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The Historical Development of Constructed Wetlands for Wastewater Treatment

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Abstract: Constructed wetlands (CWs) for wastewater treatment are engineered systems that are designed and operated in order to use all natural processes involved in the removal of pollutants from wastewaters. CWs are designed to take advantage of many of the same processes that occur in natural wetlands, but do so within a more controlled environment. The basic classification is based on the presence/absence of wastewater on the wetland surface. The subsurface flow of CWs can be classified according to the direction of the flow to horizontal and vertical. The combination of various types of CWs is called hybrid CW. The CWs technology began in the 1950s in Germany, but the major extension across the world occurred during the 1990s and early 2000s. The early CWs in Germany were designed as hybrid CWs; however, during the 1970s and 1980s, horizontal subsurface flow CWs were mostly designed. The stricter limits for nitrogen, and especially ammonia, applied in Europe during the 1990s, brought more attention to vertical subsurface flow and hybrid systems. Constructed wetlands have been used to treat various types of wastewater, including sewage, industrial and agricultural wastewaters, various drainage and runoff waters and landfill leachate. Recently, more attention has also been paid to constructed treatment wetlands as part of a circular economy in the urban environments: it is clear that CWs are a good fit for the new concept of sponge cities.

Keywords: constructed wetlands; macrophytes; pollution; wastewater

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1. Introduction

Wetlands are transitional environments. In a spatial context, they lie between dry land and open water at the coast, around inland lakes and rivers or as mires draped across the landscape. In an ecological context, wetlands are intermediate between terrestrial and aquatic ecosystems. In a temporal context, most wetlands are destined either to evolve into dry land as a result of lowered water tables, sedimentation and plant succession, or to be submerged by rising water tables associated with relative sea-level rise or climatic change. Wetlands often form part of a large continuum of community type, and therefore it is difficult to set boundaries [1].

Wetlands can be defined as areas flooded with shallow water, or soil is saturated with water for long enough to create hydric soils that support specialized macrophytes adapted to life in anaerobic conditions [1,2]. However, Mitsch and Gosselink [1] pointed out that although the concepts of shallow water or saturated conditions, unique wetland soils and vegetation adapted to wet conditions are fairly straightforward, combining these three factors to obtain a precise definition is difficult, due to a number of characteristics that distinguish wetlands from other ecosystems, yet make them less easy to define.

Natural wetlands have been used for wastewater treatment for centuries. In many cases, however, the reasoning behind this use was disposal rather than treatment, and the wetland simply served as a convenient recipient that was closer than the nearest river or other waterways [3]. Such uncontrolled wastewater disposal led to the destruction of many wetlands around the world. The attempts to use natural wetlands for wastewater treatment under controlled conditions continued even in the 1970s and 1980s, especially in the United States [4–6]. The experiments with natural wetlands revealed the difficulties with system maintenance and, also, the treatment efficiency was quite unpredictable. Therefore, the use of natural wetlands to treat wastewater was replaced with the use of constructed wetlands (CWs), which have been developed since the 1960s.

Constructed wetlands designed to treat wastewater are engineered systems that are built to utilize natural wetland processes involved in the transformation and removal of pollutants, but under more controlled conditions. Constructed wetlands can be built with a greater degree of control than natural systems, thus allowing the construction of treatment facilities with a well-defined composition of substrates, vegetation types and flow patterns. In addition, constructed wetlands offer several additional advantages compared to natural wetlands, including site selection, flexibility in sizing and, most importantly, control over the hydraulic pathways and retention time [7]. Plants are an indispensable part of constructed wetlands; however, their role in pollution removal is rather indirect, such as the insulation of subsurface flow systems, provision of oxygen to otherwise anoxic substrates, provision of surface for attached bacteria, excretion of antibacterial compounds from the roots and the reduction of wind allowing better sedimentation of the suspended solids in surface flow CWs. The direct role is restricted to the uptake of nutrients if the biomass is harvested [8–10].

2. Classification of Constructed Wetlands for Wastewater Treatment

The most comprehensive classification of constructed treatment wetlands was published by Fonder and Headley [11], who pointed out that there are three main characteristics typical of these systems: the presence of macrophytes, the existence of water-logged or saturated substrate conditions for at least part of the time and the inflow of contaminated water with constituents to be removed. Based on the predominant position of the water in the system, two major groups can be recognized: surface flow CWs (sometimes called free water surface CWs) and subsurface flow CWs. Subsurface flow systems can be further classified as horizontal and vertical, according to the direction of the flow.

2.1. Surface Flow Constructed Wetlands

Surface flow constructed wetlands usually consist of shallow basins or channels with soil or other suitable mediums, to support the growth of macrophytes if rooted macrophytes are present. One of their primary design purposes is to contact slow-flowing wastewater with reactive biological surfaces [12].

Surface flow CWs can be classified according to the macrophyte type into CWs with (a) free-floating macrophytes, (b) floating-leaved macrophytes, (c) submerged macrophytes, (d) emergent macrophytes and (e) trees [13]. In surface flow constructed wetlands, the organics are removed principally by the bacterial metabolism of both attached and free-living bacteria. Bacteria can be attached to either the roots and rhizomes of free-floating plants, or to the stems and leaves of rooting macrophytes. The removal of suspended solids occurs through gravity sedimentation. The plants minimize the wind-induced turbulence and water stirring, allowing for effective sedimentation [8]. The removal of nitrogen is primarily executed by denitrification, while ammonia volatilization and plant uptake play minor roles. Nitrification occurs in most surface flow constructed wetlands, but this process does not remove nitrogen from wastewater and only transfers ammonia to nitrate. The removal through denitrification can take place in a layer of decomposed plant material at the bottom of the wetland. Phosphorus removal is generally very low because of the limited contact of wastewater with soil particles; therefore, there is a limited precipitation with Fe, Al, Mg or Ca [14].

2.1.1. CWs with Free-Floating Macrophytes

Free-floating macrophytes are highly diverse in form and habitat, ranging from large plants, such as *Eichhornia crassipes* (water hyacinth, Figure 1) or *Pistia stratiotes* (water lettuce) with large leaves and roots, compared to very small plants, such as Lemnaceae (duckweeds, e.g., *Lemna* spp., *Sprodela polyrhiza* or *Wolffia* spp.) with tiny roots [15]. Free-floating plants are highly productive and belong to the fastest growing plants on the planet. *E. crassipes* and *P. stratiotes* are frost sensitive and do not survive in temperate and cold climatic conditions, and are restricted to the tropics and subtropics. On the other hand, Lemnaceae (Figure 2) have a much wider geographic range as they are able to survive even under light frost [16]. Constructed wetlands with free-floating macrophytes were intensively studied in the late 1970s and the early 1980s, but the high operation and maintenance costs were connected with the constant need of plant harvesting, and the subsequent disposal prevented the use of these systems from a wider application [17,18]. It is important to say that duckweed can naturally occur in all types of surface flow constructed wetlands, as these plants can easily be transported by wind or by birds.

Figure 1. Surface flow constructed wetlands with *Eichhornia crassipes* (water hyacinth) in Langtou near Guangzhou, China. Photo Jan Vymazal.

Figure 2. Constructed wetland with *Lemna* spp. (duckweed) and *Taxodium distichum* (baldcypress) designed to treat stormwater runoff in Orlando, Florida. Photo: Jan Vymazal.

2.1.2. CW with Floating-Leaved Macrophytes

Floating-leaved macrophytes (Figure 3) include plant species that are rooted in the substrate, and their leaves on long peduncles float on the water's surface. Typical examples of this type of macrophyte are water lilies (*Nymphaea* spp.), spatterdock (*Nuphar lutea*) or Indian lotus (*Nelumbo nucifera*). The plants in this group usually have large rhizomes and leaves floating on the water's surface connected to the rhizomes with long peduncles. So far, only several constructed wetlands have used floating-leaved macrophytes.

Figure 3. Constructed wetland (Ironbridge, Florida) planted with *Nuphar lutea* (spatterdock), designed for tertiary treatment of 800,000 PE in Orlando, Florida. Photo Jan Vymazal.

2.1.3. CW with Submerged Macrophytes

Submerged macrophytes root in the sediment and the entire plant is submerged in a water column. Submerged plants take up nutrients from the sediments; however, it has been discovered that at least some plants are able to absorb the nutrients directly from the water column [19,20]. The use of submerged macrophytes is restricted to well-oxygenated waters with low concentrations of suspended solids. High concentrations of suspended solids can limit the penetration of PHAR (photosynthetically active radiation) necessary for full photosynthesis. Therefore, it has been recommended to use submerged macrophytes for constructed wetlands designed for tertiary treatment [7]. There is wide variety of species that can be used for constructed wetlands and have been used in laboratory or small-scale systems; however, in full-scale constructed wetlands, *Myriophyllum spicatum* (watermilfoil, Figure 4) has mostly been used [13,21]. In some systems, naturally occurring species were used, such as in the case of the Florida Everglades Stormwater Area constructed wetlands, in which *Najas guadalupensis* (southern naiad) and *Ceratophyllum demersum* (coontail) are present. Submerged plants are naturally covered by periphyton (algal-based assemblage). Periphyton has a beneficial effect on pollutant removal through the release of oxygen necessary for the oxidation of pollutants as well as the uptake of nutrients. On the other hand, the excessive growth of periphyton can seriously limit the photosynthesis of submerged macrophytes by blocking the PHAR [22].

Figure 4. Surface flow CW with submerged macrophytes (mostly *Myriophyllum spicatum*, water milfoil) in Montréal, Canada. Photo Jan Vymazal.

2.1.4. CWs with Emergent Macrophytes

A typical surface flow CW with emergent macrophytes (Figure 5) consists of a shallow basin or sequence of basins, containing 20–30 cm of rooting soil, with a water depth of 10–60 cm and a dense stand of macrophytes. The most common plants used in this type of CW are *Phragmites australis* (common reed), *Typha* spp. (cattails) and *Scirpus/Schoenoplectus* spp. (bulrushes) [23]. The shallow water depth, low flow velocity and presence of the plant stalks and litter regulate the water flow and, especially in long, narrow channels, ensure plug-flow conditions [24].

Figure 5. Surface flow CW with emergent plants (*Eleocharis sphacelata*, tall spikerush). Otorohanga, New Zealand. Photo Jan Vymazal.

Typically, surface flow constructed wetlands have aerated zones, especially near the water surface, due to atmospheric diffusion and the production of oxygen by the photosynthetic activity of algae and cyanobacteria. The anoxic and even anaerobic conditions can occur near the bottom and especially within the layer of decaying plant material.

In Europe, this technology started during the late 1960s. One of the first examples of full-scale FWS CWs with emergent vegetation, are those built in 1967 in Lelystad, in the Netherlands [25] and near Keszthely, Hungary [26].

2.1.5. CWs with Floating Mats of Emergent Macrophytes

Some emergent macrophytes are capable of forming floating mats, even though their individual plants are not capable of such an existence. Under field conditions, the floating islands of emergent macrophytes can naturally occur as a consequence of bottom disturbance [27]. Floating mats are a common phenomenon in wetlands throughout the world, both in temperate [28] and (sub)tropical regions [29]. The floating wetlands (called "plavs"), were first described by Pallis in 1915 from the Danube delta in Romania [30].

Buoyancy in natural systems is supported by the composition of a wetland plant biomass, which contains a large amount of air space (aerenchyma) that makes the biomass less dense than water [31]. Buoyancy can also be promoted by the provision of suspended cables over the water surface, from where the roots of plants that tend to form floating mats can cover the whole surface [32]. Other materials used in constructed floating wetlands (Figure 6) are, for example, Styrofoam, coconut-peat strings or bamboo [33,34].

Figure 6. Floating constructed wetland planted with *Cyperus alternifolius*. Ningbo, China. Photo Jan Vymazal.

2.1.6. CWs with Trees

Constructed wetlands with trees are seldom used for wastewater treatment; however, there are some fine examples of such treatment wetlands. The tree species that were used in constructed wetlands are *Taxodium distichum* (bald cypress) (Figure 1), *Melaleuca quinquenervia* (paper bark tea tree) or mangroves, which can be used to treat saline (waste)waters (Figure 7) or [35,36].

Figure 7. Dapeng Bay, Taiwan: surface flow constructed wetland with mangroves (*Kandelia candel*) for the treatment of mariculture wastewater. Photo Jan Vymazal.

2.2. Subsurface Flow Constructed Wetlands

Constructed wetlands with a subsurface flow can be classified according to the direction of the flow into horizontal (HF CWs) and vertical (VF CWs). The HF CWs are continuously fed, while VF CWs are fed intermittently. The feeding mode creates different redox conditions in the filtration media being anoxic/anaerobic in HF CWs and aerobic in VF CWs. A special category of subsurface CWs is “zero-discharge” CW.

2.2.1. Horizontal Flow Constructed Wetlands

In HF CWs, mechanically pretreated wastewater slowly flows under the surface of the filtration bed filled with porous material planted with emergent macrophytes (Figures 8 and 9). During this passage through the filtration material, the wastewater comes into contact with a network of aerobic, anoxic and anaerobic zones. The aerobic zones are restricted to narrow zones adjacent to the roots and rhizomes that leak oxygen into the substrate [8,37]. The filtration bed is sealed from the surrounding area by an impermeable layer; in most cases, a plastic liner to prevent leakage to the groundwater. The water level in the filtration bed is maintained in the outflow sump using swiveling elbows (Figure 10) or flexible hoses, or plastic pipes that can be held in position by a chain (Figure 10).

Figure 8. Distribution zone filled with large stones and the filtration bed filled with crushed rocks (4–8 mm) before planting. HF CW Čejkovice, Czech Republic. Photo Jan Vymazal.

Figure 9. Constructed wetland with a horizontal subsurface flow. Roseč, Czech Republic. Photo Jan Vymazal.

Figure 10. Water level maintenance. Left: outflow pipes hanging on a chain at CW Waikeria, New Zealand. Right: swiveling elbow at CW Bouvron, France. Photo Jan Vymazal.

The early experimental HF CWs in Germany, during the 1960s and early 1970s, were filled with coarse sand [38], which was replaced in the late 1970s and early 1980s with soil [39]. However, the soil substrate did not achieve and maintain the necessary hydraulic conductivity and quickly became clogged [40]. The unsuitability of the soil as a filtration material was confirmed in Denmark in the mid-1980s and, following the research conducted in the United Kingdom, proved that gravel was the most suitable filtration medium [41,42]. At present, most constructed wetlands either use washed gravel or crushed rock with a fraction size between 5 and 20 mm, depending on the country.

The macrophytes growing in constructed wetlands help to create suitable conditions for pollution removal. Their role is rather indirect, such as the (1) insulation of the surface during periods of cold weather; the (2) provision of substrates for attached bacteria and the (3) release of the root exudates that can possess antimicrobial properties. The direct role is the sequestration of nutrients from the wastewater in the (aboveground) biomass that can be removed via harvesting [43]. Worldwide, the most frequently used macrophyte is *Phragmites australis* (Common reed), but many other species, such as Typha spp. (cattails), *Phalaris arundinacea* (Reed canarygrass, Figure 8), *Scirpus* (*Schoenoplectus*) spp. (Bulrush) and *Iris pseudacorus* (Yellow flag), are used in HF CWs [9].

HF CWs provide a high and steady removal of organics and suspended solids. Organics are degraded by both anaerobic and aerobic microorganisms, but aerobic degradation is mostly restricted to narrow zones adjacent to the roots and rhizomes, in which oxygen can be released [44,45]. Due to the predominant anoxic/anaerobic conditions in the filtration bed, HF CWs provide suitable conditions for denitrification. On the other hand, due to a lack of oxygen, nitrification is very limited and so is volatilization as there is no free water surface. Nitrogen removal through plant uptake and subsequent harvesting is limited and can reach the same values as in natural wetlands, i.e., about 30–60 g N/m^2 on an annual basis for large macrophytes, such as *P. australis* or *T. latifolia*. [46]. Phosphorus removal is usually low, provided that the common filtration materials, such as gravel or crushed rock, are used [47]. However, the removal of phosphorus can be enhanced by the use of materials with a high sorption capacity, such as steel slags, shell sand or expanded clay materials [48,49]. In such situations, it necessary to keep in mind that the sorption capacity will be exhausted, and the filter material will have to be replaced in order to keep the high removal. The removal of phosphorus by plant harvesting is limited and usually amounts to 2–5 g P m^{-2} on an annual basis [46].

Horizontal flow constructed wetlands capital costs are higher than those for the surface flow CWs, due to the costs of bed sealing and costs of filtration material, including transportation. The operation and maintenance costs are very low and are derived from the maintenance of pretreatment units. The area required for the filtration beds of HF CWs usually ranges between 5 and 6 m^2 per population equivalent [50–52].

2.2.2. Vertical Flow Constructed Wetlands

Vertical flow constructed wetlands generally consist of a bed of porous material, through which the water moves in a vertical direction. In general, this group of CWs incorporates various hydrologic characteristics. There are three arrangements of vertical subsurface flow constructed wetlands: down flow, up flow and fill and drain [11].

The most common type of vertical flow CWs is the free-drainage down flow unit, in which the outlet is open at the base of the filter bed. The wastewater is intermittently delivered to the surface of the filtration bed in batches. Each new batch is brought, only after the water from the previous batch has percolated through the filter. This allows for air diffusion in the empty bed and, thus, the filtration bed is predominantly aerobic. Wastewater is spread across the filter surface by a network of pipes (Figure 11) with multiple diffusers, to evenly distribute the wastewater to avoid short circuiting. Influent distribution pipes can be positioned on or above the surface of the filtration bed or, mostly in cold climates, can be buried within the coarse material or under the layer of insulating mulch [11]. This concept, developed as early as the mid-1960s by dr. Seidel in Germany, was used to oxidize the anaerobic outflow from a septic tank [53].

Figure 11. Wastewater distribution pipes at Changshu Advanced Materials Industrial Park VF CW, Suzhou, Jiangsu Province, PR China. Photo Jan Vymazal.

The most common filtration material in down flow CWs is sand. Coarse gravel or stones are used in the drainage layer, where perforated drainage pipes are laid. The most frequently used macrophyte in this type of constructed wetland, especially in Europe, is *P. australis* (Figure 12). In Asia, various species, such *Arundo donax* (giant cane), *Miscanthus saccharoflorus* (Amur silvergrass), *Cyperus alternifolius* (umbrella papyrus), *Thalia dealbata* (powdery alligator-flag), *Vetiveria zizanoides* (vetiver grass) or *Canna indica* (Indian shot) are used.

Figure 12. Down flow vertical constructed wetlands planted with *Phragmites australis*. Oberwindhag, Austria. Photo: Jan Vymazal.

Treatment efficiency is high for organics, suspended solids and ammonia, due to the aerobic conditions in the filter bed, and thus results in effective nitrification. As a result of the predominantly aerobic conditions, the down flow vertical CWs do not achieve denitrification. The removal of phosphorus is limited but, similar to the horizontal flow CWS, the removal can be enhanced by filtration material with a high sorption capacity [13].

The surface area required for free drain down flow CWs is smaller than for HF CWs, and it is usually set at 4 m^2 per population equivalent [52,54]. In France, down flow VFs are used to treat raw sewage in a two-step VF system, sometimes called the "French system". In the first stage, sludge treatment, the partial removal of organics and nitrification occur. In the second stage, the further removal of organics and nitrification occur. The system is designed with an area of 1.2 m^2 per PE for the first stage, and 0.8 m^2 per PE for the second stage [55].

The second standard type of system with a vertical subsurface flow is the up flow. In this system, the wastewater is distributed to the bottom of the filter and moves upwards to the filtration bed surface. The outflow can be below or above the bed surface. The up flow vertical constructed wetlands were introduced in the 1980s in Brazil as "filtering soil" (Figure 13). This system is used much less frequently, compared to down flow systems and, in general, provides the same treatment conditions as horizontal flow CWs, due to the saturation of the filtration bed.

Figure 13. Vertical up flow constructed wetlands planted with rice (*Oryza sativa*) called "filtering soil", in Piracicaba, Brazil. Photo Jan Vymazal.

The third type of vertical CW is the system called "fill and drain". The flow typically alternates between an upward and downward flow. The media in these systems has an intermittent saturation level, as it alternates between being saturated and unsaturated as a result of the filling and draining sequences [11]. Due to the alternating aerobic and anaerobic conditions, this system has the potential to remove both ammonia and nitrate [56]. The fill and drain system is also called the "reciprocating" or "tidal flow".

2.3. Zero-Discharge Constructed Wetlands

The zero-discharge constructed wetland (Figure 14) was developed in Denmark in the late 1990s. The function of the system is based on the fact that, during the growing season, the willow evapotranspiration exceeds the wastewater inflow and precipitation [57]. During the winter period without the evapotranspiration, the filtration bed is filled with wastewater and precipitation; however, during the period of evapotranspiration, the water level in the bed decreases. For a single household in Denmark (Figure 13), the area needed typically varies between 150 and 300 m^2. One third of the willow stems is harvested every year to keep the willows in a young and healthy state with high transpiration rates [58].

Figure 14. Zero discharge constructed wetlands planted with *Salix viminalis* (basket willow). Borup, Denmark. Photo Jan Vymazal.

2.4. Hybrid Constructed Wetlands

Various types of constructed wetlands can be combined to complement each other, in order to enhance treatment efficiency, especially for nitrogen. Hybrid constructed wetlands were first introduced in the 1960s in Germany [53]. The original design consisted of several parallel down flow VF CWs (called "filtration beds"), followed by two stages of HF CWs (called "eliminations beds"). In the first VF beds, nitrification was achieved while in the HF stage denitrification took place. Since then, various types of constructed wetlands have been combined [59].

3. Historical Development of Constructed Wetlands as Treatment Technology for Wastewaters

3.1. The Early Stages of Constructed Wetland Treatment Technology Development

Wallace and Knight [60] mentioned that the first documented engineered treatment wetland system was patented as early as 1901 [61]. The treatment system was a typical vertical flow CW; however, the spread of this technology is not documented. It has taken until the early 1950s for the constructed wetland treatment technology to be revived in Germany, by K. Seidel [62–64]. During the early 1960s, Seidel carried out experiments using macrophytes to improve inefficient rural treatment systems (septic tanks and Imhoff tanks). She used highly permeable substrates in modulated basins planted with various macrophytes. The first stage was vertical and aerobic to improve the oxygenation of the septic effluent; the second stage was horizontal [53]. Further cooperation with R. Kickuth in the mid-1960s, resulted in a HF CW commonly known as the "Root Zone Method". The filtration bed was filled with a heavy soil containing clay, and planted with *P. australis* [65]. However, the first full-scale HF CW was put in operation in 1974 in Liebenburg-Othfresen, to treat municipal wastewater.

Despite the fact that most research studies on constructed treatment wetlands, in the 1960s, were aimed at subsurface systems, the full-scale surface (free water surface) constructed wetlands were built in Lelystad, Netherlands [66,67] and in Keszthely, Hungary [68]. On the other hand, in North America, efforts were made in the 1960s to explore the potential of surface flow CWs, both natural and constructed. During the late 1960s, Odum [69] evaluated the use of coastal lagoons for recycling municipal wastewater in North Carolina. During the 1960s, the first experiments with floating plants, especially with *Eichhornia crassipes* (water hyacinth), were carried out. The experiments were restricted to small mesocosms and were performed in locations in which this plant occurs naturally, such as southeast Asia and southern parts of the United States [70,71].

During the 1970s, the research on constructed wetlands for wastewater treatment in Europe was mostly restricted to the Root Zone Method, and mostly only in Germany. In the United States, the research was focused on surface flow constructed wetlands, but subsurface flow technology was also explored. The surface flow large-scale installations included, for example, constructed wetlands for refinery wastewaters in North Dakota [72] or municipal wastewaters in the cold climate in Michigan [73]. During the 1970s, very intensive research was also carried out with the focus on water hyacinth-based constructed wetlands, especially in the Southern States of the United States [74–77]. The first experimental HF mesocosms were built in 1972, and the pilot scale HF CW was built in 1974, in Seymour, Wisconsin [78]. The system could be operated with the water level above as well as below the surface, although the subsurface flow was the preferred option. On the West Coast, the California sub-licensee for the Max Planck Institute (MPI) system, developed by Seidel in Germany, built a hybrid VF-HF CW in Laguna Niguel [79]. Moreover, two large national conferences were organized in the United States with the focus on the use of wetlands for wastewater treatment [80,81].

In Australia, the potential use of aquatic and wetland macrophytes for wastewater treatment was evaluated by Mitchell, during the mid-1970s [82].

3.2. The Rapid Growth of Constructed Wetlands Technology across the World

The 1980s and 1990s can be regarded as the periods that witnessed the rapid extension of the constructed wetlands for wastewater treatment across the world. While until the beginning of the 1980s the technology spread slowly and mostly on a personal exchange of the experience during the late 1980s and during the 1990s, many international conferences with a special focus on this technology were organized in Europe, Asia, Australia and both North and South America. These conferences were mostly organized under the umbrella of the International Water Association (in the 1990s, under the names International Association on Water Pollution Research and Control and International Association on Water Quality).

During the mid-1980s, the international cooperation and exchange on constructed wetland technology in Europe accelerated extensively. In October 1986, the cooperation among ten European countries resulted in the decision to form a European coordinating group, with the two major objectives being the production of design and operation guidelines and to organize a conference in 1990 to bring together experts from around the world [83]. Meanwhile, in the Unites States, two major international conferences on the use of plants and constructed wetlands for wastewater treatment were organized in Orlando, Florida (1986) [84] and in Tallahassee, Tennessee (1988) [85]. These conferences, together with the conference organized in Cambridge in 1990 by the European coordinating group [86], represented a major breakthrough in constructed wetland technology extension around the world.

In Europe during the 1980s, horizontal subsurface flows were the major focus, especially in Germany [87], Denmark [88], Austria [89] and the United Kingdom [90]. In 1983, the soil-based Kickuth-type HF CWs were introduced to Denmark and, shortly after that, about 80 full-scale constructed wetlands were built, mostly for municipal sewage. The evaluation of the performance of these systems revealed that the area originally proposed by Kickuth (m^2/PE) was not enough to provide sufficient treatment, and an area of about 5 m^2/PE was suggested [88]. Moreover, in 1983, a large pilot scale HF CW was built in Mannersdorf near Vienna, Austria. The system was monitored for seven years and the results were summarized by Haberl and Perfler [91]. After a visit to Germany from engineers from U.K. water companies, two full-scale HF constructed wetlands were built (Acle and St. Pauls Walden) in 1985 in UK, and, in the following year, another 21 full-scale systems, such as Freethorpe (Figure 15), were built [90].

Figure 15. Horizontal subsurface flow CW, Freethorpe, United Kingdom, for 900 PE. The early CWs were built as a single bed. Photo Jan Vymazal.

The systems were very intensively monitored, and the major outcome of this research was the recommendation to replace soil with gravel, 5–10 mm in size [92,93]. At the end of the 1980s, the hybrid constructed wetlands of Seidel's configuration (VF-HF) were installed in France [94] and the United Kingdom [95]. At the end of the 1980s, the national guidelines on the design and operation of constructed wetlands for wastewater treatment were issued by ATV in Germany [96], and, shortly after that, the European guidelines were published [97].

In North America, surface flow constructed wetlands were built quite regularly, during the 1980s. Many of these systems served as tertiary treatment units for municipal sewage, and the surface area was usually quite large. Examples of such systems are Incline Village, Nevada (173.28 ha), Ironbridge, Florida (494 ha, Figure 16) or Arcata, California (15.18 ha) [12,98]. In addition to the use of surface flow CWs for municipal sewage, other types of wastewaters were treated in the constructed wetlands, such as urban runoff [99], acid mine drainage [100,101] or livestock feedlot wastewaters [102]. The costly operation and maintenance of water hyacinth-based constructed wetlands, mainly connected with constant harvesting and the disposal of the biomass, caused the gradual cessation of the use of these systems [103].

Figure 16. Surface flow CW at Ironbridge. Tertiary treatment for the city of Orlando, Florida.

The CW consists of 17 cells with a total area of 4.92 km^2. The figure features two of those cells (see also Figure 3).

In North America, subsurface technology was developed slowly, compared to its development in Europe. However, several full-scale installations were put in operation for municipal sewage in California, Louisiana, Alabama, Tennessee and Kentucky [12,104–106], or the paper mill effluent [107]. In the United States, the experience with the design and operation of constructed wetlands was summarized in the manual issued by the U.S. Environmental Protection Agency [108].

The subsurface technology was also developed in Australia during the 1980s, and pilot HF CWs were built to treat piggery waste and abattoir wastewater [109,110]. Pilot scale HF CW experiments with various macrophytes were carried out at the University of Western Sydney at Hawkesbury (Figure 17), where numerous studies were conducted [111]. In Africa, the constructed wetlands have been used since the mid-1980s, especially in South Africa. The constructed wetlands were designed to treat various types of wastewater, including raw and secondary sewage, stormwater runoff and a variety of industrial and mine drainage waters. In these systems, surface flow as well as subsurface flow systems were used [112]. In South America, the constructed wetlands were applied only in Brazil [113]. Research focused on water hyacinth-based systems in combination with up flow vertical CWs, called "filtering soil" (Figure 13). There are no records of full-scale constructed wetlands in Asia during the 1980s.

Figure 17. Experimental HF CW at the University of Western Australia, Hawkesbury. Photo Jan Vymazal.

During the last decade of the 20th century, the constructed wetland technology extended to all continents and all types of constructed wetlands were used. During the 1990s, the technology started in several Asian countries, namely China, India and Nepal. In China, the first full-scale constructed wetland was put in operation in July 1990 at the Longgang Shenzen Special Economic Zone [114]. The constructed wetlands consisted of three stages of HF units with a total surface area of 4589 m^2, and a surface flow cell with a surface area of 1710 m^2. Other hybrid CWs were used to treat pig raising farm wastewater or industrial wastewater [115]. In India, mostly HF constructed wetlands planted with *Phragmites karka* were built to treat municipal sewage [116]. In Nepal, in the 1990s, constructed wetlands drew a lot of attention because of the low costs for the operation and maintenance of them; however, most systems suffered from a lack of maintenance. The hybrid system in Dhulikel was probably the first constructed wetland built to treat hospital wastewater [117].

The rapid growth of constructed wetland installations, as well as the increased knowledge on processes occurring in constructed wetlands during the treatment of various types of wastewater, resulted in the release of national guidelines in many countries, such as in Austria, [118], Denmark [119], New Zealand [120] and Canada [121], during the late 1990s.

3.3. Constructed Wetlands for Wastewater Treatment in the 21st Century

Constructed wetlands became a "certified" method for wastewater treatment, in many countries across the world in the 21st century. In some countries, such as China, the number of constructed wetlands exceeds one hundred thousand and it is still growing (Figure 18). There is also a growing number of constructed wetlands in South America, especially in Colombia, Argentina and Chile. Unfortunately, the technology has not spread significantly in Africa, where there is great potential for this technology.

Figure 18. Constructed wetlands with horizontal subsurface flow, planted with *Thalia dealbata* (**left**) and *Canna indica* and *Thalia dealbata* (**right**) in Quangdong Province near Guangzhou. Photo Jan Vymazal.

At the beginning of the 21st century, research on the wastewater treatment in constructed wetlands focused on the various design and operation aspects that can lead to the enhanced removal of pollutants [122,123]:

- operation strategies (such as aeration, microbial fuel cells and bioaugmentation);
- supply of electron donors to enhance the removal of selected inorganic anions;
- selection of filter materials for higher sorption capacity and microbial biofilm establishment;
- determination of functions of various bacteria groups on pollution removal;
- selection of macrophytes for enhanced removal of pollutants;
- effect of constructed wetlands on greenhouse gas emissions;
- efficacy of constructed wetlands to remove pharmaceuticals and personal care products.

Constructed wetlands for wastewater treatment are also gaining more attention in relation to sustainable water management in urban settlements, as part of the circular economy and "sponge" cities. Masi et al. [124] pointed out that constructed wetlands can be effectively used in cities to treat sewage, greywater, stormwater overflows and runoff, and can effectively recycle the water within cities. Constructed wetlands can also be a core part of SUDS (Sustainable Urban Drainage Systems). Moreover, Stefanakis [125] stressed that constructed wetlands for wastewater treatment have a great potential to be successfully integrated in urban and peri-urban areas, and fit well within the new concept of sponge cities and the circular economy. The importance of constructed treatment wetlands within urban circularity through the restoration and maintenance of water cycles, water and wastewater treatment, recovery and reuse as well as nutrient recovery and reuse was reported by Atanasova et al. [126].

Unfortunately, most of the research is carried out in small laboratory or greenhouse experiments, with no attempts to include the results of this experiments in a design of full-scale installations. Vymazal [127] pointed out that while, in 1995, 88% of the papers recorded on the Web of Science database were based on full-scale CWs, in 2017 it was only 26%. It seems that the transfer of the laboratory experiment results to the full-scale constructed wetlands will be the major challenge in coming years.

4. The Use of Constructed Wetlands for Various Types of Wastewater

The early use of constructed wetlands was restricted to sewage treatment. The various types of constructed wetlands and their combination enabled the use of CWs for a variety of wastewaters (Tables 1 and 2).

Table 1. The use of constructed wetlands for various types of wastewater.

Type of (Waste) Water	Examples of Use
Sewage	Domestic, municipal, combined sewer overflow
Drainage	Acid/alkaline coal mines, metal ores mines, agricultural tile drainage
Feedlots	Livestock, poultry, pigs, milking parlors
Aquacultures	Freshwater fish, marine fish, shrimp
Food processing	Dairy, cheese, winery, brewery, distillery, sugar, olive mills, fish, soft drinks, abattoir, meat processing
Other industries	Tannery, textile, electroplating, pulp and paper, glass, explosives, refineries, oil drilling water, rubber industry
Runoff waters	Urban, highway, airport, greenhouses, nurseries, golf courses, agricultural fields
Landfill leachate	

Table 2. Examples of the first use of macrophytes and/or constructed wetlands for the treatment of different types of pollution. Experimental (laboratory, mesocosms) and Operational (pilot scale, full scale). Modified and updated from Vymazal and Kröpfelová [13].

	Experimental	
Year	**Wastewater**	**References**
1952	Phenol wastewater	[128]
1956	Sewage and dairy wastewater	[129]
1956	Livestock wastewater	[64]
1965	Sludge dewatering	[130]
1973	Textile wastewater	[131]
1975	Photographic laboratory wastewater	[132]
1978	Acid mine drainage	[133]
1980	Electroplating wastewater	[134]
1980	Removal of cresol	[135]
1980	Piggery effluent	[110]
1980	Abattoir wastewater	[109]
1981	Heavy metals removal	[136]
1981	Tannery wastewater	[137]
1982	Agricultural drainage effluent	[138]

1982	Pesticides	[139]
1982	Sugar refinery wastewater	[140]
1982	Benzene and its derivatives	[141]
1982	Rubber industry effluent	[142]
1983	Pulp/paper mill wastewater	[143,144]
1985	Seafood processing wastewater	[145]
1986	Potato starch industry wastewater	[146]
1986	Cyanides and chlorophenols	[147]
1987	Meat processing wastewater	[148]
1988	Landfill leachate	[149,150]
1989	Chicken farm wastewater	[151]
1991	Fish aquaculture	[152]
1991	Phenanthrene	[153]
1994	Hydrocarbons	[154]
1995	Lignite pyrolysis wastewater	[155]
1997	Winery wastewater	[156]
1998	Coke plant wastewater	[157]
2000	Linear alkylbenzensulfonates (LAS)	[158]
2001	Steel processing industry wastewaters	[159]
2001	Brewery wastewater	[160]
2001	Electric utility wastewater	[161]
2003	Azo dyes removal	[162]
2004	Chlorobenzene removal	[163]
2004	Steel mill effluent	[164]
2006	Sugarcane molasse stillage from ethanol production	[165]
2008	Brine treatment	[166]
2008	Coffee fruit processing wastewater	[167]
2010	Saline aquaculture wastewater	[168]
2010	Brackish shrimp growout system	[169]
2105	Bauxite residue drains	[170]
2017	Rice noodles wastewater	[171]
2018	Glass industry wastewater	[172]
2019	Batik wastewater	[173]
2020	Jewelry industry wastewater	[174]
	Operational	
Year	**Wastewater**	**References**
1967	Sewage	[66]
1974	Sludge dewatering	[175]
1975	Oil refinery wastewater	[176]
1978	Textile wastewater	[177]
1979	Fish rearing pond discharge	[178]
1982	Acid mine drainage	[179,180]
1983	Urban stormwater runoff	[99]
1983	Rubber industry effluent	[142]
1985	Dairy wastewater	[41]
1986	Seepage from piled pig muck	[181]
1986	Ash pond seepage	[182]
1987	Thermally affected wastewater	[183]

1988	Livestock wastewater	[102]
1988	Pulp/paper mill wastewater	[107]
1988	Pesticides	[184]
1989	Landfill leachate	[185]
1989	Airport runoff	[186]
1989	Reduction of lake eutrophication	[187]
1990	Lake water	[188]
1991	Woodwaste leachate	[189]
1992	Bakery wastewater	[190]
1992	Channel catfish pond effluent	[191]
1992	Sugar beet processing wastewater	[192]
1992	Combined sewer overflow	[193]
1993	Pesticides in agricultural runoff	[194]
1993	Highway runoff	[195]
1994	Abattoir wastewater	[196]
1994	Airport runoff	[197]
1994	Poultry wastewater	[198]
1995	Greenhouse wastewater	[199]
1995	Nitroaromatic organic compounds	[200]
1995	Potato processing wastewater	[201]
1996	Explosives	[202,203]
1997	Hydrocarbons	[204]
1997	Hospital wastewaters	[117]
1998	Trout farm effluent	[205]
1998	Golf course runoff	[206]
1998	Nylon and ethylene polymers	[207]
1999	Molasses-based distillery effluent	[208]
1999	Winery wastewater	[156]
1999	Distillery wastewater	[208]
2000	Surfactant removal	[209]
2000	Subsurface drainage from grazed dairy pastures	[210]
2001	Tannery wastewater	[211]
2002	Tool factory wastewater	[212]
2002	Pharmaceuticals removal	[213]
2003	Olive mill wastewater	[214]
2004	Sugar factory effluent	[215]
2007	Mountain cheese factory	[216]
2009	Flower farm effluent	[217]
2010	Brewery wastewater	[218]
2010	Brackish shrimp aquaculture wastewater	[168]

Constructed wetlands have been used to treat various types of wastewater, since the 1950s. In the beginning, this treatment technology spread slowly, based only on personal contacts. The worldwide distribution of constructed treatment wetlands occurred in the 1990s, primarily due to several large international conferences. Since the beginning of the 21st century, constructed wetlands for wastewater treatment have become a worldwide phenomenon and an accepted technology in many countries around the world. However, in some countries, the treatment performance of constructed wetlands is still underestimated by water authorities and, therefore, the number of installed constructed wetlands is slow.

Until recently, constructed treatment wetlands have mostly been built and considered with the sole purpose of wastewater treatment. However, in addition to the high treatment efficiency, the constructed treatment wetlands have recently been shown to have a great potential in the new sustainable and circular economy in the urban environment. Constructed treatment wetlands can effectively treat, accumulate and recycle water and nutrients for further use, as suggested in the "sponge city" concept.

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