Constructed Wetlands for Water Quality Regulation

181

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Contents

Abstract

Constructed wetlands (CWs) have been used for wastewater treatment since the 1960s. Constructed wetlands are engineered systems that have been designed and constructed to utilize natural processes involving wetland soils, vegetation, and microbes to treat wastewater. Constructed wetlands may be categorized according to the various design parameters, but three most important criteria are hydrology (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 various systems. CWs are used to treat municipal sewage, as well as agricultural and mine drainage, industrial effluents, landfill leachate or stormwater runoff. Constructed wetlands are considered as reliable and robust treatment systems with low maintenance and operation costs.

Keywords

Wastewater · Macrophytes · Organics · Nutrients

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Introduction

Constructed wetlands (CWs) have been used for wastewater treatment since the 1960s (Vymazal 2011a). Constructed wetlands are engineered systems that have been designed and constructed to utilize natural processes involving wetland soils, vegetation, and microbes to assist in treating wastewater. They are designed to take advantage of many of the same processes that occur in natural wetlands, but do so within a more controlled environment. Constructed wetlands may be categorized according to the various design parameters, but three most important criteria are hydrology (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 various systems (Vymazal 2005).

Free Water Surface Constructed Wetlands

A typical free water surface constructed wetland (FWS CW) is a shallow basin, containing 20–30 cm of rooting soil, with a water depth of 20–40 cm (Fig. 1). There is no special requirement for the soil quality; the most important role of soil is to support macrophyte growth if emergent or submerged plants are present. If free floating plants such as water hyacinth (*Eichhornia crassipes*) or duckweed (*Lemna* spp.) are used, soil matrix is usually absent. Dense emergent vegetation covers substantial fraction of the surface, usually more than 50%. The most frequently used emergent macrophytes are common reed (*Phragmites australis*), cattail (*Typha* spp.), and bulrush (*Scirpus* spp.). The shallow water depth, low flow velocity, and presence of plant stalks, leaves, and litter regulate water flow, and especially in long, narrow channels, ensure plug-flow conditions (Reed et al. 1995). One of their primary design purposes is to contact wastewater with reactive biological surfaces (Kadlec and Knight 1996). The most important treatment processes occur in the water column and in the litter layer on the bottom. Also, periphyton growing on submerged parts of macrophytes adds to removal of pollutants.

Suspended solids are rapidly removed in FWS systems under quiescent conditions by deposition and filtration. Attached and suspended microbial growth is responsible for the removal of soluble organic compounds which are degraded aerobically in the water column as well as anaerobically in the litter layer. Oxygen is supplied to the wetland water column by diffusion through the air-water interface and via the photosynthetic activity of plants in the water column, namely algae. Nitrogen is most effectively removed in FWS constructed wetlands by nitrification/denitrification. Ammonia is oxidized by nitrifying bacteria in aerobic zones, and nitrate is converted to free nitrogen or nitrous oxide in the anoxic zones. FWS CWs provide sustainable removal of phosphorus, but at relatively slow rates. Phosphorus removal in FWS systems occurs from adsorption, absorption, complexation, and precipitation. However, precipitation with Al, Fe, and Ca ions is limited by little

Fig. 1 FWS constructed wetland at Otorohanga, New Zealand, planted with *Eleocharis sphacelata* for tertiary treatment of municipal sewage (Photo credit: Jan Vymazal © copyright remains with the author)

contact between water column and the soil (Vymazal and Kröpfelová 2008; Kadlec and Wallace 2009).

FWS CWs are used for all types of polluted water, but the most common use is for tertiary treatment of municipal sewage, stormwater runoff (e.g., urban, highway, airport, agriculture, golf course, nursery), mine drainage (Fig. 2), and agriculture drainage waters, landfill leachate, and industrial effluents such as pulp and paper, refineries, or abattoir (Vymazal 2011a; Vymazal and Kröpfelová 2008; Kadlec and Wallace 2009).

Constructed Wetland with Horizontal Subsurface Flow

In horizontal CWs (HF CWs), the wastewater flows slowly through the porous medium under the surface of the sealed bed in a more or less horizontal path until it reaches the outlet zone where it is collected before leaving via level control arrangement at the outlet. During this passage, the wastewater will come into contact with a network of aerobic, anoxic, and anaerobic zones (Cooper et al. 1996). The aerobic zones occur around roots and rhizomes that leak oxygen into the substrate. At present, coarse porous media (size fraction cca 5–20 mm) with high hydraulic permeability such as washed gravel or crushed rock (Fig. 3) are used in order to ensure subsurface flow. The major roles of plants in HF CWs include insulation of the bed surface during cold periods, provision of substrate for growth of attached bacteria on roots and rhizomes, oxygen release from roots to the adjacent

Fig. 2 FWS constructed wetlands for treatment of coal mine drainage at Monastery Run, Pennsylvania, USA, planted with *Typha latifolia* (Photo credit: Jan Vymazal © copyright remains with the author)

rhizosphere, release of antimicrobial compounds into the rhizosphere, and nutrient uptake. The most frequently used plant worldwide is *P. australis*, but many local plants have been used (Brix 1997; Vymazal 2011b).

Organic compounds are very effectively degraded aerobically as well as anaerobically by bacteria attached to the plant's underground organs (i.e., roots and rhizomes) and media surface. However, due to a constant saturation of the filtration beds, anoxic/anaerobic processes prevail. Suspended solids are removed from wastewater by filtration and sedimentation. The major removal mechanism for nitrogen in HF CWs is nitrification followed by denitrification. (Vymazal 2007). However, the field measurements have shown that the oxygenation of the rhizosphere of HF constructed wetlands is insufficient and, therefore, the incomplete nitrification is the major cause of limited nitrogen removal. Phosphorus is removed primarily by precipitation with Ca, Al, and Fe. However, media used for HF wetlands (e.g., pea gravel, crushed stones) usually do not contain great quantities of Fe, Al, or Ca, and therefore, removal of phosphorus is generally low.

HF CWs are used for all types of wastewater including municipal sewage, industrial and agro-industrial effluents, landfill leachate, and stormwater runoff. However, most installations have been used to treat municipal sewage (Fig. 4). The investment costs of HF CWs are higher than those for FWS CWs. The difference is made up by the cost for the liner and for the selected filtration material and its transportation.

Fig. 3 Filtration bed filled with crushed rock with distribution zone filled with stones at HF CW Čejkovice, Czech Republic (Photo credit: Jan Vymazal © copyright remains with the author)

Constructed Wetlands with Vertical Subsurface Flow

Vertical flow (VF) constructed wetlands comprise a flat bed of graded gravel topped with sand planted with macrophytes. The size fraction of gravel is larger in the bottom layer (e.g., 30–60 mm) and smaller in the top layer (e.g., 6 mm). The depth of the filtration bed is usually 1–1.2 m. VF CWs are fed intermittently with a large batches of wastewater through the distribution system on top of the bed (Fig. 5). Wastewater then gradually percolates down through the bed and is collected by a drainage network at the base. The bed drains completely free and it allows air to refill the bed. This kind of dosing leads to good oxygen transfer and allows for nitrification (Cooper et al. 1996). The major purpose of macrophytes in VF CWs is to help maintain the hydraulic conductivity of the bed.

The removal processes are the same as in HF CWs, but VF units are predominantly aerobic, and therefore, the removal of ammonia is very high. On the other hand, there is little or no denitrification present. Removal of organics and suspended solids is high, but removal of phosphorus is generally low unless media with high sorption capacity are used. This, however, would increase the investment costs and therefore waste products with high sorption capacity such as blast and electric arc furnaces steel slags have been evaluated (Vohla et al. 2011).

VF CWs are very often used for on-site treatment of domestic wastewater, but their use for other types of wastewater such as landfill leachate, dairy, cheese factory, abattoir, airport runoff, or refinery process waters have been recorded (Vymazal and Kröpfelová 2008).

Fig. 4 Constructed wetland with horizontal subsurface flow for 800 PE (population equivalent) at Čistá, Czech Republic planted with *Phragmites australis* (Photo credit: Jan Vymazal © copyright remains with the author)

Fig. 5 On-site vertical flow CW at Bexhill, NSW, Australia, shortly after plantation (Photo credit: Jan Vymazal © copyright remains with the author)

Hybrid Constructed Wetlands

Various types of constructed wetlands may be combined in order to achieve higher treatment efficiency, especially for nitrogen. The concept of hybrid CWs was developed as early as during the 1960s in Germany and consisted of a series of VF beds followed by a series of HF beds (Seidel 1965). In aerobic VF beds ammonia is oxidized to nitrate, and in the following anoxic HF beds nitrate is reduced via denitrification. During the 1990s, HF-VF CWs were introduced; these systems need recirculation of nitrified effluent from aerobic VF bed to the HF bed inflow where high concentration of organics can support denitrification in anoxic HF bed. Recently, hybrid constructed wetlands of both types have become very popular, and they are used for many types of wastewater including municipal wastewater, landfill leachate, diaries, fish, and shrimp aquaculture recirculating systems or wineries (Vymazal 2011a).

Future Challenges

After five decades of research and implementation, CWs have been recognized as a reliable wastewater treatment technology around the world and, at present, they represent a suitable solution for treatment of many types of wastewater. Constructed wetlands have drawn the attention because of their high treatment efficiency and very low operation and maintenance costs. Most former concerns regarding their safe and reliable application have been refuted, namely, the concern over the performance during winter periods in cold climate. The ongoing research is focused on improvement of phosphorus removal, modeling of treatment processes aimed at the optimization of design parameters, and characterization of microbial assemblages responsible for water purification.

References

Brix H. Do macrophytes play a role in constructed treatment wetlands? Wat Sci Tech. 1997;35:11–7.

Cooper PF, Job GD, Green MB, Shutes RBE. Reed beds and constructed wetlands for wastewater treatment. Medmenham: WRc Publications; 1996.

Kadlec RH, Knight RL. Treatment wetlands. Boca Raton: CRC Press/Lewis Publishers; 1996.

Kadlec RH, Wallace SD. Treatment wetlands. 2nd ed. Boca Raton: CRC Press; 2009.

Reed SC, Middlebrooks EJ, Crites RW. Natural systems for waste management and treatment. New York: McGraw-Hill; 1995.

Seidel K. Neue Wege zur Grunwasseranreicherung in Krefeld. Vol. II. Hydrobotanische Reinigungsmethode. GWF Wasser/Abwasser. 1965;30:831–3.

Vohla C, Koiv M, Bavor J, Chazarenc F, Mander Ü. Filter materials for phosphorus removal from wastewater in treatment wetlands – a review. Ecol Eng. 2011;37:70–89.

Vymazal J. Constructed wetlands with horizontal sub-surface flow and hybrid systems for wastewater treatment. Ecol Eng. 2005;25:478–90.

Vymazal J. Removal of nutrients in various types of constructed wetlands. Sci Tot Environ. 2007;380:48–65.

Vymazal J. Constructed wetlands for wastewater treatment: five decades of experience. Environ Sci Technol. 2011a;45:61–9.

Vymazal J. Plants used in constructed wetlands with horizontal subsurface flow: a review. Hydrobiologia. 2011b;674:133–56.

Vymazal J, Kröpfelová L. Wastewater treatment in constructed wetlands with horizontal sub-surface flow. Dordrecht: Springer; 2008.