CONSTRUCTED WETLANDS FOR WASTEWATER TREATMENT

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Keywords: application, benefits, **c**onstructed wetlands, case studies, costs, design, removal mechanisms, subsurface flow, surface flow, wastewater, water treatment.

Contents

Summary

Constructed wetlands (CWs) are wetlands designed to improve water quality. They use the same processes that occur in natural wetlands but have the flexibility of being constructed. Vegetation, soil and hydrology are the major components in CW. Different soil types (sand and gravel) and plant species are used in constructed wetlands. Regarding hydrology surface flow and subsurface flow constructed wetlands can be distinguished. Subsurface flow constructed wetlands are further subdivided into horizontal or vertical flow. All types of water can be treated with CWs such as wastewater (domestic, industrial), groundwater, surface water, stormwater. More or less all water constituents can be eliminated by CWs, even micropollutants and pathogens. Due to their attributes CWs are appropriate for developed as well as for developing countries.

CWs are designed by first-order equations but often rules of thumbs are applied. Recently numerical models are gaining increasing importance.

Constructed wetlands are an effective and low cost way to treat water polluted with organic compounds. Although a lot of experiences and knowledge with CW is available there is still a lack of knowledge on the detailed understanding of the degradation and transformation pathways for most of the contaminants.

Therefore a great efforts are being put into getting more insight into the black box "constructed wetland" to obtain information on both microbial biocoenosis and the contribution of the plants to the overall removal process.

1. Introduction

Wetlands are among the most important ecosystems on earth. Based on several estimates 7 – 9 mill km² wetlands exist, including swamps, bogs, marshes, mines, fens and other wet ecosystems.

Wetlands are transitional environments between dry land and open water. In an ecological context, wetlands are intermediate between terrestrial and aquatic ecosystems. Wetlands can be defined as ecosystems that depending on constant or recurrent, shallow inundation or saturation at or near the surface of the substrate (Lewis 1995, in: Vymazal et al. 1998).

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 waterway (Reddy and Smith 1987). Since the 1980s the use of constructed wetlands has become more popular and effective around the world (e.g. Reddy and Smith 1987; Kadlec and Knight 1996; Cooper et al. 1996; Kadlec and Wallace, 2008).
Constructed wetland treatment systems are engineered systems designed and constructed to utilize the natural processes involving wetland vegetation, soils, and their associated microbial assemblages to assist in treating wastewater (domestic, industrial, agricultural), stormwater, surface water etc. 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.

Development of Wastewater Treatment

Land treatment of wastewater has been known since 2000 years and was introduced in UK and Germany in the 16th century. Overland flow systems have been applied since the late 19th century.
The next step in wastewater treatment technology was the implementation of conventional systems, beginning with high-loaded systems which have been changed in the course of time to low loaded ones according to strengthening water laws and water standards.

During the last about 30 - 40 years a renaissance of wetlands has become obvious nearly all over the world. Manifold reasons have been responsible for this, like rising awareness for natural processes, the necessity of wastewater treatment in low density areas, the application of appropriate wastewater treatment in general, costs, O/M-demand etc. But not natural wetlands, rather created or engineered or constructed or treatment ones; these different wordings can be found. Experts have agreed to use constructed or treatment wetlands as a technical term although discussions on this never seem to end.

The major wetland components are:

- **Vegetation**. The prevalent vegetation consists of macrophytes that are typically adapted to areas heaving hydrologic and soil conditions described in the definition.

- **Soil**. Soils are present and have been classified as hydric, or they possess characteristics that are associated with reducing soil conditions.
- **Hydrology**. The area is inundated either permanently or periodically at mean water depth of ≤ 2 m, or the soil is saturated to the surface at some time during the growing season of the prevalent vegetation.

Compared with the vegetation of well-drained soils, wetland plants have a world-wide similarity which over-rides climate and is imposed by the common characteristics of a free water supply and the abnormally hostile chemical environment which plant roots must endure (Etherington 1983, in: Vymazal et al. 1998). Wetland plants have elaborated structural mechanisms to avoid root anoxia. The main strategy has been the evolution of air spaces (aerenchyma) in roots and stems that allow the diffusion of oxygen from the aerial portions of the plant into the roots (e.g. Armstrong and Armstrong 1990). The magnitude of oxygen diffusion through many wetland plants into the roots is apparently large enough not only to supply the roots but also to diffuse out and oxidize the adjacent soil (Teal and Kanwisher 1966, and Howes et al. 1981, in: Vymazal et al. 1998).

Four groups of aquatic macrophytes can be distinguished on a basis of morphology and physiology (Wetzel 1983, in: Vymazal et al. 1998):

1. Emergent macrophytes grow on water saturated or submersed soil from where the water table is about 0.5 m below the soil surface to where the sediment is covered with approximately 1.5 m of water (e.g. *Acorus calamus, Carex rostrata, Phragmites australis, Scirpus lacustris, Typha latifolia*).
2. Floating-leaved macrophytes are rooted in submersed sediments in water depths of approximately 0.5 to 3 m and possess either floating or slightly aerial leaves (e.g. *Nymphaea odorata, Nuphar lutea*).
3. Submerged macrophytes occur at all depths within the photic zone. Vascular angiosperms (e.g. *Myriophyllum spicatum, Ceratophyllum demersum*) can occur in water up to 10 m deep (1 atm hydrostatic pressure) but non vascular macro-algae can occur to the lower limit of the photic zone (up to 200 m, e.g. *Rhodophyceaered algae*).
4. Freely floating macrophytes are not rooted to the substratum; they float freely on or in the water column and are usually restricted to non-turbulent, protected areas (e.g. *Lemna minor, Spirodela polyrhiza, Eichhornia crassipes*).

2. Constructed Wetlands for Water Treatment

2.1. Classification

Constructed wetlands for wastewater treatment may be classified according to Kadlec and Wallace (2008) to the life form of the dominating macrophytes (see Fig 1) into

1. Free-floating macrophyte-based systems,
2. Submerged macrophyte-based systems, and
3. Rooted emergent macrophyte-based systems.

and depending on the water flow different rooted emergent systems are distinguished into

- surface flow (SF) wetlands (Fig 2)

- subsurface flow (SSF) wetlands: horizontal subsurface flow (HF) (Fig 3) vertical subsurface flow (VF) (Fig 4).

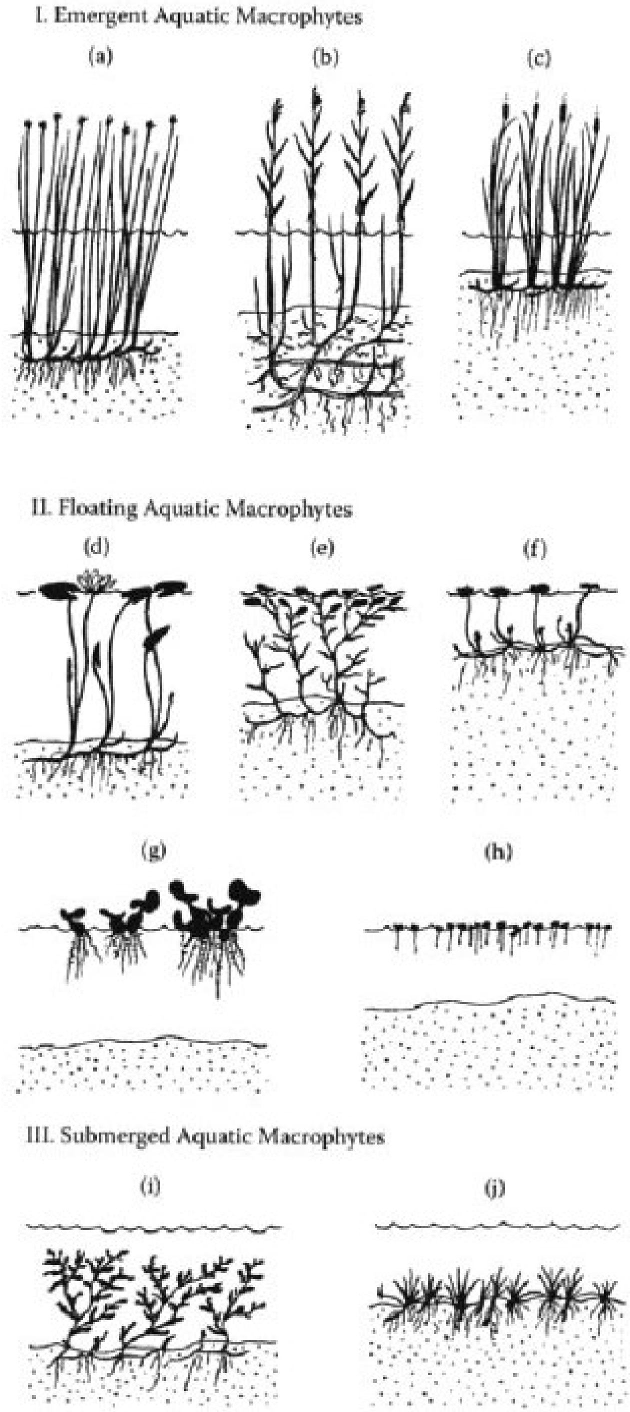

Figure 1. Different types of Constructed Wetlands according to the life forms of aquatic macrophytes. The species illustrated are (a) Scirpus (Schoenoplectus) lacustris, (b) Phragmites australis, (c) Typha latifolia, (d)Nymphaea alba, (e) Potamogeton gramineus, (f) Hydrocotyle vulgaris, (g) Eichhornia crassipes, (h) Lemna minor, (i) Potamogeton crispus, (j) Littorella uniflora (Brix and Schierup, 1989, in Kadlec and Wallace, 2008)

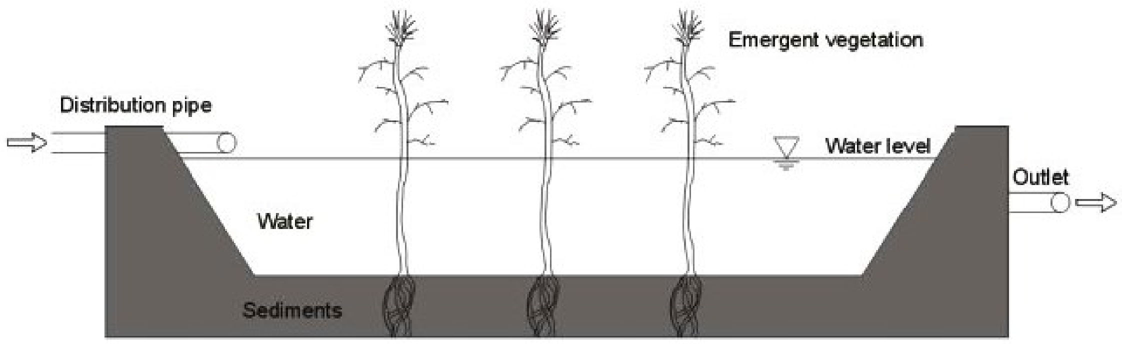

Figure 2. Basic elements of a SF CW (Langergraber and Haberl, 2004)

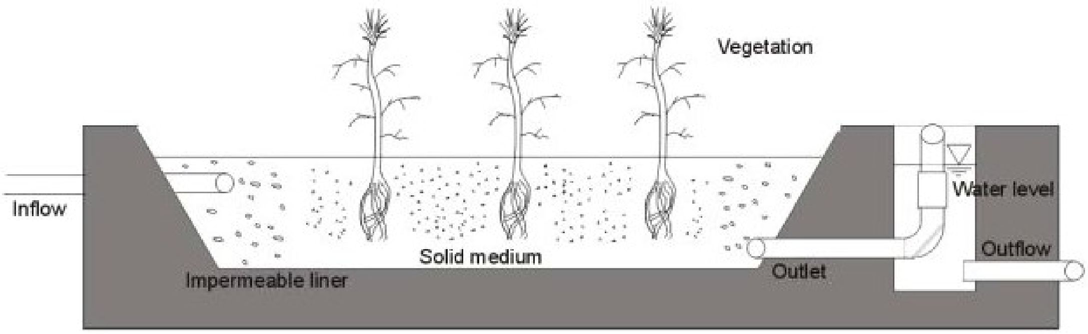

Figure 3. Typical arrangement of a HF CW (Langergraber and Haberl, 2004)

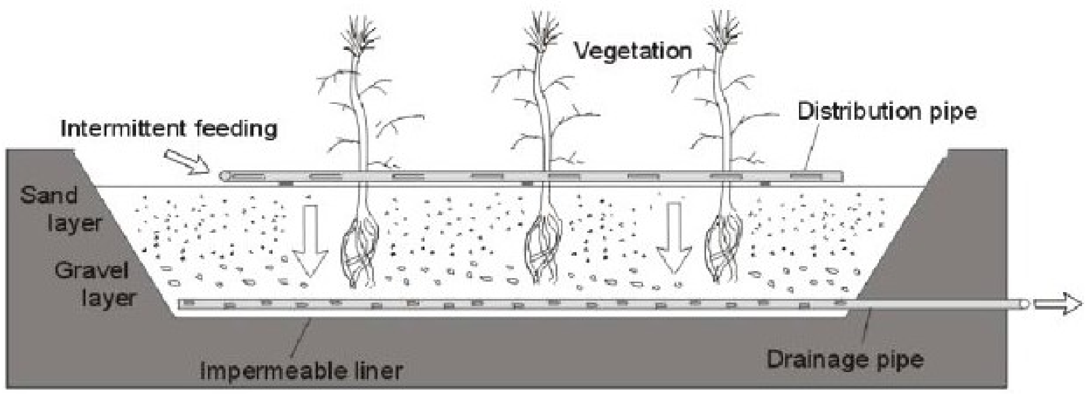

Figure 4. Typical arrangement of a VF CW (Langergraber and Haberl, 2004)

2.2. Surface Flow Wetlands

Surface flow (SF) CWs are densely vegetated by a variety of plant species and typically have water depths less than 0.4m. Open water areas can be incorporated into a design to provide for the optimization of hydraulics and for wildlife habitat enhancement. Typical hydraulic loading rates lie between 0.7 and 5.0 cm.d^{-1} (between 2 and 14 ha.1000 m^{-3}.d^{-1}).

The design criteria and recommendations developed for SF CWs can be summarized as follows (Kadlec and Knight 1996):

- pretreatment: to at least the primary level
- organic loading: < 112 kg BOD_5 ha^{-1} d^{-1}
- hydraulic loading: ST = 1.2-4.7 cm d^{-1}, TT=1.9-9.4 cm d^{-1}
- detention time: 5-15 days
- aspect ratio (L:W): > 10:1
- water depth: 0.2-0.4 m
- bottom slope: 0.5%
- soils: 20-30 cm to support the growth of emergent macrophytes, no special requirements for high hydraulic conductivity (local soils used in many cases)
- vegetation: most frequently used species: in North America *Scirpus* spp. (bulrushes), *Typha* spp. (cattails); in Europe *Phragmites australis* (Common Reed)

One of the oldest concepts of constructed wetlands with free water surface has been used in The Netherlands for nearly 30 years (Greiner and de Jong 1984). However, the most SF CWs systems are in operation in North America at present; Kadlec (1994) reported that more than 100 SFW treatment systems have been constructed in the United States for water quality improvement. North American SF CWs are often larger compared to SSF systems. The largest application of this technology to date includes the design of over 16 000 ha of surface flow wetlands for agricultural drainage water treatment in south Florida (Kadlec and Knight, 1996).

2.3. Subsurface Flow Wetlands

The subsurface flow (SSF) wetland technology is based on the work of Seidel (1967). Since then the technology has grown in many European countries and is nowadays world-wide applied. SSF CWs use a bed of sand or gravel as a substrate for the growth of rooted emergent wetland plants. Mechanically pre-treated wastewater flows by gravity, horizontally or vertically, through the bed substrate, where it contacts a mixture of facultative microbes living in association with the substrate and plant roots. The bed depth in SSF wetlands is typically between 0.6 and 1.0 m, and the bottom of the bed is sloped to minimize overland water flow.

At first the main interest was in horizontal flow (HF) systems because they were rustic, simple and promised low construction and operational costs for meeting the given standards. These systems turned out to be very appropriate technologies providing high stability in their efficiencies, with low levels of operation and maintenance. A good performance in terms of SS, BOD_5 - and COD - removal even with comparatively high loading rates (up to 75g BOD_5. m^{-2}. p.e.$^{-1}$) was stated. The effluent values normally did not exceed the effluent standards, even in cold seasons. The nutrient removal amounted only to 40-60%. Higher rates seemed to be prevented by a low hydraulic conductivity in the rooting medium resulting in reduced contact time within the system on one hand, and by an oxygenation deficiency in the root-zone on the other hand.

Macrophytes applied in constructed wetlands have air space tissue, through which oxygen is transported to the roots. For a long time the assumption was valid according to which the oxygen transport is exceeding the plant demand and thus a certain amount of oxygen can enter the rhizosphere to be available for the aerobic degradation of organic substances including nitrification. Particular studies have shown that roots of macrophytes do release oxygen to the rhizosphere but unfortunately much less than needed for oxidation of both carbon and nitrogen.

Concerning the hydraulic conductivity the greatest problems were found in soil-based systems (Haberl and Perfler, 1990). The expected improvement of the conductivity by the growth and spreading of roots and rhizomes did not occur. Even if coarse material was employed, experiments, especially in Germany and the UK, showed problems with conductivity which often resulted in short circuiting.

With respect to legislation in many countries, demanding fully nitrified effluents, and in order to improve water quality other than HF CW systems had to be applied. A lot of scientific and practical experiments in many countries showed that sand and gravel - based vertical flow (VF) systems with intermittent loading were able to meet such stringent effluent demands.

The significant differences between VF and HF CWs can obviously be seen from the different design of the construction profile. VF systems have a distribution system covering the whole surface area. Usually pre-treated wastewater is dosed on the bed in a large batch, flooding the surface. VF CWs are usually fed intermittently. The liquid then gradually percolates vertically down through the medium. The treated water is collected in a drainage system at the bottom and discharged to the receiving water. During drainage of the bed air is allowed to fill the pores of the medium. The next dose of liquid traps this air and this together with the aeration caused by the rapid dosing on the bed leads to good oxygen transfer and hence the ability to decompose BOD and to nitrify ammonia nitrogen.

Depending on the required effluent standards either HF or VF CWs have to be used. An efficient pre-treatment regarding suspended solids removal is essential for a long term operation of subsurface flow constructed wetlands in general. If low ammonia effluent concentrations are required only vertical flow constructed wetlands with intermittent feeding can guarantee a good nitrification. Sufficient oxygen supply is the main factor for a good performance of vertical flow constructed wetlands.

Besides these two types multistage systems are known, consisting of a combination of the above-mentioned ones and/or other kinds of technologies, such as wastewater ponds or conventional systems (trickling filters, activated sludge, etc.).

2.4. Hybrid Systems

Hybrid systems are combinations of HF and VF systems with the aim to utilize the advantages of both systems.

HF systems are preferable for:

i) TSS and bacterial removal because of their ability to filter

ii) BOD_5 removal up to the limit set by it oxygen-transfer capability

iii) Nitrate removal by biological denitrification. Oxygen from the nitrate can be used for BOD_5 removal.

HF systems are poor for nitrification because of their limited oxygen transfer capacity (OTC)

VF systems are preferable for:
i) Nitrification because of their good OTC
ii) BOD_5 and COD removal as well because of their high OTC

It is easy to see that several of the advantages and disadvantages of the two systems balance out if correctly designed into a hybrid arrangement.

HF followed by VF stage

This system is appropriate to eliminate suspended solids in the first stage (HF) as well as BOD and COD. In the second stage (VF) nitrification takes place and thus the opportunity is given to recycle the nitrified effluent of the VF-stage to the first stage where denitrification can occur due to the high concentration of organic carbon of the raw wastewater.

VF followed by HF stage

This alternative arrangement has been used in France and in the UK. Mostly the vertical stage (several beds in parallel) is operated intermittently, the horizontal one continuously.

For example the system at Oaklands parks uses 2 vertical stages followed by 2 horizontal stages with a total area of only 1.4 m^2. The performance data of this plant show as expected a high BOD removal, nitrification in the vertical stages and N-reduction in the horizontal ones.

The problem with denitrification in the second stage is the lack of readily degradable carbon. Therefore an external carbon source might be helpful.

In Austria Laber et al. (1997) used a system with two VF stages in series with no recirculation. The two stages used approximately 5 $m^2.p.e.^{-1}$ (2.5 each). The first stage was operated with low water table which resulted in carbon removal and in nitrification. The second stage was operated with high water level to get denitrification. Denitrification only worked when methanol was added as external carbon source. Dosing methanol increased total N removal from 28% to 78%.

In another pilot plant (1-stage VF) the nitrified effluent of the CW was recycled into the pre-treatment settlement tank. An 80% recirculation rate increased the TN elimination to 72% (from originally 34% without recirculation) (Laber et al, 1997).

3. Removal Mechanisms

3.1. General

The elimination principles are similar for all systems. Raw or pre-treated waste water flows through the constructed wetland. The elimination processes take place during this passage; they are based on various complex physical, chemical and biological processes within the association of substrate, macrophytes and microorganisms. The removal mechanisms principally depend on:

- hydraulic conductivity of the substrate,
- types and number of microorganisms,
- oxygen supply for the microorganisms, and
- chemical conditions of the substrate.

Numerous mechanisms occur in constructed wetlands to improve water quality:

- settling of suspended particulate matter,
- filtration and chemical precipitation,
- chemical transformation,
- adsorption and ion exchange on surfaces of plants, substrate and litter,
- breakdown, and transformation and uptake of pollutants and nutrients by micro-organisms and plants, and
- predation and natural die-off of pathogens.

Wetland treatment systems are effective in treating organic matter, nitrogen, phosphorus, and additionally for decreasing the concentrations of heavy metals, organic chemicals, and pathogens.

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