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Wetlands for wastewater treatment: Opportunities and limitations

Jos T.A. Verhoeven [a,*], Arthur F.M. Meuleman [b]

[a] *Department of Plant Ecology and Evolutionary Biology, Utrecht University, P.O. Box 80084, 3508 TB, Utrecht, The Netherlands*

[b] *Kiwa Research and Consultancy, P.O. Box 1072, 3430 BB, Nieuwegein, The Netherlands*

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Abstract

This paper gives some introductory information on the use of wetlands for wastewater treatment. It focuses mainly on the functioning of constructed wetlands, in particular surface-flow and infiltration wetlands. The various processes which lead to water purification are briefly explained, in relation to the factors which influence their efficiency. The possibilities for optimization of the design and management of such systems are illustrated with data on the functioning of a wastewater infiltration wetland in The Netherlands. In general, constructed wetlands can be designed to remove more than 90% of BOD, COD, suspended solids and bacteriological pollution from the through-flowing wastewater. Removal of N and P remains, however closer to 50% in most cases. © 1999 Elsevier Science B.V. All rights reserved.

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1. Introduction

Wetlands have been used for water purification in different parts of the world since the 1950s. Environmental concerns over insufficiently performing individual

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* Corresponding author. E-mail: j.t.a.verhoeven@.bio.uu.nl

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septic systems, as well as high costs involved in the construction of sewer systems with centralized water purification have spurred investigations into the suitability of wetland ecosystems for this purpose. Generally, natural as well as constructed wetlands have been loaded with several types of wastewater. The natural systems include lake marginal wetlands, extensive fen systems and floodplain marshes, in which large helophytes such as *Phragmites australis*, *Typha* spp., *Scirpus* spp., often dominate the vegetation. Constructed wetlands also have helophyte beds and are of two main types: (i) surface-flow wetlands, in which the wastewater is flowing horizontally over the wetland sediment; and (ii) infiltration wetlands, in which the wastewater flows vertically through a highly permeable sediment and is collected in drains. The wastewater applied usually has received only a primary filtration of coarse material; there are also quite a few cases in which a wetland is being used for polishing the effluent of a conventional purification plant. Wetland ecosystems have special characteristics which make them particularly suitable for wastewater purification:

1. They are semi-aquatic systems which normally contain large quantities of water. The flooding caused by wastewater addition is a normal feature of the system.
2. They have partly oxic, partly anoxic soils in which organic matter breakdown takes place through special pathways involving electron acceptors other than oxygen, e.g. nitrate, sulphate and iron. As a result, N as well as P dynamics are very different from those in upland ecosystems.
3. They support a highly productive, tall emergent vegetation capable of taking up large amounts of nutrients and responding to enrichment with nutrients with enhanced growth. The helophytes also aerate the soil rhizophere through aerenchyma in the roots.

Research over the last two decades has accumulated much quantitative information on the performance of these systems. A useful recent review of the current state of the art is the book by Kadlec and Knight (1996), which not only gives detailed documentation on the wastewater purification function of natural as well as constructed wetlands, but also gives elaborate engineering guidelines for the construction and management of wastewater wetlands. An important data base increasingly used in the literature is the North American Data Base (NADB) containing data from over 100 wastewater wetlands compiled for US-EPA by Knight et al. (1992). This data base shows that the performance of wetlands used for water purification depends strongly on the loading rate (wastewater per area per time) and on the wetland's specific hydrological and ecological characteristics. Removal percentages were generally high for COD, BOD and bacterial pollution (80–99% removal in most cases). Removal rates for P and N were lower and more variable. N removal was higher than 50% in most cases, P removal was mostly lower and subject to saturation after prolonged loading. The nutrient removal rates can be optimized by chosing the right loading rate (i.e. prevention of overloading the system), by installing a regime of fluctuating water levels and by the addition of absorbing materials to the wetland sediment.

From a practical standpoint, constructed wetlands offer better opportunities for wastewater treatment than natural wetlands. They can be designed for optimal performance of the BOD, COD and nutrient removal processes and for maximum control over the hydraulic and vegetation management of the wetland. The use of natural wetlands should also be discouraged because of the great conservational value of many of these systems. The characteristics of two types of wastewater wetlands and the processes responsible for the purification of the through-flowing water will be further outlined below. The functioning of these systems and the possibilities for optimization the purification will be illustrated by an example of an infiltration wetland in The Netherlands which has been studied in great detail by Meuleman (1994).

2. Surface-flow wetland

Surface-flow wetlands often include a presettling basin and a number of compartments with a shallow water layer (0.2–0.4 m) planted with helophytes such as *Phragmites*, *Typha* or *Scirpus* spp. The wastewater is often mixed with surface water or purified effluent and generally flows through the system with a minimum residence time of 10 days. The purification processes include:

1. Settlement of suspended solids.
2. Diffusion of dissolved nutrients into the sediment.
3. Mineralization of organic material.
4. Nutrient uptake by micro-organisms and vegetation.
5. Microbial transformations into gaseous components.
6. Physicochemical adsorption and precipitation in the sediment.

On the basis of experience in the USA, it has been established that the purification efficiency of surface-flow wetlands loaded with less than 500 people-equivalent (PE)/ha of domestic wastewater is high for COD and BOD (90%) and for bacterial pollution (99%) but substantially lower for N and P (10–15%) (Kadlec and Knight, 1996). The low removal of nutrients is due to the fact that the most important processes involved occur within the sediment, whereas the wastewater flows over the sediment, so that dissolved nutrients have to penetrate through diffusion, which is a slow process. If the water levels in the wetland are manipulated so that it has alternating wet and dry periods, the efficiency of N and P removal can be doubled.

3. Infiltration wetland

Infiltration wetlands typically have a relatively coarse sediment type (sand) so that the wastewater can easily penetrate the soil. By surrounding the wetland (compartments) with a drainage ditch with a lower water table, the wastewater is forced vertically into the sediment by gravity. The infiltration process can be enhanced by burying drainage tubes at a depth of 60–100 cm. It is essential that the wetland is sealed off from the lower sediment layers by an impervious clay layer or by plastic lining. The vertical water movement brings the wastewater directly into contact with the sediment, where nutrient removal processes are optimal. The coarse sediment also leads to a good aeration of the sediment during the dry part of a wet–dry cycle. Again, such cycles can strongly enhance the removal capacity of the wetland.

Experience with infiltration wetlands in Europe has shown that systems loaded with 800 PE/ha of domestic wastewater had a long-term removal capacity of 80–95% for COD and BOD, 99% for bacterial pollution; 35% for N; and 25% for P. The removal of nutrients can be optimized up to about 50% for N and 40% for P at these loading rates (Schierup et al., 1990; Meuleman, 1994).

4. Nutrient removal processes in wastewater wetlands

As is clear from the previous section, wastewater wetlands generally perform well for COD, BOD and bacterial pollution, but show limited capacity for nutrient removal. The high removal rates for COD and BOD are caused by sedimentation of suspended solids and by rapid decomposition processes in the water and upper soil layers. As nutrient removal is often also an important objective, optimization of the nutrient removal processes should always be attempted. Knowledge of the various nutrient removing processes and the conditions in which they operate optimally is a prerequisite for enhancement of the nutrient removal function.

Table 1 lists a number of important nutrient removal processes and the soil redox and soil acidity conditions in which they occur optimally. The processes leading to N removal are mostly bacterial transformations. Nitrification is the oxidation of ammonium to nitrate by nitrifying bacteria. This process is only operational under aerobic conditions. Denitrification is an anaerobic decomposition process in which organic matter is broken down by bacteria by using nitrate in stead of oxygen as an electron acceptor. The process occurs in two steps: first nitrate is reduced to nitrous oxide, which is subsequently further reduced to atmospheric N. Both end products

Table 1
Some important nutrient removal processes operational in wastewater wetlands with the redox and pH conditions under which they occur

	Soil redox status		Soil base status
	Aerobic	Anaerobic	pH
NO_3 production (nitrification)	+	−	
N_2O production (denitrification)	−	+	6–8
N_2 production (denitrification)	−	+	6–8[a]
P adsorption to iron	+	−	<6.5
P adsorption to aluminium	+	+	<6.5
P adsorption to calcium	+	+	>6.5
Storage in organic matter	+	++	

[a] At $pH < 4$, N_2 production is inhibited and N_2O is the end product of the denitrification.

are gases which are emitted into the atmosphere. Nitrous oxide is a greenhouse gas and excessive emissions may contribute to the global warming problem. At low pH, the second step of denitrification is inhibited, so that all N is released in the form of nitrous oxide. From an environmental quality perspective, the pH of wastewater wetland soils should remain above 6.0, so that a large percentage of the N denitrified will leave the wetland as atmospheric N.

As the N in wastewater is mostly in a reduced state, for a removal into gaseous compounds, nitrification as well as denitrification have to occur. In many wetlands, nitrification rates are much slower than denitrification rates, so that the first process determines the actual rates of the second process as well. This means that aerobic as well as anaerobic conditions are needed for optimization of the denitrification process. This can be achieved by using large emergent plants which aerate the soil through leakage of oxygen from their root aerynchyma, such as *Phragmites australis* (Brix, 1989, 1994; Reddy et al., 1989). Another possibility is to install a water regime of alternating flooded and dry conditions, e.g. a cycle of 2–3 days of flooding followed by 4–6 days of dry conditions.

For P, adsorption of phosphates to soil particles is an important removal process. The adsorption capacity is dependent on the presence of iron, aluminium or calcium in clay minerals or bound to the soil organic matter. Under aerobic, neutral to acidic circumstances, Fe(III) binds phosphates in stable complexes. If the soil turns anaerobic as a result of flooding, Fe(III) will be reduced to Fe(II), which will lead to less strong adsorption and release of phosphates (Faulkner and Richardson, 1989). Adsorption of phosphates to calcium only occurs under basic to neutral conditions. Apart from the reversible nature of the adsorption as soon as the soil redox or base status change, adsorption is also subject to saturation. Each soil has only a certain adsorption capacity and as soon as all adsorption sites will be occupied, no further adsorption will occur (Kadlec, 1985).

Apart from these fast adsorption–desorption processes, phosphates can also be precipitated with iron, aluminium and soil compounds (Nichols, 1983). These processes, which include fixation of phosphate in the matrix of clay minerals and complexation of phosphates with metals, have a much slower rate but are not so easily subject to saturation. If previously adsorbed P is precipitated, the adsorption sites become available again for adsorption of new P.

Storage in accumulating organic matter is another sustainable mechanism removing N as well as P from the through-flowing wastewater. Plant-derived litter is low in N and P just after death, as the plants retranslocate part of the nutrients during senescence. The microbes decaying the litter may take up large amounts of nutrients from the aqueous environment (immobilization), which will be released several months to years later. In most wetlands, part of the organic matter is broken down at such a slow rate that it accumulates as soil organic matter. The N and P contained in this organic matter accumulates along with it and this forms a significant 'removal' process in many wastewater wetlands (Verhoeven and Van der Toorn, 1990).

The vegetation itself functions as a temporary storage of nutrients. Particularly at the start of the growing season, large quantities of nutrients are taken up by the

Table 2
Removal percentages for COD, BOD and bacteriological pollution in the infiltration wetland near Lauwersoog, The Netherlands (after Meuleman, 1994)

	Loading (t/ha per year)	Removal (%)
COD	18	81
BOD	7	95
Total N	2.8	35
Total P	0.4	26
	Wastewater (*n*/l (summer))	
F-specific viruses	5.4×10^8	>99.9
E. coli	4.6×10^8	>99.9
MPN Thermotol. bact.	3.9×10^8	>99.9

root system. If the vegetation is not harvested, most of these nutrients end up in the litter compartment. In autumn and winter, a large part of the nutrients will be gradually released again through leaching and organic matter mineralization. Only a small part of the nutrients taken up stays in the vegetation as additional long-term storage in aggrading wood or rhizome material. If the vegetation is harvested, the amounts of nutrients released in autumn and winter is substantially lower. Harvesting the vegetation at a moment in late summer, before retranslocation of nutrients to the root system occurs, but after the senescence of the plants has started so that they will survive the mowing, can substantially contribute to the nutrient removal capacity of a wetland (Brix, 1994; Kadlec and Knight, 1996).

5. Performance of an infiltration wetland in The Netherlands

To illustrate the wastewater purification capacity of wetlands, we will give an overview of the performance of a wastewater infiltration wetland which has been in operation for 10 years as a treatment facility for a recreational housing project. The 1.3 ha constructed wetland was located near Lauwersoog in the northern part of The Netherlands and was studied intensively with respect to water and nutrient budgets, COD and BOD removal, bacterial pollution and the contribution of the plant uptake, harvesting, soil bacterial and physicochemical processes to the total nutrient removal (Meuleman, 1994). The facility consisted of four compartments planted with *Phragmites australis* which were alternately flooded for 4 days and allowed to dry for 10 days. The wastewater infiltrated in the sandy sediment and was collected in drainage tubes at a depth of 60 cm after vertical passage through the soil. No substances had been added to the sediment to promote P adsorption. The wastewater loading rate differed between the summer and winter season and averaged about 1000 people equivalents, which is similar to loading rates shown in Table 2.

The removal percentages for COD, BOD and bacteriological pollution were high to very high (Table 2). N as well as P removal were substantially lower. For N the total removal was 35% through the combined effect of four processes, i.e. harvesting of the reed stands; seed fall from the reed inflorescences; accumulation in soil organic matter and denitrification, which each had about the same importance. The total removal for P was 25%, more than half of which was due to accumulation in the soil. The removal through mowing and seed fall were quantitatively less important. The nutrient removal capacity could be enhanced in two ways. If harvesting would take place in October rather than in January and if the wet–dry cycle would be shortened to 2 days of flooding followed by 5 days of low water levels, the removal of N and P would increase to 50 and 40%, respectively (Meuleman, 1994).

The effluent quality of this infiltration wetland is compared to some existing or planned discharge standards for wastewater treatment facilities effluent in The Netherlands and Europe in Table 3. It is clear that the effluent is of sufficient quality according to the standards for BOD, COD, suspended solids and bacteriological pollution. The concentrations of N and P are, however, well above the discharge standards. Optimalization of the design and management of the wetland would make the differences distinctly smaller, but they would remain above the standard values for both elements.

6. Concluding remarks

Wetlands may be the better alternative for wastewater purification in the following examples:

1. Remote location of small residential areas which excludes the connection to conventional sewer systems. Examples of such small-scale wastewater wetlands include cases from cold climates where they proved to work under winter conditions if a snow cover is present (Brix, 1994).
2. Recreational facilities which are mostly used during the warmer season. A constructed infiltration wetland in Holland receiving sewage from 800 people-equivalents removed 99% of bacterial pollution, 80–90% of COD and BOD and 30–40% of N and P.

Table 3
Performance of the Lauwersoog wastewater infiltration wetland after prolonged loading with 800 PE/ha, in comparison with some European discharge standards (after Rijs, 1994)

Parameter	Discharge standards[a]	Effluent quality	Removal (%)
BOD (mg/l)	20	9	95
COD (mg/l)	125	100	80
N-total (mg/l)	15	28	35
P-total (mg/l)	2	7.5	25
Suspended solids	30	7	99
E. coli	10 000	20	99.99
F-specific viruses	–	<20	99.99

[a] Issued by the European Union and the Dutch Government.

3. Wastewater purification plants which discharge their effluent in relatively small streams or catchments. A well-designed wetland system is capable of further improving the effluent quality regarding nutrients.
4. Wastewater from farms can be treated in small farm reed beds. There are many examples in which grey water from cleansing milking facilities or stables has been purified with constructed wetland systems.

A good conceptual design of any wastewater wetland before it is being built is of paramount importance for a successful operation. The design should take into account the type of wastewater and the loading rate, the hydrological and climatological setting of the designed wetland, the sediment and plant types to be used and the management needed for operation of the wetland. It is much more sensible to allow a little more time and money for the design and for an evaluation of the functioning of the wetland once it has been built, than to build one which will not do the job, even without you knowing it because there is no money left for proper monitoring.

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