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CONSTRUCTED WETLANDS A COMPREHENSIVE REVIEW

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ABSTRACT

Constructed wetlands are wastewater treatment systems consisted of one or more treatment cells in a building designed and constructed to provide wastewater treatment. Constructed wetlands are classified into two types: free water surface (FWS) wetlands (also known as surface flow wetlands) closely resemble natural wetlands in appearance because they contain aquatic plants that are rooted in a soil layer on the bottom of the wetland and water flows through the leaves and stems of plants. Subsurface flow wetlands (SSF) or known as a vegetated submerged bed (VSB) systems do not resemble natural wetlands because they have no standing water. They contain a bed of media (such as crushed rock, small stones, gravel, sand, or soil) that has been planted with aquatic plants. When properly designed and operated, wastewater stays beneath the surface of the media, flows in contact with the roots and rhizomes of the plants, and is not visible or available to wildlife. Constructed wetlands are an appropriate technology for areas where inexpensive land is generally available and skilled labor is less available. In this paper, a comprehensive review covered types, characteristics, design variation and considerations, limitations, and the advantages and disadvantages of constructed wetlands.

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1. INTRODUCTION

Water quality deterioration created pressure on decision-makers to adopt stringent regulations to find new means of cost-efficient water treatment methods in order to create healthy ecological conditions Forslund et al. (2009). Constructed wetlands are a natural and cost-efficient treatment process to enhance and improve water quality Jing et al. (2001) and decrease overall eutrophication Greenaway (2001), Sirianuntapiboon and S. Jitvimolnimit (2007). Constructed wetlands being in use since the ’50s and provide better treatment for different kinds of wastewater such as (urban runoff, municipal wastewater, industrial wastewater, agricultural waste, and acid mine drainage by mimic biological, physical, and chemical processes that happen in natural wetland systems Vymazal (2011). The use of constructed wetlands for wastewater treatment has drastically increased over the last 40 years Bastian and Hammer, (2020), Vymazal (2011). Constructed wetlands are considered as an “eco-friendly” system to replace conventional secondary and tertiary municipal and industrial wastewater treatment processes Dhote and Dixit (2009), Moreira and Dias (2020). Constructed wetlands are fast gaining ground and became a practical water resource management strategy in many developing countries Yalcuk and Ugurlu (2009)

Constructed wetlands for wastewater treatment substituted conventional wastewater treatment processes and targets to create a sustainable and robust treatment system based on a complex natural ecosystem Bastian and Hammer, (2020). Wetland as an unconventional treatment technology for wastewater has great potential in developing countries which provides a comparative advantage over conventional, mechanized treatment processes. it has a high level of self-sufficiency, provides an ecological balance, and is economically feasible Galbraith et al. (2005).

Usually, constructed wetland well known consist designed basin that comprises water, substrate material, and vascular plants. These components can be deployed in constructing a wetland Vymazal (2010). additionally, wetlands contain microbial communities and aquatic invertebrates which can grow naturally Vymazal (2010) . The flow in constructed wetlands is controlled and the water spreads consistently among the wetland plants. Constructed wetlands mimic the optimal treatment conditions which could be found in natural wetlands, with supreme flexibility of being constructible at almost any location and different conditions Vymazal (2007), Batool and Saleh (2020). Constructed wetlands with developing macrophytes are well known used to treat municipal wastewater, representing a tertiary treatment stage Vymazal (2011). In the constructed wetland, wastewater either flow on top of the existing soil (surface wetland) or through a porous medium such as gravel (subsurface wetland). Different mechanisms were suggested to improve water quality in constructed wetlands systems and they are frequently interrelated. These mechanisms include Vymazal (2001):

1) Settling of suspended particular matter PM.
2) Filtration and chemical precipitation through contact of wastewater with substrate litter and plants.
3) Chemical transformation of pollutants.
4) Adsorption and ion exchange on the surfaces of plants, substrate, sediment, and litter.
5) Breakdown and transformation of pollutants by microorganisms
6) Plants uptake of nutrients and
7) Plants predation and natural die-off of pathogens.

The growing interest in wetland systems is due in part to the recognition that natural systems offer. Due to the excessive advantages that wetlands and constructed wetlands can provide over conventional activated sludge or trickling filter systems the growing interest in wetlands became prominent. wetlands often consume less energy, are more reliable, require less operation and maintenance and, as a result, costs less and had an added ecosystem value Vymazal (2010).

2. CONSTRUCTED WETLANDS CHARACTERISTICS

2.1. SUBSTRATES

Wetland substrates physically are the support the wetland vegetation, which offer sites where biochemical and chemical transformations processes occur, and provide sites for storage of removed pollutants and waste. Usually, substrates include soil type, sand, gravel, and organic materials Yang et al. (2018). Most soils are suitable for constructed wetlands Scholz and Lee (2005). But for design considerations, different soil properties should be considered in selecting soils to comprise cation exchange capacity (CEC), soil pH, electrical conductivity (EC), soil texture, and soil organic matter. It is recommended to have a constructed substrate of sand or gravel when the receiving domestic and agricultural wastewaters are highly loaded with nutrients, such as can be built with. It was reported that soils that contain more than 15% clay are generally suitable for constructed wetland substrate Vymazal (2010). Also, gravel and sands are highly suitable for constructed wetlands substrate and are considered inexpensive materials and provide an ideal texture for hand planting. Moreover, organic material found in the substrate provides a source of carbon to support microbial activity. Organic material also consumes oxygen and creates anoxic environments that are required for some treatment processes Vymazal (2001), Scholz and Lee (2005).

2.2. HYDROLOGIC CHARACTERISTICS

Periods of inundation and saturation created in the wetlands are due to the hydrologic regime of the wetlands. Hydrologic conditions affect the soils and nutrients conditions and characteristics, which in turn influence the status of the biota Vymazal (2001). The flow and storage volume determine the length of time that water spends in the wetland and, thus, the opportunity for interactions between waterborne substances and the wetland ecosystem Vymazal (2001), Scholz and Lee (2005). hydrological characteristics of wetlands include retention time, water depth, flow velocity through the wetland, and the number of days per year in which the wetland is inundated is among the most important aspects of the wetlands Vymazal (2001).

2.3. WETLAND VEGETATION

Wetlands are typically a suitable home to a variety of microbial and plant species due to the presence of ample water Brix (1994). The presence of macrophytes is one of the most obvious features of wetlands and it distinguishes constructed wetlands from unplanted soil filters or lagoons. Wetlands are home to a diverse group of plants, including emergent, floating, and submerged species Vymazal (2001). emergent macrophytes occurrence and distribution are easily managed and they are specified for wastewater treatment wetlands Fonder and Headley (2013). The main role of wetland vegetation is to assimilate nutrients into plant biomass and oxygenates the substrate in the vicinity of the plant root Brix (1994). Macrophytes remove pollutants by directly assimilating them into their tissue and providing surfaces and a suitable environment for microorganisms to transform the nutrients and decrease their concentrations Healy et al. (2007). The macrophytes growing in constructed wetlands have several properties in relation to the treatment process (Table 1) that make them an essential component of the design.

Table 1 Role of Macrophytes in Constructed Wetlands treatment system, adapted from Brix (1997), Brix (2003).

Macrophyte Property	Role in Treatment Process
Aerial plant tissue	Light attenuation → reduced growth of phytoplankton Influence of microclimate → insulation during winter Reduced wind velocity → reduced risk of re-suspension Aesthetic pleasing appearance of the system Storage of nutrients.

Plant tissue in water	Filtering effect → filter out large debris Reduced current velocity → increased rate of sedimentation, reduced risk of re-suspension Provides surface area for attached biofilms Excretion of photosynthetic oxygen → increases aerobic degradation Uptake of nutrients.
Roots and rhizomes in the sediment	Stabilizing the sediment surface → less erosion Prevent the medium from clogging in vertical flow systems Release of oxygen increase degradation (and nitrification) Uptake of nutrients Release of antibiotics.

Source (Brix (1997), Brix (2003))

Persistent emergent plants are the most often used in constructed wetlands, such as bulrushes (*Scirpus*), spikerush (*Efeocharis*), other sedges (*Cyperus*), Rushes (*Juncus*), common reed (*Phragrnites*), and cattails (*Typha*) (Table 2). Not all wetland species are suitable for wastewater treatment since plants for treatment wetlands must be able to tolerate the combination of continuous flooding and exposure to wastewater or stormwater containing relatively high and often variable concentrations of pollutants Vymazal (2013), Kadlec and Wallace (2008). Wetland plants are adapted to survive in saturated conditions Pezeshki (2001). While most plants absorb oxygen through their roots, wetland plants can also absorb oxygen through their stems and leaves and transport it to their roots through specialized root cells Pezeshki (2001).

Table 2 Common plants used in constructed wetlands in grey-water and wastewater treatment systems adapted from Davis (1995)

Species	Maximum Water Depth *	Environmental Conditions
Arrow arum *Peltandra viginica*	30 cm	Fully sunny to partial cloudy conditions. Excessive wildlife value. Foliage and rootstocks are not eatable. Slow grower. Withstand pH: 5.0 – 6.5.
Arrowhead / duck potato *Saggitaria latifolia*	30 cm	Very aggressive colonizer. Mallards and muskrats can quickly consume tubers. More water loss through transpiration.
Common three-square bulrush *Scirpus pungens*	15 cm	Fast colonizer. Can tolerate periods of dryness. High metal removal. High waterfowl and songbird value.
Soft stem bulrush *Scirpus validus*	30 cm	Aggressive colonizer. Full sun. High pollutant removal. Provides food and cover for many species of birds. pH: 6.5 – 8.5.
Blue flag iris *Iris versicolor*	7-15 cm	Attractive flowers. Can tolerate partial shade but requires full sun to flower. Prefers acidic soil. Tolerant of high nutrient levels.
Broad – leaved cattail ** *Typha latifolia*	30-45 cm	Aggressive. Tubers eaten by muskrats and beaver. High pollutant treatment. pH: 3.0 – 8.5.
Narrow – leaved cattail **	30 cm	Aggressive. Tubers eaten by muskrats and beaver. Tolerates brackish water. pH: 3.7 – 8.5.

Typha angustifolio		
Reed canary grass *Phalaris arundinocea*	15 cm	Grows on exposed areas and in shallow water. Good ground cover for berms.
Lizard's tail *Saururus cernuus*	15 cm	Rapid grower. Shade tolerant. Low wildlife value except for wood ducks.
Pickerelweed *Pontedaria cordata*	30 cm	Full sun to partial shade. Moderate wildlife value. Nectar for butterflies. pH: 6.0 – 8.0.
Common reed ** *Phragmites australis*	7 cm	Highly invasive; considered a pest species in many places. Poor wildlife value. pH: 3.7 – 8.0.
Soft rush *Juncus effuses*	7 cm	Tolerate wet or dry conditions. Food for birds. Often grows in tussocks or hummocks.
Spike rush *Eleocharis palustris*	7 cm	Tolerate partial shade.
Sedges *Carex spp.*	7 cm	Many wetlands and several upland species. High wildlife value for waterfowl and songbirds.
Spatterdock *Nuphar luteum*	150 cm 60 cm	Tolerant of fluctuating water levels. Moderate food values for wildlife, high cover value. Tolerate acidic water (up to pH 5.0).
Sweet flag *Acorus calamus*	7 cm	Produces distinctive flowers. Not a rapid colonizer. Tolerates acidic conditions. Tolerate of dry periods and partial shade. Low wildlife value.
Wild rice *Zizania aquattica*	30cm	Requires full sun. High wildlife value (seeds, plant parts, and rootstocks are food for birds). Eaten by muskrats. Annual, non-persistent. Does not reproduce vegetatively.

It is recommended that native and local species should be used for wastewater and storm-water constructed wetlands, because they are adapted to the local climate conditions, soils, and surrounding plant and animal communities, and have efficient treatment ability Vymazal (2013), Tanner (1996). Several studies measuring both types of treatment systems, with and without plants, proved that the performance of constructed wetlands is better in the presence of (Kadlec and Knight, 1996) Kadlec and Wallace (2008), Tanner (1996). Major nutrients (N, P, and K) consist on average of 2.26, 0.25, and 2.6 % dry weight of plant biomass typically used in wetland treatment systems. Studies showed that wetland vegetation can directly uptake and remove up to 20% of nutrients found within treatment effluent depending on the type of vegetation and climatic conditions. The uptake capacity of emergent macrophytes is 50 to 150 kg P ha-1 year-1 and 1000 to 25000 kg N ha-1 year-1 Vymazal (2011), Vymazal (2007), Vymazal (2001), LaFlamme (2006). However, the removal of nutrients through direct uptake by plants is only significant in the short term Vymazal (2007).

2.4. WETLAND MICROORGANISMS AND ANIMALS

Microorganisms that exist in wetlands include a diverse microflora of bacteria, fungi, and algae that are essential for nutrients cycling and pollutant transformations and removal Kadlec and Wallace (2008). Wetland microorganisms have the ability to remove soluble organic matters, coagulate and colloidal particles, stabilize organic matter, and uses organic matter and convert it into gases and new cell tissue Stottmeister et al. (2003). Microbial transformations that occur in wetlands are aerobic and anaerobic; microorganisms are the same as in the conventional wastewater treatment processes Juhanson and Truu (2009). Different types of organisms, however, have specific tolerances and requirements for dissolved oxygen, temperature ranges, and nutrients. Constructed wetlands provide enriched habitats for diverse invertebrates and vertebrates. Invertebrate animals, such as insects and worms have a special role in the treatment process by fragmenting detritus, consuming organic matter, and act as important predators of mosquito larvae, they are also attracting a variety of amphibians, birds, turtles, and mammals Kadlec and Wallace (2008), Juhanson and Truu (2009).

3. CONSTRUCTED WETLANDS TYPES

Constructed wetlands are classified into various parameters. The most significant parameters are a water flow regime (surface and sub-surface) and the type of macrophytic growth (as emergent, submerged, free-floating, and floating-leaved plants) Vymazal (2010), Vymazal (2001). The quality of the final effluent from the systems improves with the complexity and the improvement of the system Vymazal and Kröpfelová (2008). Two general types of wetlands that are typically constructed for wastewater treatment are free water surface flow (FWS) and subsurface flow (SSF) wetlands Vymazal (2001).

3.1. FREE WATER SURFACE FLOW WETLANDS

A free water surface (FWS) wetland is designed to comprise a shallow basin, soil, or another medium to support the roots of vegetation, and a water control structure that maintains a shallow depth of water Vymazal (2001), Kadlec and Wallace (2008), Davis (1995). Plug-flow conditions are achieved in FWS by maintaining shallow water depth, low water flows velocity, and the presence of the plant stalks and litter to regulate water flow and, especially in long and narrow channels. Surface-flow constructed wetlands simulate natural wetlands where water is introduced above the ground surface and flows through the wetlands at depths averaging less than 15 cm, ranging up to 30 cm (Figure 1) Kadlec and Wallace (2008). FWS wetlands can offer wildlife habitat and aesthetic benefits as well as a perfect water treatment process. In FWS wetlands, aerobic conditions are dominant near the surface layer while the deeper layers and waters and substrate are usually contained an anaerobic regime Vymazal (2011), Vymazal (2001), Kadlec and Wallace (2008). In many systems, removal efficiency is affected by the proportional relation of the inflow of concentrations. While in FWS constructed wetlands have an effluent with low concentrations of organics and suspended solids which reflect better removal. It was reported that the removal efficiency of nitrogen and phosphorus is highly variable and reaches 50% Vymazal and Kröpfelová (2008), Vymazal and Kröpfelová (2009). Also, the removal efficiency of fecal coliforms varies and could be between one and two folds Vymazal (2007), Vymazal and Kröpfelová (2008), Vymazal and Kröpfelová (2009). A potential layout would be a cell with an open water zone for initial solids settling to promote solids flocculation and separation, then an emergent vegetation zone with two days retention at maximum flow, then an open water zone of two days retention, and then an emergent vegetation zone of two days retention. FWS-constructed wetlands have been designed with an aspect ratio, (which is length: width ratio) of less than 1:1 to over 90:1 Scholz and Lee (2005), Kadlec and Wallace (2008), Davis (1995), but most recommended and optimum ratios were found to be in the range of 3:1 to 5:1.

Approximately 15 cm of soil layer was placed over the liner to support vegetation Kadlec and Wallace (2008). Wetland plants can be established either by seeding or transplanting. Maintenance of an FWS wetland may is cheap and easy, it includes periodic burning of the vegetation in the treatment wetland, monitoring and adjusting the water surface elevation, keeping the inlet and outlet structures of the wetlands clear of debris be screening, and sediment removal when necessary Bendoricchio et al. (2000)

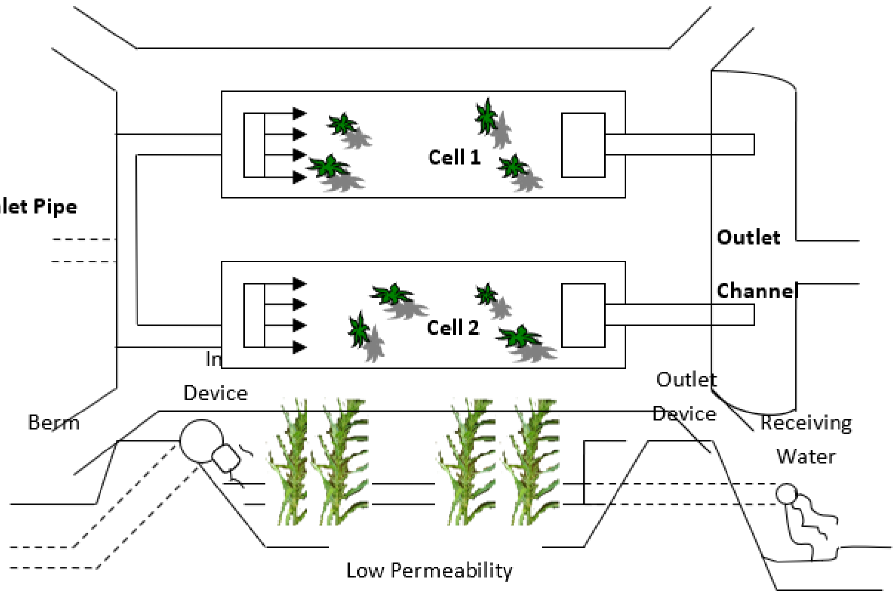

Figure 1 Plan and Profile of a Typical Free Water Surface Wetland

3.2. SUBSURFACE FLOW WETLANDS

The first subsurface flow pilot-scale wetland was designed in the 50's 1950s in Germany by Käthe Seidel Vymazal (2010). Constructed wetlands with the sub-surface flow may are classified according to the direction of the water flow either horizontal HF or vertical flow VF Vymazal and Kröpfelová (2008). A subsurface flow (SSF) wetland comprises a sealed basin with a porous substrate of rock or gravel, vegetation, and the outlet control system Vymazal (2011), Vymazal (2010), Kadlec and Wallace (2008), Davis (1995). SSF wetlands may contain up to 4 120 cm of gravel, and the water surface level is kept below the top surface of the gravel Kadlec and Wallace (2008). The flow path in SFF constructed wetlands is horizontal, while in some systems vertical flow paths could be found (Figure 2) Vymazal (2010). Generally, in SSF wetland seedlings must be planted since the gravel substrate is often not suitable and favorable to seed germination and establishment Kadlec and Wallace (2008).Organic compounds are degraded aerobically as well as anaerobically by bacteria attached to the plant's underground organs (i.e., roots and rhizomes) and media surface mimicking trickling surfaces as in the conventional biological treatment process Vymazal (2010), Scholz and Lee (2005). However, oxygenation of the rhizosphere of HF constructed wetlands is insufficient and, therefore, incomplete nitrification is the major cause of limited nitrogen removal which in best could reach 50% Vymazal and Kröpfelová (2008), Vymazal and Kröpfelová (2009). In SSF constructed wetlands volatilization, adsorption, and plant uptake play a negligible role in nitrogen removal Vymazal and Kröpfelová (2008). Phosphorus removal occurred by ligand exchange reactions, the summary of the mechanism is that could phosphate displaces water or hydroxyls group from the surface of Fe iron and (Al) aluminum hydrous oxides Jing et al. (2001), Vymazal (2007), Cui et al. (2015). Microbial pollution removal is mainly done by a combination of physical, chemical, and biological processes and factors Coban et al. (2015). Nonetheless, because of the variation in hydraulic gradient requirements, the aspect ratio (L: W) it have been recommended to be relatively low and (in the range of 0.4:1 to 3:1) in order to provide the flexibility and the reserve capacity for future operational adjustments and upgrading Kadlec and Wallace (2008), Davis (1995), Bendoricchio et al. (2000).

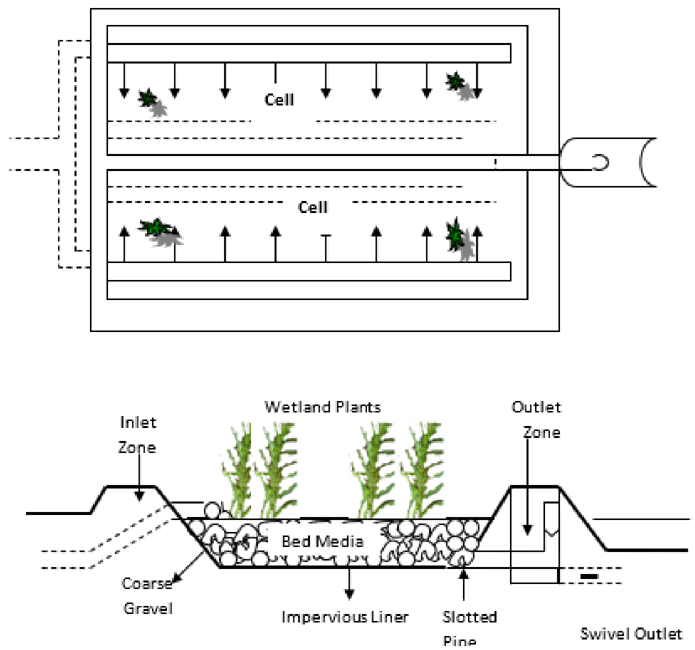

Figure 2 **Plan and Cross-Sectional View of a Subsurface Flow Wetland** Wallace and Knight (2006).

SSF constructed wetlands are best suited to treat wastewaters with relatively low solids concentrations and under relatively uniform flow conditions Because of the hydraulic constraints imposed by the substrate Vymazal (2011), Vymazal (2001), Scholz and Lee (2005), Davis (1995), Vymazal and Kröpfelová (2008),Wallace and Knight (2006).

4. DESIGN VARIATIONS

Design variations of constructed wetland affect shapes and sizes to fit match the site characteristics and optimize construction, operation, and enhance performance Carty et al. (2008). Constructed wetlands typically are fitted with liners to prevent infiltration, which depends on local soil conditions and regulatory requirements Kadlec and Wallace (2008). A large number of researches and studies have been published about constructed wetlands, nevertheless; the optimal design of constructed wetlands is still undetermined due to the absence of adequate monitoring systems and inadequate operating time to provide appropriate data for analysis Moreira and Dias (2020). In monitored systems, performance has fluctuated and the influences of the varied factors that affect performance, are the location, wastewater characteristic or runoff, the design of the wetland, climatic conditions, disturbance, and daily or seasonal changes are, challenging to estimate Kadlec and Wallace (2008), Davis (1995), Hammer (2014). Constructed wetland designs are most likely to mimic natural wetlands in all aspects of their structure in order to achieve high water quality of the treatment process Vymazal (2001), Hammer (2020). The planning phase is essential and important in constructed wetlands design variety of system types and configurations have been implemented to meet specific wastewater treatment needs, sites are often available, and a variety of native plant species can be selected. Moreover, each selected sites are unique and the design of a constructed wetland system will be site-specific Kadlec and Wallace (2008), Davis (1995), Hammer (2014), Hammer (2020).

Constructed wetlands require four components: liner, distribution media (substrate), vegetation, an under-drain system. The liner prevents water leakage and keeps the wastewater away from reaching the surrounding environment and groundwater. Generally, the liner is manufactured from a number of materials, and among the most common and reliable materials are polyvinyl chloride (PVC) (Figure 3) Davis (1995).

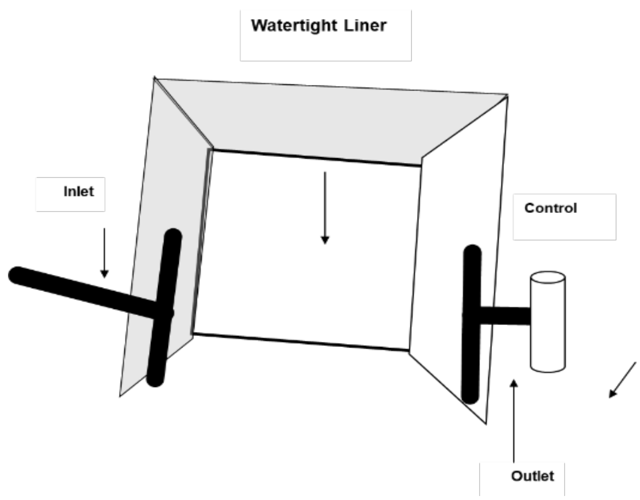

Figure 3 A Sectional View of Wetland Controls and Liner Davis (1995).

The inlet consists of a distribution medium which is usually coarse rock that is 2 to 5 cm in diameter. The first section of the distribution system spreads the wastewater influent across the width and the cross-section of the wetland. The filter contains a pea gravel media which is 1cm to 2 cm in diameter Davis (1995). The pea gravel depth varies and it is usually in the range of 45 cm to 60 cm. The under-drain system at the outlet of the wetland is a slotted 10 cm pipe covered with rock. The under-drain transfers the treated effluent out of the wetland and maintains the effluent level below the gravel surface to avoid direct contact with people and prevent mosquitoes from breeding in the wetland Davis (1995). Moreover, the water level stays high enough in order to sustain plant growth. (Figure 4 and Figure 5) depict the most common constructed wetland system design types

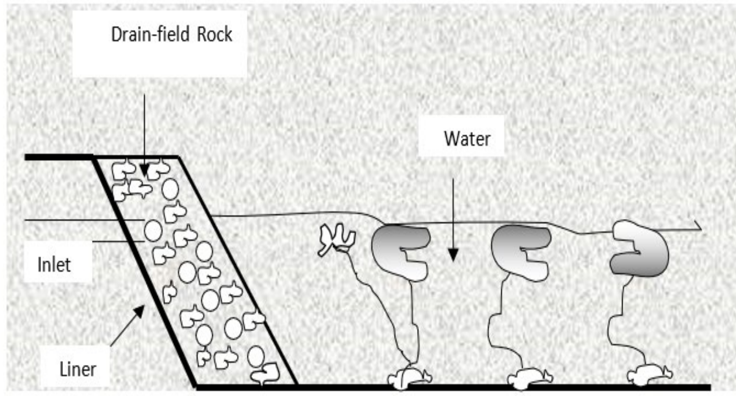

Figure 4 A Free Water Surface Flow Wetland Sketch Davis (1995)

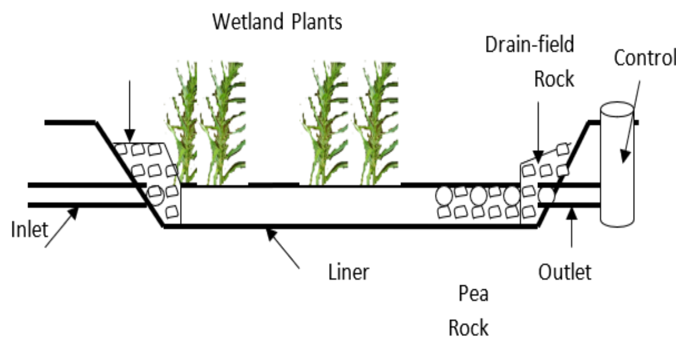

Figure 5 A Subsurface Flow Constructed Wetland Sketch Vymazal (2001)

The designing criteria for both systems are different as can be shown in (Table 3).

Table 3 Design Criteria for Constructed Wetlands LaFlamme (2006) , Crites (1994).

Design parameter	Unit	Surface wetland	Subsurface wetland
Retention time	d	5 to 14	2 to 7
Water depth/ media depth	M	0.1 to 0.8	0.3 to 0.6
Hydraulic loading rate	mm d^{-1}	15 to 65	80 to 300
Volume flow rate	m^3 d^{-1}	200 to 75000	5 to 13000

Source: [LaFlamme (2006)Crites (1994)]

Suggested design dimensions can be used for both wetland types as follows Kadlec and Wallace (2008), Davis (1995), Carty et al. (2008),Hammer (2020):

Surface Flow Wetland:

1) Surface area: (10 – 20) m^2. 60g-1.d-1.dof total BOD5;
2) Water depth: 10 – 50 cm;
3) Hydraulic retention time: minimum 10 days;
   τ = L x W x D/Q (Volume of water m3 and the Flow m^3/d);
4) Length/Width = minimum 4/1.

Subsurface Horizontal Flow Wetland:

1) Surface area: 5 – 10 m^2 60g-1. d-1of total BOD5;
2) Minimum Length is 6 m; max Length is 15 m;
3) The slope of the reed bottom is (1%) from the top surface level;
4) Depth of the inlet: ± 0.6 m; depth of the outlet: maximum depth 0.8 m; minimum depth 0.3 m.

5. DESIGN CONSIDERATIONS

In constructed wetlands, hydrology is considered the most important design parameter because it connects all of the functions and it is responsible for the success or failure of a constructed wetland Hammer (2020). Hydrology influences different components of the wetlands such abiotic components include water and nutrient availability, aerobic or anaerobic conditions of the soil, depth of water and velocity, and pH. Also, hydrology could affect biotic factors as water budget and gains through the interference of precipitation and losses through evapotranspiration through plants LaFlamme (2006), Hernandez and Mitsch (2007).

Water flows through the wetland resembling plug-flow than completely mixed flow Stairs (1993). Plug-flow conditions demands minimized short-circuiting and dead pools. Hydraulic retention time is a critical design element that assumes uniform flow behavior. Treatment wetlands are mainly designed to avoid storm-water runoff to flow through the wetland unless the intention is to treat storm-water runoff. Avoiding storm-water runoff can be achieved by placing the wetland in a highpoint and/or with the use of berms to divert storm-water runoff of the wetland inlet Davis (1995), Carty et al. (2008), Hammer (2014). Flow characteristics through the wetland comprise Davis (1995):

Velocity is controlled by a sloping bed that maintains an adequate hydraulic gradient through the wetland to achieve the desired velocity.

- Retention Time – is the time needed for a volume of water to travel from the inlet to the outlet of the wetland which is determined by the size, the depth, and the travel path through the wetland.
- Depth of Flow – it must be determined to offer adequate storage and appropriate conditions for the wetland plants.
- Travel Path – prevent short-circuiting through the system by providing an appropriate length to width ratio.
- Water Balance –the sources and sinks that will occur in the wetland must be determined. Groundwater influences are negligible due to the usage of the liners. It is important to the precipitation and evapotranspiration contribution must be determined in order to show the effect on the wetland hydrology.

Hydrological considerations include climate and weather, hydro-period, hydraulic retention time, hydraulic loading rate, groundwater exchanges (infiltration and deep percolation), losses to the atmosphere (evapotranspiration), and overall water balance Hammer (2014), Hammer (2020).

6. LIMITATIONS OF WETLAND PROCESSES

Biochemical and biological processes rate dependent on environmental factors, these factors include light period, temperature, dissolved oxygen, and pH. Metabolic activities are negatively affected by short light periods and low temperature, which hinder the rate of pollutant uptake by biota Jing et al. (2001), Moreira and Dias

(2020), Kadlec and Wallace (2008), LaFlamme (2006), Hernandez and Mitsch (2007). Low oxygen level limits disturb the aerobic respiration processes within the water column and may create anaerobic conditions Arndt et al. (2013). metabolic activities are affected by too high or too low pH- for that, they are dependent Kayombo et al. (2004). Outflow pollutant concentrations are occasionally zero, and in some cases for some parameters they can exceed inflow concentrations, because of the internal autotrophic processes of the wetland Vymazal (2007), Vymazal and Kröpfelová (2009).

Hydrology and hydraulics are the main driving forces behind the presence and functions of a constructed wetland. hydrology describes the quantity and temporal distribution of the flow from a watershed into a constructed wetland while, hydraulics is related to the patterns and velocities of water movement within a constructed wetland Braskerud (2002).

6.1. HYDROLOGY

Hydrology or the water processes that occur in the wetland are important to the design and maintain the successful operation of the constructed wetlands Scholz and Lee (2005), Tony et al. (1999).

There are two main considerations are:

- Water balance – FWS wetlands are subjected to water loss due to evapotranspiration and seepage and subjected to gains (rainfall) which cause a fluctuating in water volumes and levels within the wetland.
- Retention time – the period of time that wastewater is retained inside the wetland is critical to the various treatment processes that occur. Required retention times vary depending on the concentration of the pollutants and the desired level and the target of the treatment. it was suggested that the best retention times for BOD removal are 2 to 5 days and it was recommended for BOD and SS removal between 7 to 10 days Rowe and Abdel-Magid (2020). Moreover, it was recommended 1 to 3 days for coliform removal, and 7 to 14 days for nitrogen removal while P removal is unpredictable at any retention time Braskerud (2002).

6.1.1. WATER BALANCE

Water balance for a constructed wetland is an account of the total inflow, storage, and outflow of water. The inflow consists of either surface water (the wastewater or storm-water), groundwater infiltration (in unlined wetlands), and rainfall. Outflow comprises surface water evaporation, evapotranspiration by plants, effluent discharge, and infiltration into groundwater Davis (1995), Hammer (2020), Gorito et al. (2017). Effluent concentrations can be diluted by rainfall or increased by loss due to evaporation Vymazal (2011), Vymazal (2011), Vymazal (2001), Davis (1995). During design and operation, the constructed wetland water balance is important for determining conformance with desired limits for hydraulic loading rate, hydro-period range, hydraulic retention time (HRT), and mass balances Kadlec and Wallace (2008), Davis (1995), Hammer (2020). The water balance equation for a constructed wetland can be expressed as:

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

Where: S = net change in storage

Q = surface flow, including wastewater or storm-water inflow,

R = contribution from rainfall

I = net infiltration (infiltration less exfiltration)

O = surface outflow

ET= loss due to evapotranspiration.

Constructed wetlands are appropriate for tools for measuring water balance and ET due to having distinct inflow and outflow, and homogeneous substrate and vegetation Drexler et al. (2004). wetlands make up a large portion of the land use and ET is accounted for between 55-80% of water yield in some watersheds Białowiec et al. (2014).

6.1.2. HYDRAULIC RETENTION TIME HRT

Water treatment processes depend on the period of time that wastewater physically resides within the wetland boundaries Almuktar et al. (2018). This period is known as retention time or could be defined in literature as hydraulic retention time, or detention time. Retention time can be obtained from the following equation:

$$t = \frac{\mathbf{n}y.\mathbf{dA}}{\mathbf{Q}av}$$

Where, t = average retention time (days) = (tn) = nominal retention time

nv = void ratio or porosity, corresponding to proportion of typical wetland cross section not occupied by vegetation. Typically, equal to 0.65 to 0.75

d = wetland water depth (m)

A = wetland surface area (m2)

Qav = average discharge (m3/day) or equal to the average of Qi and Qo to water balance transit of the bed Davis (1995).

The effectiveness of (biological, chemical, and physical) processes vary with the water retention time It was reported that longer retention times accelerate the removal of more contaminants, though too-long retention times can have negative effects Kayombo et al. (2004). It was mentioned in the literature and based on empirical experiences that it should be at least 3–5 days during normal high-water periods. Moreover, some reported that constructed wetlands with average retention times of less than 2 days should not be made if the purpose is nitrogen removal Koskiaho et al. (2009). In practice, water balance changes (e.g., varying influent discharges, rainfall, and evaporation conditions that combine to change effluent discharges) fluctuate retention time Scholz and Lee (2005), Davis (1995), Hammer (2020). In practice, t is the period during which all of the water flowing into the wetland at a specific time and with an equal flow velocity Kadlec and Wallace (2008).

6.1.3. HYDRAULIC LOADING RATE HLR

Hydraulic loading is a measure of the volumetric application of wastewater into the wetland. It is often used to make comparisons between wetland systems and indicates their potential to be overloaded by wastewater Dong et al. (2011). The hydraulic loading rate can be calculated by the following equation.

$$HLR = Q/A$$

Where: HLR = hydraulic loading rate (m/day)

Q_i = influent wastewater flow (m3/day)

In some cases, Q_{av} is used instead of Q_i,

A = wetland surface area (m2) Davis (1995).

Both HLR and HRT play a major role in the extent of the interaction between wastewater and the constructed wetland system Toet et al. (2005). In natural wetlands, HLR must be in the range of 1 to 2 cm/day to minimize vegetative changes and enhance treatment to reach maximum treatment efficiency. on the other hand, hydraulic loading between 2.5-5 cm/day was optimal for FWS wetland and 6-8 cm/day for SSF wetlands Rowe and Abdel-Magid (2020).

6.2. PRECIPITATION IMPACTS

Precipitation and snowmelt can increase the flow in constructed wetland systems. It is very important to determine and estimate the runoff in areas with extended periods of precipitation and must be included in the design flow. Precipitation dilutes pollutants and washes out the chemical in the system, which raises the water level and decrease the HRT which deteriorate the efficiency of the wetland Davis (1995), Hammer (2020).

6.3. EVAPOTRANSPIRATION

Evapotranspiration (ET) is the water loss to the atmosphere from the water surface and from the soil (evaporation) and the loss of water from the vegetation of the wetland plants (transpiration).

ET is an important factor in wetland design. It affects the overall water balance of a waste treatment system, thus decreasing efficiency Davis (1995), Vymazal and Kröpfelová (2008). Usually, evaporation slows the water in the system, and that could significantly increase in retention time of the wetland. Due to high evaporation, the accumulation of concentrated pollutants could reach toxic levels if the water loss from the wetland exceeds the inflow. To reverse the effect of water loss, water must be supplied in order to keep the wetland wet and keep the wastewater treatment efficient and durable Davis (1995), Vymazal and Kröpfelová (2008).

7. HOW WETLANDS IMPROVE WATER QUALITY

Wetland is a complex and sophisticated system with combinations of water, substrate, plants and plants debris and litter, invertebrates, and microorganisms Moreira and Dias (2020), Vymazal (2010), Vymazal (2007), Vymazal (2001),Vymazal and Kröpfelová (2008), Vymazal and Kröpfelová (2009). Many physical, chemical, and biological processes occurred within treatment wetlands. The processes vary in simplicity and in complexity which makes them not fully understood in terms of the contribution to the treatment process Vymazal (2010), Kadlec and Wallace (2008), Hammer (2020). Normally, the driving factor in determining the limiting pollutant for which the wetland should be designed is the treatment level which must be very efficient to reach discharge permit requirements Davis (1995). Treatment performance of the wetlands could be judged by the capabilities and the percentage of mass removal of contaminants and depends on the contaminant concentration in the wetland outflow It is important that the selected criteria accurately reflect the actual performance of the wetland relative to the objectives and intended uses of the wetland treatment system Dotro et al. (2017). However, justification conducted on experimental results obtained from a sub-surface flow constructed wetland showed that the first few years of the constructed wetland performance is related to the initial operating stage Awad and Saleh (2001).

Immobilization and/or transformation of pollutants in constructed wetlands usually occur due to some physical, chemical, and biological processes which take place in the substrate-water matrix and in the plant rhizosphere Vymazal et al. (2006). Constructed wetlands can efficiently remove the following components from wastewaters: suspended solids, organic matter, and excess nutrients, as well as natural remains of pathogens Vymazal et al. (2006). SSF constructed wetland overtakes the FWS wetland in terms of numerous pollutants' removal. SSF wetlands have high performance to remove nutrients and chemicals. Jindal and Samorkhom, 2005 showed the same trend of higher removal efficiencies of chemical oxygen demand (COD), total Kjeldahl nitrogen TKN, total phosphorus (TP), total suspended solids TSS, volatile suspended solids VSS, and Cadmium removal efficiencies in both SSF wetland and FWS wetland Jindal and Samorkhom (2005). Constructed wetlands are considered an accepted low-cost technology for removing phosphorus from wastewater Jindal and Samorkhom (2005). Constructed wetlands are considered an accepted low-cost technology for removing phosphorus from wastewater Vymazal (2011), Vymazal (2010), Davis (1995), Almuktar et al. (2018). Researchers have examined the use of various materials as potential substrates to enhance phosphorus P removal by constructed wetland treatment systems. Further researchers have shown the addition of P-sorbing materials in separate rechargeable cells of the wetlands to improve the ability and sustainability of constructed wetlands to remove P from wastewater Zhu et al. (2003). This could be a cheap way to improve the performance, sustainability, and durability of constructed wetlands or could be used to minimize the wetland area for a given level of treatment Leader et al. (2005). Constructed wetland plants showed 80 to 90% removal efficiency of COD was shown at temperatures greater than 12° C. Moreover, emergent plants have shown high ammonia and phosphate removal efficiency. Only planted wetland cells exhibited significant long-term phosphate removal Stein et al. (1998),Yang et al. (2007), suggested that plant growth and development of fine root biomass were associated with the removal efficiency in SFW wetlands. The same author concluded that selecting highly effective wetland plants significantly depends on the development of fine roots biomass Stein et al. (1998), Yang et al. (2007). Jing et al. (2002) examined the effect of different hydraulic loading rates HLR and macrophytes type on the removal efficiency of COD, ammonia-N, and PO4-P, exhibited that planted systems are more efficient in nutrient removal than the unplanted systems; nevertheless, the type of macrophyte did not make a major contribution to the treatment Jing et al. (2002). The interacting effect of temperature and plant type on nutrient removal in wetlands was also studied. It was reported that nutrient removal efficiency depends on seasonal variation. More nutrients were removed in warmer seasons compared to the colder ones. Planted microcosms overtook the unplanted microcosms, which proves the significance of macrophysics in a wetland Khanijo (2002). Microbiological pollution removal in the wetlands is infrequently a primary target for constructed treatment wetlands Vymazal and Health (2005). However, wetlands are very effective in removing pathogens, typically reducing the pathogen number by up to five folds from wetland inflows Kayombo et al. (2004). Wetlands are known to offer appropriate physical, chemical, and biological conditions for the removal of pathogenic organisms Vymazal and Kröpfelová (2008). Removal of pathogens (indicators) in wetlands is correlated with TSS removal and HRT. HRT Required for pathogens removal varies depending on the nature of the pollutant and the level of treatment required. For design purposes, a two-log reduction is a practical approximation of vegetated submerged bed systems' performance. Peak flows in response to extreme rainfall events also disturb and decrease the removal efficiencies for fecal coliforms Davis (1995). It was shown by a study that 87% of the variance in E. coli concentrations across five monitored rainfall events with a positive correlation between solar radiation and E. coli concentratio Smith et al. (1998).

8. OPERATION AND MAINTENANCE

Constructed wetlands require routine maintenance which includes inspecting all components and cleaning and repairing the system when needed Sundaravadivel et al. (2001). The decision-maker needs to keep certain records on operation and maintenance as an aid to ensuring that the system continues to function as efficiently and required. At least, the inlet and the outlet pipes should be inspected on daily basis to avoid clogging by various types of debris which could be problematic Scholz and Lee (2005), Kadlec and Wallace (2008), Davis (1995),Carty et al. (2008). The most critical items in which operator intervention is necessary are:

- Water level adjustment
- Maintenance of inlet and outlet structures to keep flow uniformity
- Management practices to preserve vegetation
- Control of Odor
- Control of nuisance pests and insects
- Regular maintenance of berms and dikes Davis (1995), Carty et al. (2008)

9. PROS AND CONS OF USING CONSTRUCTED WETLANDS

In general, the final decision on whether to apply and adopt wetland technology has to be made in the situation of the overall treatment process (i.e., what other (primary) treatment measures are being adopted) and the available area and land. Constructed wetlands demand cautious management which enhances the water treatment capability of the wetland Aslam et al. (2004). Table 4 depicts the main advantages and disadvantages of using constructed wetlands.

Table 4 Advantages and Disadvantages of Using Constructed Wetlands Merz (2000)

Advantages	Disadvantages
Very low operational costs	Capital is ranging from medium to high costs are medium to high.
very low energy and materials inputs	Require large area and lands
Different treatment processes are available can stand a wide range of pollutants and toxicants	Operational control over treatment processes is limited may accumulate toxic substances in the sediments and may contamination of the site
Considered a natural, sustainable and suitable practice for polluted and wastewater treatment.	They are mimicking natural ecosystems and usually have seasonally activity patterns which may result in seasonal variations in performance.

Constructed wetlands for wastewater treatment may act as useful wildlife habitats and preserve nature	Attracting some wildlife to wetlands constructed for wastewater treatment performance through secondary contamination of water or through physical damage of wetland vegetation by wildlife. Depending on the actual site, the use of high trees and shrubs can interject flight routes and sight lines and reduce the systems habitat value for certain species.

(Source: Merz (2000)).

10. CONSTRUCTED WETLAND'S ROLE IN WILDLIFE ENHANCEMENT

Constructed wetlands draw wildlife. Many birds, mammals, amphibians, reptiles, and a variety of insects adopt the area and consider the wetland as home. While any arrangement of cells enhances wildlife habitat, the layout can be modified to certain conditions to attract specific types of wildlife. In areas where bio-security is a concern, consideration should be given to excluding migratory and other nonresident wildlife to minimize the potential for the spread of disease to other operations. An EPA publication EPA U. (1999) indicated that more than 1,400 species of wildlife had been branded for constructed and natural treatment wetlands and considered it home. They include 700 species of invertebrates, 78 species of fish, 21 species of amphibians, 31 species of reptiles, 412 species of birds, and 40 species of mammals. More than 800 species were reported in constructed wetlands alone EPA U. (1999).

11. AESTHETICS AND OTHER ANCILLARY BENEFITS OF CONSTRUCTED WETLANDS

Wetlands have a unique beauty. Even when planted with typical plantings, the character of the system changes as natural wild plants invades the system. While the choice of plants may be limited for the initial or upstream segments of the system because of the high concentrations of some pollutants, more colorful and a greater variety of plant species may be placed at downstream locations within the wetland system where wastewater quality improves.

In addition to water quality improvement, constructed wetlands are known to produce ancillary benefits like aesthetic improvement of landscape, increased biodiversity, recreational uses, and possibilities for hunting Koskiaho (2009). The designer can incorporate additional features into the wetland system that do not detract from the primary goal of wastewater treatment. Some of these benefits include aesthetic appeal, educational value, recreational outlets, and habitat value. Interpretive centers can be incorporated into the wetland design to provide educational opportunities on such topics as energy conservation, wastewater treatment, wetland ecology, and pollution prevention. If the wetland designer wishes to incorporate these aspects into the wetland design, planning must include a safe means of public access Zedler and Kercher (2005).

12. ECONOMIC BENEFITS OF CONSTRUCTED WETLANDS

The usage of constructed wetlands depends on whether that treatment option is more cost-effective than other available or conventional treatment technologies. Each operation must be evaluated exclusively to determine if the installation of a constructed wetland will provide an additional economic values benefit. Even if an economic analysis shows no net benefit from installing a constructed wetland, some decision-makers might be willing to forgo some measure of annual benefit to reduce the amount of time spent in waste handling Zhang et al. (2009).

Some key factors that must be considered in an economic assessment include Vymazal (2011), Vymazal (2010), Wallace and Knight (2006):

- Construction costs,
- Value of nutrients lost through treatment by the wetland,
- Equipment and labor costs to land apply wastewater,
- Value of land used by constructed wetland,
- Value of crop lost because of land taken out of production by the CW, and
- Cost of maintenance and operation.

13. CONCLUSION

Constructed wetlands are among the recently demonstrated technologies to have a great potential for efficient wastewater treatment and management in rural and developed areas. When properly designed and operated, constructed wetlands have great advantages over conventional treatment systems for their relatively low cost, easy operation, and maintenance.

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