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Constructed Wetlands for Wastewater Treatment: Five Decades of Experience†

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The first experiments on the use of wetland plants to treat wastewaters were carried out in the early 1950s by Dr. Käthe Seidel in Germany and the first full-scale systems were put into operation during the late 1960s. Since then, the subsurface systems have been commonly used in Europe while free water surface systems have been more popular in North America and Australia. During the 1970s and 1980s, the information on constructed wetland technology spread slowly. But since the 1990s the technology has become international, facilitated by exchange among scientists and researchers around the world. Because of the need for more effective removal of ammonia and total nitrogen, during the 1990s and 2000s vertical and horizontal flow constructed wetlands were combined to complement each other to achieve higher treatment efficiency. Today, constructed wetlands are recognized as a reliable wastewater treatment technology and they represent a suitable solution for the treatment of many types of wastewater.

1. Introduction

Wetlands occur in a wide range of landscapes and may support permanent shallow (generally <2 m) or temporary standing water. They have soils, substrates, and biota adapted to flooding and/or waterlogging and associated conditions of restricted aeration (*1*). Wetlands are found on every continent except Antarctica. Matthews and Fung (*2*) estimated the area of wetlands at 6.8 million km^2 including 1.5 million km^2 of rice paddies. In 1989, Aselmann and Crutzen (*3*) estimated a similar wetland area of 6.9 milion km^2 including 1.3 million km^2 of rice paddies. Recently, Lehner and Döll (*4*) using the GIS-based system, estimated the world's wetlands area between 8.3 and 10.1 million km^2. However, wetlands are far more important in the biosphere than their 5−8% of the landscape suggests (*5*). Wetlands are extremely diverse not only for their physical characteristics and geographical distribution but also within particular landscape units such as floodplains, mires, or marshes (*6*). Wetlands provide many important ecological services to human society. Ecosystem services represent the benefits that living organisms obtain directly or indirectly from the ecosystem (*7*−*9*).

Natural wetlands have been used for wastewater treatment for centuries as convenient wastewater discharge sites for as long as sewage has been collected, i.e., at least 100 years in some locations. 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 waterway (*10*). Uncontrolled discharge of wastewater, though, led in many cases to an irreversible degradation of many wetland areas.

Cooper and Boon (*11*) pointed out that the use of natural wetlands for treatment of wastewater has been practiced in the United Kingdom for more than a century. Examples of old wetland sites used to treat wastewater in North America include the Great Meadows natural wetland near the Concord River in Lexington, Massachussetts beginning in 1912, the Cootes Paradise natural wetland near Hamilton, Ontario (1919), the Brillion Marsh in Wisconsin (1923), and a natural cypress swamp near the city of Waldo, Florida (1939) (*12, 13*).

The growing knowledge about wetland functions and values have caused a radical change of attitude toward wetlands since the 1950s and the use of natural wetlands for wastewater disposal decreased in some parts of the world. Unfortunately, in some parts of the world the deterioration of wetlands with wastewater still occurs. Natural wetlands are still used for wastewater treatment under controlled conditions (*14, 15*) but the use of constructed wetlands is now preferred (*13, 16*).

The objective of this Review is to describe the development of constructed wetland technology for treatment of various types of wastewater. The paper is not aimed at detailed description of design of various types of constructed wetlands but rather on the development of public and official recognition among other types of wastewater treatment technologies.

2. Types of Constructed Wetlands Used for Wastewater Treatment

Constructed wetland treatment systems are engineered systems that have been designed and constructed to utilize the natural processes but do so within a more controlled environment. Constructed wetlands may be categorized according to the various design parameters, but the three most important criteria are hydrology (open water-surface flow and subsurface flow), type of macrophytic growth (emergent, submerged, free-floating) and flow path (horizontal and vertical). Different types of constructed wetlands may be combined with each other (i.e., hybrid or combined systems) to utilize the specific advantages of the different systems (*17, 18*).

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Constructed Wetlands with Surface Flow. Constructed wetlands with surface flow, known as *free water surface constructed wetlands* (FWS CWs), contain areas of open water and floating, submerged, and emergent plants (*13*). The shallow water depth, low flow velocity, and presence of the plant stalks and litter regulate water flow and, especially in long, narrow channels, ensure plug-flow conditions (*19*). As the water flows through the wetland, it is treated by physical (sedimentation, filtration, UV exposure), chemical (precipitation, adsorption, volatilization), and biological (microbial degradation, microbial nutrient transformations, uptake from water column and root zone, microbial competition, and bacterial die-off) processes (*20*).

The FWS CWs are very effective in removal of organics through microbial degradation and removal of suspended solids through filtration and sedimentation (*21*). Removal of nitrogen is variable and the magnitude of reduction depends on many factors including inflow concentration, chemical form of nitrogen, water temperature, season, organic carbon availability, and dissolved oxygen concentration (*13*). Ammonia is most effectively removed through nitrification in aerobic zones of the water column followed by denitrification of nitrate in anaerobic zones in the litter layer at the bottom (*22*). FWS CWs provide sustainable removal of phosphorus but at relatively slow rates. Phosphorus removal occurs from adsorption and precipitation but in the FWS system it is limited by little contact between water column and the soil (*23*).

Design methods are based on either volume or area. Volume-based methods use hydraulic retention time to optimize pollutant removal (*19*) whereas area-based methods assess pollutant reduction using the overall wetland area (*13, 24*). The design methods are based on a first-order model but many modifications can be made. Kadlec and Wallace (*13*) pointed out that with the present knowledge it would be disingenuous to provide overly simplistic design-calculation but on the other hand, it would be a mistake to think that adding more potentially significant factors results in more accurate or precise design.

The most common application for FWS wetlands is for tertiary treatment of municipal wastewater and also for stormwater runoff and mine drainage waters (*12, 13, 16*). They provide greater storm/surge capacity and thus, less chance for hydraulic failure (*25*). FWS wetlands are suitable in all climates, including the far north. However, ice formation can reduce the rates of some removal processes, especially nitrogen conversion and removal (*13*).

Constructed Wetlands with Subsurface Flow. In horizontal subsurface flow constructed wetlands (HF CWs), the wastewater is fed in at the inlet and flows slowly through the porous medium under the surface of the bed planted with emergent vegetation to the outlet where it is collected before leaving via a water level control structure. During passage the wastewater comes into contact with a network of aerobic, anoxic, and anaerobic zones. Most of the bed is anoxic/anaerobic due to permanent saturation of the beds. The aerobic zones occur around roots and rhizomes that leak oxygen into the substrate (*26*). HF CWs are commonly sealed with a linear to prevent seepage and to ensure the controllable outflow (*16*). Macrophytes planted in HF CWs have several properties that make them an essential component of the design (*27*). The most important properties are filtration bed insulation during the winter, substrate for growth of attached bacteria, oxygen release to the rhizosphere, nutrient uptake and storage, and root exudates with antimicrobial properties (*16, 27*). In Europe, HF CWs are commonly called “Reed Beds”, in the United Kingdom they are also called “Reed Bed Treatment System” (RBTS) because Common reed (*Phragmites australis*) is frequently planted (*28*).

HF CWs are commonly used for secondary treatment of municipal wastewater but many other applications have been reported in the literature (*16*). HF CWs are very effective in removal of organics, suspended solids, microbial pollution, and heavy metals. Organic compounds are degraded by bacteria under aerobic and anaerobic conditions. It has been shown that the oxygen transport capacity in these systems is insufficient to ensure aerobic decomposition and that anaerobic processes play an important role in HF CWs (*29, 30*). Suspended solids settle into micropockets in the filtration bed or are filtered out (*21*). Removal of ammonia-N is limited by the lack of oxygen and, hence nitrification, in the filtration media. HF CWs, however, provide suitable conditions for denitrification (*16*). Removal of phosphorus is low unless special media with high sorption capacity are used (*31*). It has been shown that selection of the filtration material is also very important for the longevity of the system because media too fine will clog and surface runoff will occur (*32*). HF CWs having the ability to insulate the surface of the bed are capable of operation under colder conditions than FWS systems (*27, 33*).

HF CWs have been designed using many models from simple “rules of thumb” (*34*) to complex dynamic, compartmental models (*35−37*). Between these two extremes, plug-flow first order models (*12*) and Monod-type equations have been used (*38*). However, no matter which design model is used, for municipal sewage, the area of HF CWs is usually about 5 m^2 PE^{-1} (PE = population equivalent = 60 g BOD_5 d^{-1}) (*16*).

Besides their low operation and maintenance costs (HF CWs mostly do not use electric power and the flow is supported only by gravity) the major advantage of HF CWs comes from the fact that they can treat diluted wastewaters from combined sewer systems, i.e., wastewaters which cannot be treated by conventional treatment technologies such as activated sludge. On the other hand, HF CWs are not appropriate systems when only ammonia or phosphorus are the target pollutants (*16*). From a technology point of view, the major problem with HF CWs is clogging and subsequent surface flow. This can be eliminated by efficient removal of suspended solids in pretreatment units and by selection of coarse filtration materials.

In the early 2000s, aeration of HF CWs was introduced in North America to enhance oxygen transport capacity (*39, 40*). Mechanical blowers and diffuser tubing were designed to boost treatment performance, mostly for ammonia. However, Kadlec and Wallace (*13*) pointed out that the decision to aerate HF CWs comes at significant costs through increased operation and maintenance. From the economic viewpoint, aeration is only justified when the lifecycle cost of aeration is sufficiently offset by the reduction in capital costs as the net savings of reduced wetland size less the cost of aeration equipment (*13*). Wallace et al. (*41*) compared aerated and nonaerated HF CWs and concluded that aeration improved removal of BOD_5, TSS, and to a lesser extent total Kjeldahl nitrogen (TKN) while there was no effect on total P and fecal coliform removal.

Vertical flow constructed wetlands (VF CWs) comprise a flat bed of graded gravel topped with sand planted with macrophytes. Contrary to HF CWS, VF CWs are fed intermittently with large batches, thus flooding the surface. Wastewater then percolates down through the bed and is collected by a drainage network at the bottom. The bed drains completely which allows air to refill the bed. Thus, VF CWs provide greater oxygen transfer into the bed, thus producing a nitrified (high NO_3^-) effluent (*14, 28*). On the other hand, VF CWs do not provide suitable conditions for denitrification to complete conversion to gaseous nitrogen forms which escape to the atmosphere. Removal of organics and suspended solids is high (*16*). As compared to HF CWs, vertical flow systems require less land, usually 1−3 m^2 PE^{-1} (*42*).

The early VF systems were composed of several stages with 2−4 beds in the first stage which were fed with wastewater in rotation. Such VF systems are now called first-generation VF systems (*42*). Recently, VF CWs with only one bed have been used. These systems are called second-generation VF constructed wetlands or compact vertical flow beds (*43*). VF CWs are commonly used to treat on-site domestic wastewaters or sewage from small communities, though other uses such as industrial wastewaters or storm-water runoff have been reported (*16*).

In upflow vertical CWs the wastewater is fed to the bottom of the wetland (*44*). The water percolates upward and then it is collected either near the surface or on the surface of the wetland bed. Recently, "fill and drain" or "tidal" CWs have been developed. In tidal flow systems the wastewater is fed to the bottom of the bed into the aeration pipes. It then percolates upward until the surface is flooded. When the surface is completely flooded, the pump is then shut off and the wastewater is held in the bed in contact with the microorganisms growing on the media. A set time later the wastewater is drained downward, air diffuses into the voids in the bed, and after the water has drained from the bed the treatment cycle is complete (*32*).

One of the major problems with efficient performance of VF CWs is clogging of the filtration substrate. Therefore, it is necessary to select the filtration material carefully, distribute the wastewater evenly across the wetland surface, and also select the optimum hydraulic loading rate.

Hybrid Constructed Wetlands. Various types of constructed wetlands may be combined to achieve higher removal efficiency, especially for nitrogen. Many of these systems are derived from original hybrid systems developed by Seidel at the Max Planck Institute in Krefeld, Germany (*45*). The design consists of two stages, several parallel VF beds followed by 2 or 3 HF beds in series. The VF wetland is intended to remove organics and suspended solids and to provide nitrification, while in the HF wetland denitrification and further removal of organics and suspended solids occurs. Another configuration is the HF-VF system (*46*). The large HF bed is placed first to remove organics and suspended solids and to provide denitrification. An intermittently loaded small VF bed is used for additional removal of organics and suspended solids and to nitrify ammonia to nitrate. To maximize removal of total nitrogen, however, the nitrified effluent from the VF bed must be recycled to the sedimentation tank.

The VF-HF and HF-VF constructed wetlands are the most common hybrid systems, but in general, any kind of constructed wetlands could be combined to achieve higher treatment effect (*17*).

3. Early Stage of Constructed Wetlands Development

Wallace and Knight (*25*) indicated that the first documented use of wetland within a deliberately engineered treatment vessel appears to belong to Cleophas Monjeau (*47*). Claims for this U.S. patent issued in 1901 included distributed vertical flow, a fluctuating water level, and aeration of the wastewater. However, experiments using plants in a designed system did not occur until the 1950s.

In 1953, Dr. Käthe Seidel first described vegetation-based designs for improvement of inland waterways which suffered from overfertilization, pollution from sewage, and siltation (*48*). However, at that time, views on wastewater treatment among experts were limited to physical, chemical, and biological (bacterial) methods and the deliberate use of macrophytes for water purification was not considered.

Between 1952 and 1956, Seidel carried out numerous experiments on the use of wetland plants for treatment of various types of wastewater, including phenol wastewaters, dairy wastewaters, and livestock wastewater (*49, 50*). In the early 1960s, Seidel grew macrophytes in wastewater and sludge of different origin. She also worked to improve the performance of rural and decentralized wastewater treatment which was either inefficient septic tanks or pond systems. She improved her system by using sandy soils with high hydraulic conductivity in sealed module-type basins planted with various macrophyte species. To overcome the anaerobic septic tank effluents she integrated a stage of primary sludge filtration in vertically percolated sandy soils planted with *P. australis* (*45*). In the mid-1960s, Seidel began to collaborate with Reinhold Kickuth from Göttingen Univeristy. Kickuth developed HF CWs commonly known as Root Zone Method which were built with a heavy soil media with a specific area of only 2 m^2 PE^{-1} and planted with Common reed (*51*). The first HF CW was not put into operation until 1974 in Liebenburg-Othfresen, Germany where it was used for treatment of municipal sewage (*51*).

Despite intensive research on the subsurface flow constructed wetlands in Europe, the first European constructed wetland was a FWS system built by the IJssel Lake Polder Authority in Flevoland, The Netherlands in 1967 (*52*). The system exhibited good treatment efficiency, and in early 1970s about 20 FWS of this ditch type, called planted sewage farm (or Lelystad process) were in operation in The Netherlands (*53*). Soon after that, in 1968, FWS CW was also created in Hungary near Keszthely to preserve the water quality of Lake Balaton and to treat wastewater of the town (*54*).

The free water surface (FWS) wetland technology started in North America with the ecological engineering of natural wetlands for wastewater treatment. Between 1967 and 1972, Odum (*55*) studied the use of coastal lagoons for recycling and reuse of municipal wastewaters in North Carolina. During the period 1974−1977, the use of natural cypress wetlands for municipal wastewater recycling was studied in Florida (*56*). At about the same time, Robert Kadlec and co-workers at the University of Michigan began the Houghton Lake project, the first in-depth study using engineered wetlands for wastewater treatment in a cold climate region (*15, 57*). In 1973, an engineered wetland was built near Brookhaven, New York (*58*). Industrial stormwaters and process waters were also applied to a constructed wetland/pond system in 1975 at Amoco Oil Company's Mandan Refinery in North Dakota (*59*).

In the early 1970s, subsurface flow wetlands were also introduced to North America. In 1972, the first pilot-scale constructed wetlands with horizontal subsurface flow were built in Seymour, Wisconsin to treat municipal wastewater (*60*). In Australia, the potential use of aquatic and wetland macrophytes for wastewater treatment was evaluated by Mitchell during the mid 1970s (*61*).

Since the late 1960s, the use of water hyacinth for treatment of wastewater has been tested in experimental systems, in countries where this plant grows naturally, India, southeastern Asia, southern Japan, and southern parts of the United States (*62, 63*). Full-scale water hyacinth systems were put in operation in the late 1970s, especially in the southern U.S. (*64*). However, due to high costs for operation and maintenace connected mostly with continuous harvesting and biomass disposal, these systems did not gain widespread acceptance.

Use of constructed wetlands for wastewater treatment spread quite slowly during the 1970s both in Europe and North America. In Europe, the knowledge spread mostly through individual efforts. In North America, constructed wetlands were probably first introduced during the international conference "Biological Control of Water Pollution" held in 1976 in Philadelphia, Pennsylvania (*65*). At the conference, Furia (*66*) in his introduction called his presentation "Biological Alternatives in Perspective: More than Academic Curiosities" that described very much the current thoughts of wastewater treatment by constructed wetlands at that time. He also pointed out that "There are many questions about these systems and many limitations. Although these systems can be used for highly toxic industrial effluents, there are still situations where biological systems alone would fail because the effluent itself is toxic to plants. In such situations, higher plants would have to be part of systems utilizing conventional techniques. Concern has also been expressed that plants might be less effective in colder northern climates. And although biological systems may be ideal for rural areas and underdeveloped countries where land may be readily available, these systems would probably be unsuitable for many highly urbanized areas where land is scarce." Thirty years of the research on the use of constructed wetlands for various types of wastewater have proven that most of above-mentioned worries have been successfully refuted as will be shown later in this paper.

4. Period of 1980 to 1990

During the 1980s, international exchange of information intensified in Europe. In addition international seminars held in various countries, informal arrangements to exchange information, led in October 1986 to the decision to form a European co-ordinating group. This group comprised representatives from 10 countries and was recognized by the Commission of the European Communities (CEC) and the European Water Pollution Control Association (AWPCA) as an expert contact group. When the group was established, two of the objectives were to produce Design and Operations Guidelines and to organize a conference in 1990 to draw together the leading experts in the field. The conference was organized in Cambridge in September 1990 and during the conference the European Guidelines for constructed wetlands were introduced (*67*). In the United States, after a series of national conferences aimed at the use of wetlands for wastewater treatment held in the 1970s (*68, 69*), several international conferences took place in the 1980s (*70*−*72*). The exchange of information around the world helped to spread the constructed wetland technology.

In the 1980s, much attention in Europe was focused on HF CWs, especially in Germany (*73, 74*). Outside Germany, HF constructed wetlands were built in Austria—in Weinitzen near Graz in 1981 (*75*) and in Mannersdorf near Vienna in 1983 (*76*). In 1983, German ideas were introduced in Denmark and by 1987 about 80 HF CWs were built (*26, 77*). The Danish systems were soil-based and followed the Kickuth's Root Zone Method design. Despite problems with low hydraulic conductivity of the soil media and surface flow the systems exhibited high treatment efficiency for most parameters if 3−5 m^2 PE^{-1} was used. To eliminate surface flow, Danish systems were designed with a low aspect (length/width) ratio resulting in very wide beds and short passage length. However, the design with wide inlet zones caused problems with water distribution. In later designs, the inlet zone was subdivided into two or more separate units that could be loaded separately to get more precise distribution of water (*77*).

In 1985, following visits to existing German and Danish systems, the first two HF CWs were built in the United Kingdom and by the end of 1987 more than 20 HF CWs were designed (*11*). The major change in the design was the use of coarse filtration material (gravel 5−10 mm) which ensured subsurface flow similar to the original design by Seidel (*45*). Also, a specific area of 5 m^2 PE^{-1} was used in the United Kingdom. In the early 1980s, several hybrid systems of Seidel's type (VF-HF) were built in France with the systems at Saint Bohaire and Frolois being the best described (*78*). A similar system was built in 1987 in the United Kingdom at Oaklands Park (*79*). The first European national guideline on design and operation of constructed wetlands for wastewater treatment was published in Germany by ATV in 1989 (*80*) followed by European Guidelines (*67*).

In North America, FWS constructed wetlands technology spread quickly and many systems were built for tertiary treatment of municipal sewage. Some of these systems were quite large such as the 500 ha systems in Lakeland and Orlando, Florida (*12*). Besides municipal wastewaters other types of polluted waters were treated using FWS CWs. Treatment of urban stormwater was pioneered in California in the early 1980s (*81*) and mine wastewater treatment wetlands also have been used since the early 1980s (*82, 83*).

North America was slower to adopt subsurface CW technology as compared to Europe but in the early 1980s, Wolverton and his co-workers at NASA, who had been researching floating plant treatment systems (*62*), began to study subsurface constructed wetlands (here called "rock reed filters") (*84*). Gersberg and co-workers investigated horizontal subsurface constructed wetlands in California (*85*) and, in 1986, the Tennessee Valley Authority started to evaluate this type of system (*86*). In the United States, a design manual on constructed wetlands and aquatic plant systems for municipal wastewater treatment was issued by U.S. Environmental Protection Agency in 1988 (*87*).

In the 1980s, water hyacinth systems were still used in the southern United Sates but the use of this system ceased because the operation and maintenance was not economical. Stewart et al. (*88*) pointed out that while the concept of using water hyacinth for wastewater treatment had been extensively investigated and reviewed for nearly 20 years, there still remains little information regarding the operational needs associated with large-scale applications.

In Australia, Finlayson and co-workers performed pilot-scale experiments on the use of subsurface constructed wetlands for the treatment of piggery wastes and abattoir wastewater in the early 1980s (*89, 90*). Pilot-scale experiments were also carried out at University of Western Sydney at Hawkesbury (*91*). Since the mid 1980s, constructed wetlands have increasingly been used in South Africa. By 1990, there were approximately 30 systems either in operation or under construction. These systems were designed to treat raw sewage and secondary domestic effluents, stormwater runoff, agricultural and aquaculture wastes, and a variety of industrial and mining wastewaters. Several systems were constructed based on the "root-zone" design, while other systems incorporated surface or vertical flow (*92, 93*). Since 1980, research has been conducted in Brazil on the use of water hyacinth ponds in combination with constructed wetlands planted with rice, here called "filtering soil" (*94*). These systems would be classified as vertical upflow CWs.

5. Period of 1990 to 2000

The end of the 20th century was characterized by further spread of constructed wetland technology to all inhabited continents and also for treatment of many different types of wastewater (Table 1). However, most constructed wetlands were still designed for treatment of municipal sewage. All types of constructed wetlands were used in this period but strict discharge limits for nitrogen in many European countries resulted in increased use of VF and hybrid CWs on the continent.

During the last decade of the 20th century constructed wetlands were accepted as a certified technology by issuing official guidelines in some countries. Among countries that accepted constructed wetlands were, for example, Austria in 1997 (*124*), Denmark in 1999 (*125*) and Australia in 2000 (*20*). Also, the U.S. EPA (*126*) issued updated guidelines in 2000. Finally, in 2000, the International Water Association issued

TABLE 1. Examples of the Use of Constructed Wetlands for Various Types of Wastewater

type of wastewater	type of CW	location	source
refinery	HF	South Africa	*93*
	FWS	China	*95*
pulp and paper	FWS	USA	*96*
	HF	USA	*97*
pesticides/herbicides	FWS	USA	*98*
	VF	UK	*99*
fish pond effluent	FWS	USA	*100*
	HF	USA	*101*
abattoir facility	HF	Ecuador	*102*
landfill leachate	FWS, HF	Norway	*103*
	HF	USA	*104*
	HF	Slovenia	*105*
explosives	FWS	USA	*106*
	HF	USA	*107*
mining waters	FWS	Canada	*108*
	HF	USA	*109*
dairy	VF	Netherlands	*110*
	VF-HF	France	*111*
	HF	New Zealand	*112*
cheese dairy	VF	Germany	*113*
chemical industry	HF	UK	*114*
textile industry	HF	Australia	*115*
food processing	HF	Slovenia	*116*
	HF	Italy	*117*
pig farms	HF	China	*118*
highway runoff	HF	UK	*119*
airport runoff	HF	Switzerland	*120*
greenhouse runoff	HF	Canada	*121*
urban runoff	FWS	Australia	*122*
hydrocarbons	HF	USA	*123*

its “Scientific and Technical Report” on the performance, design, and operation of constructed wetlands which furthered the acceptance of the technology by wastewater professionals (*21*).

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

In the first decade of the 21st century, the technology of wastewater treatment in constructed wetlands could be characterized by the following:

- combination of various types of constructed wetlands in hybrid systems to achieve better treatment performance, especially for nitrogen;
- treatment of specific compounds present in wastewaters;
- search for suitable media with high capacity for phosphorus removal in subsurface flow constructed wetlands;
- identification of bacteria which assist in treatment processes;
- modeling of hydraulics and pollution removal in various types of constructed wetlands.

Recently, increased demand for removal of ammonia-N from sewage resulted in more frequent use of hybrid constructed wetlands which are better suited to meet this goal as compared to use of a single CW unit (*127, 128*).

During this period constructed wetlands were used to treat not only municipal wastewaters but also effluents from tanneries (*129, 130*), wineries (*131, 132*), compost leachate (*133*), or shrimp aquaculture (*134*). For municipal sewage, increased efficiency in the removal of special compounds, such as linear alkylbenzene sulphonates (LAS) and pharmaceutical and personal care products (PPCP), was investigated. LAS are the most widely used synthetic anionic surfactants. Due to their frequent use in laundry and cleaning products, LAS are a common constituent of municipal and industrial wastewaters. It has been shown that constructed wetlands can remove substantial amounts of LAS from wastewaters (*135, 136*). PPCP constitute a large and diverse group of organic compounds used throughout the world. These substances are excreted by humans in varying degrees of degradation and discharged directly into the sewerage systems and wastewater treatment plants. Ubiquitous occurrence of PPCPs such as hormones, nonsteroidal anti-inflammatory drugs, lipid regulators, β-blockers, and psychiatric drugs has been reported for rivers, lakes, and reservoirs around the world (*137*). It has been shown that constructed wetlands are effective in removing most PPCPs (*138–140*).

Most types of constructed wetlands are not effective for phosphorus removal unless specific media with high sorption capacity are used. Among those materials, lightweight aggregates (*141*) and industrial byproduct, such as blast and electric arc furnace steel slags, are the most promising (*31*). Also, during the past decade more attention was paid to identification of microbial assemblages in CWs (*142–144*). CWs, especially subsurface flow CWs, have long been viewed as “black boxes” where wastewater enters and treated water leaves the system. During the past few years numerical models of different complexities have been developed for describing various processes in subsurface flow CWs (*36, 37, 145*).

After five decades of research and implementation, CWs have been recognized as a reliable wastewater treatment technology and, at present, they represent a suitable solution for treatment of many types of wastewater. Most former concerns regarding their safe and reliable application have been refuted. For example, it has been shown that constructed wetlands perform well under cold climatic conditions (*13, 16, 33*). Also, the land requirement is relatively small so constructed wetlands are commonly used even in countries with high population densities, such as Denmark or The Netherlands (*77, 110*). However, constructed wetlands are better suited for smaller applications. The use of constructed wetlands for various industrial effluents is now also common. Constructed wetlands do have some limitations, such as low phosphorus removal, which must be taken into consideration when treatment technology is selected. However, constructed wetlands are a viable alternative in wastewater treatment technology and, at present, there are tens of thousands of applications in all parts of the world.

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Supporting Information Available

Thirteen additional figures and photographs. This information is available free of charge via the Internet at http://pubs.acs.org/.

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