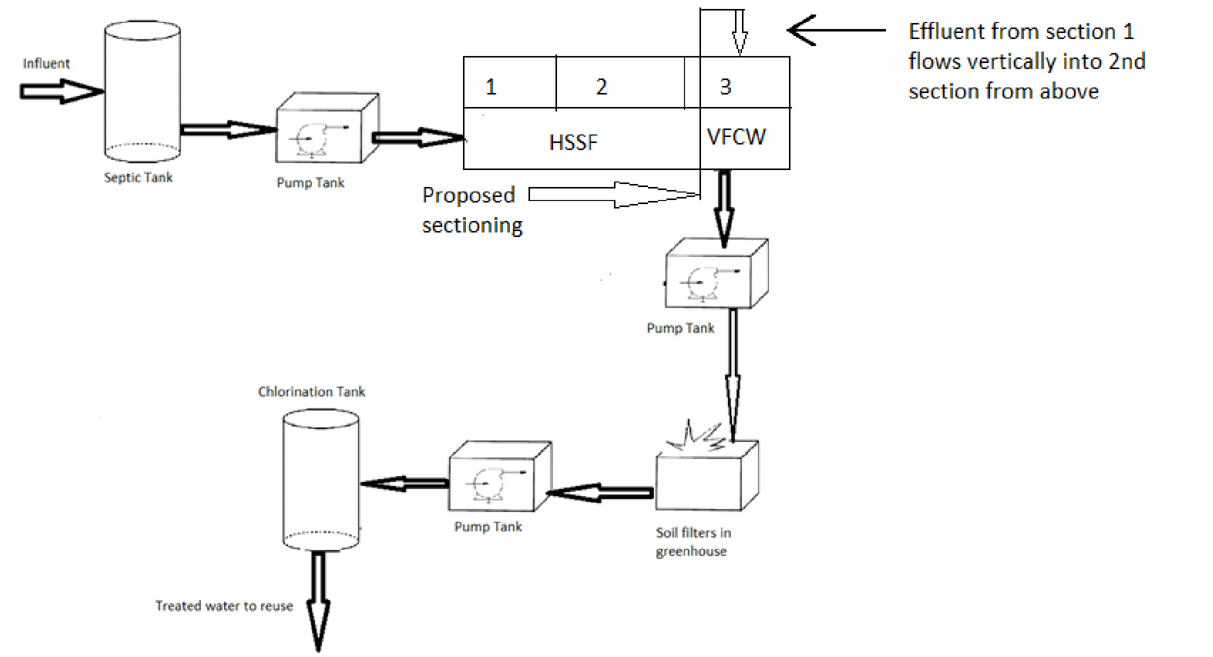


Figure 23: Proposed design modifications where section 1 refers to the combined system of vegetated sand filters 1&2 along with HSSF.

3.3 Justification of Design Modification Proposal:

The current system is comprised of a hybrid wetland system with all the CWs connected in series and modelled for horizontal flow. Wetlands reviewed in Chapter 2 show that VFCWs offer better aerobic conditions which leads to better oxygen transfer between the system and atmosphere. This is a major reason as to why the removal efficiencies of nutrients and pharmaceutical compounds is better in VFCW as compared to HFCW, which has limited oxygen transfer capability. For high ammonia influent concentrations VFCW are best for complete nitrification and denitrification processes. With a treatment goal of reuse of the water for crop irrigation purposes, the low amounts of bioavailable nitrogen and phosphorus present after various bio-chemical transformations could be used as an advantage. These nutrients, which are generally supplied externally to crops in the form of fertilizers, would not need to be additionally added if the treated water is used. Even though the presence of these nutrients would be advantageous for crop irrigation, the main aim of using a constructed wetland for the treatment of wastewater is to achieve an effluent which has quality parameters comparable to that of the regular freshwater used for edible crop irrigation. This design proposal is purely hypothetical and would require piloting before being applied at full scale.

3.4 Constructed Wetland vs. Traditional Wastewater Treatment Plants (WWTP)

The reclaimed water system at Jordan lake Business Park is already constructed and in operation. The only investment required would be for the additional piping and pumping costs incurred due to the modifications proposed. These slight modifications to the system might make the system more efficient in terms of treating the on-site wastewater and expanding the options for reuse of the treated water. Figure 24 gives a comparison of construction, operation, and maintenance costs for various wastewater treatment systems with a capacity of 0.1 to 1 million gallons per day. The operating and maintenance costs include labor, energy, chemicals and materials such as replacement equipment and parts obtained from the U.S. EPA Innovative and Alternative Technology Assessment Manual [42]. All the costs are presented in dollars per million gallons a day. The capital costs were obtained from USEPA manual as well. The construction costs included those of engineering and construction management in addition to piping, electrical systems, instrumentation and site preparation. Cost of land was, however, excluded. All costs are in March 1993 U.S. dollars.

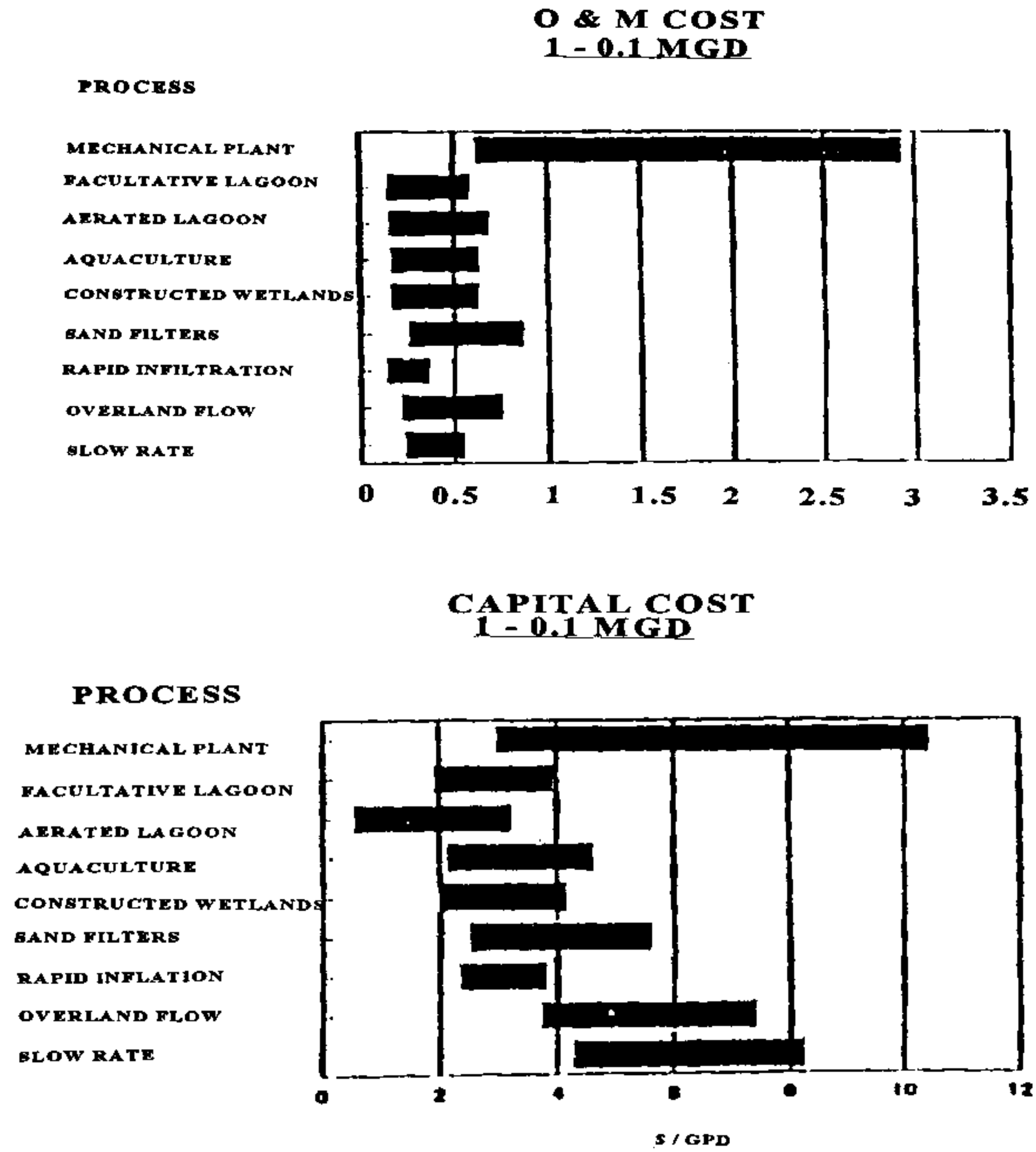


Figure 24: Construction and operation and maintenance costs of various wastewater treatment systems.

Source: UNEP-IETC 1998 [43]

Table 18 compares the environmental impact of WWTPs and CWs. It can be seen that CWs have the lowest greenhouse gas emissions which makes them not only sustainable but also environmentally friendly.

Table 18: Greenhouse gas emissions from various wastewater treatment methods.
Source: Stefanakis et al. 2014 [29]

Technique	CO_2 Emissions		Other GGH	By-products
	Investment	***Operation***		
Secondary Treatment				
Activated sludge plants (ASP)	*Medium* Use of concrete/steel tanks 21-10 kg CO_2/1000 m^3 for 2000-100,000 pe	*Medium* 55% of energy consumed for aeration. Depends on size and wastewater composition *Aeration*: 15 kWh/pe/year or 88 kg CO_2/1000 m^3 *Biological breakdown*: 55 g CO_2/pe/d or 224 kg CO_2/1000 m^3	*N_2O*: 0.004 × N load for 53 mg N/L, it is 0.2 kg N_2O/1000 m^3 *CH_4*: 39 g/pe/year or 0.4 kg CH_4/1000 m^3	Sludge
Trickling filters (TF)	*Medium* Use of concrete/steel tanks 21-10 kg CO_2/1000 m^3 for 2000 and 100,000 pe biofilter	*Low* *Biological breakdown*: 55 g CO_2/pe/d or 224 kg CO_2/1000 m^3	*N_2O*: insignificant *CH_4*: insignificant	Biomass of filter media (humus sludge)
Biological nutrient removal (BNR)	*Medium* Use of concrete/steel tanks CO_2 emissions similar to TF	*Medium* Energy consumption for aeration, sludge return, mixing (slightly higher than simple ASP) *Aerobic*: CO_2 emissions similar ASP *Anaerobic*: minimal CO_2 emissions (mainly CH_4)	*Aerobic*: similar to ASP *Anaerobic*: higher CH_4 emissions than in ASP	Sludge
Constructed wetlands	*Medium* 16 kg CO_2/1000 m^3 for 2000 pe (20 years asset life)	*Low* Passive systems, energy for pump use 4-309 mg CO_2/m^2/h	*N_2O*: insignificant *CH_4*: 0-93 mg CH_4/m^2/h	Reed biomass

Appendix

Table 19: Reference for the wetland systems reviewed in this report

	System Descriptions	System notation in the brief
1	Two parallel HSSF wetlands	a
	8 HSSF wetlands	b
2	Pair A	
3	Pair B	
4	Pair C	
5	Pair D	
	Pilot Plant system	c
6	HFCW	
7	VFCW	
	Lysimeter system	d
8	VFCW_P_2002	
9	VFCW_T_2002	
10	VFCW_P_2003	
11	VFCW_T_2003	
12	Two stage wetland system	e
13	Grand Marais SFCW	f
14	Barcelona HSSF CW	g
	Hybrid HSSF system	h
15	Anaerobic line	
16	Control line	
17	Batch line	
	CWs used for tertiary treatment	i
18	Eskiilstuna	
19	Nynäshamn	
20	Oxelösound	
21	Trosa	
	CWs used in small communities	j
22	Fresno de laga	
23	Cubillas de los Oteros	
24	Bustillo de Cea	
	Case 2	k
25	B-ST-batch-SSF	
26	B-ST-cont-SSF	
27	B-HUSB-cont-SSF	
28	L-ST-cont-SSF	
29	L-UP-S-cont-SSF	

Notes for Table 19:

VFCW_P_2002 – Vertical Flow Constructed Wetland planted with *Phragmites* sp. and operated in the year 2002

VFCW_T_ 2002- Vertical Flow Constructed Wetland planted with *Typha* sp. and operated in the year 2002

VFCW_P_2003- Vertical Flow Constructed Wetland planted with *Phragmites* sp. and operated in the year 2003

VFCW_T_ 2003- Vertical Flow Constructed Wetland planted with *Typha* sp. and operated in the year 2003

SFCW- Surface Flow Constructed Wetland

B-ST-batch-SSF- Influent wastewater was from a plant in Barcelona, pretreatment method consisted of a sedimentation tank, was operated under batch loading conditions and was a subsurface flow wetland system.

B-ST-cont-SSF- Influent wastewater was from a plant in Barcelona, pretreatment method consisted of a sedimentation tank, was operated under continuous loading conditions and was a subsurface flow wetland system.

B-HUSB-cont-SSF-Influent wastewater was from a plant in Barcelona, pretreatment method consisted of a hydrolytic upflow sludge blanket, was operated under batch loading conditions and was a subsurface flow wetland system

L-ST-cont-SSF-Influent wastewater was from a plant in León, pretreatment method consisted of a sedimentation tank, was operated under continuous loading conditions and was a subsurface flow wetland system

L-UP-S-cont-SSF-Influent wastewater was from a plant in Barcelona, pretreatment method consisted of a sedimentation tank, was operated under continuous loading conditions and was a subsurface flow wetland system with one of the wetlands remaining unplanted.

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