Introduction to Constructed Wetland Technology

Chapter · July 2018

DOI: 10.1002/9781119268376.ch0

Alexandros I. Stefanakis
Technical University of Crete

Constructed Wetlands for Industrial Wastewater Treatment

Alexandros Stefanakis

Challenges in Water Management

WILEY

Constructed Wetlands for Industrial Wastewater Treatment

Edited by
Dr. Alexandros Stefanakis
Bauer Resources, Schrobenhausen, Germany
Bauer Nimr LLC, Muscat, Oman
German University of Technology in Oman, Muscat, Oman

WILEY

This edition first published 2018

Registered Office(s)
John Wiley & Sons, Inc., 111 River Street, Hoboken, NJ 07030, USA
John Wiley & Sons Ltd, The Atrium, Southern Gate, Chichester, West Sussex, PO19 8SQ, UK

Editorial Office
The Atrium, Southern Gate, Chichester, West Sussex, PO19 8SQ, UK

For details of our global editorial offices, customer services, and more information about Wiley products visit us at www.wiley.com.

Wiley also publishes its books in a variety of electronic formats and by print-on-demand. Some content that appears in standard print versions of this book may not be available in other formats.

Library of Congress Cataloging-in-Publication Data
9781119268345

Cover image: [Production Editor to insert]
Cover design by [Production Editor to insert]

Set in 10/12pt WarnockPro by SPi Global, Chennai, India

10 9 8 7 6 5 4 3 2 1

Introduction to Constructed Wetland Technology

Alexandros I. Stefanakis

Bauer Resources GmbH, BAUER-Strasse 1, Schrobenhausen, Germany
Bauer Nimr LLC, Muscat, Oman
Department of Engineering, German University of Technology in Oman, Athaibah, Oman

1 From Natural to Constructed Wetlands

Constructed Wetlands technology is not a "new" development, if we consider the exact definition of this word. Wetlands have been used – one way or another – by humans for hundreds (or even thousands) of years. Until recently, people didn't realize this utilization of wetland systems or their benefits and role not just for humans but for the whole planetary ecosystem. The first contact of humans and natural wetlands took place thousands of years ago: the first civilizations were established close to wetland environments, since these provided them with various economic and vital sources. Early civilizations (e.g., the Mesopotamian and Egyptian) were developed near marshes and rivers. Wetlands provided raw materials for simple up to more complicated constructions and discoveries. For example, dried reeds were used to build houses, papyrus was used to make paper or even construct ships, etc. Therefore, the exploitation of wetlands by humans was already a reality. In other words, wetlands represent a critical life source for humans and wildlife, with a great contribution to our quality of life.

Wetlands are considered today as natural systems with great ecological significance, which provide habitats for numerous species and support their life. This is why natural wetlands are often called as "the Earth's kidneys" or "the biological supermarket" [1, 2], since they are among the most productive natural environments on Earth. They also act as filters, retaining the pollutants from the water that flows through on its way to lakes, streams, and oceans. Natural wetlands fulfill a series of multiple functions with important value for humanity; for example, carbon dioxide fixation by wetland plants is beneficial for the global climate, while supporting food chains adds a value (e.g., fishing) to human activity. The values of wetlands can be distinguished into three main types: ecological, socio-cultural and economic, which together define the Total Value of Wetlands (Figure 1). In general, natural wetlands offer services for [3–5]:

- Enrichment of groundwater aquifers.
- Control/amendment of flood incidents (protective buffers).
- Retention of sediments and other substances.
- Absorption of carbon dioxide.

Constructed Wetlands for Industrial Wastewater Treatment, First Edition. Edited by Alexandros I. Stefanakis.

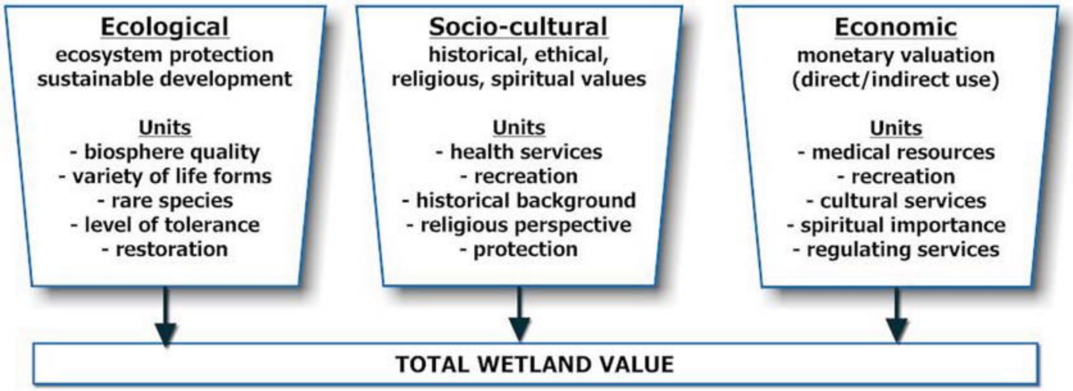

Figure 1 Individual type of values and respective criteria and value units for the determination of the Total Value of Wetlands [4, 5].

- Heat storage and release.
- Absorption of solar radiation and respective support to food chains.

Wetlands represent a considerable section of national and local economies, contributing with the provision of resources for recreational activities, pollution control and flood protection. Despite these benefits, the value of natural wetlands has only recently been recognized. Today it is understood that natural wetlands have the ability to receive and control flood incidents and alleviate their possible negative impacts. They have been used for the discharge of wastewater for centuries, for example, during the Minoan time in the Greek island of Crete (2000 BC), where advanced sewerage collection systems in Knossos and Zakros Palaces were collecting and discharging wastewater to natural wetland sites [6]. However, this use of wetlands as disposal sites resulted in their degradation in many areas around the world.

The water purification capacity of wetlands was gradually recognized and today it is known that wetlands are able to eliminate and transform various pollutants (organics, nutrients, trace elements, etc.) through physical, biological, and chemical processes. The numerous ecological and economic benefits of wetlands and their appreciation encouraged the study of wetland capacities for various technological applications. This observation of the natural wetlands resulted in the investigation of human-made wetland ecosystems and their purification functions. Several studies revealed the potential of wetland ecosystems for pollution reduction. However, it is clear today that the use of natural wetlands for treatment purposes is not a preferred or even a legal solution.

The basic concept of building constructed wetland (CWs) systems is to replicate the various naturally occurring wetland processes in a beneficial way and under controlled conditions. Of special interest here are water storage, flood protection and water quality improvement. CWs are man-made structures and they are built in a way to resemble and operate similarly to a natural wetland. A common definition of these systems is that constructed wetlands are, "*Man-made complexes of saturated substrate, emergent and submerged vegetation, animal life and water that simulate natural wetlands for human use and benefits*" [7].

Generally, it can be said that wetland technology is a relatively recent development (i.e., of the last 40–50 years) compared to conventional treatment methods which have been in use for more than

80 years. Despite this relatively long period, it is only during the last 20–30 years that a tremendous increase of interest in CWs has occurred. This could also be related to the rapid increase of interest on environmental issues. Thus, research on CWs and observation of the first full-scale systems assisted in improving the fundamental knowledge and basic understanding of the processes taking place within these bioreactors and in optimizing their efficiency.

2 The Need for Sustainable Solutions

Constructed Wetlands are a very interesting development in the field of ecological engineering during the 20th century, which could be attributed to two main facts. First, for almost a century, wastewater treatment in the developed world has been implemented via conventional centralized facilities. These heavy installations are energy-consuming with a maximum lifetime of 25–30 years, which means that new investment is required for new facilities to replace the old ones. On the other hand, low-income regions usually cannot afford the construction of such large centralized facilities and the technical expertise to run them. Thus, in both developed and developing regions alternative treatment techniques are required, apparently for different reasons, which should combine acceptable performance, cost-efficiency and, of course, the – recently added – sustainability parameter.

Hence, natural treatment systems, such as constructed wetlands, can be a solution that satisfies these parameters. The current status of the technology proved their high levels of performance. They don't depend on energy-consuming and expensive processes (since renewable sources are mostly used) and they don't demand synthetic raw materials, but mainly natural ones, e.g., plants and aggregate materials, providing from this point of view an ecological treatment. Also, the idea of using plants to purify wastewater is always viewed as innovative and attractive for society, which can therefore increase their social acceptability.

Conventional and natural treatment systems serve the same goal, i.e., wastewater treatment, but under a different approach. Natural systems provide decentralized treatment services, which may be seen as an alternative approach to treat wastewater at or near the source. This approach further satisfies the concept of sustainable development, meaning that the same function (i.e., wastewater treatment) is achieved in a more economic, environmentally friendly, and energy-efficient way.

3 Constructed Wetlands or Conventional Systems – Pros and Cons

Conventional technologies provide effective wastewater treatment, but they come with some undesired impacts. Usually, they require extensive sewer collection networks to bring the wastewater into a centralized facility. This relates to some obvious environmental and economic concerns. Conventional treatment plants usually have an unattractive appearance, including large mechanical parts (ventilators, dosing schemes, pumps, etc.), extensive use of concrete and steel and odor and noise generation. As a result, they require large amounts of energy, which means respectively high greenhouse gas emissions. In addition, the investment costs and, especially, the operation and maintenance costs are usually high. Moreover, the daily production of surplus sludge demands further handling and management, which adds to the total operational costs.

On the other hand, Constructed Wetlands can be characterized as a cost-efficient treatment technology with a usually lower or similar investment cost, and significantly reduced costs for operation and maintenance than conventional treatment methods. Global experience from many countries has shown that operational costs of CW facilities can be up to 90% lower compared to conventional/mechanical plants. Moreover, CWs operate without the need for the addition of chemical substances, which is not typically the case in conventional treatment plants. Locally available resources are used for the construction of a CW facility (i.e., high in-country value), which is relatively easy and simple to build in the absence of big and complex infrastructure. Energy is required in very low amounts, e.g., for the lighting of the facility, and, possibly, for the operation of few pumps. The use of pumps can even be avoided if the natural ground slope is exploited to use the gravity flow along the system. Additionally, there is no need for specialized staff to run the facility and only periodic inspection is required. Furthermore, they have a prolonged useful lifetime, which extends to 30 years or even more.

Wastewater treatment in Constructed Wetlands does not practically generate any by-product. Sludge can be accumulated and dewatered within the system. In conventional treatment plants, large amounts of excess sludge that need to be managed and stabilized are produced on a daily basis. Although the sludge volume represents only a small portion (1–3%) of the total treated wastewater volume, its management and handling can reach up to 50% of the total facility costs [5]. However, it should be noted that periodic sludge removal (e.g., 1–2 times/year) should take place in a CW facility if there is a pretreatment stage (e.g., sedimentation or Imhoff tank), but this cost is usually 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 annually or every few years. However, this biomass can further be exploited as biofuel for energy or for compost production.

At this point, it should be mentioned that the technology of Constructed Wetlands should not be viewed as directly competing with conventional technologies. Given that the main limitation of CWs is the larger area demands, they cannot completely replace conventional treatment facilities. Therefore, they can be viewed as complementary to conventional facilities, providing the benefit of decreasing the required number and capacity of centralized conventional plants by implementing several onsite treatment plants based on Wetland Technology.

However, Constructed Wetlands are appropriate for a series of installations of different scales. Due to their flexible design, they can easily be built on most sites. They become very competitive systems for wastewater generated from single households or residential complexes. In rural, remote, insular and mountainous areas, where usually no sewer system exists and it is difficult to build a centralized plant, CWs can be an extremely attractive alternative from both an economic and environmental point of view. They can effectively serve villages and small or medium cities/settlements up to few thousands of population. And, of course, for onsite application in numerous industrial facilities, CWs can be an ideal solution. Table 1 summarizes the main characteristics of conventional treatment plants and Constructed Wetlands.

Despite the long list of advantages, CWs have also limitations – as any technology. 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 artificially aerated systems), area demands are still higher (e.g., 3–10 times) for a CWs solution than for conventional systems [5]. Furthermore, false design could also result in odor issues and the occurrence 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.

Table 1 Main characteristics and comparison of conventional treatment methods and Constructed Wetlands [5, 8–11]

	Conventional treatmentmethods	Constructed Wetlands
Investment	Moderate – High	Moderate
Facility	Many/large mechanical parts and equipment	No mechanical parts (maybe pumps)
Operational costs	High	Low
Application scale	Small to large	Small to medium
Performance	High quality effluent	High quality effluent
Raw materials	Use of non-renewable materials during construction (concrete, steel, polymer membrane material etc.) and operation (electricity, chemicals)	Almost exclusive use of renewable sources (solar, wind) – "ecological" character
Corrosion resistance	Low	High (medium)
Odour nuisance	Medium to high	Low
Energy input	High	Low
Use of chemicals	Required	Not required
Greenhouse gas emissions	High	Low
Lifetime	5–10 years (MBR), 20–25 years (activated sludge)	25–30 years or more
Monitoring	Need for frequent monitoring	Need for periodical monitoring
Staff during operation	Demand for specialized personnel	No specialized personnel needed
Maintenance	High needs/costs – regular membrane failures, reinvestment after 10 years	Low, e.g., reed harvesting every 2–5 years
Response to flow variations	Higher/shock inflow rates negatively affect the performance	Robust to short-term high flow variations
Robustness to toxic substances, e.g. oil	Toxic pollutants may lead to system breakdown	Robust to some toxic constituent, e.g. heavy metals
Recovery period	Prolonged time to re-gain full treatment performance	Robust with no downtime
By-products	Large daily volumes of sludge, which need handling on a daily basis	No sludge by-product
Appearance	Unattractive	Aesthetically accepted
Social responsibility	Low	High
Biodiversity enhancement	No	Yes
In-country value	Only 20% of materials/equipment sourced within the country	More than 80% of materials/equipment sourced within the country

4 Classification of Constructed Wetlands

Based on their functions, Constructed Wetlands can be classified into three main areas [5, 12–14]:

- **Habitat creation:** systems designed to provide an upgraded wildlife habitat and to enhance the existing ecological benefits, e.g., attracting birds and creating green spaces, while addressing water/wastewater treatment. Four different CW types exist here: ponds, marshes, swamps and ephemeral wetlands.
- **Flood control:** systems that function as runoff receivers during flood incidents and increase the stormwatwer storage capacity, especially in urban areas.
- **Wastewater treatment:** systems designed and operated to receive and treat wastewater of different origin.

The most widely used classification of CWs is based on the water flow direction and the type of vegetation used (Figure 2). Also, based on the flow path across the CW system, there are two general types:

- Free Water Surface Constructed Wetlands (FWS CWs), also called Surface Flow Constructed Wetlands (SFCWs) and
- Subsurface Flow Constructed Wetlands (SSF CWs).

A further classification of SSF CWs can be made according to the flow path direction between horizontal (HSF CWs) or vertical (VFCWs) flow systems. The type of vegetation used in CWs is also one of the main characteristics of CWs systems (Figure 2). Therefore, CWs can be also classified according to the wetland plant species used as:

- Emergent macrophyte wetlands
- Submerged macrophyte wetlands and
- Floating treatment wetlands (FTWs).

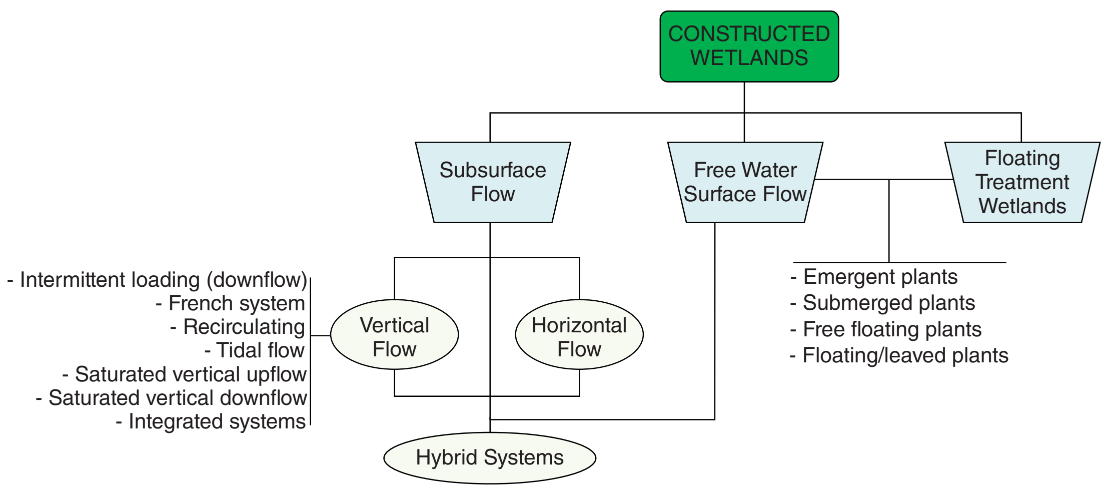

Figure 2 Classification of Constructed Wetlands [5, 13].

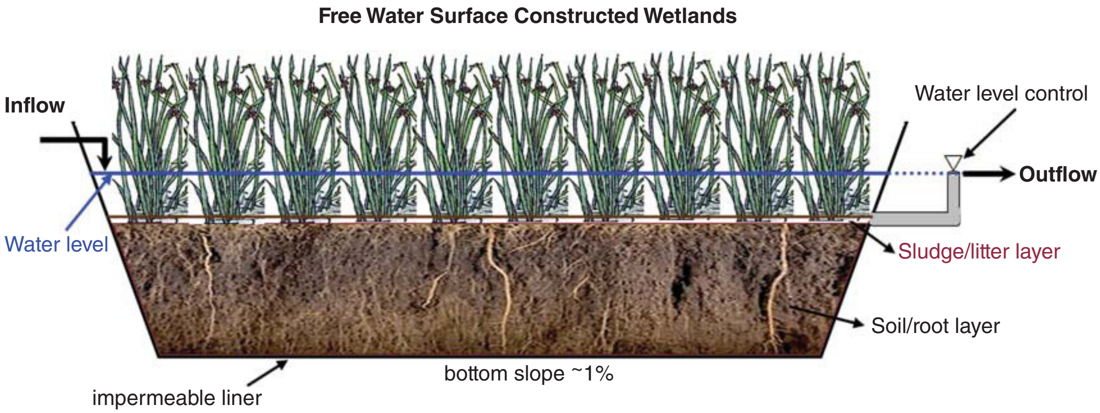

Figure 3 Schematic representation of a typical cross-section of a Free Water Surface Constructed Wetland.

Among these types, CWs with rooted emergent macrophytes are the most widely used. A brief description of the different constructed wetland designs is now presented.

4.1 Free Water Surface Constructed Wetlands (FWS CWs)

This type of CW is a shallow basin or channel containing a soil layer of 30–40 cm thickness, in which the macrophytes are planted. Common plants species used are common reeds (*Phragmites australis*), cattails (*Typha* spp.), bulrush (*Scirpus* spp.) and herbs (*Juncus* spp.) [5, 15]. The bottom of the basin (as in all CW systems) is covered by a geo-textile/geo-membrane or clay material to prevent wastewater leakage to the groundwater. A water column of 10–50 cm in depth exists above the soil layer, which means that water is exposed to the atmosphere and the solar radiation. Water level can be adjusted at the outlet of the system (Figure 3). The water flows horizontally through the plant stems and rhizomes and comes into contact with the top layer of the soil, the different plant parts and the associated biofilm, which enables pollutant removal through various physical, biological and chemical processes. FWS CWs could attract mosquitos if the water remains almost stagnant inside the system due to false design or improper construction.

The performance of this wetland type is good for suspended solids (SS) and biochemical oxygen demand (BOD) removal and satisfactory removal of nitrogen (N) and pathogens, but phosphorus (P) removal is usually limited [5, 13, 14, 16]. FWS CWs have been applied for the treatment of primary and secondary municipal effluents, but mainly for polishing treated effluents, stormwatwer and highway runoff, as well as for agricultural effluents [5, 15]. This type is also used for produced water treatment, i.e., water containing petroleum hydrocarbons [17, 18]. FWS CWs have higher area demands compared to the other wetland types, but they resemble natural wetlands to the most.

4.2 Horizontal Subsurface Flow Constructed Wetlands (HSF CWs)

HSF CWs are more widely used in Europe than in the USA [19]. They are basins containing gravel material planted with common reeds (*Phragmites australis*) or other wetland plant species such as *Typha* (e.g., *latifolia*, *angustifolia*) and *Scirpus* (e.g., *lacustris*, *californicus*) [20, 21]. The substrate

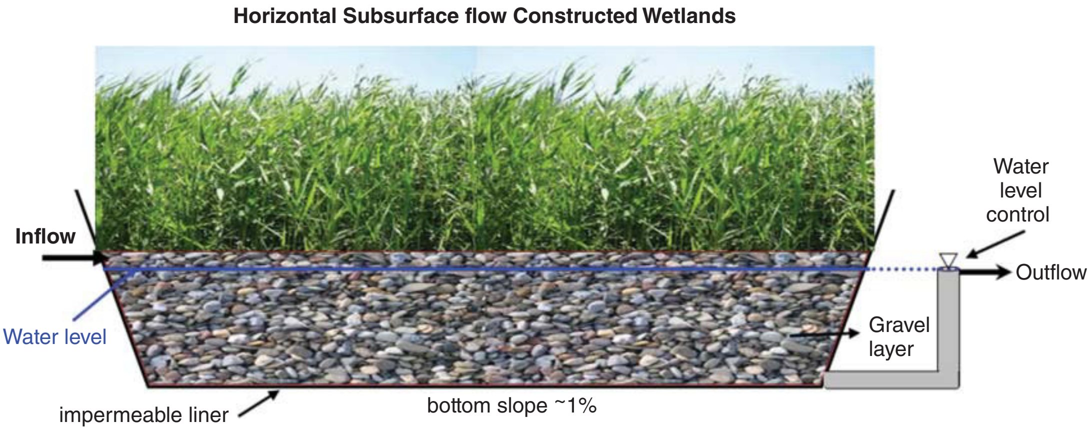

Figure 4 Schematic representation of a typical cross-section of a Horizontal Subsurface Flow Constructed Wetland.

used is rock and gravel of different origin and composition. In this CW type, there is no water surface exposed to the atmosphere and the water level is kept 5–10 cm below the gravel surface (Figure 4). The water flows horizontally through the pores of the substrate media and comes into contact with the media grains, the plant roots and the attached biofilm [5]. Thus, respective health risks due to possible human contact with the wastewater and mosquito issues are limited in this CW type [14]. The substrate layer thickness varies from 30 to 100 cm [14, 22]. The bottom of the bed is usually covered with an impermeable geo-membrane and has a slight slope (1–3%). 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, while step-feeding of the wastewater at different points along the wetland length could enhance the performance [23]. HSF CWs have the advantage of lower area demands compared to FWS CWs, although capital costs might be higher [5, 14].

This CW type has been proved to be very effective in the treatment of municipal wastewater, removing SS and organic matter (BOD) at high rates, although nutrient removal (nitrogen, phosphorus) is usually lower [5, 13, 14, 22]. Various modifications of the system design have been proposed in order to improve the performance, such as effluent recirculation [19], wastewater step-feeding [23], water level raising [19] and effluent treatment with gravity filters containing special substrate [19, 24]. HSF CWs are applied for the treatment of a wide range of industrial wastewater, e.g., mine drainage, dairy, swine, olive mills, landfill leachate, cork effluent, contaminated groundwater, hydrocarbons, etc. [25–29].

4.3 Vertical Flow Constructed Wetlands (VFCWs)

At the early years of wetland technology, FWS and HSF CWs were the dominant types, mainly due to higher costs for VFCWs construction and operation. However, the interest in VFCWs was gradually increased with time; especially when the higher oxygen transfer capacity of this system was realized compared to the other types. Today, there are various available modifications of VF systems applied or under investigation (for much more detail, see [5]). VFCWs are mainly used in Europe, especially in Denmark, Austria, Germany, France, and the UK [5, 14]. The most common setup is a basin containing several layers of gravel and sand with increasing gradation from top to the

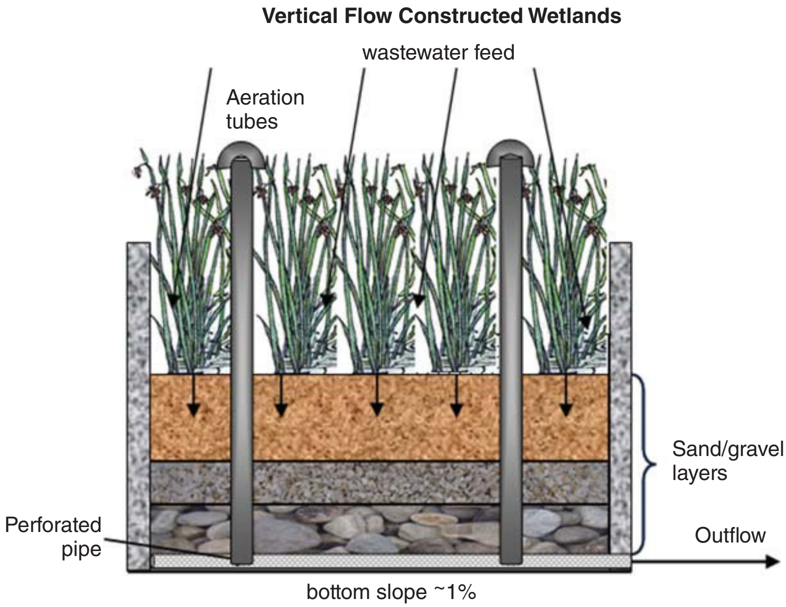

Figure 5 Schematic representation of a typical cross-section of a Vertical Flow Constructed Wetland [5, 30, 31].

bottom [5, 30] (Figure 5). The total thickness of the substrate varies from 30 to 180 cm [5]. Usually, the top layer of the bed is a sand layer. Plants are established in the gravel surface or in the sand layer (if any). Common reeds (*Phragmites australis*) and cattails (*Typha latifolia*) are the two most widely used plant species [5, 21]. The bottom of the bed is covered by a geo-membrane/geo-textile material and has a slight slope 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 [30].

The most commonly used mode is that of intermittent loading; wastewater is applied uniformly across the entire surface of the bed in batches and drains vertically by gravity [5, 24, 30]. VFCWs have smaller surface area demands compared to HSF and FWS CWs. Due to the better aeration capability, they are very effective in organic matter (BOD) and ammonia nitrogen removal [5, 13, 14]. Phosphorus removal remains limited and alternative modifications have been proposed for the performance improvement, e.g., an additional stage with gravity filters containing bauxite, zeolite or other reactive material for effluent treatment [24, 31]. Their overall effectiveness has enabled the use of this CW type for the treatment of wastewater with different origins, e.g., domestic, municipal, industrial, agro-industrial and landfill leachate [5, 27, 29].

4.4 Floating Treatment Wetlands (FTWs)

This type is a relatively new version of wetland technology, which combines both a traditional CW system and a pond [32]. These systems consist of a floating element (usually made of a plastic material) on which the plants are established (Figure 6). Thus, 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

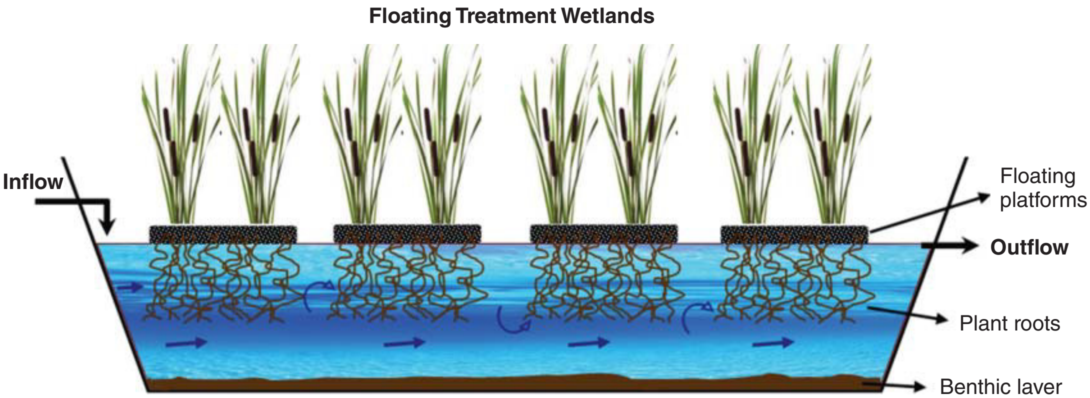

Figure 6 Schematic representation of a typical cross-section of a Floating Treatment Wetland [5].

water column [5, 33]. Since the combined system of the porous plastic mat and the plants floats on the water surface, the system is not affected by water level fluctuations. FTWs have been used for water purification in rivers, channels, lakes etc., and also for stormwater, domestic and municipal wastewater treatment [5, 32].

4.5 Sludge Treatment Wetlands (STWs)

These systems represent a special application of CW technology for the dewatering and management of excess sludge produced in conventional wastewater treatment plants. STWs appear as alternative systems to mechanical dewatering methods, such as centrifuges or filter presses. They practically are vertical flow constructed wetlands (Figure 3) modified for wastewater sludge dewatering and drying [3, 5–37]. STWs can be rectangular or trapezoidal excavated basins filled with gravel and planted with reeds. Usually the basin contains 1–2 gravel layers and a sand layer on top, although there have been systems designed without a top sand layer [34, 36, 38]. The total thickness of the porous media layers varies between 30–70 cm [5].

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 or even longer [5, 34, 35, 38]. The beds can be constructed with concrete or can be excavated basins covered with a liner, typically with a material of low-permeability (i.e., HDPE geo-membrane covered in both sides with geo-textile or clay) [5]. 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 substrate layer.

On top of the bed organic solids are gradually accumulating. With the alternating feeding/resting periods, the accumulated solids are dewatered and, in the long-term, they are converted to a stabilized material. After few years of operation (depending on the loading rate and the climatic conditions), the residual sludge layer is removed and reused as valuable biosolids, e.g., in agriculture as fertilizer. STWs achieve high rates of sludge dewatering (volume reduction up to 96%; [5, 34, 37], through evapotranspiration and draining processes [39].

4.6 Aerated Constructed Wetlands

Given that the level of oxygen inside the system affects many pollutant aerobic removal processes and is often the limiting factor of the performance, many modifications have been tested and applied to increase oxygen concentration. One modification that increasingly attracts interest over the last years uses artificial means for oxygen supply in subsurface CW beds. The concept is based on the use of an air pump (usually a small blower) to provide compressed air [40]. This alternative has been tested in HSF CWs, where oxygen availability is lower [41–43]. The same modification has also been applied in saturated VFCW systems [40, 44, 45]. Although wastewater aeration is a common practice for other treatment methods (e.g., in activated sludge systems), aeration of gravel beds appeared only during the last 10–15 years. Effective aeration in SSFCWs is implemented with uniform distribution of small air quantities across the bottom of the bed. The main advantage of bottom additional aeration in VFCWs is that the combined action of the vertical downward drainage of the wastewater with the upflow movement of air bubbles results in a very good air/water mixture in the bed.

Improved results are reported in intensified saturated VFCWs receiving primarily treated wastewater with low effluent pollutant concentrations (<5 mg/L BOD_5 and <5 mg/L NH_4^+-N) compared to non-aerated systems [46]. The increased oxygen availability makes these systems appropriate not only for domestic/municipal wastewater treatment, but also for stronger wastewater – especially industrial effluents. Generally, artificial aeration appears as an attractive alternative when an additional oxygen amount is desirable. The main advantage is that, due to the enhanced removal processes via the artificial aeration, the area demand becomes significantly lower, which has a positive impact on the respective construction costs. Renewable energy sources, e.g., wind or solar power, could be a potential sustainable solution to cover the small needs for energy for the artificial aeration equipment [47, 48].

5 Design Considerations of Constructed Wetlands

CWs construction is generally considered easy; however, in reality the proper design of a CW facility is not as easy as it may seem to the non-expert eyes. Currently, there are still not unanimously accepted guidelines, or a widely applied methodology. System design tends to differ not only from country to country, but also among designers and experts/engineers. Personal experience is a key parameter, especially in the more demanding and complicated industrial wastewater applications. However, there are some general rules and some basic design considerations used in the design process, especially for simple applications, e.g., domestic wastewater, including meteorological, topographical and operational parameters such as [5]:

- Climatic conditions of the area where the system will be installed.
- Topographical information in order to choose the most appropriate installation site and ensure gravity flow (if possible).
- Geological structure of the area to ensure the stability of the bunds.
- Availability of the required land.
- Legal permits that are required.
- Any ecologically sensitive areas in the vicinity or wildlife habitats.
- Current and future wastewater flow and volumes.

- Any legal limits that apply in the area for the effluent quality or the desired treatment performance.
- Appropriate or desired treated effluent reuse application.
- A nearby water body to receive the treated effluent.
- Total costs.

As it is understood, most of these general factors are common prior the implementation of any treatment technology. There are three main design parameters for constructed wetland systems, which are usually taken into account: unit area demand (m^2/pe); organic and hydraulic loading; and oxygen transfer capacity.

The unit area demand expresses the surface area demand (m^2) per person equivalent (pe). This parameter is generally accepted as a good indication of the land area demands. Apparently, this parameter is affected by climatic conditions. However, even for the same region different values are commonly proposed based on the experience of different individuals/experts. Generally, VFCWs have lower area demands (1–3 m^2/pe) than HSF CWS (5–10 m^2/pe) [5]. Organic (e.g., g BOD_5 or COD/m^2/yr) and hydraulic (m^3/m^2/d or m/d) loads are also widely used expressions and can be very helpful in the estimation of the optimum load to avoid operational problems. The hydraulic loading rate (HLR or q) is also widely used and is calculated by the ratio of the inflow rate (m^3/day) to the surface area (m^2) of the system. Finally, oxygen transfer capacity (OTC) provides important information on the oxidation potential of the system, especially for organic matter decomposition and nitrification.

Another important parameter, mostly applied in horizontal CWs, is the hydraulic retention time (HRT), which is given as the ratio of volume (m^3) to flow rate (m^3/d). Its value is crucial since it defines the time of direct contact between wastewater and the wetland parts (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 5–10 days, depending on the climatic conditions, the level of treatment etc. Aerated HSF CWs can be designed with much lower HRT (e.g., < 1 day). Proper dimensioning of horizontal beds is also very important to ensure the hydraulic efficiency of the system. HSF and FWS CWs usually 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 reaction equation (known as the kC* model) was widely used in the past. A simple equation for the calculation of the required surface area for BOD_5 removal is the following:

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

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 concentration (mg/L); and
C_e = the required effluent concentration (mg/L).

Other advanced design approaches are lately frequently used such as the *PkC** model [14]. The required wetland area can be calculated using the following equation:

$$A = \frac{PQ_i}{k_A}\left[\left(\frac{C_i - C^*}{C_o - C^*}\right)^{1/P} - 1\right] = \frac{PQ_i}{k_V\, h}\left[\left(\frac{C_i - C^*}{C_o - C^*}\right)^{1/P} - 1\right] \tag{2}$$

Where:

A = the surface area of the bed (m^2);
P = apparent number of tanks-in-series (TIS) (–);
Qi = influent flow rate (m^3/d);
k_A = modified first-order areal rate coefficient (1/d);
C_i = inlet concentration (mg/L);
C_o = outlet concentration (mg/L);
C^* = background concentration (mg/L);
P = apparent number of tanks-in-series (TIS) (–);
k_V = modified first-order volumetric rate coefficient (1/d);
h = wetland water depth (m).

This approach can give more accurate designs, since it considers the rate coefficients and temperature correction. However, it includes several variables, which are not always known to allow for the design using this equation.

Usually, BOD_5 is used as the main target parameter, but other pollutants such as suspended solids (SS), total or 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*, faecal coliforms) and heavy metals. Physical characteristics (e.g., dissolved oxygen, electrical conductivity, pH etc) are also used to describe CW 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 surplus sludge production of the wastewater treatment plant [5]. As for other CW types, the design and sizing 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 [35]. Higher SLRs have been proposed for the Mediterranean region: up to 90 kg dm/m^2/yr in Greece [34], 45 kg dm/m^2/yr in Italy [49] and 55–110 kg dm/m^2/yr in Spain [50, 51]. Stefanakis et al. [5] 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 a period (a few months up to 1 year), then the accumulated sludge residual is removed and a new feeding cycle begins [5, 34, 35].

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 worldwide occurrence. However, other locally available species may also be used; for example in tropical regions bamboo has been tested. Generally, the selected species should be well adapted to the local climatic conditions, tolerant against the various pollutants and able to uptake certain constituents such as nitrogen. 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 [5].

The selection of an appropriate substrate medium is also important for 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 deteriorate 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 where the plants are established; thus, it supports plant growth and enhances the bed stability, provides filtration effects and together with the plants supports the various transformation/removal processes [5, 13]. 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) [5].

Proper design and construction of a CW system allows for an effective and reliable performance. Problems such as bed clogging, water runoff from the surface or limited plant development may be caused by inadequate design or construction [5]. Typical problems such as pump/valve failure may occur as in conventional plants [52]. Slightly increased maintenance time and more advanced skills may be required only in the case of more complex modifications, such as artificially aerated beds.

6 Constructed Wetlands as a Sustainable Solution for the Industrial Sector

Generally, the term “green” for such a technology includes specific factors such as effective treatment, robustness, no by-products, recycled/reuse of materials, minimum energy consumption, use of renewable energy sources, no use of chemicals and minimum environmental nuisance [53]. The sustainable character of a treatment system is defined by its economic viability, technical feasibility, environmental protection contribution and social acceptance [54]. 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 [53, 54].

As described above, it can be said that the concept of Constructed Wetlands itself places them in the sustainability field. Although nowadays the term “sustainability” is used so often that its content is confusing or misinterpreted, its use here refers to the integration of environmental aspects in the treatment process. Especially for the industry, the claim for the sustainable character of wetland systems relates to the advantage of promoting both economic growth, as well as protection of ecosystems and public health. This is the real benefit that wetland technology can bring to the industry.

Low energy consumption and use of natural materials (gravel, soil, sand and plants) are two crucial factors for the sustainable character of the system. One of the largest wetland projects is the Everglades restoration, USA, where CWs were used to remove nutrients from agricultural runoff entering the Everglades [55]. This project showed in the most emphatic way the sustainable dynamic of CWs. Similar projects of sustainable design using wetland technology have been developed for the removal of non-point source pesticide pollution in river catchments [56] and diffuse pollution at the catchment scale [57]; the protection of coastal zones from human activities and pollution in China [58]; and the treatment of produced water from oilfields in desert environments [17, 18], among others.

Effective treatment and high removal efficiencies significantly decrease the pollution load discharged to final receivers (surface and ground water bodies), thus limiting the risk for ecosystem and aquatic life degradation. The construction of CW systems usually involves locally available natural materials (gravel/sand, plants), with minimum use of synthetic or non-renewable materials. This means that the use of raw materials does not include significant energy-consuming and pollution generating processes. The minimum energy consumption in CW facilities preserves natural resources and minimizes pollution generation, especially when the main energy source is non-renewable (e.g., fossil fuels). These environmental benefits can be translated to low levels of greenhouse gas emissions [5, 52].

Quantification of greenhouse gas emissions during construction and operation phases is important for the estimation of the ecological impact and the global warming potential. Several studies report that CWs 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 [11]. Life cycle analysis studies on CW systems and comparison with conventional treatment methods have shown that the global warming potential of CWs is lower in terms of CO_2 emissions [5, 59, 60]. It is also interesting that in CW systems the major portion of the environmental impact occurs during the construction phase [59, 60], while in conventional treatment systems the environmental impact of the operational phase is higher than that of the construction phase [59, 61, 62]. 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 [63]. Hybrid CW systems (i.e., combination of different CW types) 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 a habitat for various wetland organisms; water savings; and multiple hydrological functions [52]. For example, it is reported that a large FWS CW system built in a desert environment in the Middle East, i.e., in a former arid and dry area, for the treatment of water containing petroleum hydrocarbons from oilfields, provides a habitat for more than 120 different migratory bird species [17].

These findings become even more obvious in sludge dewatering applications using Sludge Treatment Wetlands [5]. The comparison with conventional mechanical methods, such as centrifuges (considering all aspects of sludge management, i.e., transport, investment, construction, raw materials, energy consumption) reveals that STWs have the lowest environmental impact [51]. As for CWs for wastewater treatment, the major impact occurs during the construction phase. If the CW basin is simply earth-excavated or built with recycled concrete, the impact of the construction phase can be reduced. Centrifuges have the highest environmental impact, since their operation requires high energy input. It is reported that the overall environmental impact of Sludge Treatment Wetlands is 500 times lower than centrifuges and 2,000 times lower than sludge transport to a centralized dewatering facility [5, 51]. Moreover, studies have shown that the final digested sludge product after treatment in STWs (biosolids) is a well stabilized and non-phytotoxic material, which can be reused, e.g., as fertilizer in agriculture [51, 64, 65].

The economic aspect is also important for the characterization of a treatment method as sustainable. The major costs during the construction phase of CWs include earthworks (excavation and fill of the basin), the filter media and the bottom liner [5, 14]. Most of the items are usually locally available, which can decrease the transportation costs, especially for short distances. The liner and mechanical equipment (e.g., pumps) may represent a higher portion of the costs if they are imported. Labor costs also vary from country to country. Generally, construction costs of CW facilities are comparable or slightly lower to those of conventional treatment plants [5, 52]. 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, even for higher flow rates, is the significantly reduced costs for operation and maintenance due to significantly lower energy consumption and equipment used [5, 52, 53, 59].

Finally, the social aspect of CWs – the last component of sustainability – as treatment systems is steadily increasing. The green, aesthetic appearance of CW facilities compared to the conventional treatment plants (Figure 7) makes them more acceptable by society. Many industries and municipal-private companies select more and more often CW technology for the treatment of wastewater produced in their premises, as a mean to enhance their green profile and incorporate the CW system into their corporate social responsibility plan.

7 Scope of this Book

Wetland technology is attracting more and more the interest of stakeholders and institutions as an effective wastewater treatment technology. After almost 20–25 years of intensified research efforts

Figure 7 Typical view of a Constructed Wetland implemented in the industrial sector (courtesy of Bauer Resources GmbH).

and an exponentially increasing number of successful full-scale applications across the world, it is already considered an established technology. It can be said that for the majority of applications (i.e., mainly domestic and municipal wastewater) current efforts focus on performance and design optimization, for example, how to maintain high efficiency in nutrient removal (especially phosphorus) in the long run and to reduce the area demands without jeopardizing the performance.

As the treatment capacity of constructed wetland systems was recognized, it was reasonable to investigate the feasibility of these systems in other applications with higher pollutant loads than domestic/municipal wastewaters. Thus, the interest is gradually shifting to applications in the industrial sector. Over the previous few years there has been an apparent increase of studies testing different wetland systems in various industrial applications. It can be stated that the new challenges for wetland technology occur now in the industrial sector. And the results so far indicate that there is a respectively high potential for wetland systems to be further expanded in various industrial sectors.

Based on this, this book is the first in the published literature to summarize and present various applications and case studies of Constructed Wetlands in the industry. In the 25 chapters of the book you will find several different industrial applications and an interesting discussion on the various aspects of wetland technology. Since there is a large variety of wetland systems applied in industries, the book is divided into different sections. Each section covers a specific industrial sector, i.e., petrochemical industry, food industry, agro-industry, mine drainage and leachate, wood and leather industry, pharmaceuticals industry etc. and includes a number of chapters, each one presenting a different application. Some individual applications on specific industrial areas are presented under a separate section, as they can be seen as novel applications. Finally, a last section includes two chapters, which for the first time discusses the construction and HSE aspects of Constructed Wetlands facilities, and the integration of wetland technology within a Corporate Social Responsibility context with the industry's strategic management.

References

1 Barbier EB, Acreman M, Knowler D. Economic valuation of wetlands – A guide for policy makers and planners. Gland, Switzerland: Ramsar Convention Bureau; 1997.

2 USEPA. Constructed Treatment Wetlands. EPA 843-F-03-013, U.S. D.C., USA: Environmental Protection Agency: Office of Water, Washington; 2004.

3 MEA (Millennium Ecosystem Assessment). Ecosystems and Human Well-being: Wetlands and Water Synthesis. Washington DC: MEA, World Resources Institute; 2005. Available at: www.millenniumassessment.org.

4 De Groot R, Stuip M, Finlayson M, Davidson N. Valuing Wetlands: Guidance for valuing the benefits derived from wetland ecosystem services. Ramsar Technical Report No. 3, CBD Technical Series No. 27. Gland, Switzerland: Ramsar Convention Secretariat; 2006.

5 Stefanakis AI, Akratos CS, Tsihrintzis VA. Vertical Flow Constructed Wetlands: Eco-engineering Systems for Wastewater and Sludge Treatment. Oxford, UK: Elsevier Science; 2014.

6 Angelakis AN, Koutsoyiannis D, Tchobanoglous G. Urban wastewater and stormwater technologies in ancient Greece. Water Res. 2005; 39:210–220.

7 Hammer DA, Bastian RK. Wetlands ecosystems: natural water purifiers? In: Hammer DA, editor. Constructed wetlands for wastewater treatment. USA: Lewis Publisher; 1989.

8 Fenu A, de Wilde W, Gaertner M, Weemaes M, de Gueldre G, De Steene B. Elaborating the membrane life concept in a full scale hollow-fibers MBR. J Membrane Sci. 2012; 421–422: 349–354.
9 Ozgun H, Dereli RK, Ersahin ME, Kinaci C, Spanjers H, van Lier JB. A review of anaerobic membrane bioreactors for municipal wastewater treatment: Integration options, limitations and expectations. Sep Puri Technol. 2013; 118:89–104.
10 Ayala DF, Ferre V, Judd SJ. Membrane life estimation in full-scale immersed membrane bioreactors. J. Membrane Sci. 2011; 378(1–2): 95–100.
11 Georges K, Thornton A, Sadler R. Transforming Wastewater Treatment to Reduce Carbon Emissions: Resource efficiency programme, Evidence Directorate. Report SC070010/R2. Environmental Agency, Rio House, Waterside Drive, Aztec West, Almondsbury, Bristol, UK; 2009.
12 Knight RL. Wildlife habitat and public use benefits of treatment wetlands. Water Sci Technol. 1997; 35(5):35–43.
13 Vymazal J. Removal of nutrients in various types of constructed wetlands. Sci Total Environ. 2007; 380(1–3):48–65.
14 Kadlec RH, Wallace SD. Treatment Wetlands, 2nd edn. Boca Raton, FL: CRC Press; 2009.
15 Vymazal J. Emergent plants used in free water surface constructed wetlands: A review. Ecol Eng. 2013; 61(B):582–592.
16 Kotti IP, Gikas GD, Tsihrintzis VA. Effect of operational and design parameters on removal efficiency of pilot-scale FWS constructed wetlands and comparison with HSF systems. Ecol Eng. 2010; 36:862–875.
17 Stefanakis AI, Al-Hadrami A, Prigent S. Treatment of produced water from oilfield in a large Constructed Wetland: 6 years of operation under desert conditions. In: Proceedings, 7th International Symposium for Wetland Pollutant Dynamics and Control (WETPOL), Montana, USA, August 21–25; 2017.
18 Breuer R, Headley TR, Thaker YI. The first year's operation of the Nimr Water Treatment Plant in Oman-Sustainable produced water management using wetlands. Soc Petrol Eng. 2012; 156427.
19 Stefanakis AI, Akratos CS, Gikas GD, Tsihrintzis VA. Effluent quality improvement of two pilot-scale, horizontal subsurface flow constructed wetlands using natural zeolite (clinoptilolite). Microp Mesop Mat. 2009; 124(1–3):131–143.
20 Vymazal J. Constructed Wetlands for wastewater treatment: five decades of experience. Environ Sci Technol. 2011; 45:61–69.
21 Vymazal J. Vegetation development in subsurface flow constructed wetlands in the Czech Republic. Ecol Eng. 2013; 61(B):575–581.
22 Akratos CS, Tsihrintzis VA. Effect of temperature, HRT, vegetation and porous media on removal efficiency of pilot-scale horizontal subsurface flow constructed wetlands. Ecol Eng. 2007; 29:173–191.
23 Stefanakis AI, Akratos CS, Tsihrintzis VA. Effect of wastewater step-feeding on removal efficiency of pilot-scale horizontal subsurface flow constructed wetlands. Ecol Eng. 2011; 37(3):431–443.
24 Brix H, Arias AC. The use of vertical flow constructed wetlands for on-site treatment of domestic wastewater: New Danish guidelines. Ecol Eng. 2005; 25:491–500.
25 Vymazal J. The use constructed wetlands with horizontal sub-surface flow for various types of wastewater. Ecol Eng. 2009; 35:1–17.

26 Tatoulis T, Stefanakis AI, Frontistis Z, Akratos CS, Tekerlekopoulou AG, Mantzavinos D, Vayenas DV. Treatment of table olive washing water using trickling filters, constructed wetlands and electrooxidation. Env Sci Pollut Res. 2016; 1–8: doi10.1007/s11356-016-7058-6.
27 Wu S, Wallace S, Brix H, Kuschk P, Kirui WK, Masi F, Dong R. Treatment of industrial effluents in constructed wetlands: Challenges, operational strategies and overall performance. Environ Pollut. 2015; 201:107–120.
28 Tanner CC, Clayton JS, Upsdell MP. Effect of loading rate and planting on treatment of dairy farm wastewaters in constructed wetlands – I. removal of oxygen demand, suspended solids and faecal coliforms. Water Res. 1995; 29:17–26.
29 Sultana MY, Akratos CS, Pavlou S, Vayenas DV. Constructed wetlands in the treatment of agro-industrial wastewater: A review. Hemijska Industrija 2015; 69:127–142.
30 Stefanakis AI, Tsihrintzis VA. Effects of loading, resting period, temperature, porous media, vegetation and aeration on performance of pilot-scale vertical flow constructed wetlands. Chem Eng J. 2012; 181–182:416–430.
31 Stefanakis AI, Tsihrintzis VA. Use of zeolite and bauxite as filter media treating the effluent of Vertical Flow Constructed Wetlands. Microp Mesop Mater. 2012; 155:106–116.
32 Van de Moortel AMK, Meers E, De Pauw N, Tack FMG. Effects of vegetation, season and temperature on the removal of pollutants in experimental floating treatment wetlands. Water Air Soil Pollut. 2010; 212(1–4):281–297.
33 Tanner CC, Headley TR. Components of floating emergent macrophyte treatment wetlands influencing removal of stormwater pollutants. Ecol Eng. 2011; 37:474–486.
34 Stefanakis AI, Tsihrintzis VA. Effect of various design and operation parameters on performance of pilot-scale sludge drying reed beds. Ecol Eng. 2012; 38:65–78.
35 Nielsen S, Bruun EW. Sludge quality after 10–20 years of treatment in reed bed systems. Env Sci Pollut Res. 2015; 22(17): 12885–12891.
36 Brix H. Sludge Dewatering and Mineralization in Sludge Treatment Reed Beds. Water. 2017; 9(3): 160.
37 Masciandaro G, Peruzzi E, Nielsen S. Sewage sludge and waterworks sludge stabilization in sludge treatment reed bed systems. Water Sci Technol. 2017; 75(10).
38 Stefanakis AI, Akratos CS, Melidis P, Tsihrintzis VA. Surplus activated sludge dewatering in pilot-scale Sludge Drying Reed Beds. J Hazard Mater. 2009; 172(2–3):1122–1130.
39 Stefanakis AI, Tsihrintzis VA. Dewatering mechanisms in pilot-scale sludge drying reed beds: Effect of design and operational parameters. Chem Eng J. 2011; 172:430–443.
40 Wu S, Kuschk P, Brix H, Vymazal J, Dong R, Wu H. Development of constructed wetlands in performance intensifications for wastewater treatment: A nitrogen and organic matter targeted review. Water Res. 2014; 57:40–55.
41 Chazarenc F, Gagnon V, Comeau Y, Brisson J. Effect of plant and artificial aeration on solids accumulation and biological activities in constructed wetlands. Ecol Eng. 2009; 35:1005–1010.
42 Zhang L-Y, Zhang L, Liu Y-D, Shen Y-W, Liu H, Xiong Y. Effect of limited artificial aeration on constructed wetland treatment of domestic wastewater. Desalination 2010; 250:915–920.
43 Fan J, Zhang B, Zhang J, Ngo HH, Guo W, Liu F, Guo Y. Intermittent aeration strategy to enhance organics and nitrogen removal in subsurface flow constructed wetlands. Bioresour Technol. 2013; 141:117–122.

44 Fan J, Wang W, Zhang B, Guo Y, Ngo HH, Guo W, Zhang J, Wu H. Nitrogen removal in intermittently aerated vertical flow constructed wetlands: Impact of influent COD/N ratios. Bioresour Technol. 2013; 143:461–466.

45 Dong H, Qiang Z, Li T, Jin H, Chen W. Effect of artificial aeration on the performance of vertical-flow constructed wetland treating heavily polluted river water. J Environ Sci. 2012; 24(4): 596–601.

46 Nivala J, Wallace S, Headley T, Kassa K, Brix H. Oxygen transfer and consumption in subsurface flow treatment wetlands. Ecol Eng. 2012; 61(B):544–554.

47 Nivala J, Headley T, Wallace S, Bernhard K, Brix H, van Afferden M, Müller RA. Comparative analysis of constructed wetlands: The design and construction of the ecotechnology research facility in Langenreichenbach, Germany. Ecol Eng. 2013; 61B:527–543.

48 Tao M, He F, Xu D, Li M, Wu Z. How artificial aeration improved sewage treatment of an integrated vertical-flow constructed wetland. Pol J Environ Stud. 2010; 19(1):183–191.

49 Bianchi V, Peruzzi E, Masciandaro G, Ceccanti B, Mora Ravelo S, Iannelli R. Efficiency assessment of a reed bed pilot plant (*Phragmites australis*) for sludge stabilisation in Tuscany (Italy). Ecol Eng. 2011; 37(5):779–785.

50 Uggetti E, Llorens E, Pedescol A, Ferrer I, Castellnou R, García J. Sludge dewatering and stabilization in drying reed beds: characterization of three full-scale systems in Catalonia, Spain. Bioresour Technol. 2009; 100(17):3882–3890.

51 Uggetti E, Ferrer I, Molist J, García J. Technical, economic and environmental assessment of sludge treatment wetlands. Water Res. 2011; 45:573–582.

52 Langergraber G. Are constructed treatment wetlands sustainable sanitation solutions? Water Sci Technol. 2013; 67(10):2133–2140.

53 Brix H. How green are aquaculture, constructed wetlands and conventional wastewater treatment systems? Water Sci Technol. 1999; 40(3):45–50.

54 SunSanA. Towards more sustainable sanitation solutions – SuSanA Vision Document. Sustainable Sanitation Alliance (SuSanA); 2008. Available at www.susana.org/docs_ccbk/susana_download/2-267-en-susana-statement-version-1-2-february-2008.pdf.

55 Guardo M, Fink L, Fontaine TD, Newman S, Chimney M, Baerzotti R, Goforth G. Large-scale Constructed Wetlands for nutrient removal from stormwater runoff: an Everglades restoration project. Environ Manage. 1995; 19(6):879–889.

56 Schulz R, Peall SKC. Effectiveness of a Constructed Wetland for retention of nonpoint-source pesticide pollution in the Lourens river catchment, South Africa. Environ Sci Technol. 2001; 35:422–426.

57 Harrington R, O'Donovan G, McGrath G. Integrated Constructed Wetlands (ICW) working at the landscape-scale: the Anne Valley project, Ireland. Ecol Inform. 2013; 14:104–107.

58 Zuo P, Wan SW, Qin P, Du J, Wang H. A comparison of the sustainability of original and constructed wetlands in Yancheng Biosphere Reserve, China: implications from emergy evaluation. Environ Sci Policy. 2004; 7:329–343.

59 Dixon A, Simon M, Burkitt T. Assessing the environmental impact of two options for small-scale wastewater treatment: comparing a reedbed and an aerated biological filter using a life cycle approach. Ecol Eng. 2003; 20(4):297–308.

60 Machado AP, Urbano L, Brito AG, Janknecht P, Salas JJ, Nogueira R. Life cycle assessment of wastewater treatment options for small and decentralized communities. Water Sci Technol. 2007; 56(3):15–22.

61 Ortiz M, Raluy RG, Serra L, Uche J. Life cycle assessment of water treatment technologies: wastewater and water-reuse in a small town. Desalination 2007; 204:121–131.
62 Renou S, Thomas JS, Aoustin E, Pons MN. Influence of impact assessment methods in wastewater treatment LCA. J Clean Prod. 2008; 16:1098–1105.
63 Mander Ü, Dotro G, Ebie Y, Towprayoon S, Chiemchaisri C, Nogueira SF, Jamsranjav B, Kasak K, Truu J, Tournebize J, Mitsch WJ. Greenhouse gas emission in constructed wetlands for wastewater treatment: a review. Ecol Eng. 2014; 66:19–35.
64 Stefanakis AI, Komilis DP, Tsihrintzis VA. Stability and maturity of thickened wastewater sludge treated in pilot-scale Sludge Treatment Wetlands. Water Res. 2011; 45:6441–6452.
65 Stefanakis AI, Tsihrintzis VA. Heavy metal fate in pilot-scale Sludge Drying Reed Beds under various design and operation conditions. J Hazard Mater. 2012; 213–214:393–405.