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CRITICAL DESIGN PARAMETERS FOR CONSTRUCTED WETLANDS NATURAL WASTEWATER TREATMENT SYSTEMS

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Abstract
Constructed wetlands, also known as natural treatment systems, are designed for wastewater treatment especially in rural sections. They are used primarily for domestic wastewater treatments of small communities. Influent wastewater is treated in specially design basins containing graded substrate material and planted with aquatic plants. Since there are several physical, chemical and microbiological processes happening in these basins, a special attention should be paid for design parameters of these systems. Improper design and operation may result in serious failures and malfunction of the system. Instead of simple or general design parameters, site-specific parameters considering local climate, site topography, influent wastewater characteristics and locally available materials should be taken into consideration both to have optimum operation and to minimize the system costs. Proper operation, maintenance and monitoring processes should also be performed in these systems since the success of the system is not totally depend on design parameters. In this study, critical design parameters of constructed wetlands were assessed and potential mistakes made in design of constructed wetland systems of Kayseri province of Turkey were provided and solutions were proposed for already existing problems.

Keywords: Constructed wetlands, design parameters, natural treatment, wastewater.

1. INTRODUCTION

Together with ever-increasing world population, water and food demands of people are increasing continuously. World population has already reached to 7.5 billion and there is a great demand for water and food just to feed this huge and continuously increasing population. Since agricultural, industrial and domestic water users are in a challenging competition for limited fresh water resources, there is an increasing pressure exerted over available water resources. Besides, current global warming and climate change aggravate this pressure over water resources. Thus, world countries have put water resources and water-related problems into first place in their agendas and assigned uppermost significance to water resources.

Among the water-user sectors, agriculture is the greatest water user sector especially in developing countries. Thus, agricultural water use should initially be handled to overcome water-related problems, then the problems in other water using sectors should be taken into consideration. Water losses and wastes in all sectors should be prevented, efficient water use should be provided and possible use of wastewater and treated water should be investigated (Akuzum et al., 2010).

Municipal Wastewater Statistics revealed that 1,309 municipalities out of 1,396 municipalities were served by sewerage systems in Turkey. Out of 4.3 billion m^3 of wastewater collected by sewerage

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systems, 44.6% was discharged into sea, 44.2% was discharged into river, 2.8% into dam, 2.2% into lake and artificial lake, 0.4% onto land, and 5.8% to other receiving bodies. Out of 4.3 billion m^3 of wastewater discharged via sewerage system, 3.5 billion m^3 was treated in wastewater treatment plants. It means treatment was applied to 81% of discharged wastewater. The rate of advanced treatment was 41.6%, while the rate of biological treatment was 33.2%, the rate of physical treatment was 25.0% and the rate of natural treatment was 0.2%. About 50.5% of the treated wastewater was discharged into sea, 40.5% was discharged into river, 1.8% was discharged into dam, 1.4% was discharged into lake and artificial lake, 0.2% was discharged onto land and 5.6% was discharged into other receiving bodies. It is determined that, in 2014, population served by sewerage systems has a share of 84% in Turkey's population and a share of 90% in total municipal population. Rate of population served by wastewater treatment plants was 64% in Turkey's population, and 68% in total municipal population. Average amount wastewater discharged from municipal sewerage systems per capita per day was calculated as 181 liters. Considering the three largest cities, average amount of wastewater discharged per capita per day was 230 liters for Istanbul, 183 liters for Ankara, and 214 liters for Izmir (Anonymous, 2015a).

Constructed wetlands, also called natural treatment systems with their cheaper and easy construction, low energy and labor costs, easy operation, maintenance and monitoring were specified as the primary issue in rural development strategy document of State Planning Organization of Turkey (Anonymous, 2006). Natural and constructed wetlands are treatment systems employed as an alternative to conventional treatment systems because of their low construction, operation and maintenance costs, low energy demands, simple operation and low sludge generation (Knight et al., 1987; Kadlec & Knight, 1996). These systems are specially designed systems imitating the natural wetlands and include soil, plant and microorganisms to remove the pollutants from wastewaters. An excavated constructed wetland basin is lined with compacted clay or synthetic membrane and filled with graded sand-gravel substrate (Anonymous, 2011a). Today, constructed wetlands are widely used to treat domestic wastewaters, agricultural wastewaters, industrial wastewater and runoff waters. Treated effluent water can be used for irrigation and other water recycling purposes.

In present study, initially brief information was provided about the natural wetlands to present an insight into natural treatment systems. Then, possible use of constructed wetlands imitating these natural wetlands for waste water treatment in rural parts of Turkey, especially in villages, was assessed. Brief information was also provided about potential drawbacks and problems observed in construction, operation and maintenance of these systems

2. NATURAL WETLANDS

A wetland is a land area that is saturated with water, either permanently or seasonally, such that it takes on the characteristics of a distinct ecosystem (Anonymous, 2011b). The primary factor that distinguishes wetlands from other land forms or water bodies is the characteristic vegetation of aquatic plants, adapted to the unique hydric soil. According to Ramsar Convention, wetlands include a wide variety of habitats such as marshes, peatlands, floodplains, rivers and lakes, and coastal areas such as saltmarshes, mangroves, and seagrass beds, but also coral reefs and other marine areas no deeper than six meters at low tide, as well as human-made wetlands such as waste-water treatment ponds and reservoirs (Anonymous, 2011c).

Wetlands have various significant roles in environment such as water purification, flood control, carbon sink and shoreline stability. They are also considered as the most biologically diverse of all ecosystems and serve as home for a wide range of plant and animal species. Nutrient inflow to

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wetlands supports the growth of vegetation and vegetation constitutes the primary component of wetland food-chain and converts inorganic materials into organic materials (Hammer & Bastain, 1989). The functions and benefits provided by the wetlands can be summarized as follows (Ayvaz, 2005);

- Purify waters through retaining residues and poisonous materials or using nutrients (nitrogen, phosphorus).
- Raise the humidity of the region where they are located and have positive impacts primarily on local climate parameters such as precipitation and temperature.
- Stabilize the water regimes of the regions where they are located through charging or discharging groundwater tables, storing floodwater, controlling floods, preventing see water intrusion.
- Provide a habitat for a rich flora and fauna.
- They are the ecosystems with the highest biological production like tropical rainforests.
- They have a high economic value with their supports provided in fishery, agriculture, livestock, reed production and tourism.

Just because of wastewater discharges into wetlands because of water treatment functions, they are under serious pollution threats and such a case brought the preservation of such sites into consideration. Although researches indicated high waste water treatment performance of natural wetlands (Knight et al., 1987; Kadlec & Knight, 1996), such implementations may have some adverse effects with regard to preservation of these sites. Toxic elements in wastewaters, negative impacts of pathogens and additional hydraulic loading and nutrients can cause long-term degradations in these natural systems. Therefore, constructed wetland technologies have been developed instead of natural ones for wastewater treatment purposes.

3. CONSTRUCTED WETLANDS (NATURAL TREATMENT SYSTEMS)

Many terms are used to denote constructed wetlands, such as reed beds, soil infiltration beds, constructed treatment wetlands, treatment wetlands, etc. Beside "engineered" wetlands, the terms of "man-made" or "artificial" wetlands are often found as well (Hoffmann et al., 2011). Constructed wetlands imitate the natural wetlands in treatment of domestic wastewaters. They are also called natural treatment systems and contain soil, plant and microorganisms within specially-designed and constructed basins to remove pollutants from wastewaters (EPA, 1993). These systems are commonly composed of a compacted clay or synthetic liner overlaid with graded sand and gravel substrate material, reed like aquatic plants and the other engineering structures adjusting hydraulic loading rates, hydraulic retention times and water levels within the basin (Fig. 1). Constructed wetlands are engineered systems that use natural functions of vegetation, soil, and organisms to treat different water streams. Depending on the type of wastewater that must to be treated the system has to be adjusted accordingly which means that pre- or post-treatments might be necessary.

Constructed wetlands have several advantages over the conventional treatment systems. The primary advantage is their low costs and easy construction. They require quite low or even zero-energy for operation and have significantly lower operational costs than the conventional ones. Constructed wetlands are environment-friendly systems and provide habitat for various wetland plants and organisms. Beside these advantages, they have also some disadvantages. They require larger construction areas than regular and conventional treatment systems to treat the same capacity wastewater influent. The system performance is less stable, dominantly depend on wastewater characteristics and can easily be altered by changing climate conditions (EPA, 1995).

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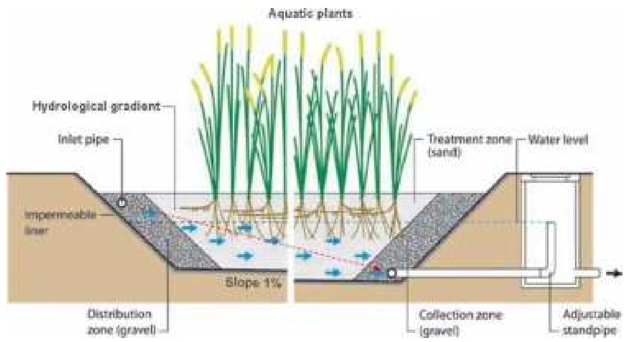

Figure 1. Constructed wetland components (Anonymous, 2003)

A successful constructed wetland design should take the following general criteria into consideration (EPA, 1995):

- The design should comply with the natural landscape and topography.
- The design should be kept as simple as possible.
- Extreme weather and climate conditions should be considered in design.
- The design should be so performed as to require the least maintenance.
- The wastewater flow should be supplied through gravitational flow.
- The systems should be allowed time to reach the desired performance values.

Constructed wetlands are commonly designed as surface flow and sub-surface flow constructed wetlands. Based on flow regime, sub-surface flow wetlands are also classified as vertical and horizontal flow constructed wetlands. In Turkey, mostly sub-surface horizontal flow constructed wetland systems are used for domestic wastewater treatment in rural sections of the country. Thus, brief information was provided about surface flow systems and then sub-surface horizontal flow systems were explained in detail.

3.1. Surface flow constructed wetlands

Surface flow constructed wetland systems are composed of a natural or excavated bed or canal, a compacted impervious layer at the bottom, soil or another substrate media for plant rooting and relatively low water level flowing through the system (Fig. 2). Water surface is open to atmosphere and above the filtrate or substrate material. These systems look more like the natural wetlands and provide various benefits for wild life beside water treatment (Shutes et al., 2002). The primary advantage of these systems are their low investment, operation and maintenance costs, easy construction and operation and the basic disadvantage is the land requirement to construct such systems since they require significantly larger areas than the other constructed wetland or conventional treatment systems (EPA, 1999).

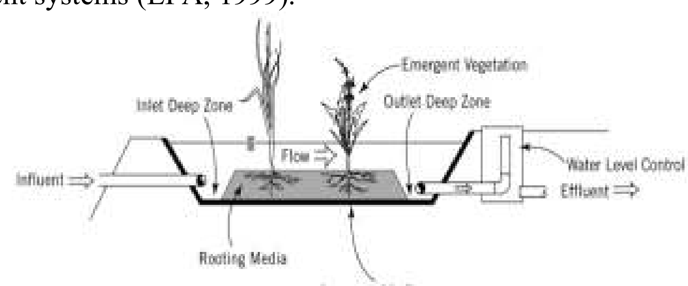

Figure 2. Surface flow constructed wetlands (Anonymous, 1999)

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Table 1. Design parameters for surface flow constructed wetlands

Parameter	**Design Criteria**
Influent quality	BOD ≤20 – 30 mg L^{-1} TSS ≤20 – 30 mg L^{-1}
Pre-treatment	Oxidation basins
Design flows	Q_{max} (maximum monthly flow) Q_{ave} (average flow)
Maximum BOD loading	20 mg L^{-1} : 45 kg ha^{-1} day^{-1} 30 mg L^{-1} : 50 kg/ha^{-1} day^{-1}
Maximum TSS loading	20 mg L^{-1}: 45 kg ha^{-1} day^{-1} 30 mg L^{-1}: 50 kg ha^{-1} day^{-1}
Water depth	0.6 – 0.9 m (full plant cover sections) 1.2 – 1.5 m (Open water surfaces) 1.0 m (Inlet settling section)
Maximum HRT	2 days (full plant cover sections) 2 – 3 days (Open water surfaces)
Basin geometry	Optimum 3:1 – 5:1
Inlet settling section	In case of failed pretreatment in settling
Inlet	Uniform influent distribution in inlet
Outlet	Uniform effluent collection in outlet

3.2. Sub-surface flow constructed wetlands

Contrary to surface flow systems, water does not come out to surface in sub-surface flow constructed wetland systems, in other words, water level is not open to atmosphere and flows through a substrate material and reaches to outlet. Sub-surface flow constructed wetlands are usually composed of an excavated basin, a compacted clay or synthetic impermeable liner overlaid by graded gravel and sand substrate material planted with aquatic plants and water level control structures (Fig. 3). Based on flow regime, they are designed in either horizontal flow or vertical flow and can be used with and without emergent plants (Young, 2000). Certain parameters should be taken into consideration in design of these systems and recommended design criteria are provided in Table 2 (EPA, 1999).

Table 2. Design parameters for sub-surface flow constructed wetlands

Parameter	**Design Criteria**
BOD	6 g m^{-2} day^{-1} – 30 mg L^{-1} for inlet
TSS	20 g m^{-2} day^{-1} – 30 mg L^{-1} for inlet
Depth	Substrate: 0.5-0.6 m Water 0.4-0.5 m
Length	Minimum 15 m
Width	Maximum 61 m
Bed bottom slope	0.5 – 1%
Bed surface slope	Flat or almost flat
Hydraulic conductivity	1000 m day^{-1} for the first 30% of length 10000 m day^{-1} for the last 70% of length
Substrate	Inlet section: 40-80 mm Process section: 20-30 mm Outlet section: 40-80 mm Planting section: 5-20 mm

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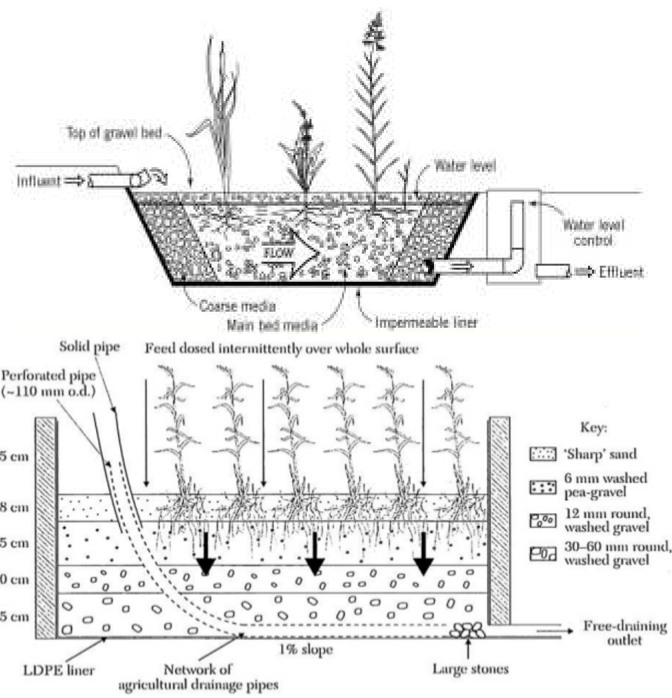

Figure 3. Horizontal and vertical flow sub-surface constructed wetlands (Anonymous, 2015b)

Commonly sub-surface horizontal flow constructed wetlands are used for domestic wastewater treatment in rural parts, especially in villages of Turkey. Municipal waste water administrations or special provincial administrations are responsible for the construction of these systems. However, most of them have already been constructed by special provincial administrations. The administrations usually use type-projects designed to serve certain populations. Since these systems are constructed in villages, they are commonly designed for 250, 500, 750 and 1000 people. A type project designed for a population of 750 people is presented in Fig 4. Concrete septic tanks (usually with 4 cells) are constructed in front of constructed wetland systems to provide a pre-treatment for influent. Suspended soils are mostly settled in septic tanks.

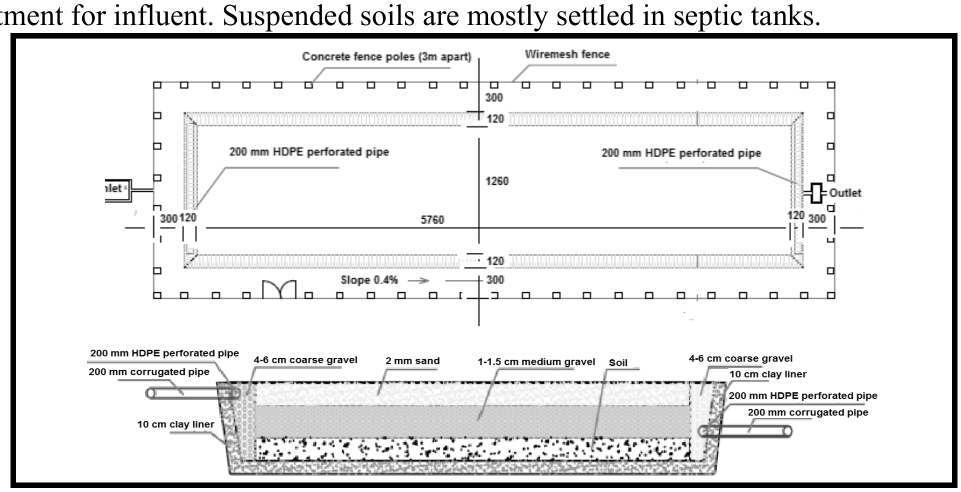

Figure 4. A pilot project designed for a population of 500 people (Gokalp et al., 2014)

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About 1.0 m deep basin is excavated with construction machinery just by taking the population into consideration. Usually about 1 m^2 base area was considered for each person. An aspect ratio (L:W) of about 5:1 is generally used in sub-surface flow constructed wetland systems in Turkey. Excavation of slopes usually performed at a ratio of 1H:2V. Once the basin was excavated, about 10 cm clay liner is placed over the bottom and slopes and the liner is then compacted. Instead of using geotextile or synthetic liners, compacted clay is generally used in Turkey to provide bottom lining and to prevent possible seepage through the bottom and slopes.

The most significant component of these systems is the substrate material filtering the wastewater. The material both provides a medium for rooting of aquatic plants and distributes influent, directs and collects effluent, provides surface area for microbial activity and filters suspended solids. Although various size and composition of substrate materials have been tried, there are not any concrete evidences about which size or type of material is the best. The basic criterion is not to allow small particles settle into the pores of coarser ones. About 15 cm agricultural soil is placed over the clay liner for rooting of aquatic plants to be planted later on. Over the soil, about 25-30 cm medium gravel (1.0-1.5 cm diameter) layer is placed and over that layer, about 20 cm sand (2.0 mm) layer is placed. Substrate upper surface is leveled and about 1% slope is provided at bottom surface. Coarse gravel (4.0-6.0 cm diameter) is placed at the influent entrance and effluent outlet sections to provide easy influent flow into substrate material through the perforated pipe placed around the top of coarse gravel and easy discharge of effluent through perforated drainage pipe placed beneath the coarse gravel.

Side berms are slightly elevated from the substrate surface to prevent runoffs and erosion of fine materials into the reed bed. Usually common reed (*Phragmites australis*) is used for surface plantation of constructed wetlands in Turkey. A usual density is taken as 3-5 plants (rhizomes) per square meter. Finally entire red bed is surrounded with wire-mesh fences to prevent access to reed bed. The system is then handed over to local administration (village administration) for operation.

In Turkey, only the population to be served was taken into consideration while designing horizontal flow sub-surface constructed wetlands. Local topography, climate conditions, influent wastewater characteristics, hydraulic loading rates, hydraulic retention times, site-specific characteristics, discharge criteria and most important of all standard design procedures are not taken into consideration. Thus, various failures are experienced because of such design errors and majority of already constructed systems are not either well-operating or not-operating at all (Gokalp & Cakmak, 2013).

The common failures are classified as: failures in site selection, inlet clogging, substrate clogging and consequent water ponding over the surface, outlet clogging, leakage through slopes, plantation failures, failures in operation and maintenance (Gokalp et al., 2014). Site selection is a failure observed in some cases where reed bed was constructed just by small streams adjacent to high slopes (Fig. 5a). While design manuals for sub-surface systems recommend 5 m^2 basin surface area per capita, or at least 3-5 m^2 in case of limited land resource, the systems constructed in Turkey usually allocate about 1 m^2 basin surface area per capita. Then clogging is experienced at the influent input section because of excessive loading (Fig. 5b, c). Seepage is another problem in constructed wetlands of Turkey. Commonly clay liners are used to prevent possible seepage. It is easy to compact clay liner over the bottom, but compaction is quite difficult over the sloped surfaces. Therefore, seepage commonly is observed from the sloped surfaces of reed beds. A regular and well-developed plant cover is not established in majority of the systems. Reed beds just turned into 'weed beds' because of improper and insufficient plantation (Fig. 5d). The constructed wetland systems should be properly operated, maintained and monitored. System performance

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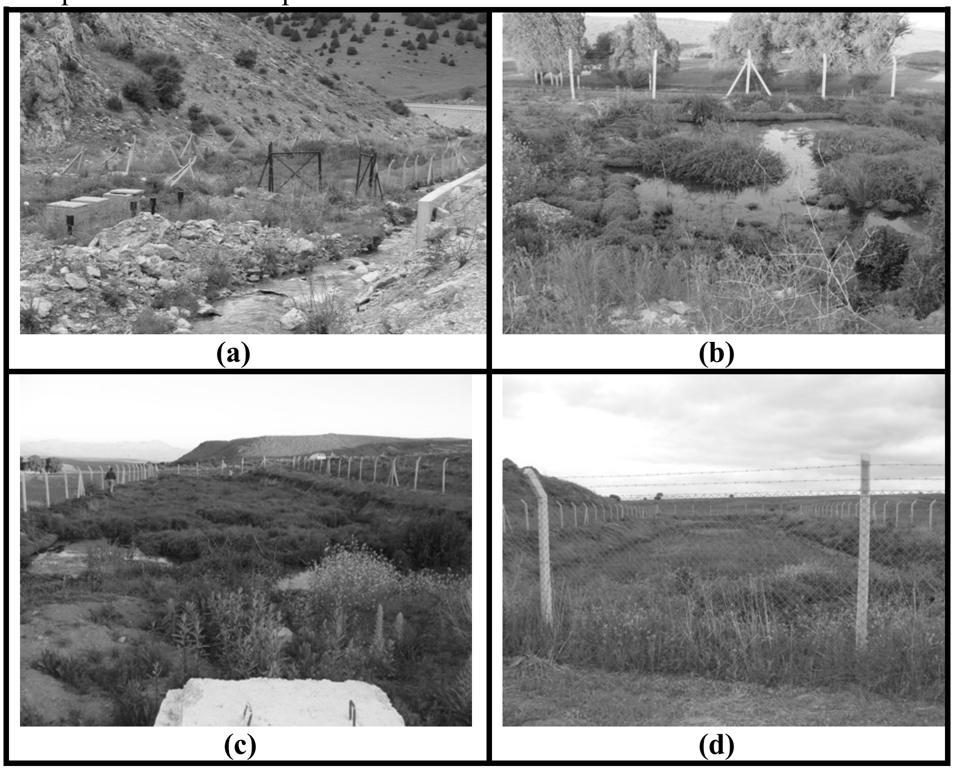
should regularly be assessed through routine analyses for different pollution parameters to see if the system performance meets the relevant discharge criteria. In Turkey, none of these post-construction implementations are performed.



(a) (b) (c) (d)

Figure 5. Common failures experienced in practice (Gokalp et al., 2014)

4. CONCLUSIONS

As long as appropriate design criteria were taken into consideration, constructed wetlands, also called natural treatment systems, can reliably be implemented in sites with low land costs and limited labor force. These systems, especially sub-surface horizontal flow constructed wetland systems, are getting common in rural parts of Turkey, especially in villages to treat domestic wastewater. Such implementations were also specified as the primary issue in rural development strategy document of State Planning Organization of Turkey. However, most of the already constructed systems are not either well-operating or not operating at all just because of errors and mistakes made in their design, operation and maintenance processes. Such errors must urgently be corrected to prevent the waste of investment made on these systems. Valid design specifications, site-specific conditions, local climate conditions and extreme values, influent wastewater characteristics, hydraulic loading rates and retention times should all be taken into consideration while designing a natural treatment system for a specific location. As to conclude, constructed wetlands are the significant systems to prevent water resources pollution since the wastewater previously was being discharged into receiving bodies without any treatments. Now, treated effluents are discharged into water bodies with these systems and consequently both water quality and aquatic life are preserved against the toxic and hazardous impacts of untreated sewage.

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