International Journal of Engineering Innovation & Research
Volume 3, Issue 5, ISSN: 2277 – 5668

Efficiency of Constructed Wetlands in Arid Regions

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***Abstract* – Economic pressures, high cost of constructing conventional water treatment plants and/or water pollution control facilities, high energy prices and high labor costs worldwide are the main reasons for the engineers and environmentalists to search for alternatives and for unconventional methods and facilities for water pollution control.**

A well-designed, managed, operated and maintained constructed wetland can perform better than natural wetlands and can perform many of the functions of conventional wastewater treatment systems.

They are mainly cost effective mechanisms in construction and operation compare to conventional wastewater treatment mechanisms. For designing a constructed wetland engineers rely on the performance expectation of the system and starting the design with the required effluent quality.

To design a Constructed Wetland System in arid region, take an area in central Qatar as an example, influent data, climatic and soil information and data are required.

With inflow volume of 950 m^3/day and BOD of 130 mg/l to be reduced to 20 mg/l outflow, calculations for a constructed wetland in a climate of central Qatar concluded to a required cross sectional area of 198 m^2 and surface area of 1.81 and 0.36 hectares in winter and summer respectively, and the volume of the outflow is calculated to be 810.44 m^3/day and 869.33 m^3/day in summer and winter respectively.

***Keywords* – Wetlands, Arid Region, Wastewater Treatment, Effluent Quality.**

I. INTRODUCTION

Constructed wetlands (CWs) are systems that use relatively more land and are lower in energy use and labor costs, they are significantly cost effective for communities operating them, and therefore are becoming attractive alternatives for them. In CWs wastewater is reused successfully as a water and nutrient resource (water and plant nutrients) rather than as waste or pollution.

CWs are water treatment systems designed and constructed to imitate the function of natural wetlands using natural chemical, physical and biological processes involving wetland vegetation, soils/bed media and their associated microbial populations, solar energy and gravity to improve the quality of supplied inflow, they are used for the treatment of municipal, industrial and agricultural wastewater, as well as storm water to remove pollutants and produce effluent of a quality suitable for reuse or for release into the environment. Pollutants that CWs help in removing are:

- Suspended solids,
- Soluble organics,
- Phosphorus and nitrogen,
- Metals and ,
- Pathogens.

CWs with different configurations, scales and designs have been used worldwide and their use is in continuous increase because of:

- Their high nutrient capturing capacity,
- Simplicity,
- Low construction, operation and maintenance costs,
- Low energy demand and process stability,
- Low excess sludge production,
- Effectiveness and potential for creating biodiversity,
- Its aesthetic value that add attraction factor and allow CW to be suitable for recreational activities, and
- Its suitability for flood control as retention ponds collecting excess water during flood seasons.

The most widely spread used constructed wetland configurations are the Free Water Surface systems (FWS systems resemble a shallow pond systems) and subsurface flow systems (SF systems resemble filters), they are shallow excavations 1-1.5 m deep their bottom is lined with a synthetic or clay liner to prevent infiltration of water and are filled with a media to support the vegetation growth and allow the filtration process.

II. THE OPTIMUM PERFORMANCE OF CONSTRUCTED WETLANDS

The basic CWs treatment mechanisms include sedimentation, chemical precipitation and adsorption, microbial interactions with BOD_5, SS, and nitrification as well as uptake by the vegetation.

Therefore performance efficiency of CWs is highly depend on appropriate decision during wetland design, construction, management, operation and maintenance. Other factors affect the performance of the system are climatic and environmental conditions (e.g. precipitation, temperature, soil type), and engineering elements in the design and operation (e.g. hydraulic retention time and hydraulic loading rate) these factors govern the design and construction elements of any CW; which are:

a) Selection of CW configuration/type.
b) CW design and basin construction.
c) Lining of the basin.
d) Constructing the bed media (fillings), and the inlet/outlet of the inflow/outflow.
e) Vegetation selection and plantation.

CWs are usually more efficient when the inflow is pretreated to a primary or secondary level before entering the CWs. CWs can be a very reliable system producing effluent that meets the requirements not only with well design and construction but also through perfect:

f) Operation and management,
g) and suitable and good timing maintenance.

a) Selection of CW configuration/type:

CWs type is a key factor in its efficiency depending on the inflow's load/quality, they can significantly reduce:

i) Biological oxygen demand (BOD_5),
ii) suspended solids (SS),
iii) Nitrogen,
iv) Phosphorus,
v) Metals and,
vi) Pathogens

For influent rich in fecal coliform and nitrogen FWS systems could be a better preference, while SF system is a better choice when influent is rich in COD, TSS and TP, Subsurface Flow CWs. Fig. 1 & 2 below represent FWS & SF systems.

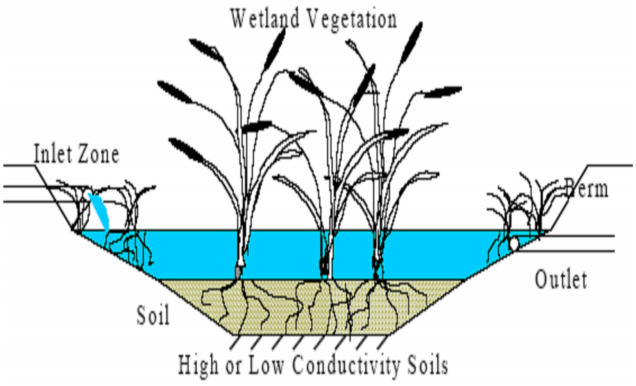

Fig.1. Free Water Surface system.

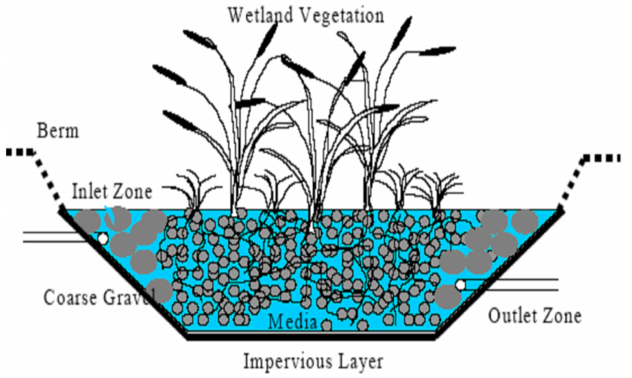

Fig.2. Subsurface Flow system

b) CW design and basin construction:

Although CW site selection can be anywhere but it is preferable to be selected near the inflow's source and in area with suitable topography to minimize excavation and grading cost and with a permeability that support vegetation growth and allow water flow , the most desirable soil permeability is 10^{-6} to 10^{-7} m/s, however soil permeability can be adjusted or improved by many means to meet its function.

The construction of CW's basin consists of earth work (excavation), leveling and compaction with graded levels along the sides (up to 2-3 levels) and with slight slope in the direction of flow, inlets and outlets are designed for the effluent to be supplied into the CW area such that it distribute the effluent evenly across the area and allow its flow without disruption controlling its level across the CW, sometimes control structures like weirs are used, then collecting the effluent for discharge or reuse.

For designing a constructed wetland engineers rely on the performance expectation of the system and starting the design with the required effluent quality:

i) Biological oxygen demand (BOD_5):

The ratio of the daily inflow load (BOD_5) and the required effluent's load (BOD_5) to be meet (mg/l) commensurate with time, from which the following relation or Equation (1) can be used for calculation.

$$C_e/C_o = \exp(-K_T\, t) \qquad (1)$$

where,
C_e = effluent BOD_5, mg/l
C_o = influent BOD_5, mg/l
K_T = temperature-dependent first-order reaction rate constant (day^{-1}).
t = hydraulic residence time (day)

To design and construct a CW basin for SF system the following agronomic and hydrologic parameters and data need to be collected:

1. Choose the vegetation that best suits the climate and location, and find data about the maximum depth of its rhizomes penetration into the soil or the media (depth) this should be the minimum depth of the flow cross-sectional area.
2. Choose The bed slope based on the site topography (to minimize construction cost), however most systems are designed with slope of 1 percent or slightly higher (s = 0.01).
3. Find the characteristics of the media (soil for FWS system and filling bed for SF system) according to the media type including media porosity (n, dimensionless), hydraulic conductivity (K_s in m^2/m^3 per day), and the temperature-dependent first-order reaction rate constant of the media (K_T in per day^{-1}), a value of reaction rate constant at temperature (20°C) (K_{20}) is used to calculate (K_T in different temperatures) as shown in Equation (2), characteristics of some selected medias are presented in Table (1) below.

$$K_T = K_{20}\,(1.1)^{(T-20)} \qquad (2)$$

Table 1: Characteristics of Selected Medias for Subsurface Flow Systems.

Media Type	Max. 10% Grain Size (mm)	Porosity (n)	Hydraulic Conductivity (K_s) m^3/m^2-d	K_{20}
Medium Sand	1	0.42	420	1.84
Coarse Sand	2	0.39	480	1.35
Gravelly Sand	8	0.35	500	0.86

4. Calculate the surface area of the system, and the cross-sectional area perpendicular to the direction of the flow as follows:

Calculate the surface area of SF system

Equ. (1) is used and rearranged by reversing the exp. then multiply by Q both sides of the equation as follows;

$Q * (\ln C_o - \ln C_e) = Q * (K_T\, t)$;
$Q * (\ln C_o - \ln C_e) = (As * v) * (K_T\, t)$ (v is the flow velocity in the porous media);
Divide both sides by $(v) * (K_T\, t)$,
where $(v * t)$ is the distance (d) that an influent can flow in a media with porosity (n), i.e. $t * v = d * n$, this gives equation (3).

$$A_s = Q\,(\ln C_o - \ln C_e) \div (K_T\, d\, n) \quad (3)$$

Where;
Q = average flow rate through the system, in (m^3/d)
d = depth of submergence, in (m)
n = porosity of the bed, as a fraction
As = surface area of the system, m^2

Calculate the cross-sectional area of SF system

Darcy's law and equation are used as follows:

$$A_c = Q \div k_s\, S \quad (4)$$

Where,
A_c = d*W, cross-sectional area of wetland bed, perpendicular to the direction of flow,
d = bed depth, m
W = bed width, m
K_s = hydraulic conductivity of the medium,m^3/m^2 per day.
S = slope of the bed, or hydraulic gradient (as a fraction or decimal)

The value of Ks*S need to be checked such that Ks*S has to be < 8.60.

To calculate the surface area of FWS system

The following two equations (5) and (6) were combined in equation (1) to form equation (7).

Hydraulic residence time for an unrestricted flow system can be represented as:

$$t = LWd \div Q \quad (5_a)$$

Where:
L = length
W = width
d = depth
Q = average flow rate = $(flow_{in} + flow_{out}) \div 2$

But a portion of the available volume will be occupied by the vegetation, so the actual detention time will be a function of the porosity (n), which can be defined as the remaining cross-sectional area available for flow.

Where:

$$n = V_v \div V \quad (6)$$

V_V and V are volume of voids and total volume, respectively, and n is the porosity of system (as a decimal fraction), that changes Equation (5_a) to be (5_b).

$$t = V_v \div Q \quad (5_b)$$

$$Ce/Co = A \exp[(-0.7\, K_T (A_v)^{1.75}\, L\, W\, d\, n) \div Q] \quad (7)$$

Where;
A = fraction of BOD_5 not removed as settleable solids near head-works of the system (as decimal fraction)
K_T = The temperature-dependent rate constant
A_v = specific surface area for microbial activity, m^2/m^3
Q = average hydraulic loading on the system, m^3/d

5. Now the following basin's dimensions are calculated:

- The basin depth is determined (d, the plant roots depth),
- The temperature-dependent rate constant (K_T) is calculated using equation (2),
- The surface area (A_s) is calculated using equation (3) and from which the basin length (L) is calculated (A_s = w*L),
- The cross-sectional area is calculated (A_c) and from which the basin width (w) is calculated (A_c = d*w) using equation (4),
- The hydraulic residence time (t) is calculated using equation (5).
- And for better hydraulic control at the inlet zone the required area/width is divided into individual cells with small sizes wide.

ii) Suspended Solids (SS):

A proper diffuser pipe design can control even loading, dispersion of the influent and insuring low flow velocities in the wetland so that anoxic conditions are prevented at the upstream end of the channels where most of the suspended solids removal occurs within the first few meters beyond the inlet, depending on the designed conditions including the shallow depth of liquid in the system.

iii) Nitrogen:

Nitrification/denitrification is the major path of nitrogen removal in constructed wetlands, process of denitrification are fueled by using carbon sources derived from biomass produced within the wetlands itself depending on the detention times to produce an effluent of acceptable quality.

iv) Phosphorus:

Phosphorus removal mainly occur through absorption or deposition in soils, in many wetland systems phosphorus removal is not very effective because of the limited contact opportunities between the wastewater and the soil. The exceptions are the SFS system when proper soils are selected as the system medium. A significant clay content and the presence of iron and aluminum in soils will enhance the potential for phosphorus removal. Use of such soils will, however, reduce the hydraulic capacity and require a much greater area for treatment.

v) Metals:

There are limited data available on the metal removal capability of FWS wetlands; because the removal mechanisms are similar to those described above for phosphorus, the response is not very effective. There is greater opportunity for metal removal and sorption in SFS systems. The predominant removal mechanisms in the artificial wetlands were attributed to precipitation-absorption phenomena.

c) Lining of the basin:

The bottom of the bed basin should not allow influent seepage, this depends on the soil type and permeability, if it is greater than 10^{-6} m/s then lining the basin's bottom is required, but if the soil is composed mostly of clay then lining might not be required.

Liner should be placed with high profession to avoid puncture, if the basin bottom is very rough then a layer of sand got to be placed first beneath the liner to fill in between spaces.

d) Constructing the bed media (fillings), and the inlet/outlet of the inflow/outflow:

The placement of the inlet and outlet structures take place before filling the basin with the filling strata, they are placed according to the CW design and the flow type (horizontal or vertical). For the inlet a perforated pipe that discharge the influent in the CW should be laid perpendicular to the flow direction and the inlet should be designed such that no short-circuiting nor clogging are occurred in the media, and that an even flow distribution takes place, while the outlet should be designed to allow a uniform flow of the influent through-out the CW and control the water level in it.

e) Vegetation selection and plantation:

Plants are planted in CW - and allowing them time to grow enough - before introducing influent into the system. There are 3 types of wetlands plants to be planted floating, submerge, and emergent plants, all the 3 types have the capability to absorb large amounts of harmful nutrients, metals and bio-toxins.

Submerge and emergent plants provide a canopy over the water column that restrict atmospheric reaeration and enhance reduction of suspended solids within SF system.

Each plant or group of plants has different requirements including required area, water level, soil type, climatic conditions plus different maintenance methods, these plants when grow large are either harvested, died or eaten by animals and fishes.

However some plants need to be avoided in CW are those have high proliferation rate and produce a massive mat that will obstruct light penetration to the lower layer of the water column this will affect the efficiency of the living organism and thus will decrease water quality in the long run. Moreover using these plants in CWs will increase the maintenance cost of removing them continuously on regular basis in spite of their ability of removing BOD, TSS, Total phosphorus and total Nitrogen

f) CW operation, management and maintenance:

CWs need time to operate with its full efficiency, however SF systems need less time than FWS systems because of the smaller role of the plants in SF systems, CWs that are well managed can operate for several years before the need for removing accumulated litter and settled non-degradable components from the surface area or the cross-sectional area at the influent supply end, however studies had found that there is a need to remove these solids from only around 10 to 25% of the surface or cross-sectional area. Operation and maintenance of CWs are not complicated the following monitoring factors are needed:

- Weekly sampling of the influent and make sure its volume and quality are steady all times.
- Weekly sampling of the effluent and make sure the quality is improving.
- Periodic sampling between CWs cells.
- Monthly or weekly inspection of influent supplying systems (weirs, pipes,…).
- Harvest unwanted plants or plants' over growth.
- Using the best management practices to control pests (e.g. rats, insects, mosquitoes).
- When required using best management practices for cleaning blockage and undesired sediments.
- When required annual thinning or removal of undesired vegetation and replacement of vegetation.
- Use the best management practices for odour control.
- Mosquitoes can be a problem in FWS systems but it can be solved through effective controls for example:
  - ○ Designing the inlet and outlet for each CW cell such that water level and drainage off the wetland cells are controlled.
  - ○ The development of a balanced ecosystem that includes aquatic invertebrates, insects, fish, birds and mammals that mosquitoes will be a component in a balanced food cycle that leads to maintain an acceptable level of mosquitoes.

III. CWS WATER BALANCE

For a constructed wetland, the water balance can be expressed by the following equation (Ground-water inflow and infiltration are excluded because of the impermeable barrier and for simplicity):

$$Q_i - Q_o + P - ET_{ac} = [dV/dt] \qquad (8)$$

where,

Q_i = Influent wastewater flow, volume/time,

Q_o = Effluent wastewater flow, volume/time,

P = Precipitation, volume/time,

ET_{ac} = Actual evapotranspiration, volume/time,

V_t = V is the volume of water, and t is the detention time.

When the system operates at a relatively constant water depth then (dV/dt) is taken as zero (0).

ET_{ac} is the crop actual evapotranspiration, this data is the one need to be estimated for the plants uptake in the constructed wetlands. The (K_c) is the plant water uptake coefficient depends on the morphology and physiology of the plant, and the management of the irrigation or water availability for the plant.

Having got the crop coefficient (K_c) and the measured evapotranspiration ET_m, the actual evapotranspiration ET_{ac} in mm/day now can be calculated as follows:

$$ET_{ac} = K_c * ET_m \qquad (9)$$

IV. DESIGNING A CONSTRUCTED WETLAND IN ARID REGION

To design a Subsurface Flow System in arid region - take an area in central Qatar as an example, and the following influent (from a secondary wastewater treatment plant in central Qatar), climate information and data (from Al-utoriyah metrological station in central Qatar) are used:

Influent data:

- Supplied influent load BOD_5 to the wetlands,
- Desired effluent BOD_5 ,
- Average water temperatures in winter and summer,
- And available volume of influent to be supplied.

Table 2: Supplied influent data.

Influent volume	**Influent BOD_5**	**effluent BOD_5**	**Average water temp. (summer)**	**Average water temp. (winter)**
m^3/d	mg/l	mg/l	°C	°C
950	130	20	32	15

Agronomic, climatic and hydrologic data:

Climatic data of Al-utoriyah station in central Qatar and FAO agronomic guidelines for wetlands vegetation in arid/semi-arid regions (these are adjusted from the FAO mean crop coefficients (K_c) for sub-humid climates per day time) are as follows:

- The predominant wetland plant type is cattail (bulrush, or reed-mace),
- The average crop coefficients of the cattail vegetation (average during the whole crop growing cycle) (K_c) for summer and winter.
- Penman computed reference average daily evapotranspiration adjusted for differences in day-time/night-time temperatures (ET_m) in (mm/day) in summer and winter.
- Average daily rainfall (P) in (mm/day) in summer and winter.

Table 3: Agronomic and climatic data

Average crop Coefficients (K_c)		**Cattali Roots depth**	**Average daily evapotranspiration (ET_m)**		**Average daily rainfall (P)**	
		mm	mm/day		mm/day	
Summer	Winter		Summer	Winter	Summer	Winter
1.6	1.2	300	4.8	3.7	0	0.4

Table 4: Hydrologic data of the coarse sand media/bed.

hydraulic conductivity (K_s)	**Porosity (n)**	**Slope (s)**	**K_s*s**
m3/m2-d	decimal	decimal	< 8.60
480	0.39	0.01	4.80

The design steps:

1. It is known from several studies that cattail rhizomes or roots depth is approximately 0.3m, therefore the bed media depth (d) for the CW should be 0.3 m.
2. The bed slope of the systems can be designed with slope of 1% for ease of construction (s = 0.01).
3. Some designs have indicated the need to check the valu of (hydraulic conductivity (K_s) multiply the bed slope (s) i.e. K_s*s< 8.60.
   From Table 1 above a media of coarse sand was chosen and its hydraulic conductivity (K_s in m^2/m^3 per day) is used to calculate (K_T).
4. Equation (2) to solve for the temperature-dependent first-order reaction rate constant of the media (K_T) per day using the value of reaction rate constant at temperature (20°C) (K_{20}) presented in Table 4.

Table 5: Reaction rate constant of the coarse sand at summer and winter

Reaction rate constant of the media K_T at (T °C)		
Standard K_{20}	Summer K_{32}	Winter K_{15}
1.35	4.24	0.84

5. Determine the cross section area (perpendicular to the direction of flow(A_c)) and the system's bed width using equation (4):
   $A_c = Q \div k_s S$ and $A_c = d*W$
   $A_c = 950 \div (480)(0.01) = 198\ m^2$
   $w = 198 \div 0.3 = 660$ m
6. Determine the surface area required using equation (3):
   $A_s = Q\ (\ln C_o - \ln C_e) \div (K_T\ d\ n))$
   In winter:
   $A_s = [(950)(4.87-3.00)] \div [(0.84)(0.3)(0.39)] = 18{,}131\ m^2 = 1.81$ ha
   While in summer:
   $A_s = [(950)(4.87-3.00)] \div [(4.24)(0.3)(0.39)] = 3{,}587\ m^2 = 0.36$ ha
   The design continues with the biggest bed area which is the area required for winter (1.81 ha).
7. Determine the bed length (L) and the detention time (t) in the system.
   $L = A_s \div W$ $\quad L = 18{,}131 \div 660 = 27.48$ m
   $t = Vv \div Q = LWdn \div Q$
   $t = (27.48)(660)(0.3)(0.39) \div 950 = 2.23$ days
   Divide the required width into individual cells (e.g. 60 m wide) for better hydraulic control at the inlet zone.

Table 6: Surface and x-sectional area of constructed wetland system

X-section area (A_c)	**Bed width (w)**	**Surface Area (A_s)**		**bed length (L)**	**detention time (t)**
m2	**m**	**m2**		**m**	**day**
		summer	**winter**		
197.92	660	3587.17	18131.23	27.48	2.23

When the constructed wetland system operates at a relatively constant water depth then (dV/dt) in equation (8) above is taken as zero (0), and the volume of effluent flows out of the system (Q_o) is calculated as follows:

$$Q_o = Q_i + P - ET_{ac} \qquad (10)$$

(all units in volume/time)

Penman equation is used in Qatar to calculate (ET_{ac} in mm/day) because it considers all of the climatic elements that impact directly and indirectly the evapotranspiration process (the country has 3 main highly equipped metrological stations for measuring and recording climatic data including air temperature, humidity, wind speed, daily sun shine hours and radiation, air/vapour pressure), Penman equation used is:

$$ET_m = c(W * R_n + (1-W) * f(u) * (e_a - e_d)) \qquad (11)$$

Where:

C = correction coefficient used only when there is big variation in wind speed between day and night, and reduction in relative humidity.

W = A balance coefficient related to air temperature.

Rn = Net radiation in (mm/day).

F(u) = coefficient related to the wind.

e_a = Saturated vapor pressure.

e_d = Average real vapor pressure (in millibar).

Using equation (9) above, $ET_{ac} = K_c * ET_m$, and the metrological data presented in Table 3 to calculate (ET_{ac}).

ET_{ac} (summer) = 1.6 * (0.0048 m/day * 18131.23 m^2) = 87.22 m^3/day.

ET_{ac} (Winter) = 1.2 * (0.0037 m/day * 18131.23 m^2) = 67.25 m^3/day.

The volume of effluent (Q_o) flows out of the system is calculated using Equation (10) above and the recorded and calculated data (Q_i), (P) and (ET_{ac}), such that

Summer

Q_o = 950 m^3/day + 0 m^3/day – 139.56 m^3/day = 810.44 m^3/day

Winter

Q_o = 950 m^3/day + 0.01 m^3/day – 80.70 m^3/day = 869.33 m^3/day

V. POTENTIAL RISKS FROM CONSTRUCTED WETLANDS AND REQUIRED INVESTIGATIONS/RESEARCHES

Constructed wetlands have some reputation as "mosquito-friendly habitats." Therefore an appropriate thresholds for mosquito control need to be developed to avoid nuisance conditions in differing areas, the management of mosquito issues in constructed wetlands may include investigations on:

- design and O&M,
- water quality and mosquito production,
- types of vegetation (emergent, floating, and submerged species),
- Pollutant loading rates, flow/velocity rates, etc. is warranted.

This will help to investigate whether minor modifications in flow rates, water quality conditions and plant cover in the constructed wetlands significantly reduce the abundance of immature mosquitoes or change species composition.

Investigations may also include the ecological risk of all biological and chemical control agents need to be tested in constructed wetland environments.

These investigations/research efforts all together may provide a successful strategy for resolving the mosquito/ treatment wetland conflict.

VI. CONCLUSION

CWs are recognition of the natural treatment functions of aquatic plant systems and wetlands, particularly as nutrient sinks and buffering zones, they also enhances aesthetically the surrounding environment by attracting many species e.g. birds, insects and other kinds of wildlife, and as well used by human for recreational and educational activities. They are mainly cost effective mechanisms in construction and operation compare to conventional wastewater treatment mechanisms.

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