

Article

The Role of Constructed Wetlands as Green Infrastructure for Sustainable Urban Water Management

Alexandros I. Stefanakis 

School of Environmental Engineering, Technical University of Crete, GR73100 Chania, Greece;
stefanakis.alexandros@gmail.com

Received: 14 November 2019; Accepted: 4 December 2019; Published: 6 December 2019



Abstract: Nowadays, it is better understood that the benefits of green infrastructure include a series of ecosystem services, such as cooling, water storage and management, recreation and landscaping, among others. Green technologies are still developing to provide sustainable solutions to the problems that modern cities and peri-urban areas face at an ever-increasing rate and intensity. Constructed wetlands technology is an established green multi-purpose option for water management and wastewater treatment, with numerous effectively proven applications around the world and multiple environmental and economic advantages. These systems can function as water treatment plants, habitat creation sites, urban wildlife refuges, recreational or educational facilities, landscape engineering and ecological art areas. The aim of this article is to highlight the synergies between this green technology and urban areas in order to reconnect cities with nature, to promote circularity in the urban context and to apply innovative wetland designs as landscape infrastructure and water treatment solutions. This approach could be a step further in the effort to mitigate the current degradation process of the urban landscape. Following the concept of green infrastructure, the article presents and suggests ways to integrate wetland technology in the urban environment, namely: (i) stormwater and urban runoff management (storage and treatment of water during storm events) to provide protection from flood incidents, especially considering climate change, (ii) innovative low-impact infrastructure and design solutions for urban wastewater treatment, and (iii) wetland technology for habitat creation and ecosystem services provision.

Keywords: green infrastructure; constructed wetlands; circular economy; sustainability; nature-based solutions; ecosystem services; water management; wastewater treatment; urban areas; urban runoff

1. Green Infrastructure and Urbanization

Green infrastructure (GI) is a modern approach to deal with issues that mainly arise in the urban environment. It is viewed as an alternative to traditional infrastructure that is mostly based on concrete (often called as grey infrastructure). The term of GI initially referred to open green areas in the urban environment, usually connected to each other to provide various services and/or to create a new ecosystem [1]. Typical applications of GI are urban runoff and stormwater management, reducing the effects of urban heat islands, improving air quality, etc. However, over the last years the content of that term has been further expanded to include other approaches, e.g., provision of ecosystem services, creation of new wildlife habitats, reduction of greenhouse gas emissions, among others [2]. In other words, GI nowadays represents a wide set of solutions aimed at increasing the resilience of urban environments.

The moving force towards this direction is the increasing risks that modern cities face due to the more and more frequent appearance and increasing extent of extreme events such as urban

floods or extended dry periods. Today, it is realized more than ever before that ecosystem services, i.e., all services and goods that nature provides to humans, possess a tremendous value, which should not be neglected [3]. Therefore, it is clear that, under this frame, GI is strongly related to sustainability.

The adoption of sustainable development dictates that environmental protection should have a complementary character to economic development. Wise extraction and use of natural resources is a prerequisite for both economic growth and limitation of the environmental degradation. Especially, the sustainability approach integrates the concept of intergenerational solidarity, i.e., the current needs should be met without compromising the ability to meet those of future generations. Therefore, GI alternatives can better and more effectively contribute to this direction than grey infrastructure.

Across the globe, there are pressing issues due to rapid urbanization and continuous expansion of modern cities. Local authorities and governments face increasing challenges related to urban runoff and stormwater management. Current problems have to do with aging of existing infrastructure, shifts in precipitation patterns with more frequent and intense storm events, watershed deforestation, degradation of natural wetlands, extensive use of impervious surfaces (e.g., roadways, parking lots) that all result in urban floods and pollution of water sources. As climate change is expected to further enhance these phenomena, adoption of GI could make a more beneficial and targeted use of the multiple ecosystems services in order to mitigate these impacts of climate change in urban areas [4]. In addition, as cities expand worldwide and become densely populated, there is a respectively growing demand for improved sanitary and ecological conditions and a more intelligent way to exploit urban space. Moreover, the increasing water demand in urban areas and freshwater withdrawal calls for improved water efficiency.

This need is further arising from the gradual global transition to a circular economy that follows the 5Rs rules, i.e., reduce water losses and enhance water efficiency, reuse water, recycle water resources and wastewater, restore water of a specific quality to where it was taken from, and recover resources out of wastewater. In the context of urban water management, strategies that are already implemented include the reduction in water consumption, the further promotion of water reuse and recycle, and the recovery of materials from wastewater streams. The ultimate goal of such initiatives is not only the reduction of greenhouse gas emissions related to water resources management compared to conventional solutions, but also to enhance the resiliency of urban areas to the impacts of climate change [5]. It becomes therefore apparent that GI is at the center of the new vision to achieve greater circularity within urban systems.

2. Green Infrastructure for Urban Water Management

One of the main fields where GI can play an important role and bring a modern view is water management, specifically stormwater management and wastewater treatment. Stormwater runoff management is a major issue in modern cities. Often, stormwater contributes to combined sewer overflow (CSO) in cities (especially in older cities in Europe and in the USA), where domestic/municipal wastewater, urban runoff and stormwater are collected in the same pipe network that routes the collected volume to an end-of-the-pipe centralized wastewater treatment plant [6,7]. The occurring overflow volume can be higher than the capacity of the treatment plants, which means that the excess CSO and/or wastewater volume is discharged into surface water bodies (i.e., streams, rivers, lakes or sea) to avoid overloading of the existing treatment plants and thus results in flood incidents in urban areas [8]. Another consequence is the further contamination of surface waters and the respective damage of the receiving ecosystems, considering that during flood events water from the first flush of roads and concrete surfaces, sewer washout and sanitary wastewater carry high loads of organics, nutrients, suspended solids and microbiological contaminants [6,9,10]. This means that high volumes of water with high pollutant loads occurring over a short period of time need to be effectively treated in many different locations to reach the desired and/or legal effluent quality limits, e.g., the European Union (EU) limits set by the Water Framework Directive [11]. Management of these water volumes is

also important to prevent damage to public infrastructure and private properties and to protect the health status of the community and the ecosystems.

GI can also contribute to wastewater treatment in the urban and peri-urban environment. The established solution today is the centralized approach, i.e., the implementation of large end-of-the-pipe centralized treatment plants using conventional/mechanical treatment technologies. However, these facilities are typically not viewed as an environmentally friendly solution since they are heavy installations made of non-renewable materials (e.g., concrete, steel), consume large amounts of energy and chemicals and have high operational and maintenance costs [12]. In the urban environment, installing a conventional wastewater treatment plant usually downgrades the surrounding area in terms of aesthetic appearance and market value. Hence, an alternative eco-friendly solution that would combine effective treatment with added ecological values is preferable in this context.

It is clear that there is the necessity for new infrastructure that will meet the requirements for water treatment and sanitation and, at the same time, create green spaces in the urban environment, which could also partially compensate the lack of sufficient green areas. Nature-based solutions and, specifically, the eco-friendly technology of CWs (constructed wetlands) appears as an ideal option that can provide the desired added values to ecosystem services and promote water circularity in the urban context [5]. This article presents the so-called wetland technology in brief and discusses the opportunities to implement treatment wetland systems in the urban environment along with the available technological advances, as well as the main benefits that this green technology offers.

3. The Technology of Constructed Wetlands

Wetland systems are able to transform and/or remove various pollutants (organics, nutrients, trace elements, etc.) through a series of physical, biological, and chemical processes, and therefore improve water quality [12]. The wide range of economic and ecological benefits of wetlands stimulated the interest to exploit their natural water purification capacity for different applications, particularly for wastewater treatment. Human-made wetland ecosystems exploit these purifying functions of natural wetlands, which have been used for the disposal and treatment of secondary and tertiary wastewater effluents for many years in the past [13].

Nowadays, natural wetlands are rarely used for the polishing of light-contaminated effluents in some areas, but generally their use for wastewater treatment purposes is mostly avoided around the world, since this could cause irreversible damage to ecosystems. The basic concept of CW systems is to replicate the various naturally occurring processes under controlled conditions for a beneficial purpose, e.g., treatment of wastewater. This means that CWs are designed in such a way as to mimic and enhance the functions of natural wetlands. Although CWs offer in general the same values and functions with natural wetlands, they provide a wider range of ecosystem services; it has been shown that CWs possess a higher value in terms of flood and stormwater control, water quality improvement and biodiversity restoration [5,12,14–17]. Their main design characteristics make them more easily adopted and integrated into the built environment by urban planners, engineers, and landscape architects. CWs represent a very interesting and effective development in the field of ecological engineering. According to their function and purpose, they can be classified in three main application areas [12]:

- (a) *Constructed wetlands for habitat creation:* these systems aim at providing a new wildlife habitat. The main goal is to exploit the ecological benefits of CWs and not only their function as a treatment facility [18]. The main characteristics of CWs (i.e., presence of water and vegetation) make them suitable for the creation of a new ecological habitat or for the restoration of a degraded ecosystem, by attracting wildlife species, especially birds, and establishing a green area. These systems can also be utilized as a source of food and fiber, and as public recreation and education sites [18,19]. Several such facilities have been constructed in North America [14], such as the CWs in the Greater Vancouver region [20].
- (b) *Constructed wetlands for flood control:* these systems receive the runoff during flood events [21]. Their implementation increases stormwater storage capacity and infiltration volumes, while reducing

the volume of water reaching the sewer system and eventually the treatment plants. Within the urban hydrologic cycle, these CWs may significantly contribute to the integrated urban water management and also provide the ability to recycle the stored water volume [19,22]. Such examples can already be found in many countries, e.g., the Ouagadougou Park of Grenoble in France [23] and a network of urban wetlands built in Beijing, China [24,25].

- (c) *Constructed wetlands for wastewater treatment*: these are engineered systems designed to receive and purify wastewater from various sources, exploiting the naturally occurring treatment processes [12]. This is the most widely used application of CWs internationally. A flagship facility in this category is the constructed wetland in Nimr, Oman, the largest industrial CW system treating the industrial effluent from oil exploration activities [26].

From a technical point of view, CWs can be further classified based on the vegetation type and the water flow path through the system [12,27], as shown in Figure 1. Based on the flow path, two main types can be distinguished: (a) free water surface constructed wetlands (FWS CWs), and (b) subsurface flow constructed wetlands (SF CWs). The design of FWS systems includes a water column of 10–50 cm above a substrate layer (usually soil). Subsurface flow CWs are typically gravel beds and can be of vertical flow (VF) or horizontal flow (HF). According to the vegetation type, further classification includes emergent macrophytes wetlands and submerged macrophytes wetlands. The most common systems are those with rooted emergent macrophytes [12]. When more than one CW type is combined in one facility, this is called a hybrid wetland system. Furthermore, floating treatment wetlands (FTWs) are artificial wetland systems that mimic the water treatment processes occurring in natural floating wetland islands and consist in a floating structure planted with emergent macrophytes [28].

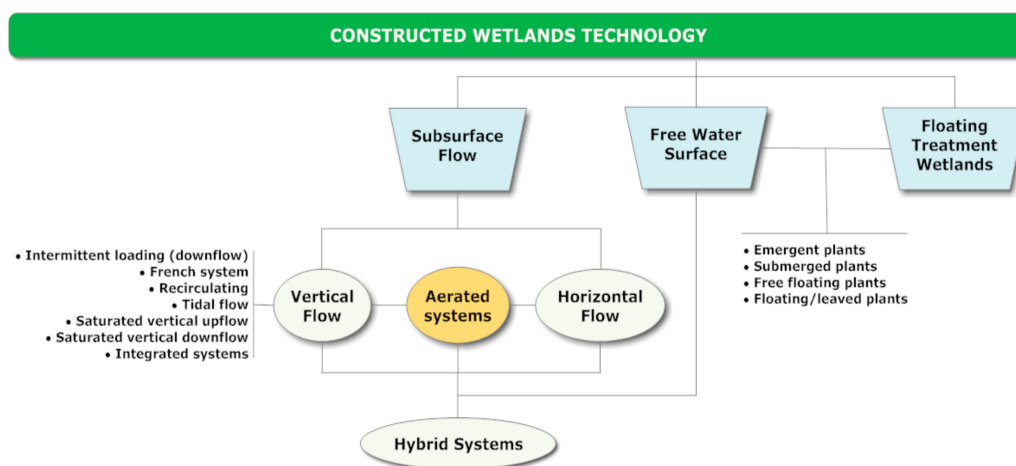


Figure 1. Classification of the various types of constructed wetlands.

The two key characteristics of CWs are the plant species and the substrate media. The most widely used emergent plant species are common reeds (*Phragmites australis*), cattails (*Typha latifolia*), and *Scirpus* spp.; these species are found in most regions around the world [12]. However, other locally available species may also be used, for example bamboo in tropical regions [29,30]. The main principle is that the selected species should be native, i.e., already adapted to the local climate and also tolerant against the pollutant loads. Indigenous species are always preferred in CWs and not exotic ones, to avoid potential risks such as invasion of the exotic species and/or diseases [12]. The role of plants in CWs in water treatment is mostly indirect; they promote and support the development and growth of the microbial community along their roots, through the transfer and release of oxygen in microsites along the roots [12,31,32].

The selection of the substrate media is also a critical parameter in CW systems. Selection of the proper gravel grain size is crucial to prevent any clogging issues due to inappropriate porosity and/or high hydraulic loads. Substrates have also the capacity of removing some constituents from

water through various processes (e.g., ion exchange, adsorption, precipitation). Plants are established in the substrate layer, which also provides filtration effects and together with the plants supports the various transformation/removal processes [12,27]. 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) [12,33].

3.1. Constructed Wetlands for Wastewater Treatment

One of the first uses of CWs is the treatment of point-source wastewater. Today, this technology is established as a sustainable treatment method [5,12,29]. Recent developments in this field proved that wetland technology possesses a high treatment capacity, as indicated, for example, by its various industrial applications [34].

The main issues with the dominant conventional–mechanical treatment systems are their large energy demand and the related high construction and operation costs. Conventional treatment plants have usually an industrial, unattractive appearance, and thus are placed away from residential areas. Their equipment includes large mechanical parts (e.g., aeration units, pumps, etc.) and extensive use of non-renewable materials (e.g., concrete and steel). Especially in low-income regions, the construction of a centralized mechanical facility is often economically infeasible due to lack of funds and technical expertise to manage and operate them. Installing such facilities is usually avoided in urban and/or peri-urban areas, which means that centralized facilities come along with an extensive wastewater collection and transfer pipe network [12]. This fact has negative impacts, both environmental and economic. Because of the many mechanical parts, damages and failures happen frequently. At the same time, their operation results in daily production of by-products, such as sludge, which requires further handling and management and significantly increases the total operational costs [12]. In total, the investment costs and the costs for the continuous and effective operation are usually high, including the need for specialized staff.

The realization of the negative aspects related to conventional systems gradually increased the focus given on sustainable technologies capable of providing alternative solutions to effective wastewater treatment at or near the source. The use of decentralized technologies as green infrastructure systems, coupled with the rising environmental concerns globally and the desire for green solutions, follows the principle of sustainable development, considering that the same activity (i.e., wastewater treatment) can be achieved in a cost-effective, environmentally friendly and energy-efficient way. The fundamental difference of natural treatment systems such as CWs, compared to conventional–mechanical treatment methods, is that they follow this decentralized approach, i.e., they are designed to collect, treat and enable the reuse the wastewater onsite, i.e., close to the source.

Especially in urban areas, the decentralized approach of wastewater management becomes more attractive. This approach can be a solution for blocks of buildings, neighborhoods, commercial facilities, industrial facilities, isolated communities, till remote areas, small islands etc., even for maritime applications such as sea vessels and offshore platforms. For example, in the USA, more than half of the 25 million decentralized systems are located in suburban areas, while one-third of all new housing and commercial developments use decentralized systems [35]. Decentralized systems also offer flexibility in their design and a modular approach is possible to provide simple and cost-effective expansion to meet the required demands and sizes. In the urban context, wetland technology applications used to be rare, mainly due to space limitations. Wetland technology has not yet reached a deep integration into the urban environment, although there has been a rapid development over the last two decades. However, the research developments and the advanced designs of the last 10–15 years gradually close this gap between land availability and area demand, and related costs (Figure 2).

The implementation of a green technology for wastewater management is also called “ecological sanitation” (i.e., ecosan in short), referring to a new philosophy of dealing with wastewater. The goal is the recovery of nutrients from human feces, urine and greywater and the beneficial reuse for irrigation, e.g., in agriculture or of urban green areas, in order to minimize water pollution and ensure the

optimum and economical reuse of water. Thus, the approach of decentralized wastewater management is directly related not only with the provision of an alternative, green and cost-effective treatment solution, but also with the onsite extraction and exploitation of beneficial elements present in the treated effluents.

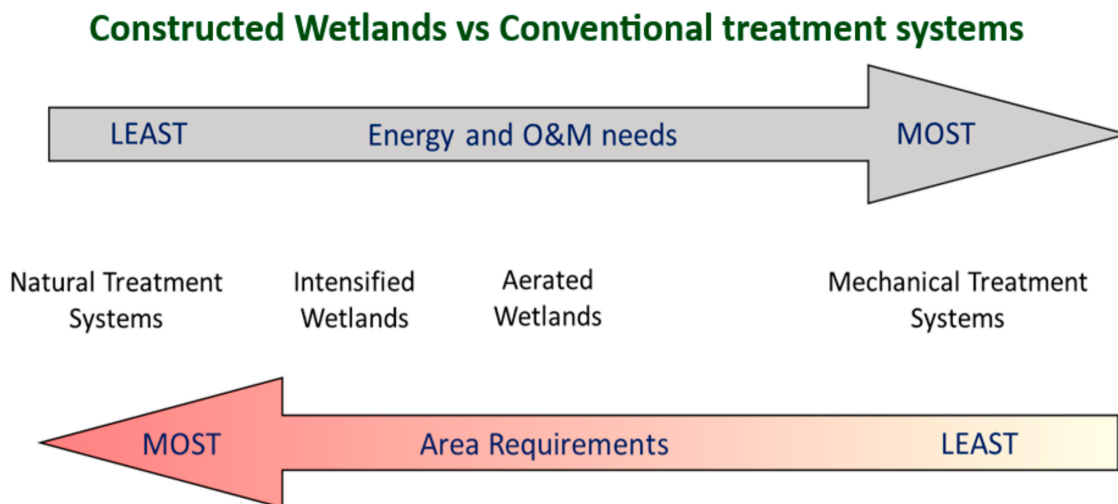


Figure 2. Qualitative comparison of constructed wetlands and mechanical treatment systems in terms of energy, operation and maintenance demands and area requirements.

However, the main argument here is not whether decentralized systems such as CWs can fully replace centralized facilities—something that will probably never happen. The wider use, though, of decentralized systems can contribute to a better management option of the generated volumes and minimize the required numbers and size of centralized facilities, thus reducing their negative footprint, while enhancing the positive environmental footprint of wastewater management through the use of nature-based technologies. The use of CWs particularly in suburban areas is today possible and feasible. In these areas, land is usually cheaper, the population density is smaller and the building volumes are not as massive and dense as in the central urban areas. These are parameters that allow for the easier implementation of CW systems. The technical developments and improvements in CW design make it also easier to adopt such treatment solutions, even in areas with relatively limited available space.

One of the most widely applied designs today is the vertical flow constructed wetland (VFCW) [12]. The increase in VFCW applications is a result of the fact that horizontal subsurface flow (HSF) CWs have a lower oxygen transfer capacity to fulfil the demands for secondary treatment, hence their oxidation and nitrification capacity is limited [36,37]. On the other hand, VFCW systems can transfer higher oxygen amount to the wetland body due to their feeding regime, i.e., intermittently loading and instantaneously flooding the whole bed surface, promoting this way the gravitational drainage through the media layers [38]. This means that the VFCWs have a smaller area demand (up to 2 m²/person equivalent (PE)) compared to HSF systems (typically 5–10 m²/PE), which also implies lower investment costs [12].

Furthermore, the VFCW design gives the option to apply raw wastewater without any pre-treatment (e.g., settling tanks) [12,39]; this design eliminates the need for separate sludge management and handling (and, thus, the related costs), since organic solids are accumulated in the bed, dewatered and stabilized through aerobic processes mediated by the plants. In the long-term operation, the accumulated sludge is converted to biosolids, forming a 50–80 cm deep layer of a stabilized and well-composted sludge material. This layer is then removed, without damaging the gravel media and the plant roots, and the digested sludge is reused in agriculture as fertilizer [40], while plants naturally regenerate and a new sludge loading cycle of 5–8 years starts. A notable example of this wetland design is the Orhei wastewater treatment plant in Moldova that serves a population of

20,000 inhabitants (Figure 3). This facility treats the municipal wastewater from the Orhei town in a two-staged VFCW system that receives up to 2,700 m³/day, figures that make this facility the largest such CW design in the world [41]. It should also be mentioned that the treated effluent from that facility is reused in the urban areas for irrigation.



Figure 3. Vertical flow constructed wetland at Orhei's wastewater treatment plant in Moldova, treating municipal wastewater from 20,000 inhabitants [41]. (Courtesy: Iridra Srl—www.iridra.com).

The most decisive step towards the use of CWs in urban areas comes with the development of intensified-aerated systems, mainly over the last 5–10 years. To further improve the oxygen availability in the wetland bed, artificial aeration is applied (Figure 1). This concept is based on the use of a small blower to provide compressed air through aeration lines placed at the bottom of the bed. Wastewater aeration is a common practice in other treatment technologies, but new in gravel beds such as CWs. The energy demand in this case is lower, typically 10–15% of the energy need for a conventional technology [42,43]. The main advantage of this modification is that the combined vertical downward water drainage and the upflow movement of air bubbles results in well mixing of air with wastewater in the bed, thus, in enhanced aerobic pollutant removal processes and, therefore, in increased performance [43]. The increased treatment capacity of this design enabled its use not only for domestic-municipal wastewater [43–45], but also for many industrial effluents [34,46]. Aerated VFCWs have been found to be up to 10 times more efficient in nitrogen removal through nitrification compared to passive CW systems. This means that the area demand is also significantly lower (e.g., 0.5 m² per PE; [47,48]), making these CWs a somehow compact system, while the low amount of energy required for the air blowers can be covered by renewable energy sources, e.g., solar or wind energy [44,49].

Considering that the typical area demand of conventional treatment technologies (e.g., activated sludge) lies within the range of 0.2–0.5 m²/PE [50–52], it becomes obvious that the aerated wetland systems significantly close the gap on area demand with conventional technologies, thus, enhancing the potential of using this wetland design in suburban and even urban areas. One of the first such facilities is the aerated VFCW at Petersfield, Hampshire, UK (Figure 4). In this facility, the aerated wetland was used to upgrade an existing sewage treatment works that serves 20,000 inhabitants and consists of sedimentation tanks and trickling filters, in order to improve the effluent quality [45]. The aerated VFCW (1200 m²) receives 1250 m³/day, which represents about 1/4 of the total inflow. The wetland effluent is then blended with the secondary effluent. It is noteworthy that, although there is no disinfection step, the final effluent complies with the legal standards for environmental discharge.



Figure 4. Aerated constructed wetland at Petersfield sewage treatment works, Hampshire, UK [45].

Innovative ideas and applications are important for the successful integration of CWs in the urban environment. A characteristic example is the use of an aerated CW on a swimming pool boat located in the city center of Antwerp, Belgium [53]. A recycled ferry boat operating as a restaurant included an on-board aerated wetland system (surface area 188 m²) designed to treat the wastewater generated from approximately 140 persons equivalent, i.e., a peak load of 69 m³/day of wastewater from the visitor locker rooms, showers, toilets, two bars, and the restaurant kitchen, aiming at making the ship and the business concept an environmentally friendly installation.

Furthermore, a compact CW unit called ReedBox has also been developed using the aerated wetland design [54]. This unit is light in order to ease its transportation and site installation wherever required. The design of the system uses an aerated CW that follows the concept of a plug-and-play system (Figure 5). This mobile CW can serve a small population (up to 40 and 75 persons producing 7 and 15 m³/day, respectively) in areas where public sewage network and/or a treatment plant is not available, as well as in areas where space is limited and a minimum footprint is required (the unit's area demand is 0.4 m²/PE), treating domestic wastewater of high strength and typical composition (suspended solids, organic matter, nitrogen). It can provide a wastewater treatment solution for blocks of flats, residential compounds, tourism facilities, hotels etc., as a compact system that can be easily installed without the need for earthworks and permanent infrastructure. The containerized wetland is filled with light substrate materials such as recycled HDPE, on top of which native wetland plants are established [54]. The unit also integrates sludge accumulation and dewatering while purifying wastewater using artificial aeration in a single unit. This design has the benefit of avoiding primary treatment (e.g., a septic/sedimentation tank), since raw wastewater is applied on top of the bed and separated, as it is the case of VFCWs treating raw wastewater (described above).

Another innovative approach is the use of wetlands to create green roofs. The concept consists of the construction of roofs with a vegetated surface. Studies have shown that this practice can regulate the temperature inside a building, reduce the urban heat-island effects, and act as carbon sink, while providing a range of ecological services [55,56]. In addition, such roof wetland systems treating water or even wastewater can be one possible solution to the lack of clean water in urban centers, since these systems are capable of filtering rainwater, enabling this way its onsite reuse for non-potable purposes [57]. This green roof development can easily be adapted to climate change and in accordance with the strategy for green cities [58].



Figure 5. The compact, mobile aerated constructed wetland unit “ReedBox” [54] (Courtesy: Bauer Resources GmbH—<https://www.bauer.de/bre>).

Additionally, the cost parameter is apparently one of the most crucial factors for technology and infrastructure selection. In general, the main advantage of CWs is the reduced operational costs compared to conventional technologies [12,59–61]. There are even large-scale facilities where the reported overall operational costs are 99% reduced compared to grey infrastructure solutions [26]. In the case of urban and peri-urban areas, land requirement would be the main issue. However, as it is shown, the latest advances in wetland technology indicate that this obstacle is gradually overcome. In addition, although conventional technologies have lower area demand, they are usually not installed in urban areas for obvious reasons (e.g., odor, insects, noise, unattractive view, etc.). This means that they come along with an extended sewer network system, which has a significant impact on the required investment, though not directly related to the facility itself. Nevertheless, although land is more expensive in urban and peri-urban areas, it is the life cycle costing that would reveal if and at which level the land purchase cost affects the overall costing of a system. Various life cycle studies report lower overall costs of CW solutions compared to conventional systems over the entire operational life time [12,62,63]. For example, the operation of CWs, including materials use and energy consumption, was found to be 83% lower compared to a centralized facility [64]. Life cycle costing revealed that using a CW to upgrade an activated sludge plant is cost-effective for populations of 5000 and 50,000 and also provided an effluent quality for reuse for a tenth of the carbon footprint of a membrane bioreactor plant [65]. As it is easily understood, it is practically difficult to present global cost estimates for CWs. However, current experiences imply the cost-competitiveness of these systems, which represent another strong point for further implementation in the urban environment.

Summarizing, the green technology of CW in urban and peri-urban areas can provide multiple benefits and services, such as a new habitat for animals and plants, while treating wastewater, improving water quality and reducing pollution [23,66]. Given that these systems are dominated by dense clusters of reeds, they also provide a cooling effect to the surrounding areas particularly during

summer months and they also moderate strong winds. A recent study in a large industrial constructed wetland facility in the Middle East revealed that the presence of the CWs reduced the temperature by 10 °C between the wetland body and its perimeter up to 1 km distance [67]. Furthermore, considering their appearance, CWs also act as aesthetically pleasant urban green spaces, which contribute to the well-being of the residents, and provide options for recreational activities. They also provide the opportunity for local people to get involved in activities such as bird watching, which is not usual in urban environments [68]. It is also reported that contact with green spaces, such as wetland systems in the urban context, supports physical and psychological health [69,70]. In this frame, wetland technology can be a key option to increase the resilience of modern cities to address existing stressors on water and wastewater management.

3.2. Constructed Wetlands for Stormwater Management

Another sustainable application of CWs is stormwater management. In urban and suburban areas, the water cycle is different compared to natural undisturbed land. The main difference is the lower rate of infiltration (both shallow and deep) and the limited evapotranspiration due to the extended coverage of land with building infrastructure, roads, pavements etc. and the (in some cities extremely) limited green spaces. This results in significantly higher volumes of runoff occurring in urban areas, which can be more than 50% higher compared to natural land [71,72]. For example, it has been estimated that 1 acre of parking lot generates 16 times higher stormwater volume than 1 acre of meadow [73]. Public and private urban infrastructure face today frequent damages due to uncontrolled stormwater runoff. The modern approach of GI takes into consideration multiple issues such as water quality improvement, resources protection, flow volume control and cost-effective long-term operation and maintenance. Considering these, CWs can be viewed as an ecological solution to stormwater and CSO management following the GI concept [8,17,74]. The use of CWs for stormwater management provides a series of advantages such as:

- reduction in runoff volumes, peak flows and duration;
- protection of downstream water resources;
- reducing the risk of flooding;
- reducing the risks associated with combined sewer overflow (CSOs);
- water quality improvement;
- enhancement of groundwater recharge/discharge;
- increase of runoff infiltration;
- sediment stabilization;
- creation of wildlife habitat;
- options for recreation activities.

The main element of stormwater wetlands (as in all CWs) is the presence of plants, which play a significant role in the processes taking place within the system, as also in the increased rate of evapotranspiration. Urban stormwater contains a variety of pollutants at varying concentrations, thus, the removal of these pollutants is a key target in the design of such systems. For example, runoff from parking areas and commercial streets produces high levels of suspended solids, while residential streets produce high concentrations of pathogens (e.g., *E. coli*) [75,76]. Other constituents such as phosphorus and heavy metals (especially from highways) can also be present. Usually, the concentrations of these pollutants are above the respective standards for environmental discharge. This means that if this water reaches any surface water body, significant environmental pollution and degradation will occur. In the case of CSO, the pollutant concentrations are also high (especially for carbon, nitrogen and phosphorus), considering that this flow includes the first flush of roads [9], sewer washout, industrial effluents and domestic wastewater [6].

The traditional approach to runoff and CSO management is to collect it through a sewer network and route this water to underground storage tanks and publicly owned wastewater treatment plants

(wwtps). Conventional wwtps are usually designed to receive a predefined maximum flow; however, it is common that the actual load that reaches the plant is higher, especially considering the uncertainties due to climate change impact. The excess volume is often directly discharged into the receiving water bodies without proper treatment or with no treatment at all (Figure 6). CWs treating stormwater or CSO are mainly targeted to hold and retain peak flows, to reduce the suspended solids load by filtration and to reduce the soluble and particulate pollutants through adsorption and biological degradation [77].

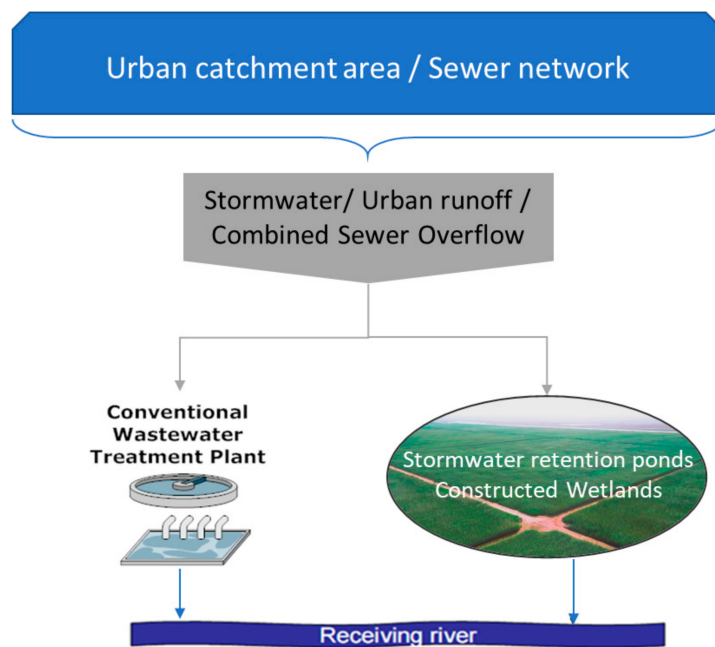


Figure 6. Schematic representation of stormwater/combined sewer overflow management with conventional methods and constructed wetlands (modified from [17]).

The same processes that take place in CWs for wastewater treatment also occur in stormwater wetlands [12]. Especially in CSO volumes, detected pollutant loads can exceed respective loads from wwtp effluents. CWs designed for CSO and wastewater treatment can differ enough, considering the differences of the inflow quality and the hydraulic load applied. Taking also into account the diffuse spatial character of these flows, there should be many treatment facilities in different locations. Under this context, CWs appear as a feasible solution, both economically and ecologically, given that they serve the decentralized approach of water management [8].

Various designs have been developed for the treatment of CSO in different countries. VFCWs are the most widely applied system, also known as “retention soil filter (RSFs)” in Germany. RSFs in Germany are usually sand filters combined with stormwater tanks in series and their development started in the 1990s [8]. National design guidelines have already been adopted [8] and today more than 17,000 sites exist in Germany [78]. One characteristic facility is the CW for CSO treatment in Bergheim (Erft), Germany [79]. This system is a VFCW bed (Figure 7) that receives approximately 1000 m³/hour of CSO and covers an area of 2200 m², while the reported removal rates for solids and organic matter are well documented.

The German guidelines have been adopted in France and Italy with some modifications. The French approach does not include storage tanks and the overflow is directed to two alternately loading filter beds [39]. The second bed is loaded during high flows, e.g., 5–6 times higher than the dry weather flow. Moreover, the Italian design focuses on the treatment of the first flush; four filter beds are operating in parallel to receive the first flush (which is highly polluted), and the exceeding volume (i.e., treated first flush and second flush) is by-passed and routed to a FWS CW [17]. Other configurations have been applied in the USA [74]. In the UK, tertiary CWs have been occasionally used for CSO treatment [80]. A combination of a VF, a HF and a FWS CW in series for CSO treatment has also been

tested in Spain [81]. Such practices have also been widely adopted in Australia; for example, several treatment wetlands were built in the city of Orange, New South Wales to slow down the flow and treat stormwater while providing a new urban habitat (Figure 8; [82]). It is characteristic that the treated stormwater volume covers up to 29% of the city's drinking water demand.



Figure 7. Constructed wetland in Bergheim (Erfurt), Germany for combined sewage overflow (adopted from [79]).



Figure 8. The constructed wetland at the Somerset Park, Orange, New South Wales, Australia that collects and treats stormwater [82].

Innovative solutions can also be designed for urban stormwater and runoff management. Such practices include the replacement of concrete pavements with wetlands, the use of wetlands as green roofs, the creation of rain gardens, etc. The ultimate goal is to increase the rate of rainwater that is absorbed back into the soil, rather than creating flood flows, and hence make it work for the city and not against it. A latest advance in wetland technology is the development of floating treatment wetlands (FTWs; Figure 1). This design is increasingly applied for runoff treatment in urban rivers and canals, as well as in stormwater retention ponds [83]. This system is also used to restore receiving water through a variety of biological and physical processes and for nutrients removal. Their advantage is that FTWs can be installed in most urban water bodies and ponds without a significant infrastructure required, providing an efficient, sustainable and cost-effective water purification solution, while creating terrestrial and aquatic habitats for wildlife and enhancing the ecological diversity [83,84]. A successful example of FTWs for stormwater management comes from the Bribie Island in Queensland,

Australia [83]. The FTW system installed receives stormwater from the nearby residential catchment with a very small treatment area to catchment ratio (0.14%).

Overall, the use of CWs for stormwater management is feasible and promising in urban and peri-urban areas [65,85]. A notable example is the so-called China's Sponge City Plan (Figure 9) that promotes the use of soil and vegetation as part of the effective urban runoff control strategy, rainwater harvest, water quality improvement and ecological restoration [25]. It is characteristic that the Shanghai government set a target of creating 400,000 m² of new green roofs.



Figure 9. An example of China's Sponge City Plan: Qunli Stormwater Park. Haerbin City, Heilongjiang Province, China designed to treat 500,000 m³ of stormwater; American Society of Landscape Architects Award of Excellence 2012, Turenscape and Peking University [86].

Another characteristic example is the Staten Island Bluebelt Drainage Basins in New York City, where wetland systems were placed within the watershed to temporarily store and treat more than 350,000 GPD of stormwater during storm events, covering an area of 14,000 acres and saving more than \$80 million in conventional sewer costs [87]. Furthermore, the so called Tres Rios Constructed Wetland in Phoenix is one of the most known green infrastructure projects (Figure 10). This wetland was created to further polish treated wastewater from a nearby large conventional treatment plant and urban runoff. This system acted as a demonstration project and was gradually developed and expanded to provide several services, such as flood control, habitat restoration, public outreach, water reuse and availability, carbon footprint offset [87].

The potential for integrating wetland technology in urban areas should further be investigated and smart ideas can be expanded and adapted, e.g., converting open areas such as roundabouts in small wetland filters for runoff retention and treatment. In a larger context, the use of CWs for runoff management provides not only control of flooding and water quality improvement, but within the urban landscape, wetlands contribute to limited carbon emissions and enhanced carbon sequestration, resulting in a reduced carbon footprint [16]. It should also be noted that the first research results in full-scale CWs indicate that these systems have also the potential to improve urban water quality in terms of micro-pollutants removal such as pharmaceuticals, personal care products, antiseptics, etc. [88]. These pollutants are a rising concern worldwide due to their potential negative impact to public health and the ecosystems. The research of various treatment technologies is currently ongoing to identify the ones with the highest performance, whereas CWs appear as one of the most effective solutions [89].



Figure 10. The Tres Rios Constructed Wetland in Phoenix, Arizona [87].

4. Conclusions

Rapid global urbanization is one of the biggest transformations observed in human history. Challenges like this that modern cities face, along with increasing resource consumption and demand, land use, and air and water pollution, indicate the necessity to find and implement new ways to promote sustainability and circularity and make modern cities more resilient to all kinds of stressors. Green infrastructure can increase the green coverage in the urban environment and create new ecosystems within the cities, while dealing with major urban issues such as urban water management, to limit the risks associated with urban heat islands, flooding and water–air quality. The technology of constructed wetlands can play a significant role in this transition as a sustainable method for water treatment and management. Until recently, CWs were mainly implemented in rural, remote areas and small communities to provide domestic wastewater treatment services.

However, the latest technological advances managed to significantly close the gap with conventional—mechanical technologies in terms of land requirement. This gives now the option to integrate engineered wetlands in urban and peri-urban areas for wastewater treatment and urban runoff control and management, following the decentralized approach.

Climate change, environmental health, and resource scarcity are the main drivers for planning and design; therefore, CWs as multi-purpose landscape infrastructure can contribute to the mitigation of the present complex environmental challenges. Densely populated areas are usually served by centralized wastewater treatment plants and extensive sewer networks. At the same time, the built environment alters the hydrologic cycle, resulting in high volumes of stormwater and related flooding risks. Especially the suburban areas, where the impervious coverage is lower, possess a higher potential for the integration of CWs to treat stormwater and enhanced ecosystem services within the hydrologic network. CWs can provide an alternative and cost-effective solution to wastewater treatment of single households, blocks of houses, residential neighborhoods/complexes, commercial areas, small industries, etc. The design flexibility that wetland technology provides allows for even more innovative approaches for wetland integration in the urban environment, e.g., on river boats, compact/mobile units, top of buildings, in roundabouts, roofs etc.

The distribution of several CWs throughout a green infrastructure network allows the usage of treated effluents to create new habitats, for irrigation, and open space uses. The economic value

of the ecosystem services provided by CWs justifies their installation to realize the wide range of provisioning, regulating, and cultural benefits. When connected to urban ecological corridors, CWs support the creation of large-scale multifunctional landscapes, altering this way the characteristics of the urbanized development. Particularly the CWs built for wastewater treatment or stormwater/rainwater management promote biodiversity and habitat creation, establish new corridors for wildlife and become part of the urban recreational network. Their integration in the urban environment supports a healthier ecological balance of the existing water streams by providing water purification services, while protecting downstream urban areas from flooding. The provision of additional green space with aesthetic values is also a way for people to feel connected with nature and enhance psychological wellbeing. Summarizing, the multiple benefits of CWs provide several opportunities to further include these green systems in current and future urban planning.

Funding: This research received no external funding.

Conflicts of Interest: The author declare no conflict of interest.

References

1. Mell, I.C. Green infrastructure: Concepts and planning. *FORUM Electron. J.* **2008**, *8*, 69–80.
2. Haines-Young, R.; Potschin, M. Common International Classification of Ecosystem Services (CICES): Consultation on Version 4, August–December 2012. EEA Framework Contract No EEA/IEA/09/003. 2013. Available online: https://cices.eu/content/uploads/sites/8/2012/07/CICES-V43_Revised-Final_Report_29012013.pdf (accessed on 29 November 2019).
3. Potschin, M.B.; Haines-Young, R.H. Ecosystem services Exploring a geographical perspective. *Prog. Phys. Geogr.* **2011**, *35*, 575–594. [CrossRef]
4. Lennon, M. Green infrastructure and planning policy: A critical assessment. *Local Environ.* **2015**, *20*, 957–980. [CrossRef]
5. Masi, F.; Rizzo, A.; Regelsberger, M. The role of constructed wetlands in a new circular economy, resource oriented, and ecosystem services paradigm. *J. Environ. Manag.* **2018**, *216*, 275–284. [CrossRef]
6. Barco, J.; Papiri, S.; Stenstrom, M.K. First flush in a combined sewer system. *Chemosphere* **2008**, *71*, 827–833. [CrossRef]
7. Barbosa, A.E.; Fernandes, J.N.; David, L.M. Key issues for sustainable urban stormwater management. *Water Res.* **2012**, *46*, 6787–6798. [CrossRef]
8. Meyer, D.; Molle, P.; Esser, D.; Troesch, S.; Masi, F.; Dittmer, U. Constructed wetlands for combined sewer overflow treatment-comparison of German, French and Italian approaches. *Water* **2013**, *5*, 1–12. [CrossRef]
9. Bach, P.M.; McCarthy, D.T.; Deletic, A. Redefining the stormwater first flush phenomenon. *Water Res.* **2010**, *44*, 2487–2498. [CrossRef]
10. Gasperi, J.; Gromairea, M.; Kafia, M.; Moillerona, R.; Chebboa, G. Contributions of wastewater, runoff and sewer deposit erosion to wet weather pollutant loads in combined sewer systems. *Water Res.* **2010**, *44*, 5875–5886. [CrossRef]
11. EC (European Commission). *Water Framework Directive 2000/60/EC of the European Parliament and of the Council of 23 October 2000 Establishing a Framework for Community Action in the Field of Water Policy*; Official Journal of the European Community: Brussels, Belgium, 2000.
12. Stefanakis, A.I.; Akratos, C.S.; Tsihrintzis, V.A. *Vertical Flow Constructed Wet-Lands: Eco-Engineering Systems for Wastewater and Sludge Treatment*, 1st ed.; Elsevier Science: Waltham, MA, USA, 2014.
13. Mander, Ü.; Jenssen, P. *Natural Wetlands for Wastewater Treatment in Cold Climates*; Advances in Ecological Sciences; WIT Press: Southampton, UK, 2002.
14. Knight, R.L.; Clarke, R.A.; Bastian, R.K. Surface flow (SF) treatment wetlands as a habitat for wildlife and humans. *Water Sci. Technol.* **2001**, *44*, 27–37. [CrossRef]
15. Ghermandi, A.; Van den Bergh, J.C.J.M.; Brander, L.; De Groot, H.L.F.; Nunes, P.A.L.D. Values of natural and human-made wetlands: A meta-analysis. *Water Resour. Res.* **2010**, *46*, 1–12. [CrossRef]
16. Moore, T.L.C.; Hunt, W.F. Predicting the carbon footprint of urban stormwater infrastructure. *Ecol. Eng.* **2013**, *58*, 44–51. [CrossRef]

17. Masi, F.; Rizzo, A.; Bresciani, R.; Conte, G. Constructed wetlands for combined sewer overflow treatment: Ecosystem services at Gorla Maggiore, Italy. *Ecol. Eng.* **2016**, *98*, 427–438. [CrossRef]
18. Knight, R.L. Wildlife habitat and public use benefits of treatment wetlands. *Water Sci. Technol.* **1997**, *35*, 35–43. [CrossRef]
19. Sundaravadivel, M.; Vigneswaran, S. Constructed wetlands for wastewater treatment. *Crit. Rev. Environ. Sci. Technol.* **2001**, *31*, 351–409. [CrossRef]
20. Li, W. A Case Study of Constructed Wetlands Application to Restore Habitats and Treat Wastewater. Master Thesis, University of British Columbia, Vancouver, BC, Canada, 2018. Available online: <http://mlws.landfood.ubc.ca/2018/10/02/a-case-study-of-constructed-wetlands-application-to-restore-habitats-and-treat-wastewater> (accessed on 29 November 2019).
21. Tsihrintzis, V.A.; Hamid, R. Modelling and management of urban stormwater runoff quality: A review. *Water Resour. Manag.* **1997**, *11*, 137–164.
22. Shutes, B.; Revitt, M.; Scholes, L. Constructed Wetlands for Flood Prevention and Water Reuse. In Proceedings of the 12th International Conference on Wetland Systems for Water Pollution Control, Venice, Italy, 3–6 October 2010.
23. Dou, T.; Troesch, S.; Petitjean, A.; Gabor, P.T.; Esser, D. Wastewater and rainwater management in urban areas: A role for Constructed Wetlands. *Procedia Environ. Sci.* **2017**, *37*, 535–541. [CrossRef]
24. Jia, H.; Ma, H.; Wei, M. Urban wetland planning: A case study in the Beijing central region. *Ecol. Complex.* **2011**, *8*, 213–221. [CrossRef]
25. Jia, H.; Wang, Z.; Zhen, X.; Clar, M.; Wu, S.L. China's sponge city construction: A discussion on technical approaches. *Front. Environ. Sci. Eng.* **2017**, *11*. [CrossRef]
26. Stefanakis, A.I.; Prigent, S.; Breuer, R. Integrated produced water management in a desert oilfield using wetland technology and innovative reuse practices. In *Constructed Wetlands for Industrial Wastewater Treatment*; Stefanakis, A.I., Ed.; John Wiley & Sons Ltd.: Chichester, UK, 2018; pp. 25–42.
27. Vymazal, J. Removal of nutrients in various types of constructed wetlands. *Sci. Total Environ.* **2007**, *380*, 48–65. [CrossRef]
28. Schwammberger, P.; Walker, C.; Lucke, T. Using Floating Wetland Treatment systems to reduce stormwater pollution from urban developments. *Int. J. GEOMATE* **2017**, *12*, 45–50. [CrossRef]
29. Masi, F. Water reuse and resources recovery: The role of constructed wetlands in the Ecosan approach. *Desalination* **2009**, *247*, 28–35. [CrossRef]
30. Yu, R.; Wu, Q.; Lu, X. Constructed Wetland in a Compact Rural Domestic Wastewater Treatment System for Nutrient Removal. *Environ. Eng. Sci.* **2012**, *29*, 751–757. [CrossRef]
31. Stefanakis, A.I.; Seeger, E.; Dorer, C.; Sinke, A.; Thullner, M. Performance of pilot-scale horizontal subsurface flow constructed wetlands treating groundwater contaminated with phenols and petroleum derivatives. *Ecol. Eng.* **2016**, *95*, 514–526. [CrossRef]
32. Ramírez, S.; Torrealba, G.; Lameda-Cuicas, E.; Molina-Quintero, L.; Stefanakis, A.I.; Pire-Sierra, M.C. Investigation of pilot-scale Constructed Wetlands treating simulated pre-treated tannery wastewater under tropical climate. *Chemosphere* **2019**, *234*, 496–504. [CrossRef]
33. Vohla, C.; Köiv, M.; Bavor, H.J.; Chazarenc, F.; Mander, Ü. Filter materials for phosphorus removal from wastewater in treatment wetlands—A review. *Ecol. Eng.* **2011**, *37*, 70–89. [CrossRef]
34. Stefanakis, A.I. *Constructed Wetlands for Industrial Wastewater Treatment*, 1st ed.; John Wiley & Sons Ltd.: Chichester, UK, 2018.
35. Hoffmann, S.J. *Planet Water: Investing in the World's Most Valuable Resource*, 1st ed.; John Wiley and Sons: Waltham, NJ, USA, 2009.
36. Cooper, P. A review of the design and performance of vertical-flow and hybrid reed bed treatment systems. *Water Sci. Technol.* **1999**, *40*, 1–9. [CrossRef]
37. Stefanakis, A.I.; Tsihrintzis, V.A. Effect of outlet water level raising and effluent recirculation on removal efficiency of pilot-scale horizontal subsurface Flow Constructed Wetlands. *Desalination* **2009**, *248*, 961–976. [CrossRef]
38. Stefanakis, A.I.; Tsihrintzis, V.A. Effects of loading, resting period, temperature, porous media, vegetation and aeration on performance of pilot-scale vertical flow constructed wetlands. *Chem. Eng.* **2012**, *181*, 416–430. [CrossRef]

39. Molle, P.; Lienard, A.; Boutin, C.; Merlin, G.; Iwema, A. How to treat raw sewage with constructed wetlands: An overview of the French systems. *Water Sci. Technol.* **2005**, *51*, 11–21. [[CrossRef](#)]
40. Stefanakis, A.I.; Komilis, D.P.; Tsihrintzis, V.A. Stability and maturity of thickened wastewater sludge treated in pilot-scale sludge treatment wetlands. *Water Res.* **2011**, *45*, 6441–6452. [[CrossRef](#)]
41. Masi, F.; Bresciani, R.; Martinuzzi, N.; Cigarini, G.; Rizzo, A. Constructed Wetland at Orhei's wastewater treatment plant, Moldova. *Water Sci. Technol.* **2017**, *76.1*, 134–146. [[CrossRef](#)]
42. Boog, J.; Nivala, J.; Aubron, T.; Wallace, S.; Sullivan, C.; Van Afferden, M.; Mueller, R.A. Treatment Wetland aeration without electricity? Lessons learned from the first experiment using a wind-driven air pump. *Water* **2016**, *8*, 502. [[CrossRef](#)]
43. Langergraber, G.; Dotro, G.; Nivala, J.; Rizzo, A.; Stein, O.R. *Wetland Technology; Practical Information on the Design and Application of Treatment Wetlands*; Scientific and Technical Report No. 27; IWA Publishing: London, UK, 2009.
44. Nivala, J.; Headley, T.; Wallace, S.; Bernhard, K.; Brix, H.; Van Afferden, M.; Mueller, R.A. Comparative analysis of constructed wetlands: The design and construction of the ecotechnology research facility in Langenreichenbach, Germany. *Ecol. Eng.* **2013**, *61*, 527–543. [[CrossRef](#)]
45. Stefanakis, A.I.; Bardiau, M.; Silva, D.; Taylor, H. Presence of bacteria and bacteriophages in full-scale trickling filters and an aerated constructed wetland. *Sci. Total Environ.* **2019**, *659*, 1135–1145. [[CrossRef](#)]
46. Wallace, S.; Liner, M. Design and performance of the wetland treatment system at Buffalo Niagara International Airport. In *Newsletter of the Specialist Group on Use of Macrophytes in Water Pollution Control*; International Water Association: London, UK, 2011; Volume 38, pp. 36–42.
47. Stefanakis, A.I.; Prigent, S. A Novel Two-Stage Constructed Wetland with Integrated Sludge Management and Artificial Aeration to Meet Strict Effluent Quality Standards. In Proceedings of the 16th IWA International Conference on Wetland Systems for Water Pollution Control, Valencia, Spain, 30 September–4 October 2018.
48. Stefanakis, A.I. A two-stage Constructed Wetland design with artificial aeration and sludge mineralization for municipal wastewater treatment. In *Phytoremediation/Bioremediation and Environmental Sustainability, Environmental and Microbial Biotechnology Series*, 1st ed.; Prasad, R., Ed.; Springer Nature: New York, NY, USA, 2019.
49. 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*, 183–191.
50. Chambers, B. Batch operated activated sludge plant for production of high effluent quality at small works. *Water Sci. Technol.* **1993**, *28*, 251–258. [[CrossRef](#)]
51. Von Sperling, M. Comparison among the most frequently used systems for wastewater treatment in developing countries. *Water Sci. Technol.* **1996**, *33*, 59–72. [[CrossRef](#)]
52. Metcalf & Eddy. *Wastewater Engineering: Treatment and Resource Recovery*, 5th ed.; McGraw Hill: New York, NY, USA, 2014.
53. Van Oirschot, D.; Wallace, S.; Van Deun, R. Wastewater treatment in a compact intensified wetland system at the Badboot: A floating swimming pool in Belgium. *Environ. Sci. Pollut. Res.* **2015**, *22*, 12870–12878. [[CrossRef](#)]
54. Stefanakis, A.I. Reedbox: An Innovative Compact, Mobile Constructed Wetland Unit for Wastewater Treatment. In Proceedings of the Oman Water & Wastewater Conference 2019, Oman Convention & Exhibition Centre, Muscat, Oman, 22–23 April 2019.
55. Oberndorfer, E.; Lundholm, J.; Bass, B.; Coffman, R.R.; Doshi, H.; Dunnett, N.; Gaffin, S.; Koehler, M.; Liu, K.K.Y.; Rowe, B. Green Roofs as Urban Ecosystems: Ecological Structures, Functions, and Services. *Bioscience* **2007**, *57*, 823–833. [[CrossRef](#)]
56. Song, U.; Kim, E.; Bang, J.H.; Son, D.J.; Waldman, B.; Lee, E.J. Wetlands are an effective green roof system. *Build. Environ.* **2013**, *66*, 141–147. [[CrossRef](#)]
57. Naked, A.H.; Vazquez, E.G.; Alves, L.A.; Peçanha, L. Proposal for implementation of green roof project using the wetland technique. *J. Sustain. Dev. Energy Water Environ. Syst.* **2019**. [[CrossRef](#)]
58. Vo, T.D.H.; Bui, X.T.; Lin, C.; Nguyen, V.T.; Hoang, T.K.D.; Nguyen, H.H.; Nguyen, P.D.; Ngo, H.H.; Guo, W. A mini-review on shallow-bed constructed wetlands: A promising innovative green roof. *Curr. Opin. Environ. Sci. Health* **2019**, *12*, 38–47. [[CrossRef](#)]
59. UN. *Wastewater Treatment Technologies: A General Review*; United Nations: New York, NY, USA, 2003.
60. Kadlec, R.H.; Wallace, S.D. *Treatment Wetlands*, 2nd ed.; CRC Press: Boca Raton, FL, USA, 2009.

61. Gunes, K.; Tuncsiper, B.; Masi, F.; Ayaz, S.; Leszczynska, D.; Hecan, B.F.; Ahmad, H. Construction and maintenance cost analyzing of constructed wetland systems. *Water Pract. Technol.* **2011**, *6*. [\[CrossRef\]](#)
62. Manino, I.; Franco, D.; Piccioni, E.; Favero, L.; Mattiuzzo, E.; Zanetto, G. A Cost-effectiveness analysis of seminatural wetlands and activated sludge wastewater-treatment systems. *Environ. Manag.* **2008**, *41*, 118–129. [\[CrossRef\]](#)
63. Georges, K.; Thornton, A.; Sadler, R. *Transforming Wastewater Treatment to Reduce Carbon Emissions: Resource Efficiency Programme, Evidence Directorate*; Report SC070010/R2; Environmental Agency: Bristol, UK, 2009.
64. Luederitz, V.; Eckert, E.; Lange-Weber, M.; Lange, A.; Gersberg, M.R. Nutrient removal efficiency and resource economics of vertical flow and horizontal flow constructed wetlands. *Ecol. Eng.* **2001**, *18*, 157–171. [\[CrossRef\]](#)
65. Besancon, A.; Le Corre, K.S.; Dotro, G.; Jefferson, B. Assessment of activated sludge, membrane bioreactors and vertical flow wetlands for upgrading sewage treatment works. *Environ. Technol.* **2016**. [\[CrossRef\]](#)
66. Elzein, Z.; Abdou, A.; Abd, E.I. Constructed Wetlands as a sustainable wastewater treatment method in communities. *Procedia Environ. Sci.* **2016**, *34*, 605–617. [\[CrossRef\]](#)
67. Stefanakis, A.I.; Charalampopoulos, I.; Psomiadis, E.; Prigent, S. The Thermal Regime of a Large Constructed Wetland in the Desert Environment. In Proceedings of the 16th IWA International Conference on Wetland Systems for Water Pollution Control, Valencia, Spain, 30 September–4 October 2018.
68. Boyer, T.; Polasky, S. Valuing urban wetlands: A review of non-market valuation studies. *Wetlands* **2004**, *24*, 744–755. [\[CrossRef\]](#)
69. Dallimer, M.; Irvine, K.N.; Skinner, A.M.J.; Davies, Z.G.; Rouquette, J.R.; Maltby, L.L.; Warren, P.H.; Armsworth, P.R.; Gaston, K.J. Biodiversity and the feel-good factor: Understanding associations between self-reported human well-being and species richness. *Bioscience* **2012**, *62*, 47–55. [\[CrossRef\]](#)
70. Keniger, L.E.; Gaston, K.J.; Irvine, K.N.; Fuller, R.A. What are the benefits of interacting with Nature? *Int. J. Environ. Res. Public Health* **2003**, *10*, 913–935. [\[CrossRef\]](#)
71. McGrane, S.J. Impacts of urbanisation on hydrological and water quality dynamics, and urban water management: A review. *Hydrol. Sci. J.* **2016**, *61*, 2295–2311. [\[CrossRef\]](#)
72. Zölch, T.; Henze, L.; Keilholz, P.; Pauleit, S. Regulating urban surface runoff through nature-based solutions—An assessment at the micro-scale. *Environ. Res.* **2017**, *157*, 135–144. [\[CrossRef\]](#)
73. Schueler, T.R. Performance of grassed swales along east coast highways. *Watershed Prot. Tech.* **1994**, *1*, 122–123.
74. Tao, W.; Bays, J.S.; Meyer, D.; Smardon, R.C.; Levy, Z.F. Constructed Wetlands for Treatment of Combined Sewer Overflow in the US: A Review of Design Challenges and Application Status. *Water* **2014**, *6*, 3362–3385. [\[CrossRef\]](#)
75. Kadlec, R.H. The Houghton Lake wetland treatment project. Wastewater treatment at the Houghton Lake Wetland: Hydrology and Water Quality. *Ecol. Eng.* **2009**, *35*, 1287–1311. [\[CrossRef\]](#)
76. Peters, D.P.C.; Groffman, P.M.; Nadelhoffer, K.J.; Grimm, N.B.; Collins, S.L.; Michener, W.K.; Huston, M.A. Living in an Increasingly Connected World: A Framework for Continental-scale Environmental Science. *Front. Ecol. Environ.* **2008**, *6*, 229–237. [\[CrossRef\]](#)
77. Dittmer, U.; Meyer, D.; Langergraber, G. Simulation of a subsurface vertical flow constructed wetland for CSO treatment. *Water Sci. Technol.* **2005**, *51*, 225–232. [\[CrossRef\]](#)
78. DWA. *Empfehlungen für Planung, Konstruktion und Betrieb von Retentionsboden-Filteranlagen zur Weitergehenden Regenwasserbehandlung im Misch- und Trennverfahren (Recommendations for Planning, Construction and Operation of Retention Soil Filters for Rainwater Treatment in Mixed and Separated Sewer Systems)*; Deutsche Vereinigung für Wasserwirtschaft, Abwasser und Abfall e.V. (DWA): Hennef, Germany, 2005.
79. Tondera, K. Case study 1—CSO Treatment Wetland (Germany). In *Wetland Technology, Practical Information on the Design and Application of Treatment Wetlands*, 1st ed.; Langergraber, G., Dotro, G., Nivala, J., Rizzo, A., Stein, O.R., Eds.; Scientific and Technical Report No. 27; IWA Publishing: London, UK, 2009; p. 129.
80. Green, M.B.; Martin, J.R.; Griffin, P. Treatment of combined sewer overflows at small wastewater treatment works by constructed reed beds. *Water Sci. Technol.* **1999**, *40*, 357–364. [\[CrossRef\]](#)
81. Ávila, C.; Salas, J.J.; Martín, I.; Aragón, C.; García, J. Integrated treatment of combined sewer wastewater and stormwater in a hybrid constructed wetland system in southern Spain and its further reuse. *Ecol. Eng.* **2013**, *50*, 13–20. [\[CrossRef\]](#)

82. CRCWSC. *Orange Stormwater to Potable: Building Urban Water Supply Diversity*; Cooperative Research Centre for Water Sensitive Cities: Clayton, Australia, 2018; Available online: www.watersensitivecities.org.au (accessed on 1 December 2019).
83. Walker, C.; Tondera, K.; Lucke, T. Stormwater treatment evaluation of a Constructed Floating Wetland after two years operation in an urban catchment. *Sustainability* **2017**, *9*, 1687. [[CrossRef](#)]
84. Xu, B.; Wang, X.; Liu, J.; Wu, J.; Zhao, Y.; Cao, W. Improving urban stormwater runoff quality by nutrient removal through Floating Treatment Wetlands and vegetation harvest. *Sci. Rep.* **2017**, *7*, 7000. [[CrossRef](#)]
85. Salminen, O.; Ahponen, H.; Valkama, P.; Vessman, T.; Rantakokko, K.; Vaahtera, E.; Taylor, A.; Vasander, H.; Nikinmaa, E. Benefits of Green Infrastructure—Socio-Economic Importance of Constructed Urban Wetlands (Nummela, Finland). In *Socio-Economic Importance of Ecosystem Services in the Nordic Countries—Synthesis in the Context of The Economics of Ecosystems and Biodiversity (TEEB)*; Kettunen, M., Vihervaara, P., Kinnunen, S., D’Amato, D., Badura, T., Argimon, N., Brink, P.T., Eds.; Nordic Council of Ministers: Copenhagen, Denmark, 2012; pp. 247–254.
86. American Society of Landscape Architects. *Green Infrastructure: Constructed Wetlands*. Available online: <https://www.asla.org/ContentDetail.aspx?id=43537> (accessed on 29 October 2019).
87. Economides, C. *Green Infrastructure: Sustainable Solutions in 11 Cities across the United States*; Columbia University Water Centre: New York, NY, USA, 2014.
88. Gorito, A.M.; Ribeiro, A.R.; Almeida, C.M.R.; Silva, A.M.T. A review on the application of constructed wetlands for the removal of priority substances and contaminants of emerging concern listed in recently launched EU legislation. *Environ. Pollut.* **2017**, *227*, 428–443. [[CrossRef](#)]
89. Ávila, C.; Bayona, J.M.; Martín, I.; Salas, J.J.; García, J. Emerging organic contaminant removal in a full-scale hybrid constructed wetland system for wastewater treatment and reuse. *Ecol. Eng.* **2015**, *80*, 108–116. [[CrossRef](#)]



© 2019 by the author. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<http://creativecommons.org/licenses/by/4.0/>).