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Constructed wetlands and vegetation filters: an ecological approach to wastewater treatment*

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SUMMARY

Constructed wetlands (CWs) are man made vegetation filter systems, which simulate the ability of natural wetlands to remove pollutants from water. Eco-technical treatment can facilitate the re-use of process waters, drainage waters and effluents.

Aquatic microbial communities, in association with plant roots and a supporting mineral matrix, are effective at removing pollutants, such as suspended solids, dissolved and particulate organic matter, nitrogen, phosphorus, metals and pathogenic organisms from effluent streams. Treatment of polluted waters in a small, self-contained CW bed is relatively inexpensive and involves low technology with a "green" image. CWs can enable contaminated waters to be re-used productively, for example in agriculture, horticulture and energy forestry. Applications for CWs include wastewater (sewage) treatment at secondary or tertiary stages, sludge drying, surface runoff (commercial, industrial), groundwater treatment, industrial and agricultural process water treatment, and for ecological habitat creation.

CW systems vary in design, including surface flow vegetated channels and sub-surface soil/vegetation filters. The latter may employ horizontal flow (HF), vertical flow (VF) or tidal flow (TF) hydraulic regimes and these may be combined in hybrid systems to optimise pollutant removal. Macrophyte species planted in the bed include reeds (*Phragmites*), cattails (*Typha*), rushes (*Juncus*) and willow (*Salix*). The porosity of the bed fill material is critical for the hydraulic loading rate and retention time of effluent passing through it, which in turn determines the efficiency of water treatment. The microbial community in the bed is responsible for the processes of degradation and chemical transformation, which result in pollutant removal. Both aerobic and anaerobic processes are involved, but degradation of carbonaceous matter (BOD) to CO_2 and transformation of ammonia to nitrate require biological oxidation, and hence a continual supply of oxygen. This is achieved most efficiently in compact VF systems; as the surface is flooded, air is forced into the bed, while effluent percolates downwards through the matrix. Horizontal flow (HF) beds typically achieve lower oxygen transfer rates but, with largely anaerobic conditions, they are effective in removing nitrogen to atmosphere *via* de-nitrification. The role of plant roots in providing an oxygen source in the subsurface environment, according to the Root-Zone Model, and in creating reduced/oxidised micro-environments in the matrix, is considered. Evidence for the release of oxygen by plant roots and the presence of aerobic/anaerobic micro-gradients is discussed, with reference to measurements in laboratory microcosms and *in-situ* field systems. The importance of plant uptake in removing N and P from effluent is assessed.

CWs are effective in treating polluted waters arising from a wide range of domestic, industrial and agricultural operations and are particularly appropriate for isolated rural situations, enabling water of acceptable quality to be discharged to environment, or to be re-used locally as fertilizer. CW technology offers a cost-effective means of protecting water resources from contamination, whilst providing local habitat diversification.

INTRODUCTION

Constructed Wetlands (CWs) are man-made vegetation filter systems, which simulate the ability of natural wetlands to remove pollutants from water (Kangas 2004; Stottmeister et al. 2003). CWs are complex, structured systems with many components, flooded with water, at least for part of the time. They are relatively inexpensive, "low-tech", low-maintenance systems, and they create new wildlife habitats. Clean water is a vital, increasingly limited resource. Cost-effective treatment enables the re-use of water, so that it becomes not a burden on the environment, but an asset.

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A simple design of CW is a buffer strip of trees planted to intercept water draining from agricultural land into a stream. In passing through such a vegetation filter, nitrogen and phosphorus are greatly reduced compared to water draining directly from the field reducing the risk of eutrophication (Ryszkowski et al. 1990; Ryszkowski and Kedziora 2007).

Plants, microbes and the soil matrix are interdependent (Figure 1) (Randerson 2007). Important features include the particle size and porosity of the soil, the diversity and attachment sites of the microbial community, and the types of plants in the CW. Plants are adapted to survive in flooded soil (helophytes), by having air channels in their roots (Evans 2003).

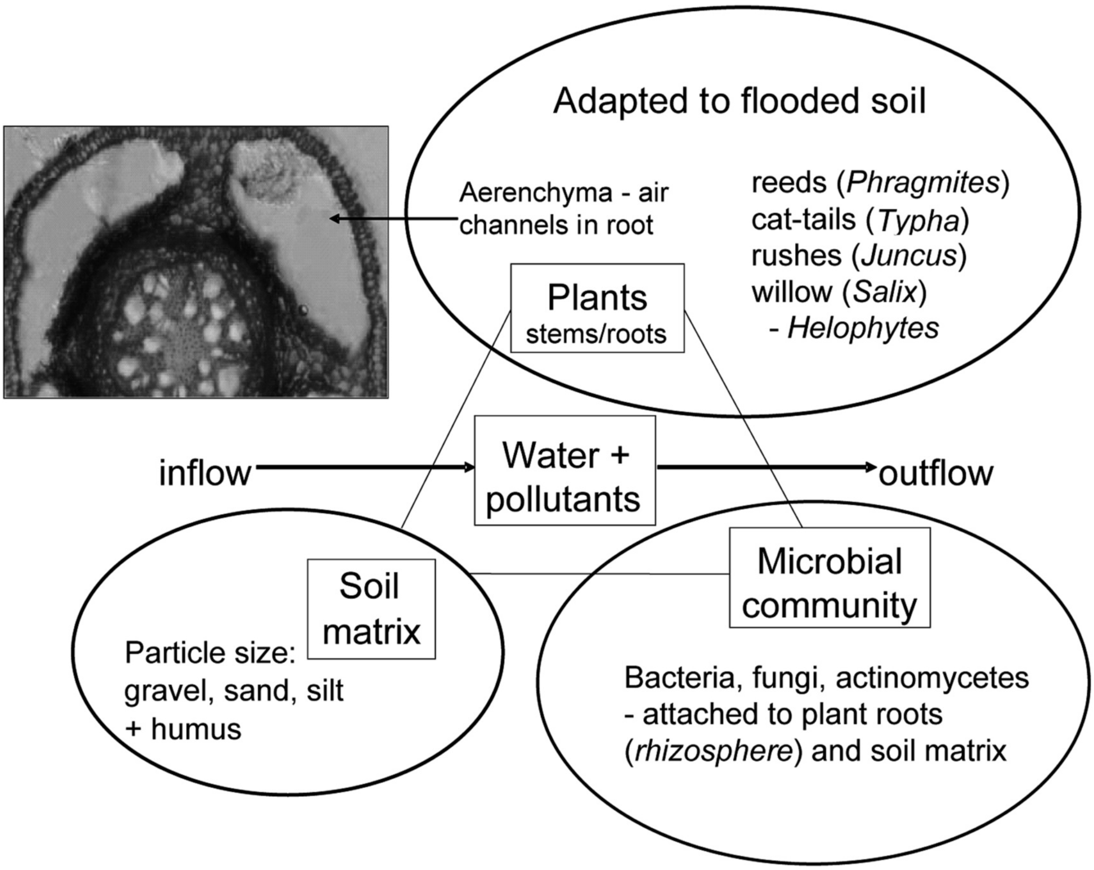


Figure 1. Interactions in the constructed wetland (CW) complex.

POLLUTANT REMOVAL IN CONSTRUCTED WETLANDS

Pollutants are removed, firstly, by aerobic microbial processes. Organic matter is degraded, releasing carbon dioxide, and also ammonia (ammonification), which may then be oxidised to nitrate (nitrification). These processes consume oxygen – hence the term "biological oxygen demand: BOD". Organic matter is broken down also under anaerobic conditions, producing methane, but more slowly. Complex organics and recalcitrant molecules such as pesticides may be degraded. If there is nitrate, it may be removed as nitrogen gas (denitrification). Adsorption (binding to electrostatic exchange sites on clay particles and clay-humus aggregates), can remove phosphate and metals. Plant uptake and assimilation into plant biomass can remove inorganic nutrients N and P, as well as metals, such as cadmium (Perttu and Kowalik 1997).

In the case of nitrogen, different transformations are separated spatially between aerobic and anaerobic zones, because different microbes are involved (Figure 2) (Cooper et al. 1996; Wong et al. 2003). The BOD load arising from ammonia is, gram for gram, over 4 times that from organic matter.

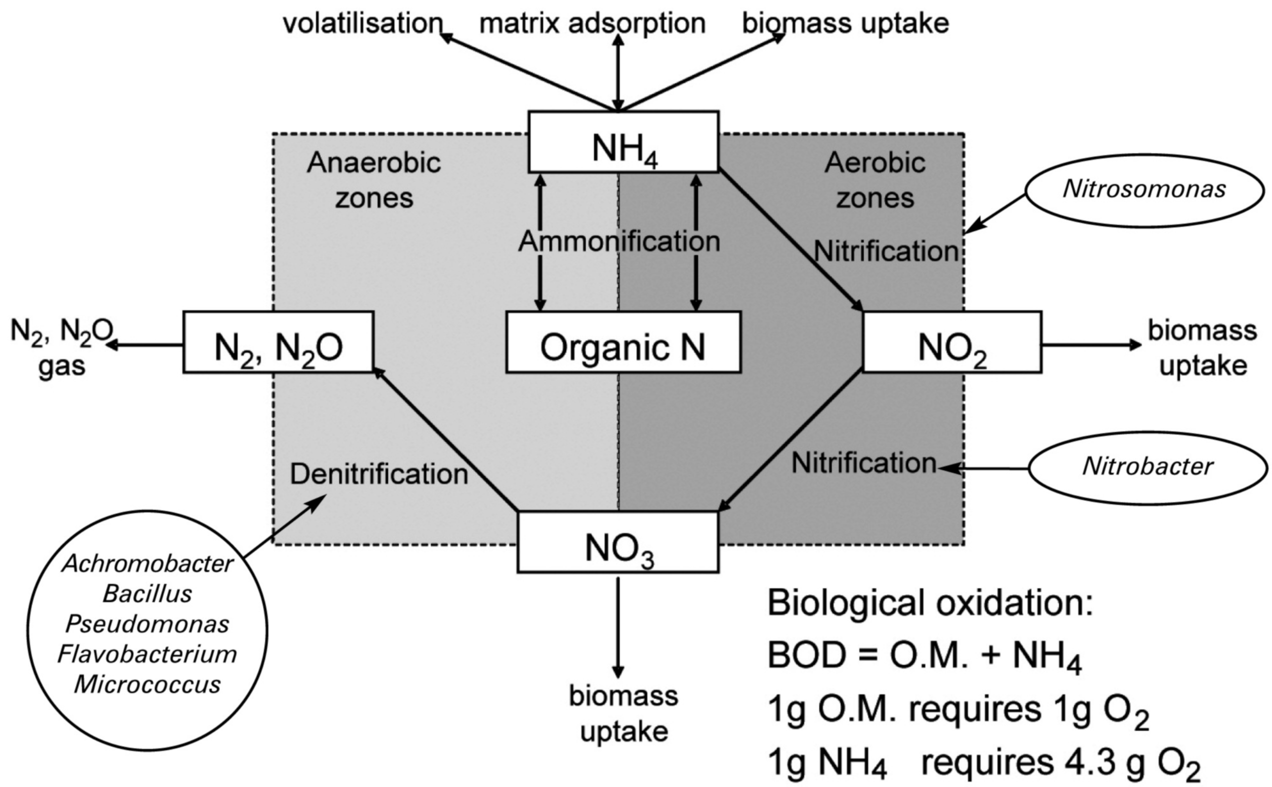


Figure 2. Nitrogen transformations in a constructed wetland (CW).

Plants play an active role in CW beds, which has been highlighted in the "Root Zone Treatment concept" developed by Brix (1987, 1997), Brix and Schierup (1989), Kadlec and Knight (1996) and Kowalik (personal communication). The root system provides a large surface area for microbial attachment (rhizosphere). Exudates of carbon compounds from the roots provide substrate for carbon limited microbes (*e.g.* denitrifying organisms may have access to nitrate, but may lack assimilable carbon). Oxygen transfer to the roots may provide an aerobic zone to enable nitrification (the extent of this oxygen supply is unclear and has been the subject of much debate) (*e.g.* Brix 1993, 1997; Sorrel and Armstrong 1994). Nitrogen is removed by plant uptake (important in nutrient-demanding, fast-growing plants such as willow trees). Metals may also be removed by plant uptake (*e.g.* manganese, zinc, copper, cadmium); some willow varieties are especially tolerant (Dickinson and Pulford 2005; Landberg and Greger 1994; Riddel-Black 1994). Evapo-transpiration (about 600 litre $\cdot$ m^{-2} $\cdot$ y^{-1} for a willow canopy), can greatly reduce the volume of water passing through the system.

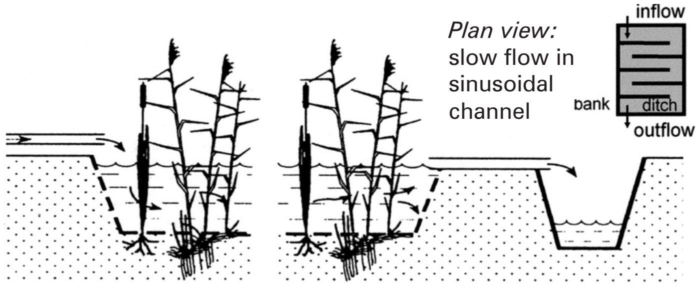
USES OF CONSTRUCTED WETLANDS

Probably the best known application is for the treatment of sewage waste-water in reed beds, often following a biological treatment stage (Cooper et al. 1996; Green and Uptown 1995; Hiley 1995; Kowalik et al. 1995; Kowalik and Randerson 1994). Other applications for CWs include treating agricultural drainage and wastewater. In an example from north Wales, polluted farmyard runoff with high levels of BOD and ammonia, previously draining directly into a local stream, was passed via a holding pond into a system of drainage channels, inter-planted with willow trees to form a bio-filter. Under normal flow conditions very good removal of pollutants was achieved (unpublished data), but with heavy rainfall there was a problem with surface overflow. In this case, the capacity of the pond was not sufficient for the potential hydraulic load. In rural Wales, CWs are used to treat leachate with high levels of ammonia and iron arising from small closed landfill sites (Kowalik et al. 1996; Randerson and Slater 2005; Williams et al. 2001). Iron and manganese-rich drainage water from abandoned coal mines, which produces very damaging orange deposits of iron in streams, is treated in wetland peat beds planted with *Juncus*

Microbial biofilmis attached to stems and litter – plastic mesh is equally good.

A

Plan view:
slow flow in
sinusoidal
channel

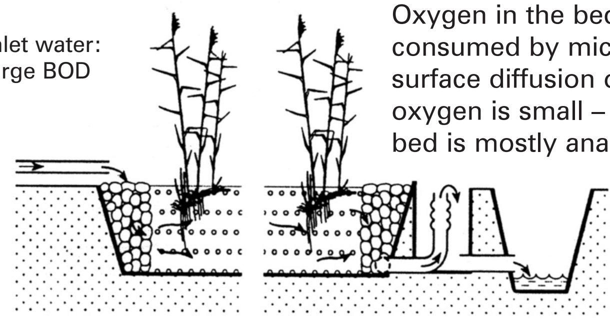


Pollutants are efficiently removed *only* if there is good contact between polluted water and microbes (long *Residence Time*). CWs are designed to achieve this in a small surface area.

B

Inlet water:
large BOD

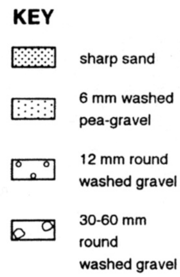
Oxygen in the bed is consumed by microbes: surface diffusion of oxygen is small – so the bed is mostly anaerobic.

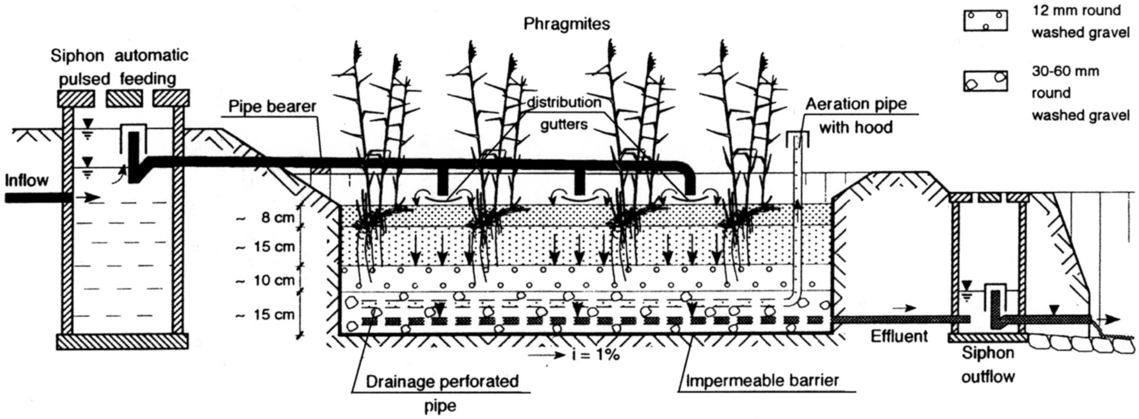


Reeds tolerate hypoxia: pump O_2 down to root zone – create aerobic microsites, O_2 supply is limiting for nitrification: NO_3 and C supply is limiting for denitrification.

C

Down-flow of water in a pulsed flood/drain cycle aerates the bed efficiently – improved BOD + SS removal and nitrification – but not NO_3 and P levels, usually too high for discharge to surface waters.





Surface clogging problem – set up parallel beds for alternate loading/resting.

Figure 3. A - Surface flow (SF) wetland; B – Sub-surface, horizontal flow (HF) bed; C – Sub-surface, vertical flow (VF) bed.

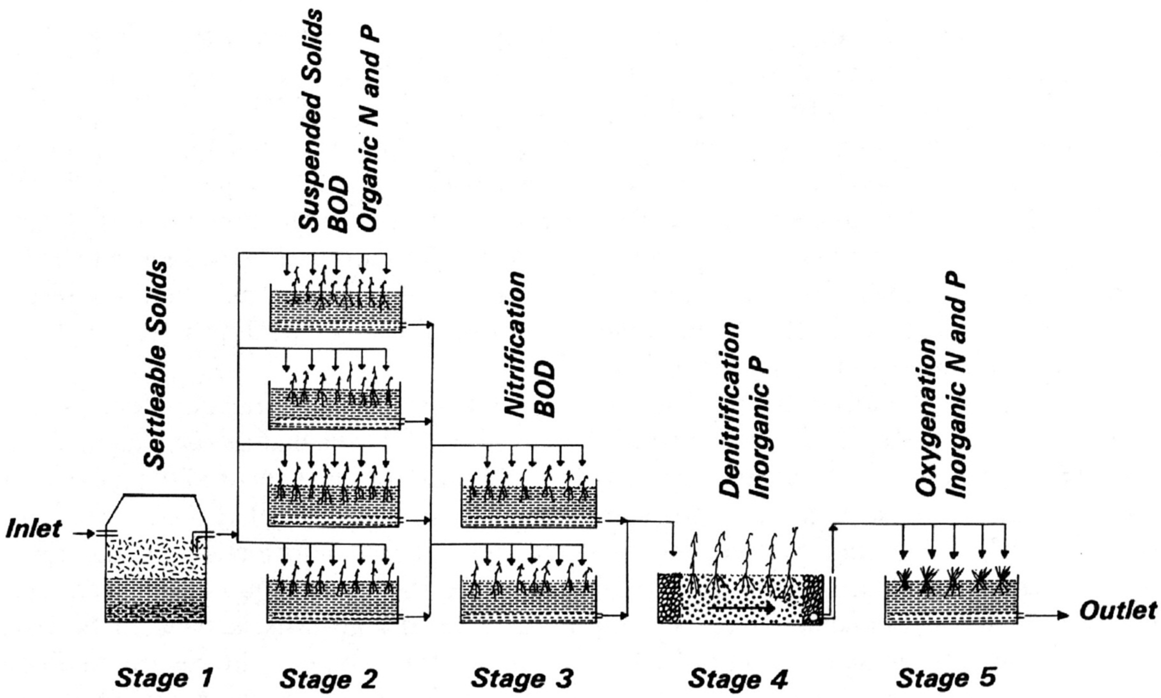


Figure 4. Multi-stage system combining vertical flow (VF) and horizontal flow (HF) stages.

(Dalyell 1995). CWs also provide a cost-effective way to avoid surface water pollution from storm water runoff from industrial sites and road surface runoff. At Llanwern steelworks in south Wales, effluent from washing the coke ovens, high in ammonia and phenolics, is treated in large reed beds before discharge to a local water course. Trials in Sweden have shown groundwater nitrogen levels reduced by passing through a willow vegetation filter. Sewage sludge drying beds, another form of CW, employ the evapo-transpiration ability of macrophytes for efficient de-watering of sludge.

DESIGN AND FUNCTION OF CONSTRUCTED WETLANDS

Surface flow (SF) wetlands most resemble natural wetlands, as the water level is typically above the soil surface. Plant stems provide attachment sites for microbial biofilm, but plastic mesh has been shown to be equally effective (Figure 3A). It is important to allow sufficient residence time for contact between pollutants and microbes; a sinusoidal channel design achieves this within a minimum footprint (Kowalik et al. 1995). In sub-surface flow systems, there are two distinct hydraulic flow regimes. With horizontal flow (HF), water flows laterally below the surface, through a gravel bed (Figure 3B). Oxygen is consumed by microbial activity, and oxygenation of the bed is limited by surface diffusion, so that anaerobic conditions predominate. Hence nitrification is limited by oxygen, and denitrification is limited by the supply of nitrate and usable carbon compounds. In the vertical flow (VF) system, pulses of water flow downwards through layers of increasing particle size (Figure 3C). Air is drawn into the bed between each pulse of water. Removal of BOD and nitrification is very efficient, for a given surface area, but nitrate and phosphate are typically high in the outflow (Cooper et al. 1997). Problems of erosion of the sand surface can be avoided using tiles and gravel placed below inlet nozzles. Surface clogging by humus (organic debris and biofilm) becomes a problem after a period of time, but is best solved by "resting" a bed for several days to allow humus to decompose. Combining VF and HF beds in a multi-stage system provides conditions for both aerobic and anaerobic processes, *e.g.* removal of both BOD and N (Figure 4) (Cooper 1999, 2001). Table 1 shows BOD and NH_4N was reduced in VF stages; NO_3 increased, but then reduced in HF beds; PO_4 reduced a little by adsorption. Rural communities in Portugal and in Poland have recently adopted such CW technology to treat domestic sewage (Alberquerque, Kowalik, personal communication). In one example, problems of clogging and hydraulic overload at the inlet end of the initial HF stage were apparent; in another the need to maintain water level at the surface of the gravel bed to avoid weed growth during the establishment of reed plants (*Phragmites*) was noted. Managers of such facilities need to plan for the costs of maintenance, as well as those of initial construction.

Compact Vertical Flow (CVF) systems are an efficient alternative for small scale domestic sewage treatment (up to 30 person-equivalents). The most recent Danish design of CVF uses re-circulation for increased nitrogen removal, and chemical precipitation to remove phosphorus (Figure 5, Table 2) (Brix and Arias 2005).

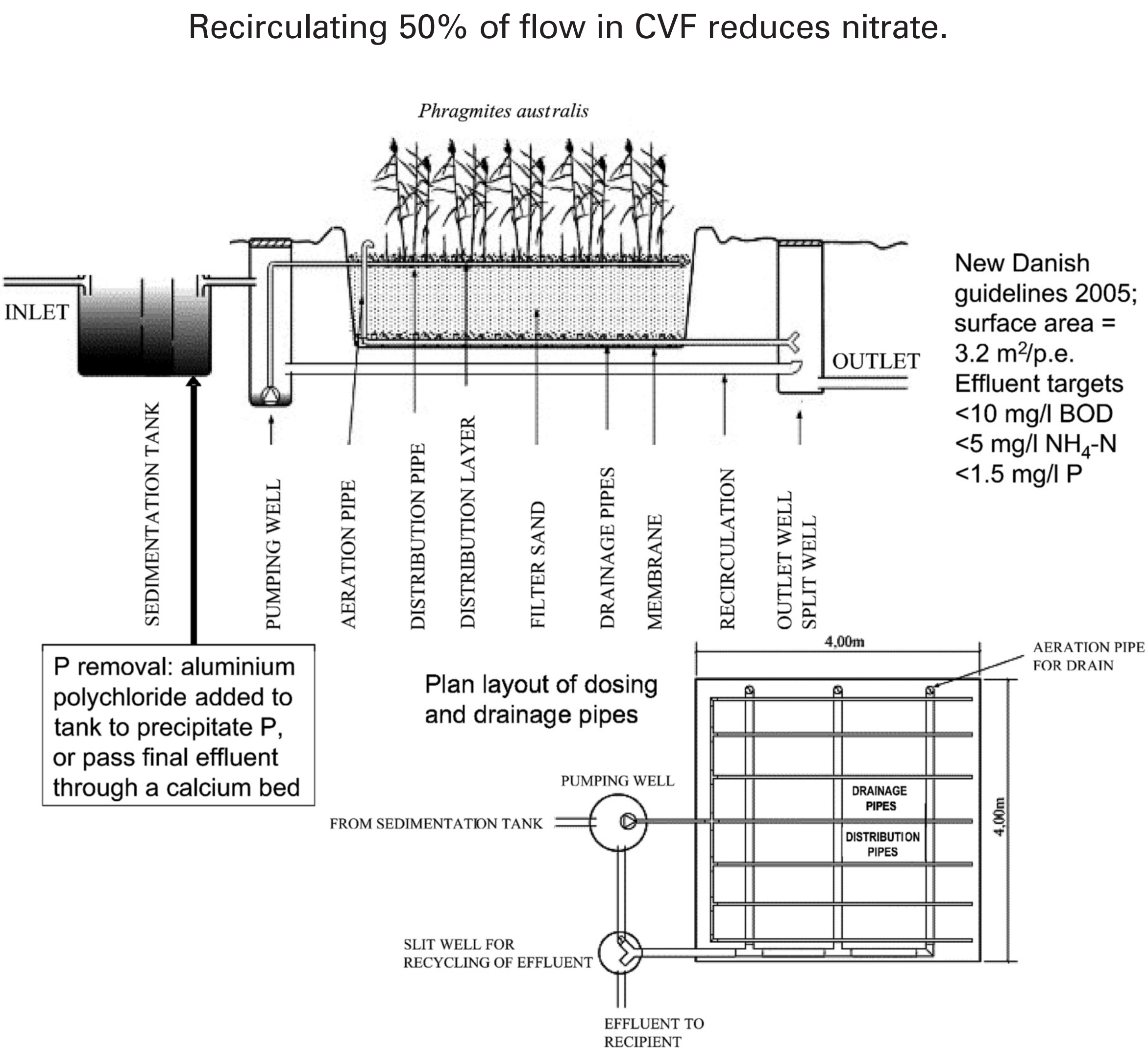


Figure 5. Compact Vertical Flow (CVF) System (Brix and Arias 2005).

Table 1. Multi-stage system, vertical flow (VF) plus horizontal flow (HF), (VF + HF) Oaklands Park, U.K.; performance data (Cooper et al. 1996). BOD and NH_4N reduced in VF stages; NO_3 increased in VF, then reduced in HF beds; PO_4 reduced a little by adsorption.

mg/l	Influent	VF 1	VF 2	HF 1	HF 2	Pond
BOD	285	57	14	15	7	11
NH_4N	51	29	14	15	11	8
NO_3N	2	10	23	10	7	2
PO_4	23	23	17	15	12	11

CALCULATION OF POLLUTANT REMOVAL RATE

Removal kinetics are assumed to follow the law of exponential decline, as in a plug-flow bioreactor, the rate being dependent on both temperature and residence time (Figure 6), according to the equation:

$C_e = C_i\, e^{(-k \cdot tr)}$ equation 1 (Kickuth 1981; EPA 1988)

where: C_e = effluent concentration mg · l^{-1}; C_i = influent concentration mg · l^{-1} ; k = first order reaction rate constant ($days^{-1}$); tr = hydraulic residence time.

It follows that, for a given hydraulic flow, and pollutant load, the required surface area of a CW bed (A) to achieve a particular target output concentration, can be calculated by:

$A = Q\,(\ln C_i - \ln C_e) / (k.\, d.\, n)$ equation 2 (Kowalik et al. 2004)

where: Q = flow rate; d = bed depth; n = porosity; Q, d, n together affect residence time (tr), k is specific for each type of bed and is determined from measurements of C_i, C_e and tr (based on past experience).

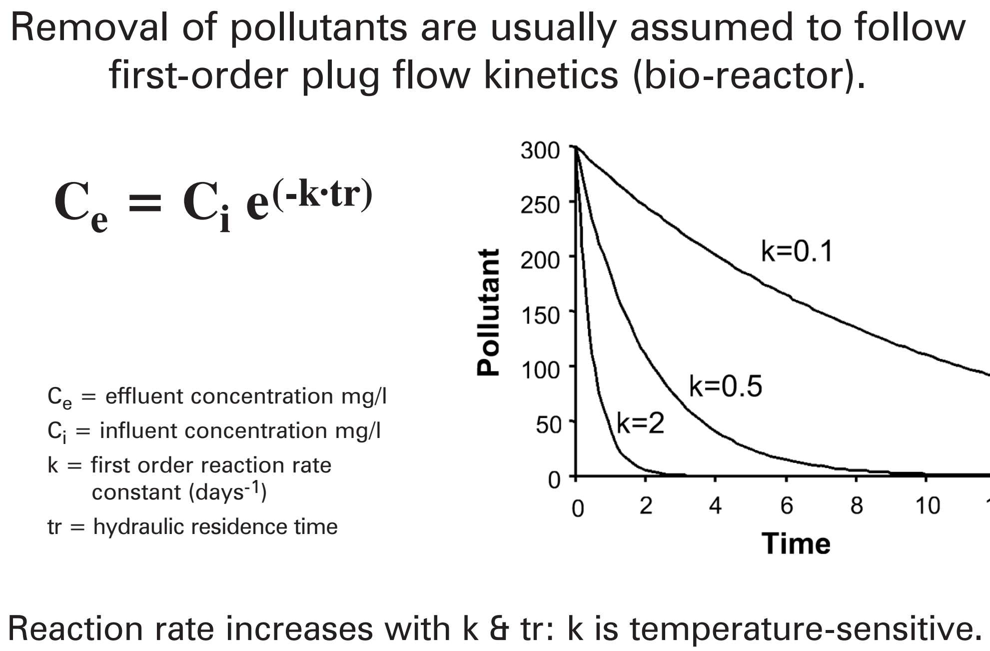


Figure 6. Removal kinetics for a plug-flow bioreactor.

Table 2. Compact Vertical Flow (CVF), Denmark; performance data (2 Hydraulic Loading Rates) (Brix 2003). Area = 2.7 m^2 · $p.e.^{-1}$ Excellent reduction of pollutants in small surface area – suitable for up to 30 p.e. (population equivalent) systems.

mg/l	Influent	CVF 1	CVF 2
HLR mm/d	na	472	236
BOD	237	39	9
NH_4N	137	14	3
NO_3N	<1	7	2

na – not applicable

Hence, in practice, size estimates depend on the design of bed. Areas for sewage treatment CVF beds have been estimated directly from Population Equivalent (p.e.) loads (Cooper 2005). Most estimates are in range 1-3 $m^2 \cdot p.e.^{-1}$, while Cooper's "Rule of Thumb" (Cooper et al. 1996) states: 1 $m^2 \cdot p.e.^{-1}$ for BOD removal only; 2 $m^2 \cdot p.e.^{-1}$ for BOD and NH_4N. Brix (2003) gives 0.9-1.5 $m^2 \cdot p.e.^{-1}$, whereas new Danish guidelines indicate 3.2 $m^2 \cdot p.e.^{-1}$ with 1m depth (assumes load of 60 g BOD $\cdot p.e.^{-1} \cdot d^{-1}$; 12 g $NH_4N \cdot p.e.^{-1} \cdot d^{-1}$; 200 l $\cdot p.e.^{-1} \cdot d^{-1}$) (Brix and Arias 2005).

The critical factor is the oxygen transfer rate (OTR), which can be estimated from empirical data of input/output concentrations for BOD and ammonia.

$$OTR = Q\,[(BODin - BODout) + 4.3\,(NH_4Nin - NH_4Nout)]\,/\,A$$

equation 3 (Cooper 2005)

where: OTR = $gO_2 \cdot m^{-2} \cdot day^{-1}$; Q = flow rate ($m^3 \cdot day^{-1}$); A = total surface area of beds.

The OTR for VF and 2-stage systems are much greater than can be explained by surface diffusion alone (Table 3). Oxygen diffusion rate, calculated from bed surface area, is only 20 $gO_2 \cdot m^{-2} \cdot day^{-1}$ for HF beds (Kowalik, personal communication). These data show that VF systems of a given area are more effective for nitrification than HF, due to greater OTR.

POLLUTANT REMOVAL IN FIELD SYSTEMS

An alternative type of sub-surface flow is a "tidal flow" (TF) system, where water fills the bed from below, and then rapidly discharges through a pump, allowing air to enter from the surface. Hence the sediment matrix cycles between water-filled and aerated phases. Vegetation filter beds with pumped TF (2 small gravel-filled reed beds and 2 gravel / soil willow beds), were used for treating landfill leachate in mid Wales (Kowalik et al. 1996). Leachate, rich in iron and ammonia, flows either via the 2 reed beds to the first willow bed, or directly to the second willow bed, before discharge. In the 2-stage system (reed-willow), ammonia is oxidised in the reed beds producing nitrate, but the nitrate is then removed in the willow bed by uptake and denitrification (Table 4). Alternatively, passing the leachate through a single willow bed works equally well in removing both forms of nitrogen, as it apparently provides both aerobic and anaerobic conditions. A fluorescent dye tracer was used to demonstrate that, as expected, hydraulic flow in the TF bed was well mixed, rather than plug flow (unpublished data).

Another type of vegetation filter is a channel irrigation

Table 3. Oxygen transfer rates calculated for vertical flow (VF) and mixed systems (Cooper 2005). VF beds are more effective for nitrification than horizontal flow (HF), due to greater oxygen transfer rate (OTR).

System type	OTR	Area ($m^2 \cdot p.e.^{-1}$)
2VF + 2HF	40 to 79	1.3
2VF	57 to 71	0.6
1CVF	40	2.1
1VF + 1HF	28	nd
2CVF	51	0.9
3TF (Tidal Flow)	30	2.5

nd – no data

Table 4. Nitrogen reduction in tidal flow (TF) reed and willow filter beds treating landfill leachate in Wales (Kowalik et al. 1996).

(mg/l)	NH_4N in	NH_4N out	NO_3N in	NO_3N out
2 Reed beds (stage 1)	56.0	0.5	4	30
Willow bed (stage 2)	0.5	5.0	30	4
Willow bed (only)	56.0	1.0	4	4

Table 5. Pollutant removal in Poland: willow filter irrigated with wastewater (Kowalik and Randerson 1994). Good removal of BOD, but outlet concentrations of N and P are too high for discharge into water course; hydraulic loading of wastewater too great (insufficient residence time).

Parameter	Pollutant removal	
	% removal	outlet mg/l
BOD	88	19
Total N	41	32
Total P	43	6

system, inter-planted with trees, and flooded intermittently with effluent. Data from such a system planted with willow trees, used for waste-water treatment in Poland (Kowalik and Randerson 1994), shows good removal of BOD, but inadequate reduction of N and P for discharge to a watercourse (Table 5). In this case, the hydraulic loading rate was too great to allow sufficient residence time of the waste-water within the root zone for treatment to be effective. A similar system comprising a 33 ha *Eucalyptus* plantation irrigated with meat processing effluent in New Zealand (Sims, personal communication) also suffered from hydraulic overload, with problems of surface ponding.

Willow vegetation filters are widely used in Sweden for treatment of municipal wastewater and leachate (Aronsson 2000; Aronsson and Perttu 2001; Dimitriou and Aronsson 2003; Elowson 1999; Hasslegren 1998; Wilson and Dawson 2001). The potential for such systems in the U.K. is reviewed by Duggan (2005). Figure 7 shows estimated nitrogen budgets for the willow / soil system under two intensities of application (Aronsson 2000). Fast-growing willow coppice has a high capacity for N removal (~200 kgN $\cdot$ ha^{-1} $\cdot$ y^{-1}), by root uptake, soil binding and denitrification in the root zone, so that even under high N-loading, leaching losses are almost zero. Re-use of wastewater provides a cost-effective fertilizer for biomass crops. Uptake of metals such as cadmium by willow roots, also facilitates soil and water remediation (Dickinson and Pulford 2005; Dickinson et al. 1994; Ostman 1994).

SUB-SURFACE HETEROGENEITY IN CONSTRUCTED WETLANDS – MODELS AND ROOT ZONES

Oxygen has been shown to emerge from willow roots (Figure 8) (Randerson 2007). Methylene blue dye indicates the presence of oxygen; over time, oxygen coming from the roots diffuses throughout the gel.

The sub-surface environment of the CW is non-uniform,

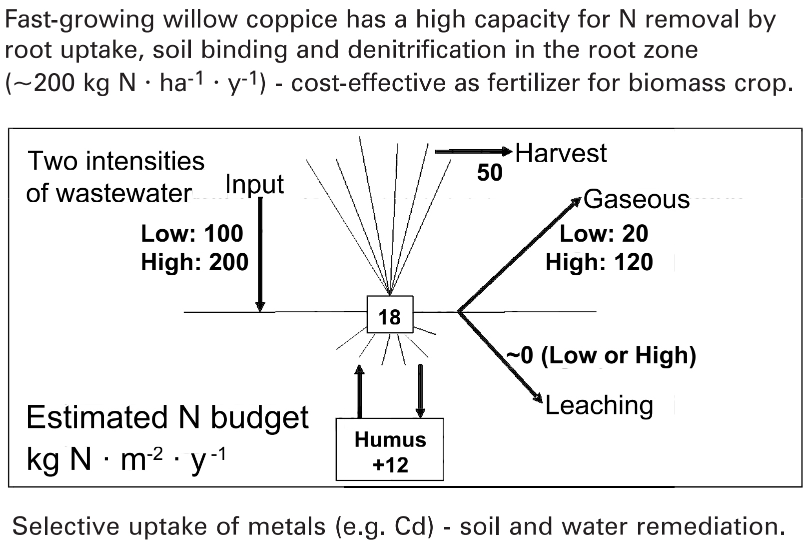


Figure 7. Nitrogen filtration by willow vegetation filters (adapted from Aronsson 2000).

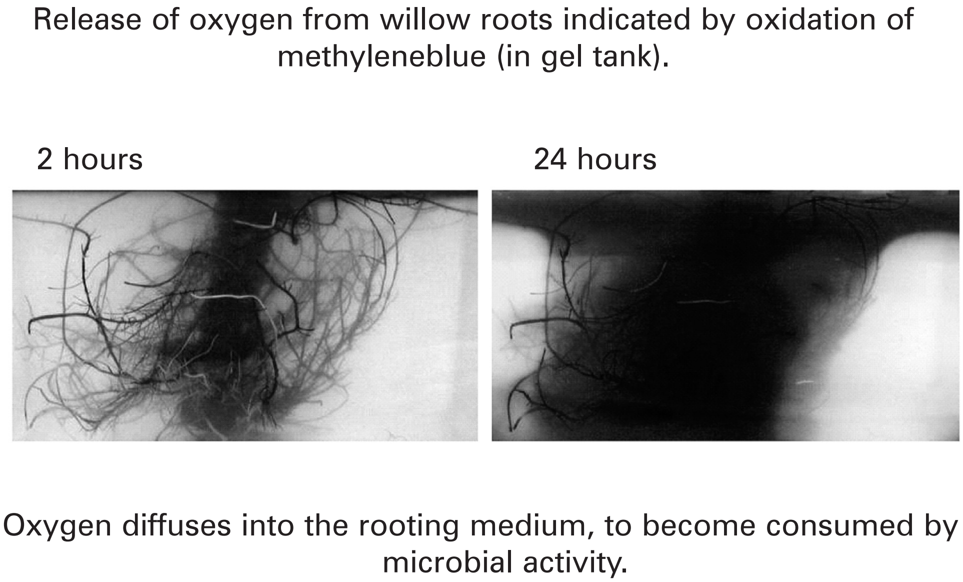


Figure 8. Oxygen emergence from willow roots in a gel tank.

both in space and time and there are micro-zones and micro-gradients which relate to the position of plant roots. Following the concept of root zone oxygenation (Brix 1987), gradients of oxygen and redox potential have been measured in the root zone of wetland plants in the laboratory using micro-electrodes (Allen et al. 2002; Armstrong et al. 2000; D'Angelo and Reddy, unpublished data; Hook et al. 2003; Sorrel and Armstrong 1994). Hence particular microbial transformations take place in restricted locations and aerobic processes such as nitrification, can occur only where there is a source of oxygen. Clearly, this will affect the function of the wetland bed for pollutant removal. According to this model (Figure 9), along the redox gradient different microbial processes take place at different points, using different terminal electron acceptors (Kowalik, personal communication; Randerson 2007).

These processes have been monitored using a mass spectrometer with membrane inlet probes, allowing detection of particular dissolved gases *in situ* in the sub-surface environment, as indicators of local oxic status (Lloyd et al. 1996, 2002; Randerson et al. 2005). Using willow plants in a simple laboratory microcosm, it has been shown roots produce oxygen rapidly in the light, but that process stops in darkness. Clearly, this is related to photosynthesis by the plants. Over a period of several days, the amount of oxygen in the container peaks in the day and declines in the night, when it is consumed. The opposite pattern was shown for carbon dioxide (CO_2). If artificial waste water is added to the container, oxygen is rapidly consumed and stays near zero for 2-3 days while the BOD load is metabolised by the bacteria in the system. When the organic matter has been removed, then oxygen released from the roots starts to accumulate again.

In the field, four probes were used to detect spatial heterogeneity in the root zone of a willow bed treating landfill leachate. The general trend is the same but there are local differences, indicating spatial differences between the depth profiles for oxygen, carbon dioxide and methane. An unexpected result is that there are oxygen peaks at 60 cm depth. A similar depth profile but on a finer scale (lowering the probe at 2.5 cm intervals), showed evidence of both aerobic and anaerobic pockets of microbial activity at various depths (Randerson et al. 2005; Williams et al. 2001).

A camera system was developed to provide images of the undisturbed bed, using a rhizotron tube. It was important to know the location of the probe in relation to the heterogeneity of the soil. Peaks in the oxygen trace were found to correlate with the position of lateral roots of the willow trees, providing direct evidence that oxygen is leaking out from the roots, and locally oxygenating the sub-surface environment.

At a bigger scale, the level of oxygen in the bed was found to fluctuate between high and low in 24 hour cycles. The biggest swings (from fully saturated to anaerobic), occurred on bright sunny days, when photosynthesis was driving the willows at a maximum rate. Carbon dioxide showed the inverse pattern. In a cloudy period the range was greatly reduced. Methane levels remained low during sunny days, but under low oxygen (cloudy) conditions, methane begins to accumulate in

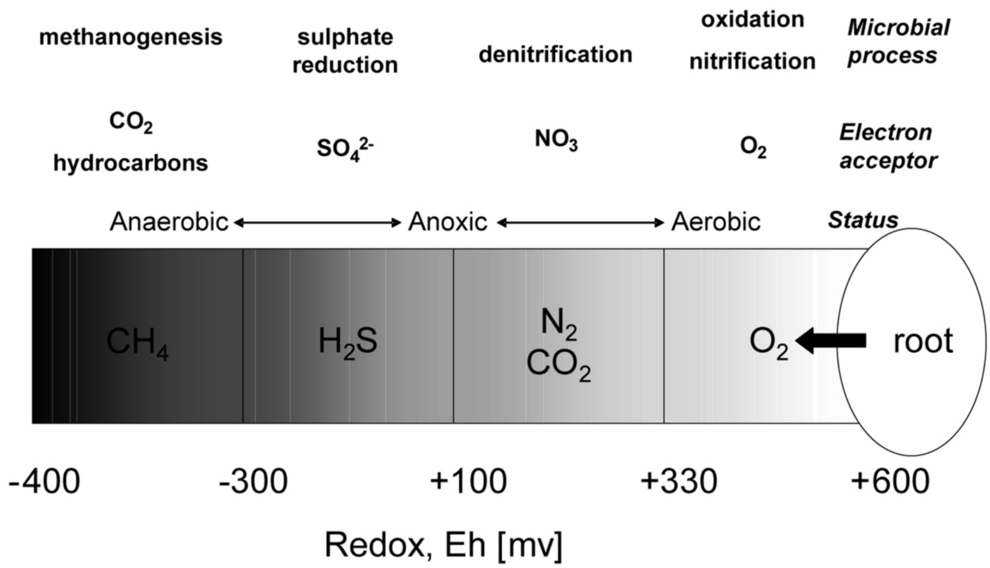


Figure 9. Gas metabolism in the root zone – soil matrix gradient.

the bed. This indicates that methanogenesis, an anaerobic process, can occur alongside oxygen production, due to local spatial heterogeneity in the sub-surface environment (Randerson et al. 2005; Williams et al. 2001).

CONCLUSION

Constructed wetlands are effective in treating polluted waters arising from a wide range of domestic, industrial and agricultural operations. Such eco-technology enables us to re-use water in a cost-effective way, at the same time as creating small areas of wetland wildlife habitat.

REFERENCES

Allen, W.C., P.B. Hook, J.A. Biederman, O.R. Stein. 2002. Temperature and wetland plant species effects on wastewater treatment and root zone oxidation. Journal of Environmental Quality 31: 1010-1016.

Armstrong, W., D. Cousins, J. Armstrong, D.W. Turner, P.M. Beckett. 2000. Oxygen distribution in wetland plant roots and permeability barriers to gas-exchange with the rhizosphere: a microelectrode and modelling study with *Phragmites australis*. Annals of Botany 86: 687-703.

Aronsson, P. 2000. Nitrogen retention in vegetation filters of short-rotation willow coppice. Doctoral Thesis, Swedish University of Agricultural Sciences, Uppsala, Sweden.

Aronsson, P., K.L. Perttu. 2001. Willow vegetation filters for wastewater treatment and soil remediation combined with biomass production. Forestry Chronicle 77: 293-299.

Brix, H. 1987. Treatment of wastewater in the rhizosphere of wetland plants – the root zone method. Water Science and Technology 19: 107-119.

Brix, H. 1993. Wastewater treatment in constructed wetlands: system design, removal processes and treatment performance. In: Constructed Wetlands for Water Quality Improvement (ed. G.A. Moshiri), pp. 9-22. CRC, Boca Raton.

Brix, H. 1997. Do macrophytes play a role in constructed treatment wetlands? Water Science and Technology 35: 11-17.

Brix, H. 2003. Danish experiences with wastewater treatment in constructed wetlands. In: The Use of Aquatic Macrophytes for Wastewater Treatment in Constructed Wetlands (ed. V. Diaz, J. Vymazal), pp. 327-361. Ministerio das Cidades, Ordenamento do Territorio E Ambiente, Lisboa, Portugal.

Brix, H., C.A. Arias. 2005. The use of vertical flow constructed wetlands for on-site treatment of domestic wastewater: New Danish guidelines. Ecological Engineering 25: 491-500.

Brix, H., H.H. Schierup. 1989. Use of aquatic macrophytes in water pollution control. AMBIO AMBOCX 18: 100-107.

Cooper, P.F. 1999. A review of the design and performance of vertical flow and hybrid reed bed treatment stystems. Water Science and Technology 40: 1-9.

Cooper, P.F. 2001. Nitrification and denitrification in hybrid constructed wetland systems. In: Transformations of Nutrients in Natural and Constructed Wetland (ed. J. Vymazal), pp. 257-270. Backhuys Publs. Leiden. The Netherlands.

Cooper, P.F. 2005. The performance of vertical flow constructed wetland systems with special reference to the significance of Oxygen Transfer and Hydraulic Loading Rates. Water Science and Technology 51: 81-90.

Cooper, P.F., G.D. Job, M.B. Green, R.B.E. Shutes. 1996. Reed Beds and Constructed Wetlands for Wastewater Treatment. 184 p. WRc Publ., Medmenham, Marlow, Bucks. U.K.

Cooper, P.F., M. Smith, H. Maynard. 1997. The design and performance of a nitrifying vertical flow reed bed system. Water Science and Technology 35: 215-221.

Dalyell, T. 1995. Down the valley something stirs. New Scientist 21. October 1995. http://www.newscientist.com/article/mg14820006.400-down-the-valley-something-stirs.html

Dickinson, N.M., I.D. Pulford. 2005. Cadmium phytoextraction using short-rotation coppice *Salix*: the evidence trail. Environment

International 31: 609-613.
Dickinson, N.M., T. Punshon, R.B. Hodkinson, N.W. Lepp. 1994. Metal tolerance and accumulation in willows. In: Willow Vegetation Filters for Municipal Wastewater and Sludges: A Biological Purification System (ed. P. Aronsson, K. Perttu), pp. 121-127. Report 50, Swedish University of Agricultural Sciences, Uppsala, Sweden.
Dimitriou, I., P. Aronsson. 2003. Wastewater phytoremediation treatment systems in Sweden using short rotation willow coppice. In: SRC Crops for Bioenergy: New Zealand, pp. 225-228. Swedish University of Agricultural Sciences, Uppsala.
Duggan, J. 2005. The potential for landfill leachate treatment using willows in the UK—A critical review. Resources, Conservation & Recycling 45: 97-113.
Elowson, S. 1999. Willow as a vegetation filter for cleaning of polluted drainage water from agricultural land. Biomass & Bioenergy 16: 281-290.
EPA. 1988. Constructed wetlands and aquatic plant systems for municipal waste water treatment: Design Manual. 83 p. US EPA Publication 625/1-88/022, Centre for Environmental Research Information, Cincinnati, OH 45268.
Evans, D.E. 2003. Aerenchyma formation. New Phytologist 161: 35-49.
Green, M.B., J. Uptown. 1995. Constructed reed beds: an appropriate technology for small communities. Water Science and Technology 32: 339-348.
Hasselgren, K. 1998. Use of municipal waste products in energy forestry: highlights from 15 years of experience. Biomass & Bioenergy 15: 71–74.
Hiley, P.D. 1995. The reality of sewage treatment using wetlands. Water Science and Technology 32: 329-338.
Hook, P.B., O.R. Stein, W.C. Allen, J.A. Biederman. 2003. Plant species effects on seasonal performance patterns in model subsurface wetlands. Advances in Ecological Science 11: 87-106.
Kadlec, R.H., R.L. Knight. 1996. Treatment Wetlands. 893p. CRC Press LLC, Florida.
Kangas, P.C. 2004. Ecological Engineering: Principles and Practice. 504 p. CRC Press LLC, Florida.
Kickuth, R. 1981. Abwasserreinigung in Mosaikmatrizen aus anaeroben und aeroben Teilbezierken. Grundlangen der Abwasserreiningung. GWF Schriftreihe Wasser-Abwasser, 19. Oldenburg Verlag, Oldenburg.
Kowalik, P.J., M. Mierzejewski, H. Obarska-Pempkowiak, I. Toczylowska. 1995. Constructed wetlands for wastewater treatment of small communities. 70 p. Center of Environmental Studies, CENVIG, Polytechnical University of Gdansk.
Kowalik, P.J., M. Mierzejewski, P.F. Randerson, H.G. Williams. 2004. Performance of subsurface vertical flow constructed wetlands receiving municipal wastewater. Archives of Hydro-Engineering & Environmental Mechanics 51: 349-370.
Kowalik, P.J., P.F. Randerson. 1994. Nitrogen and phosphorus removal by willow stands irrigated with municipal wastewater – a review of the Polish experience. Biomass & Bioenergy 6: 133-139.
Kowalik, P.J, F.M. Slater, P.F. Randerson. 1996. Constructed wetlands for landfill leachate treatment. In: Ecotechnics for a Sustainable Society: Proceedings of Ecotechnics 95 – International Symposium on Ecological Engineering (ed. L. Thofelt, A. Englund), pp. 189-200. Mid Sweden University, Harnosand, Sundsvall, Ornskoldsvik, Ostersund.
Landberg, T., M. Greger. 1994. Can heavy metal tolerant clones of *Salix* be used as vegetation filters on heavy metal contaminated land? In: Willow Vegetation Filters for Municipal Wastewater and Sludges: A Biological Purification System (ed. P. Aronsson, K. Perttu), pp. 133-144. Uppsala, Swedish University of Agricultural Sciences, Uppsala, Sweden.
Lloyd, D., K. Thomas, D. Price, B. O'Neil, K. Oliver, T. Williams. 1996. A membrane-inlet mass spectrometer miniprobe for direct simultaneous measurement of multiple gas species with spatial resolution of 1mm. Journal of Microbiological Methods 25: 145-151.
Lloyd, D., K.L. Thomas, G. Cowie, J.D. Tammam, A.G. Williams. 2002. Direct interface of chemistry to microbiological systems: membrane inlet mass spectrometry. Journal of Microbiological Methods 48: 289–302.
Ostman, G. 1994. Cadmium in *Salix* – a study of the capacity of *Salix* to remove cadmium from arable soils. In: Willow Vegetation Filters for Municipal Wastewater and Sludges: A Biological Purification System (ed. P. Aronsson, K. Perttu), pp. 153-155. Report 50, Swedish University of Agricultural Sciences, Uppsala, Sweden.
Perttu, K.L., P.J. Kowalik. 1997. *Salix* vegetation filters for purification of waters and soils. Biomass & Bioenergy 12: 9-19.
Randerson, P.F. 2007. Water quality and Constructed Wetlands. In: Water and Agriculture. Report from International Conference (Bertebos), 14-16 May 2006, Falkenberg, Sweden, pp. 35-38. Kungl. Skogs-och Lantbruksakademiens Tidskrift 1 2007.
Randerson, P.F., F.M. Slater. 2005. The role of willow plants in the treatment of iron-rich landfill leachate. In: Proceedings of the 6th International Conference on Environmental Engineering, Vilnius, Lithuania, pp. 420-424. Vilnius Gediminas Technical University.
Randerson, P.F., G. Jordan, H.G. Williams. 2005. The role of willow roots in sub-surface oxygenation of vegetation filter beds – mass spectrometer investigations in Wales, U.K. In: Wastewater Treatment in Wetlands. pp. 159-165. Technical University of Gdansk, Poland.
Riddel-Black, D. 1994. Heavy metal uptake by fast growing willow species. In: Willow Vegetation Filters for Municipal Wastewater and Sludges: A Biological Purification System (ed. P. Aronsson, K. Perttu), pp. 145-152. Report 50, Swedish University of Agricultural Sciences, Uppsala, Sweden.
Ryszkowski, L., A. Bartoszewicz, J. Marcinek. 1990. Bariery biogeochemiczne [Biogeochemical barriers]. In: Obieg wody i bariery biogeochemiczne w krajobrazie rolniczym [Water Circulation and Biogeochemical Barriers in Agricultural Landscape] (in Polish), pp. 167-181. Poznan, Zaklad Badan Srodowisk Rolniczych i Lesnych, Polish Academy of Sciences (PAN).
Ryszkowski, L., A. Kedziora. 2007. Modification of water flows and nitrogen fluxes by shelterbelts. Ecological Engineering 29: 388-400.
Sorrel, B.K, W. Armstrong. 1994. On the difficulties of measuring oxygen release by root systems of wetland plants. Journal of Ecology 82: 177-183.
Stottmeister, U., A. Wießner, P. Kuschk, U. Kappelmeyer, M. Kästner, O. Bederski, R.A. Müller, H. Moorman. 2003. Effects of plants and microorganisms in constructed wetlands for wastewater treatment. Biotechnology Advances 22: 93–117.
Williams, H.G., P.F. Randerson, F.M. Slater, R.J. Heaton. 2001. Can willow roots oxygenate leachate in vegetation filter beds? – A mass spectrometer investigation in Wales. In: Leachate and wastewater treatment with high-tech and natural systems (ed. W. Hogland, V. Vysniauskaite), pp. 75-81. University of Kalmar, Sweden.
Wilson, F.E.A., W.M. Dawson. 2001. Bioremediation of municipal wastewater using short rotation coppice. Aspects of Applied Biology 65: 329-335.
Wong, C.H., G.W. Barton, J.P. Barford. 2003. The nitrogen cycle and its application in wastewater treatment. In: The Handbook of Water and Wastewater Microbiology (ed. D. Mara, N. Horan), pp. 427-440. Academic, London.