Constructed Wetlands: Description and Benefits of an Eco-Tech Water Treatment System

Chapter · January 2016

DOI: 10.4018/978-1-4666-9559-7.ch012

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Chapter 12
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Description and Benefits of an Eco-Tech Water Treatment System

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ABSTRACT

Constructed Wetlands are an alternative, promising technology for water/wastewater treatment and pollution mitigation. They belong to the wider category of natural treatment systems. The main principle is to exploit natural materials (gravel, sand, plants) and naturally occurring processes under controlled conditions for treatment purposes. Constructed Wetlands have been characterized as an environmentally friendly, sustainable technology which provides multiple economic, ecological, technical and societal benefits. It is a rising technology which can be effectively used for domestic, municipal and industrial wastewater treatment, as also for sludge dewatering and drying. This chapter presents an overview of this eco-technology; its different types, main design considerations and various advantages over conventional treatment methods.

INTRODUCTION

The use of natural processes is not something new in waste/wastewater processes. Practically, most known technologies and techniques are based on these processes, such as sedimentation, filtration, biological activity etc, and are often constructed with complex and energy-consuming mechanical equipment. The difference that separates natural treatment systems from conventional ones is that only natural components are used for the treatment. Naturally occurring processes are utilized under a controlled environment, without the input of external energy source, unless perhaps for pump operation. Among the various natural treatment systems such as facultative and oxidation ponds, Constructed Wetlands (CWs) appear as one of the most promising eco-tech treatment methods, which have been attracting increasing worldwide interest. Their excellent treatment performance, coupled with an environmentally friendly character and reduced overall costs are gradually placing Constructed Wetlands in the forefront of the scientific and marketing interest. This chapter discusses the multiple environmental, economic

DOI: 10.4018/978-1-4666-9559-7.ch012

and technical advantages of these treatment systems and includes a brief description of their design and the wide range of their applications. These characteristics aim at presenting current research progress on sustainability issues in innovative wastewater treatment systems.

Background

Wetlands are considered today as natural systems with great ecological significance which provide habitat for numerous species and support their life. Natural Wetlands includes various benefits such as groundwater aquifer enrichment, control of flood incidents, absorption of carbon dioxide, heat storage and release, sediment trapping and other (Stefanakis, Akratos & Tsihrintzis, 2014). Their values can be translated in ecological, social, cultural and economic units (De Grot, Stuip, Finlayson, & Davidson, 2006). It was gradually realized that natural wetlands had always been capable of providing water purification and improving water quality, at least up until the point where industrial contamination had become so intensive. This observation initiated the investigation of re-assessing existing wetland purification potential. Natural wetlands have been utilized as disposal sites for secondary or tertiary wastewater effluents for many years, even some thousands years ago. Sewerage collection systems were constructed in the Zakros and Knossos Palaces during the Minoan era in the Greek Island of Crete, where nearby torrents and wetlands were used as disposal sites (Angelakis, Koutsoyiannis, & Tchobanoglous, 2005; Stefanakis et al., 2014). In modern times, the transition from Natural to Constructed Wetlands (CWs) was based on the potential exploitation of naturally occurring processes in a controlled environment for beneficial human and environmental usage and the healthy perpetuation of the natural environment. In this context, man-made Constructed Wetlands are designed to mimic and, thus, enhance the functions and operations of natural wetlands. While Constructed Wetlands generally offer the same functions and values as natural wetlands do, they also may appear as a more ecologically endowed system. Studies have shown that Constructed Wetlands possess a higher value in terms of flood and stormwater control, water quality improvement and biodiversity restoration (Ghermandi, Van den Bergh, Brander, De Groot, & Nunes, 2010). This may be because they are more easily integrated into the built infrastructure by urban planners, engineers, and landscape architects.

Today, the term "Constructed Wetlands" (also known as ""Treatment Wetlands" or "Reed Beds") refers to engineered systems which are designed to exploit under controlled conditions the processes that occur in nature (Stefanakis et al., 2014). Constructed Wetlands belong to the wider category of natural treatment systems which primarily rely on natural processes and/or natural components for wastewater treatment, where intensive use of external energy input can be avoided. Natural treatment systems are mainly classified into terrestrial, aquatic and wetland systems. Aquatic systems include stabilization or oxidation ponds and terrestrial systems slow rate systems and soil aquifer treatment (Stefanakis et al., 2014). Constructed Wetlands are in the middle of these two categories. The technology of Constructed Wetlands began with laboratory experiments in the Max Planck Institute in Germany in the 1950s. The first system in Europe was constructed in the 1960s and in the USA in the 1970s-1980s. Despite these early experiments and attempts, until the end of the 1980s Constructed Wetlands technology was not widely tested or utilized. Failure incidents of some of the first systems due to inadequate design, indicating lack of experience, and competition from conventional treatment methods in use for more than 80 years, were considered as the main initial obstacles for this limited expansion. However, over the last 20 years the interest for alternative treatment methods has increased and the Constructed Wetlands technology has experienced a tremendous increase in both research and applications, due to the simultaneous increase of environmental awareness and sensitivity. Stefanakis et al. (2014) reported that the number of published scientific papers on Constructed Wetlands during the decade 2000-2010 has more than doubled, compared to the previous decade (1990-2000).

Constructed Wetlands represent one of the most interesting and attractive developments in environmental/ecological engineering. The philosophy behind this type of wastewater system is based on the decentralized approach in contrast to what had been regarded as the centralized approach of conventional biological treatment methods which dominate the wastewater market. This new approach also introduces new parameters and views in wastewater treatment, such as sustainability and overall environmental impact. The following section of this chapter presents an overview of constructed wetland classification, technology and description of its principal characteristics, with a focus on its advantages and benefits and its various wastewater treatment applications.

CONSTRUCTED WETLANDS TECHNOLOGY

Classification

Constructed Wetlands can be classified according to their functions and aims in three main application areas (Knight, 1997; Stefanakis et al., 2014):

- **Habitat creation:** these systems are designed to provide a revitalized wildlife habitat and to enhance the pre-existing ecological benefits of the technology such as attracting animals such as birds and creating a green area, while addressing the water/wastewater treatment and mitigation. In this category, four different types of CWs exist: ponds, marshes, swamps and ephemeral wetlands.
- **Flood control:** these systems operate as runoff receivers during flood incidents and increase the storm water storage capacity in urban areas.
- **Wastewater treatment:** systems designed and operated to receive and treat wastewater of different origin.

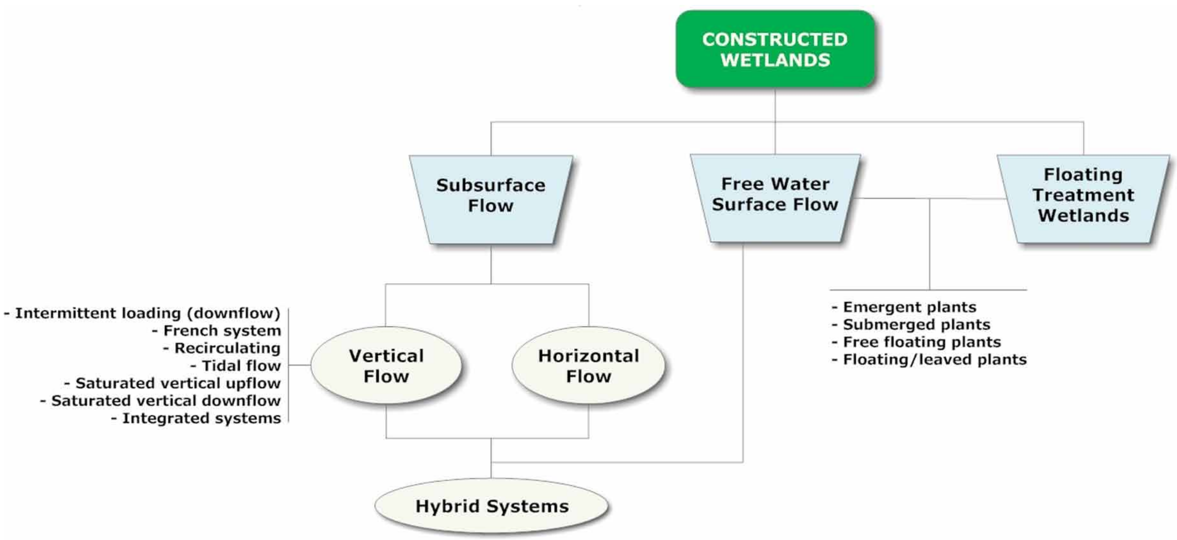
Another widely used classification of CW systems is based on the main characteristics of the system such as the direction of the water flow and the type of vegetation used, as it is depicted in Fig. 1. Thus, based on the flow path across the CW system, there are two general types (Kadlec & Wallace, 2009; Stefanakis et al., 2014):

A. Free water surface constructed wetlands (FWS CWs) and
B. Subsurface flow constructed wetlands (SF CWs).

A further classification of SF CWs can be made depending on the flow path direction; horizontal (HSF CWs) or vertical (VFCWs).

The type of vegetation used in CWs is one of the major characteristics of the system. Thus, based on the vegetation type, CWs can be also classified as (a) emergent macrophyte wetlands, (b) submerged macrophyte wetlands and (c) floating treatment wetlands (FTWs) (Vymazal, 2007; Stefanakis et al., 2014). CWs with rooted emergent macrophytes are the most widely used.

Figure 1. Classification of Constructed Wetlands.



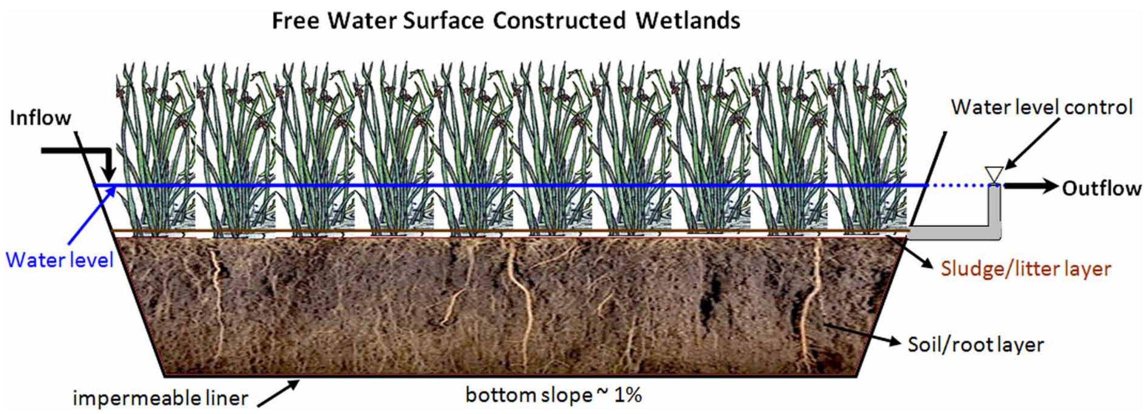
Free Water Surface Constructed Wetlands (FWS CWs)

This type of CWs is widely used in North America, almost exclusively for wastewater treatment applications (Kadlec & Wallace, 2009). They are shallow basins or channels containing a soil layer (30-40 cm thick), in which the macrophytes are planted. Most common plants species used are common reeds (*Phragmites australis*), cattails (*Typha* spp), bulrush (*Scirpus* spp) and herbs (*Juncus* spp) (Vymazal, 2013; Stefanakis et al., 2014). The bottom of the basin (as in all CW systems) is covered by a geo-textile/geo-membrane or clay material in order to prevent wastewater leakage to the groundwater. Above the soil layer there is a water column (20-40 cm deep or deeper) which is exposed to the atmosphere and the solar radiation (Vymazal, 2013). Appropriate water level control at the outlet of the system regulates the depth of the water column; usually there is flexibility in the depth adjustment. The water flows through the plant stems and comes into contact with the top layer of the soil and the plant parts, which allows for the pollutant removal through various physical, biological and chemical processes. FWS CWs tend to attract mosquitos, especially when the water remains almost stagnant. This system performs well for suspended solids (SS) and biochemical oxygen demand (BOD_5) removal. Removal of nitrogen (N) and pathogens is satisfying, but phosphorus (P) removal is usually limited (Vymazal, 2007; Kadlec & Wallace, 2009; Kotti, Gikas, & Tsihrintzis, 2010; Stefanakis et al., 2014). FWS CWs have been applied for the treatment of primary and secondary municipal effluents, storm water and highway runoff and agricultural wastewater (Vymazal, 2013; Stefanakis et al., 2014). This type of CWs has higher area demands when compared with other types for the same wastewater characteristics (origin, flow). Since these systems have an open water surface they tend to resemble natural wetlands at a greater level.

Horizontal Subsurface Flow Constructed Wetlands (HSF CWs)

HSF CWs are more widely used in Europe than in the USA (Stefanakis & Tsihrintzis, 2009a). These systems are basins containing gravel material, usually planted with common reeds (*Phragmites austra-*

Figure 2. Schematic Representation of Free Water Surface Constructed Wetlands.

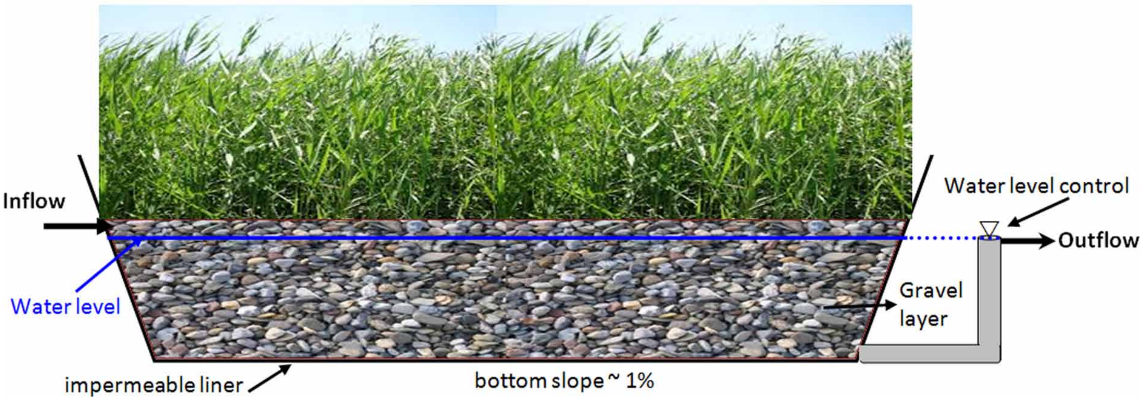


lis) or other species such as *Typha* (e.g., latifolia, angustifolia) and *Scirpus* (e.g., lacustris, californicus) (Vymazal, 2011). The substrate used is rocks of different origin and composition. Unlike FWS CWs, in this CW type there is no water surface exposed to the atmosphere; the water level is kept 5-10 cm below the gravel layer surface and water flows through the pores of the substrate media and comes into contact with the media grains, the plant roots and the attached biofilm (Stefanakis et al., 2014). Thus, respective health risks due to possible human contact with the wastewater and mosquito issues are limited in this CW type (Kadlec & Wallace, 2009). The substrate layer thickness varies from 30 to 80 cm (Akratos & Tsihrintzis, 2007; Kadlec & Wallace, 2009). The bottom of the bed is usually covered with an impermeable geo-membrane and has a slight slope (1-3%) to allow the water flow. As for FWS CWs, the uniform distribution of the wastewater across the wetland width at the inflow point is a key parameter for the proper function of the system (Akratos & Tsihrintzis, 2007), while step-feeding of the wastewater along the wetland length has been found to enhance the system performance (Stefanakis, Akratos, & Tsihrintzis, 2011a). HSF CWs have the advantage of lower area demands compared to FWS CWs, although capital costs might be higher (Kadlec & Wallace, 2009; Stefanakis et al., 2014). This CW type has been proved to be very effective in the treatment of municipal wastewater, removing SS and organic matter (BOD_5) at high rates, although nutrient removal (nitrogen, phosphorus) is usually lower (Akratos & Tsihrintzis, 2007; Vymazal, 2007; Kadlec & Wallace, 2009; Stefanakis et al., 2014). Various modifications of the system design have been proposed in order to improve the performance such as effluent recirculation (Stefanakis & Tsihrintzis, 2009a), wastewater step-feeding (Stefanakis et al., 2011a), water level raising (Stefanakis & Tsihrintzis, 2009a) and effluent treatment with zeolite gravity filters (Stefanakis, Akratos, Gikas, & Tsihrintzis, 2009a). HSF CWs have been also applied for the treatment of industrial wastewater, e.g., mine drainage, dairy, swine, olive mills, landfill leachate, cork effluent, contaminated groundwater, hydrocarbons etc. (Vymazal, 2009; Santos et al., 2012; Stefanakis et al., 2013).

Vertical Flow Constructed Wetlands (VFCWs)

Until recently, this type of CWs was the least developed and applied. At the early stages of CW technology, FWS and HSF CWs were the dominant types, mainly due to higher overall costs for VFCWs construction and operation. However, the interest in VFCWs was gradually increased with time; espe-

Figure 3. Schematic representation of Horizontal Subsurface Flow Constructed Wetlands.



cially when the higher oxygen transfer capacity of this CW type was realized compared to the horizontal flow beds. Thus, over the last 15 years research on VFCW systems was substantially intensified. Today, there are various modifications of VF systems which are either already applied or under investigation. VFCWs are mainly used in Europe, and especially in Denmark, Austria, Germany, France, and the United Kingdom (Kadlec & Wallace, 2009; Stefanakis et al., 2014). The most common setup is a basin containing several layers of gravels and sand with increasing gradation from top to the bottom (Stefanakis & Tsihrintzis, 2009b; 2012a; Stefanakis et al., 2014). The total thickness of the substrate varies from 30 to 180 cm (Stefanakis et al., 2014). Usually, the top layer of the bed is a sand layer. Plants are established in the top gravel layer or in the sand layer (if any). As for the other CW types, common reeds (*Phragmites australis*) and cattails (*Typha latifolia*) are the two most widely used plant species. The bottom of the bed is covered by a geo-membrane/geo-textile material and has a slight slop of 1-2%. VFCWs also contain perforated vertical aeration tubes which are connected at the bottom of the bed with the drainage collection pipeline system. These aeration tubes allow for the better aeration of the deeper parts of the bed (Stefanakis & Tsihrintzis, 2012a). The wastewater is applied in batches on top of the bed and drains vertically by gravity, while it should be uniformly distributed across the entire surface of the bed (Stefanakis & Tsihrintzis, 2012a; Stefanakis et al., 2014). VFCWs have smaller surface area demands compared to HSF and FWS CWs. Due to the better aeration capability, VFCWs are very effective in organic matter (BOD_5) and ammonia nitrogen removal, usually more effective than HSF CWs (Vymazal, 2007; Kadlec & Wallace, 2009; Stefanakis et al., 2014). Phosphorus removal remains limited and alternative modifications have been proposed for performance improvement, e.g., an additional stage with gravity filters containing bauxite, zeolite or other material for effluent treatment (Brix & Arias, 2005; Stefanakis & Tsihrintzis, 2012b). Their overall effectiveness enabled the use of this CW type for the treatment of wastewater with different origin, e.g., domestic, municipal, industrial, agro-industrial and landfill leachate (Stefanakis et al., 2014).

Floating Treatment Wetlands (FTWs)

This type is the latest version of CW technology, combining both a traditional CW system and a pond (Van de Moortel, Meers, Pauw, & Tack, 2010). These systems consist of a floating element (usually made of a plastic material) on which the plants are established; thus, it could be stated that these systems optically look like floating islands. As in the other CW types, the plants develop a deep and dense root system within the underlying water column (Tanner & Headley, 2011; Stefanakis et al., 2014). Since the combined system of the porous plastic basis and the plants floats on the water surface, the system is not affected by fluctuations of the water level. FTWs have been used for water purification in rivers, channels, lakes etc., as also for stormwater, domestic and municipal wastewater treatment (Van de Moortel et al., 2010; Stefanakis et al., 2014).

Sludge Treatment Wetlands (STWs)

These systems represent a special and very promising application of CW technology, for the treatment and management of excess sludge that is produced in conventional wastewater treatment plants. STWs appear as alternative systems to mechanical dewatering methods such as centrifuges or filter presses. They resemble vertical flow constructed wetlands (Fig. 4) in the design and construction, but they are modified systems for wastewater sludge dewatering and drying (Stefanakis & Tsihrintzis, 2012c; Stefanakis et al., 2014). As the vertical flow systems, STWs are rectangular or trapezoidal excavated basins filled with substrate materials planted with reeds (Nielsen, 2003). Usually the basin contains 1-2 gravel layers and on top a sand layer (Nielsen, 2005), although there have been systems designed without a top sand layer (Stefanakis et al., 2009b; Stefanakis & Tsihrintzis, 2012c). The total thickness of the porous media layers varies between 30-70 cm (Stefanakis et al., 2014). Sludge is applied on top of the bed in feeding cycles: a typical feeding scheme is 2-10 days of sludge feeding followed by 1-3 weeks of resting (Nielsen, 2003; Stefanakis et al., 2009b; Stefanakis and Tsihrintzis, 2012c). The bottom of the beds can be either constructed with concrete or excavated and covered with a liner, typically with a material of low-permeability as for the other CW types (i.e., HDPE geo-membrane covered in both sides with geotextile or clay) (Stefanakis et al., 2014). The bottom layer also contains a network of perforated plastic pipes for the collection of the drained water that flows vertically through the bed body. This bottom pipe network is connected with the atmosphere with vertical perforated plastic aeration pipes which are extended above the top layer and are open on their top end. STWs achieve high rates of sludge dewatering (volume reduction up to 96%; Stefanakis & Tsihrintzis, 2012c; Stefanakis et al., 2014), through evapotranspiration and draining processes (Stefanakis & Tsihrintzis, 2011).

Figure 5. Schematic representation of Floating Treatment Wetlands.

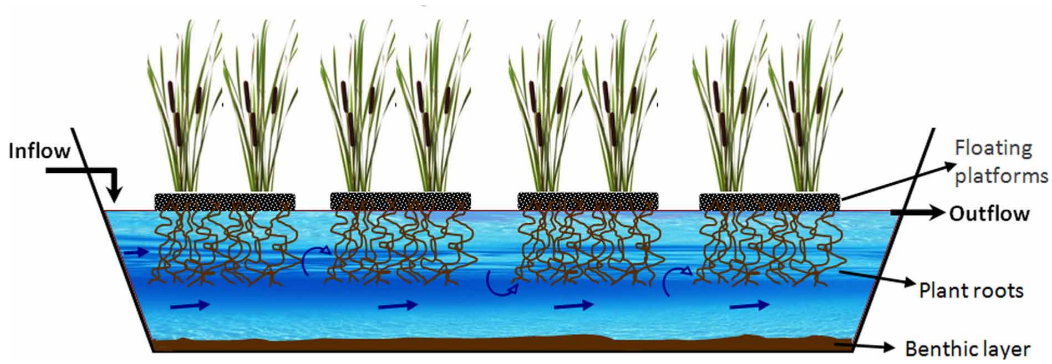
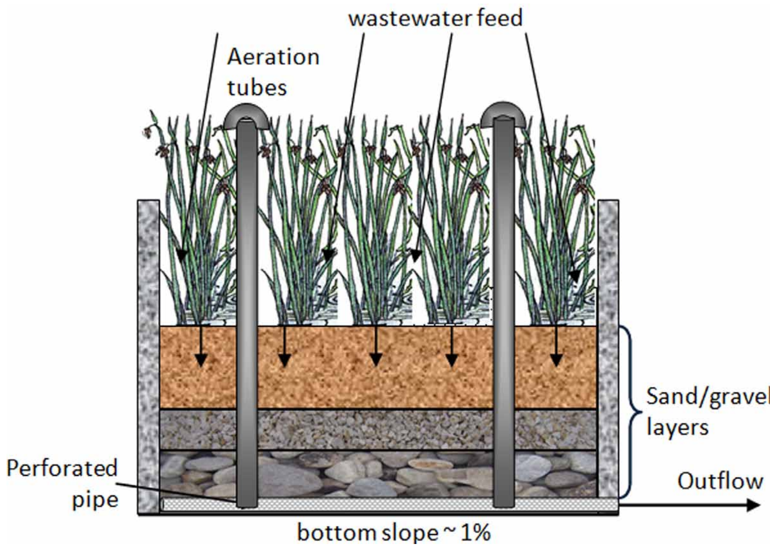


Figure 4. Schematic representation of Vertical Flow Constructed Wetlands.



Design Considerations of Constructed Wetland Facilities

CW beds are generally considered as easy to build and operate; however, the proper design of a CW facility is not as easy as it seems. Since it is a relatively new technology, there are not unanimously accepted guidelines or a widely applied setup. System design tends to differ not only from country to country but also among designers and experts/engineers. Personal experience is usually a key parameter. However, there are general rules and some basic design considerations which are used during the design process, including meteorological, topographical and operational parameters such as (Stefanakis et al., 2014):

- Climatic conditions of the area where the system will be installed,
- Topographical information in order to choose the most appropriate installation site,
- Geological structure of the area,
- Availability of the necessary land,
- Current and future wastewater flow and volumes,
- Any legal limits that apply in the area for the effluent quality – desired treatment performance
- Possibilities/desire for effluent reuse options,
- A nearby water body-effluent receiver,
- Total costs.

As it is obvious, most of these general parameters are common prior the implementation of any treatment technology. There are three main design parameters for constructed wetland systems which should be taken into account: (a) unit area demand (m^2/pe), (b) organic and hydraulic loading and (c) oxygen transfer capacity (Stefanakis et al., 2014). The unit area demand expresses the surface area demand (m^2) per person equivalent (pe). This parameter is generally accepted and serves as a good indication of the overall land area demands. Apparently, this parameter is affected by the climatic conditions. However, it is common than even for the same region different values are proposed based on the individual experience. Generally, VFCWs have lower area demands (1-2 m^2/pe) than HSF CWS (5-10 m^2/pe) (Stefanakis et al., 2014). Organic (e.g., g BOD_5 or COD/m^2/yr) and hydraulic (m^3/m^2/d or m/d) loads are also used and give a good idea of the system load. These parameters are very helpful in the determination of the optimum loading which will cause no operational problems. Finally, the oxygen transfer capacity (OTC) provides important information concerning the oxidation potential of the system, especially for organic matter decomposition and ammonia nitrogen nitrification.

Another important parameter which is mostly applied in horizontal CWs (either surface or subsurface) is the hydraulic retention time (HRT), which is described as the ratio of volume (m^3) to flow rate (m^3/d). Its value is crucial since it defines the available time for direct contact of the wastewater and the wetland elements (porous media grains, plant roots, biofilm) and, thus, the extent of the various removal/transformation processes. The selection of an appropriate HRT is directly related to the system surface area (and so to the unit area demand) and performance. Currently, there are many published studies and results from pilot and full-scale installations. For example, typical HRT in HSF CWs varies between 5-20 days, depending on the climatic conditions, the level of treatment etc. Dimensions of horizontal beds are also important; usually HSF and FWS CWs have a rectangular plan view with a varying width to length ratio of 1:3-5. Longer length than width is preferred in order to ensure plug flow hydraulics.

Generally, designing and sizing a wetland bed varies from simple "rule of thumb" to more complex models. The plug-flow first order k (known as the kC* model) is often used, as also Monod-type equations (Kadlec & Wallace, 2009). A simple equation which is often used for the calculation of the required surface area for BOD_5 removal is the following:

$$A = \frac{Q\ [\ln(C_o / C_e)]}{K_T\ d\ n} \qquad (1)$$

where, A = the surface area of the bed (m^2), d = the saturated depth of the bed (m), n = the substrate porosity (decimal fraction), K_T = the first-order areal rate constant (m/d), Q = the average daily flow rate (m^3/d), C_o the mean influent BOD_5 concentration (mg/L) and C_e the required effluent BOD_5 concentration (mg/L). For example, for a bed depth of 0.6 m at 10°C, K gets the value 5.2. K values depend on the biodegradability of the wastewater. Usually, BOD_5 is used as the main target parameter, but other pollutants such as suspended solids (SS), ammonia nitrogen and total phosphorus have also been used. The parameters used for the evaluation of CWs performance are the same pollutant indicators as for every wastewater treatment technology, such as organic matter (BOD_5 and COD), nitrogen compounds (total nitrogen, ammonia nitrogen, nitrate, nitrite), phosphorus (total phosphorus, ortho-phosphate), coliform bacteria (*E. coli*, feacal coliforms) and heavy metals. Physical characteristics (e.g., dissolved oxygen, electrical conductivity, pH etc) are also used to describe CWs operating conditions.

In Sludge Treatment Wetlands, the design is based on the quality of the raw sludge and the local climatic conditions, as well as on the annual sludge production of the wastewater treatment plant (Stefanakis et al., 2014). As for other CW types, the design and dimensioning of STWs follows mostly empirical observations and personal experience of the designer. Again, there are no commonly accepted guidelines and the design varies from country to country. The basic design parameter is the sludge loading rate (SLR; kg dm/m^2/yr), which expresses the annual dry mass (dm/yr) or dry solids (ds/yr) that will be applied to the bed per surface unit (m^2). It is directly related to the climate of the installation area. For example, proposed SLR for Denmark is 60 kg dm/m^2/yr for activated sludge and 50 kg dm/m^2/yr for sludge with higher fat content (Nielsen, 2003). Higher SLRs have been proposed for the Mediterranean basin: up to 90 kg dm/m^2/yr in Greece (Stefanakis & Tsihrintzis, 2012c), as also 45 kg dm/m^2/yr in Italy (Bianchi et al., 2011) and 55-110 kg dm/m^2/yr in Spain (Uggetti et al., 2009; Uggetti, Ferrer, Molist, & Garcıa, 2011). Stefanakis et al. (2014) presented an overview of SLRs applied in various countries around the world. The operational life time of STWs can last up to 30 years and more and it is divided in 2-3 phases of 8-12 years, based on the applied SLR. After the completion of each phase, the bed is left to rest for some period (a few months up to 1 year), then the accumulated sludge residual is removed and a new feeding cycle begins (Nielsen, 2003; Stefanakis & Tsihrintzis, 2012c; Stefanakis et al., 2014).

Two important design features of CW facilities are the plant species and the substrate media. The most common emergent plant species used are common reeds (*Phragmites australis*) and cattails (*Typha latifolia*) and also *Scirpus* spp, due to their wide presence in most parts of the world. However, other locally available species may also be used, for example in tropical regions bamboo has been tested in CW systems. Generally, the selected species should be well adapted to the local climatic conditions, tolerant against the various pollutants and with uptake capabilities of certain constituents such as nitrogen. It should be noted that indigenous species are always preferred for use in CWs and not exotic ones, to avoid ecological risks such as invasion of the new species and/or diseases (Stefanakis et al., 2014).

The selection of an appropriate substrate media is also important for the CW system and, as plants, is connected with the system performance. The grain size should be carefully selected, especially for subsurface systems, since clogging problems due to low porosity and high hydraulic loads might occur and affect the system efficiency. An ideal substrate would also have the capacity of removing some constituents from wastewater by various processes (e.g., ion exchange, adsorption, precipitation). The substrate layer is also where the plants are established, thus, it supports plant growth and enhances system stability, provides filtration effects and together with the plants supports the various transformation/removal processes (Vymazal, 2007; Stefanakis et al., 2014). Media used in CW systems include natural materials (e.g., minerals, rocks and soils), synthetic materials (e.g., synthetic zeolites, activated carbon) and industrial by-products (e.g., slags, blast furnace) (Stefanakis et al., 2014).

Facility Layout

A full-scale CW facility comprises of several treatment stages. The first treatment stage is usually the pre-treatment stage. In this stage, large material (e.g., papers, leaves, plastics etc.) and coarse particles are firstly removed using mechanical equipment (e.g., screens and bars), along with a portion of the SS and organic matter. Most common pre-treatment methods are septic or Imhoff tanks and primary sedimentation tanks, although anaerobic digesters and stabilization ponds have also been used (Stefanakis et al., 2014). This pre-treatment stage is very important in CW facilities, since a good performance limits the clogging potential of the following CW beds. In case of industrial or agricultural wastewater, pre-treatment can be more complex and intensive due to the heavier loads of these wastewater types.

Different CW types can be combined in the second and third (or even fourth if necessary) treatment stages of a full-scale facility, usually HSF CWS and VFCWs (Stefanakis et al., 2014). These combined systems are also known as *hybrid CW systems*. The concept is to exploit the specific treatment advantages of each type in one facility and reach higher treatment efficiencies. For example, low nitrification capacity of HSF CWs (due to limited OTC) is counterbalanced by VFCWs (good nitrification capacity, high OTC). Additionally, HSF CWs can be used to provide denitrification of the nitrified effluent from

VFCWs. The most common combination is a two-stage system of a first VFCW bed followed by a HSF CW. Stefanakis et al. (2014) presented several possible combinations of CW types in hybrid systems that have been tested, e.g., VF-HSF, HSF-VF, HSF-VF-HSF, VF-HSF-HSF, VF-HSF-FWS.

The two-stage VFCW system gains increasingly interest since it has been proved very effective. VFCWs operate with parallel beds in each treatment stage. The presence of parallel VFCWs beds is necessary to ensure the continuous operation of the facility, since VFCWs usually operate with intermittent wastewater application (2-4 days of feeding followed by 2-8 days of resting) (Stefanakis & Tsihrintzis, 2012a; Stefanakis et al., 2014). The number of parallel beds in the third treatment stage is lower, since the pollution load is respectively lower due to the prior treatment in the second-stage CW beds. A modification of the two-stage VFCW system has been developed in France, also known as the French system (Molle, Liénard, Boutin, Merlin, & Iwema, 2005; Stefanakis & Tsihrintzis, 2012a). This setup includes two stages of VFCWs but no pre-treatment stage (only screens are used). The wastewater is applied directly on the surface of the first-stage VFCW bed. The key here is that the first-stage beds contain only coarser material (no sand), in order to avoid clogging and gradually accumulate sludge on the surface. The advantage of the French system is that it may have lower costs since no pre-treatment is applied.

A final post-treatment stage is not a basic element in the design of CW facilities but it is often applied when stringent effluent quality criteria have to be met, especially concerning pathogenic microorganisms. Of course, the goal is not to produce a final effluent appropriate for use as potable water, but to further improve the effluent quality and reach higher sanitation levels, in order to minimize or even eliminate the environmental impact. This final stage could include disinfection methods such as chlorination, ozonation or UV radiation. Maturation ponds or a final FWS CW system have also been used as a final treatment stage. A post-treatment stage could also improve the overall system efficiency, e.g., in phosphorus removal.

Facilities of Sludge Treatment Wetlands are similar to those of VFCWs. A STW facility consists of several beds which are alternately loaded with sludge. The presence of several beds allows for the application of feeding and resting periods in the beds and provides flexibility in the loading cycles applied which may vary during winter and summer months (Stefanakis et al., 2014). The number of beds in a STW facility depends on the sludge production of the wastewater treatment plant, the chosen SLR, the cycles of feeding/resting periods and the climatic conditions. For example, Uggetti et al. (2009) used 3 beds, Stefanakis & Tsihrintzis (2012c) 4 beds and Nielsen (2003) 18 beds, which correspond to 400 and 123,000 pe served, respectively.

Advantages of Constructed Wetlands Technology

As an alternative, ecological treatment technology, CWs provide a series of multiple significant advantages compared to conventional treatment methods such as activated sludge systems. Conventional treatment systems are in use for more than 100 years now, serving a different approach of wastewater treatment than CWs. The approach of conventional treatment systems consists in the construction of large, centralized facilities and respectively extended sewer networks for the collection and transport of wastewater. It is not difficult to understand that big end-of-the-pipe centralized plants and the accompanied sewer network represent high required investments. These facilities are also expensive in their operation and maintenance. Of course, this type of facilities appears as the only solution to provide wastewater treatment for large cities, capitals, and other populated urban areas. For these cases, high investment costs are considered as reasonable and unavoidable. However, the question is whether this approach of centralized treatment systems is even applicable in smaller cities, communities and rural areas. Over the last years, an alternative approach of wastewater treatment has risen; the decentralized approach.

Although there have been in the past huge investments in infrastructure for centralized plants, gradual population increase was not accompanied by respective increase in budgets to meet the needs for new wastewater treatment facilities. Insufficient funding was even more realized due to the aging of existing infrastructure, which means that additional investments are needed not only for new installations but also for the refurbishment and technological upgrade of existing facilities. This means that new, innovative and cost-effective methods are more welcome than in the past and the approach of decentralized treatment becomes gradually more attractive. CWs belong exact to this category and serve this philosophy. They are point-of-use treatment systems which can deliver effluents of the desired quality. They can be installed in many areas and regions with reduced overall costs. However, the CW technology should not be viewed as a direct and total competitor of conventional treatment systems. A complete replacement of centralized facilities with CW systems is practically infeasible, since the required land area would be very high; a demand which cannot be met in large densely populated urban areas. But CW systems appear as an ideal solution for small and medium communities, small cities, villages, single households or block of flats and generally rural, mountainous and remote areas, where sewer network does not exist and the construction of a conventional treatment plant is economically unfeasible. For these areas, CW technology provides many technical, economic and ecological benefits, which are summarized in Table 1.

CWs are in general easy to build, simple to operate and provide treatment robust to flow fluctuations and pollutant concentrations. They appear as an ideal solution especially for small communities and settlements and for onsite treatment, where current requirements and needs for effective wastewater treatment are high. CWs facilities can satisfy general effluent discharge limits (e.g., $BOD_5 < 30$ mg/L, COD < 100 mg/L, total nitrogen < 15 mg/L), while effluents of even higher quality can also be achieved (Kadlec & Wallace, 2009; Stefanakis et al., 2014).

Although conventional treatment systems provide effective wastewater treatment for many decades now, they have certain disadvantages. Typical facilities of this type have an industrial appearance and are unattractive, thus, they are usually installed away from residential areas. Centralized plants include large and complex mechanical equipment such as ventilators for aeration, pumps etc., while extensive use of non-renewable materials (concrete, steel) takes place for the construction of the various basins, tanks and equipment. This means that construction of such facilities can be expensive and non-environmentally friendly, despite the fact that the aim is environmental-oriented (wastewater treatment). On the other hand, CW facilities do not include mechanical parts. The only mechanical equipment is pumps to transfer the water from one stage to the other, which - however - can be avoided with a proper design and exploitation of the topography of the installation area. Moreover, conventional treatment plants are energy-intensive systems and they require a large energy input for their operation. Facilities having many complex mechanical parts and equipment may also require high maintenance demands. This means that operational costs of such facilities are also high. On the contrary, minimum operational costs probably represent the main advantage of CW facilities. In CWs, the energy input needed is very small, usually only for the pumps that may exist in the facility. Energy requirements for the treatment processes are covered by renewable energy sources used by plants (solar, wind energy). At the same time, maintenance needs are also low, since the operation of a CW facility is practically autonomous; at the stage of full operation, a typical maintenance scheme applied is one visit at the site on a monthly basis. There may also be far less need for specialized personnel to run the CW facility, contrary to conventional plants

Table 1. Main characteristics of conventional treatment systems (CTS) and Constructed Wetlands (CWs) (Stefanakis et al., 2014).

	Conventional Treatment Systems	Constructed Wetlands
Infrastructure	Many and complex mechanical parts	No mechanical parts (maybe only pumps)
Investment	High construction costs	Usually lower construction costs than CTS (especially if there is available land)
Operational costs	High	Very low to zero
Land area demand	Low	High demand (e.g., 2-10 m^2/pe)
Application scale	Small - medium	Medium - large
Performance	Continuous effluent of high quality	Similar with CTS, small fluctuations may appear with temperature variations
Raw materials	Use of non-renewable materials during construction (concrete, steel, etc.) and operation (electrical power, chemicals)	Almost exclusive use of renewable sources (solar, wind, etc.) - “ecological” character
Energy consumption	High	Low
Greenhouse Gas Emissions	High	Very low
Operation	Need for daily monitoring Useful lifetime up to 25-30 years	Need for periodical check only (e.g., on a monthly basis) – autonomous operation, Prolonged lifetime (>30 years)
Staff during operation	Demand for specialized personnel	No specialized personnel needed
Maintenance	High maintenance needs and costs - regular damages due to large/complex mechanical equipment	Low maintenance cost (only small mechanical parts – pumps)
Odors	Large open air tanks, odor production	Small problems only in free water surface systems
Insects	Usually no significant problems	Small problems only in free water surface systems
Response to flow variations	Higher/shock inflow rates negatively affect the performance	Robust to high flow variations
Robustness to toxic substances	Toxic pollutants may lead to system breakdown	Robust to some toxic constituents
By-products	Large daily volumes of sludge production, which needs handling and management on a daily basis	Zero production of by-products
Appearance	Unattractive, “industrial appearance”	Aesthetically accepted, green view

where specialized staff is necessary. Global experience from many countries and professionals has shown that operational costs of CW facilities can be up to 90% lower compared to conventional plants. Moreover, CWs operate without the need for the addition of any chemical substances, which is not the case in conventional treatment plants.

Additionally, the treatment in CWs does not generate any by-product. Produced sludge is accumulated within the system. On the other hand, in conventional treatment plants large amounts of excess sludge are produced on a daily basis. This excess sludge needs to be managed, dewatered and stabilized in order to be further exploited. Although the sludge volume represents only a small portion (1-3%) of the total treated volume, its management and handling can reach up to 50% of the total facility costs (Stefanakis et al., 2014). It is then realized the significant advantage of CWs of no by-product production. To be accurate, though, it should be noted that occasional sludge removal (e.g., 2-3 times/years) should take place if there is a pre-treatment stage (e.g., sedimentation or Imhoff tank), but this cost is by far lower than the sludge production and handling cost in conventional systems. The only product that could potentially be viewed as by-product in CW facilities is the plant biomass. Usually, the produced plant biomass is harvested and collected once annually. However, this biomass can be exploited as biofuel for energy production or for compost production. Additionally, in most CW systems problems with mosquito and odor production are very low, especially in systems with subsurface flow, which is not the case in conventional treatment facilities where the open wastewater tanks for settling and/or aeration attracts mosquitos and insects and produce odors.

Disadvantages of Constructed Wetlands

Despite the various advantages of this technology, CWs have also some downsides which should be taken into account. The major one is that CWs require a larger land area compared to a conventional treatment facility. Although continuous research managed to reduce the total footprint of CW facilities and optimize their design (e.g., the use vertical flow systems and lately of aerated systems), area demands are still higher (e.g., 3-10 times) for CWs than for conventional systems (Stefanakis et al., 2014). Furthermore, false design could also result in odor problems and the appearance of a water surface in subsurface systems. However, it should be noted that if properly designed and constructed, CWs generally do not create odor issues.

Since the wetland technology still remains relatively new, the CW system is often viewed using the “black box” approach and simple regression equations are used for the design (Button, Nivala, Weber, Aubron, & Müller, 2014). On the other hand, it is known that most of the pollutant removal mechanisms are based on microbial processes (Faulwetter et al., 2009), which means that a better understanding of the fundamental processes taking place inside the system is necessary, in order to provide an optimum design and performance (Stefanakis et al., 2014). Thus, the design of CWs is still largely based on empirical data and professional experience. This also explains the fact that there are not yet widely accepted design guidelines for CW systems. Additionally, optimum performance is usually reached after one or two years of operation, when the plants are fully developed, while there might be some seasonal variations in the overall efficiency.

It should be noted that all the above mentioned drawbacks are currently under investigation by the scientific community. Intensified research over the last 10-15 years has managed to abate most of these issues and further improvements are anticipated in the future.

Sustainable Character of Constructed Wetlands

Based on the above, it is obvious that CW systems possess various and multiple characteristics which attach to this treatment technology an ecological character. They are often characterized as sustainable systems. Low energy consumption and use of natural materials (gravel, soil, sand and plants) are the two main treatment parameters in CWs. One of the largest projects using the wetland technology is the Everglades restoration project, where CWs were used to remove nutrients from agricultural runoff entering the Everglades (Guardo et al., 1995). This project is the largest restoration project in the USA for stormwater treatment and presented in the most emphatic way the sustainable dynamic and treatment capacity of CWs. Similar projects of sustainable design using the wetland technology have been developed for the removal of nonpoint-source pesticide pollution in river catchments (Schulz & Peall, 2001) and diffuse pollution at the catchment scale (Harrington, O'Donovan, & McGrath, 2013), the protection of coastal zone from human activities and pollution in China (Zuo, Wan, Qin, Du, & Wang, 2004), stream restoration (Wang, Gao, Guo, Li, & Zhang, 2012; Palmer, Filoso, & Fanelli, 2014), among others.

However, in order to characterize a technology as "green" there are specific factors which should be met such as effective treatment, robustness, no by-products, recycle/reuse of materials, minimum energy consumption – use of renewable energy sources, minimum/no use of chemicals and minimum environmental nuisance (Brix, 1999). The sustainable character of a treatment system is defined by its economic viability, technical feasibility, environmental protection and social acceptance (SunSanA, 2008). Additionally, it should close the flow cycle of materials, i.e., provide the option for safe reuse of the treated effluents. The approach of sustainable sanitation systems integrates aspects such as public health and hygiene, protection of the environment and natural resources, technological and operational parameters, financial parameters and socio-cultural aspects (SunSanA, 2008; Langergraber, 2013).

Health aspects are of crucial importance since they would determine the level of exposure risk to pathogenic microorganisms and other hazardous compounds. CW systems have been found to be effective in pathogens elimination (Kadlec & Wallace, 2009; Stefanakis et al., 2014). In VFCWs reported elimination rates reach up to 3 logs (i.e., 99.99%) (Stefanakis et al., 2014), while in FWS CWs respectively high rates are reported due to direct UV radiation and disinfection (Kadlec & Wallace, 2009).

The level of environmental protection and natural resources preservation in CW systems is also high. Effective treatment and high removal efficiencies significantly decrease the pollution load that reaches the final receivers (surface and ground water bodies), thus, limiting the risk for ecosystem and aquatic life degradation. Moreover, the construction of CW systems takes place with natural materials (gravel/sand, plants) which are locally available worldwide and minimum use of synthetic or non-renewable materials takes place. This means that the production and provision of raw materials for CWs construction does not include significant energy-consuming and pollution generating processes. The minimum energy consumption in CW facilities also saves natural resources and minimizes pollution generation, especially when the energy source is non-renewable (e.g., fossil fuels). These environmental benefits can be translated to low levels of greenhouse gas emissions (CO_2, CH_4 and N_2O) (Langergraber, 2013; Stefanakis et al., 2014).

Quantification of these gas emissions for various wastewater treatment methods during both construction and operation phases is important for the estimation of the ecological impact and the global warming potential. Studies report that CW systems have a slightly lower environmental impact during the construction phase compared to other conventional methods (e.g., activated sludge, trickling filters), but a much lower impact for the operation phase (Georges, Thornton, & Sadler, 2009). Life cycle analysis studies on CW systems and comparison with alternative scenarios of using conventional treatment methods have also shown that the global warming potential of CWs is lower in terms of CO_2 emissions (Stefanakis et al., 2014). It is also interesting that in CW systems the major portion of the environmental impact occurs during the construction phase than the operation phase (Dixon, Simon, & Burkitt, 2003; Machado et al., 2007), while in conventional treatment plants the environmental impact of the operational phase is higher than the impact of the construction phase (Dixon et al., 2003; Ortiz, Raluy, Serra, & Uche, 2007; Renou, Thomas, Aoustin, & Pons, 2008; Stefanakis et al., 2014). Among the various CW types, FWS systems produce the lowest CO_2 emissions, VFCWs the lowest CH_4 emissions, while N_2O emissions are reported to be comparable in all CW types (Mander et al., 2014). It should be noted that hybrid CW systems, where different CW types are combined, achieve higher removal efficiencies and minimum greenhouse gas emissions at the same time. The ecological character of CWs is also enhanced by the fact that they promote biodiversity, they provide habitat for various wetland organisms, water savings and multiple hydrological functions (Langergraber, 2013).

Similar results are reported for sludge dewatering in Sludge Treatment Wetlands (Stefanakis et al., 2014). The comparison with conventional centralized facilities such as centrifuges, including all parameters of sludge management (transport, construction, raw materials, energy consumption), has shown that STWs have the lower environmental impact (Uggetti et al., 2011). As for CWs for wastewater treatment, the main impact occurs during the construction phase due to the raw materials used, while respective impact for the operational phase is minimum. If the basin for the CW is simply excavated or recycled concrete is used, when the impact of the construction phase can be reduced. Centrifuges have the highest environmental impact, since their operation requires a high energy input. The contribution of STWs to global warming is negligible. It is reported that the overall environmental impact of Sludge Treatment Wetlands is 500 times lower when compared with centrifugation technique and 2000 times lower compared to sludge transport to a centralized facility (Stefanakis et al., 2014). Moreover, studies have shown that the final sludge product after treatment in STWs (biosolids) is a well stabilized and non-phytotoxic valuable material which is safe for reuse and recycle, e.g., as fertilizer in agriculture (Stefanakis et al., 2011b; Uggetti et al., 2011; Stefanakis & Tsihrintzis, 2012d)

CW systems are in general easy to build and simple in the design and operation (Kadlec & Wallace, 2009). This facilitates the efficient installation of CW facilities, especially in remote areas. Proper design and construction of a CW system allow it to perform in an effective and reliable manner. Problems such as bed clogging, water runoff from the surface or limited plant development may be caused by inadequate design or construction (Stefanakis et al., 2014). Typical problems such as pump/valve failure may occur in CW systems as in conventional plants (Langergraber, 2013). Increased maintenance time and more advanced skills may be required only in case of more complex CW modifications such as aerated beds.

The economic aspect is also an important factor in order to characterize a treatment method as sustainable. The major costs during the construction phase of CWs are, in general, for the earthworks (excavation and fill of the basin), the filter media to be used as substrates, the plants and the bottom liner (e.g., geomembrane/geotextile) (Kadlec & Wallace, 2009; Stefanakis et al., 2014). Most of items are usually locally available, which can decrease transportation costs, especially for short distances. The liner and mechanological equipment (e.g., pumps) may represent a high portion of the costs if they are to be purchased or imported. Labor costs also vary from country to country. Generally, construction costs of CW facilities are comparable or slightly lower with those of conventional treatment plants (Langergraber, 2013; Stefanakis et al., 2014). For small-scale applications (e.g., up to 1,000 pe) CWs offer an economic advantage in terms of investment but as the population served increases, the investment costs become comparable mainly due to the higher land requirements. However, the main economic benefit of CWs are the significantly reduced costs for operation and maintenance due to lower energy consumption and technical equipment used (Brix, 1999; Dixon et al., 2003; Langergraber, 2013; Stefanakis et al., 2014).

The social aspect of CWs as treatment systems is increasingly enhanced. The green, aesthetical appearance of CW facilities compared to the conventional treatment plants (Fig. 6) makes them more acceptable by the society. Many enterprises (e.g., industries, municipal-private companies) choose the CW technology for the treatment of wastewater produced in their premises as a mean to enhance their green profile and incorporate the CW installation to their corporate social responsibility plan.

Figure 6. Typical view of a Constructed Wetland facility.

Providing Clean Water for Better Health

Being a wastewater treatment technology, the main goal of Constructed Wetland systems is to purify wastewater and provide a final effluent of high quality. Degradation of the natural environment and ecosystems is a result of the various human activities and the respective production and uncontrolled discharge of wastewaters to surface- and groundwater. Wastewater treatment is today an absolutely necessary process not only to protect the natural environment and the habitat, but also to protect human health. Water pollution is an existent threat to human health, since surface water bodies (e.g., rivers, lakes) as well as groundwater and aquifers are used as potable water supplies. Therefore, it is crucial that wastewater generated by the various and multiple human activities is treated and purified prior the final discharge, in order to reduce and eliminate the pollutant load. Under this frame, eco-friendly systems such as Constructed Wetlands play a significant role. Their ability to provide wastewater treatment and sanitation in a sustainable way adds credits to their role in the protection of the ecosystems and human health. The further exploitation of the treatment potential of the Constructed Wetland technology will bring additional benefits for the society, since it will contribute to the issues of human health protection and natural environment conservation without causing an additional environmental impact.

FUTURE RESEARCH DIRECTIONS

The CW technology is a relatively new technology, although first attempts were made almost 50 years ago. Actual interest and increasing research and applications mainly occurred only during the last 20 years and have been intensified over the last decade. This means that design optimization and basic understanding of the fundamental processes are still under investigation. Currently, there are not widely accepted design guidelines, although some general parameters and assumptions are used by the majority of researchers and engineers. Thus, the challenges in the field of CW technology are to further improve the design of the system and optimize their performance. Design optimization is crucial since it may allow for the decrease of the required surface area or footprint of the wastewater treatment facility. Furthermore, future studies under varying climatic conditions will assist in the development of design guidelines for extended regions. Additionally, the use of CWs for the treatment of more complex water sources such as industrial wastewater is another field of great interest. While it is has been proven that domestic and municipal wastewater can be effectively treated in CWs, recent applications for various industrial wastewater, such as tanneries, textile mills, landfill leachates, olive oil mills etc., reveal the great potential of the CW technology. Also, the development of reliable modeling tools for the performance prediction and design improvement of CWs will be a major step forward. Finally, it is realized that the various economic and environmental benefits of CW technology make them appropriate systems for water sanitation in developing countries, a topic which is expected to be further developed in the near future.

CONCLUSION

The technology of natural treatment systems and especially of Constructed Wetlands is appearing today as one of the most attractive alternative technologies for wastewater treatment and sludge dewatering. These treatment systems provide multiple economic, environmental, technical and societal benefits over the conventional treatment methods such as activated sludge. Following the decentralized approach, the technology of Constructed Wetlands is particularly appropriate in areas where the implementation of a conventional treatment method is economically infeasible, such as in small-medium settlements and communities, rural, mountainous and remote regions and for onsite treatment for single households or block of flats. Especially for small-scale applications (i.e., up to 1,000 pe), Constructed Wetlands possess significantly lower investment costs. Their main economic advantage comes from their operation phase due to the minimum energy requirements and the low needs for maintenance and personnel. Constructed Wetland systems have been proved to provide very effective treatment of domestic and municipal wastewater. Their overall effectiveness enables their application for various industrial and agro-industrial wastewaters with very promising results. As natural treatment technology, Constructed Wetlands can be characterized as sustainable systems, fulfilling sustainability criteria such as effective sanitation, contribution to public health and hygiene aspects, environmental protection, protection of natural resources, simple, reliable and robust operation and social acceptance. The potential of this treatment technology is today widely recognized and further future expansion of the technology is anticipated in both developed and developing countries.

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KEY TERMS AND DEFINITIONS

BOD: Biochemical Oxygen Demand. An organic pollution indicator which expresses the part of organic pollution which can be removed biologically (using microorganisms).

COD: Chemical Oxygen Demand. An organic pollution indicator which expresses the total organic pollution which can be removed by using a strong oxidant agent.

CH_4: Chemical formula of methane. Atmospheric methane represents one of the greenhouse gases.

N_2O: Chemical formula of nitrous oxide. It is a greenhouse gas and an air pollutant.

Facultative Pond: A pond type of natural systems where wastewater is treated biologically under low oxygen conditions. The wastewater remains in this open-air pond for a prolonged period and then is transferred to the next treatment stages.

HDPE: High-density polyethylene, a material made from petroleum. It is used in the production of geomembranes that cover the bottom of tanks, constructed wetlands etc to prevent leaching of liquids to the groundwater.

Imhoff Tank: A V-shaped tank used as primary treatment for wastewater. Its design aims at the removal of solids and the separation from the liquid wastewater, as also the accumulation of sludge at the bottom.

Landfill Leachate: The liquid which percolates from landfill sites and which contains several contaminants, sometimes toxic chemicals.

Log: Logarithm, the mathematical operation that is the inverse of exponentiation. It is used to express the bacteria removal during wastewater treatment. Thus, 1log removal mean 90% kill of bacteria, 2log 99%, 3log 99.9%, 4log 99.99% etc.

Macrophytes: Aquatic plants that grow in water (or near water sources). Can be emergent, submergent or floating.

OTC: Oxygen Transfer Capacity. An indicator of the oxygen amount that can be transferred to wastewater with different treatment technologies.

Oxidation Pond: A pond type of natural systems for wastewater treatment. They are large, shallow basins where wastewater is treated through natural processes such as bacterial activity, sunlight and algae. Mechanical aeration can also be used to increase the levels of oxygen required for the treatment processes.

Plug Flow: A flow type of a fluid inside a pipe, where it is assumed that the fluid has a constant velocity across the cross-section of the pipe and no back mixing takes place.

Zeolite Gravity Filter: Filters containing a natural rock (zeolite) which operate with gravity (i.e., the use of pumps is avoided). These filters are used in wastewater treatment to remove pollutants mainly through filtration and other processes.