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USE OF CONSTRUCTED WETLANDS IN WATER POLLUTION CONTROL: HISTORICAL DEVELOPMENT, PRESENT STATUS, AND FUTURE PERSPECTIVES

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ABSTRACT

During the last two decades the multiple functions and values of wetlands have been recognized not only by the scientists and managers working with wetlands, but also by the public. The ability of wetlands to transform and store organic matter has been exploited in constructed wetlands. This paper summarizes the state-of-the-art of the uses of constructed wetlands in water pollution control by reviewing the basics of the technology, the historical development, and the performance expectations with focus on the use of free water surface and subsurface flow constructed wetlands for municipal wastewater treatment. Performance data from a total of 104 subsurface flow systems and 70 free water surface flow systems are reviewed. The present state of knowledge is sufficient to apply constructed wetlands as a tool for improving water quality. The potential applications range from secondary treatment of municipal and various types of industrial wastewaters to polishing of tertiary treated waters and diffuse pollution. In many situations constructed wetlands is the only appropriate technology available. The treatment capacity of subsurface flow systems can be improved by selecting vertical flow systems with intermittent loading, by proper media selection, and by recycling of the wastewater. Further research is needed to help define and optimize engineering design criteria and the long-term performance capabilities and operational problems.

KEYWORDS

Subsurface flow systems, free water surface flow systems, suspended solids, biochemical oxygen demand, nitrogen, phosphorus, reaction rate constants

INTRODUCTION

Wetlands are among the most important ecosystems on Earth because of their unique hydrologic conditions and their role as ecotones between terrestrial and aquatic systems (Mitsch and Gosselink, 1993). Although many uses and values of wetlands are evident, historically wetlands have been regarded as wastelands which if possible, should be turned into something else that would be more useful (Patten, 1990). Wetlands have been drained, turned into agricultural land and commercial and residential developments at an alarming rate (Mitsch and Gosselink, 1993). However, during the last two decades the multiple functions and values of wetlands have been recognized not only by the scientists and managers working with wetlands, but also by the public. The ability of wetlands to transform and store organic matter and nutrients has resulted in wetlands often being described as "the kidneys of the landscape" (Mitsch and Gosselink, 1993). This ability is being exploited in wetlands used for water quality improvement. With the proclamation of the now famous wetland policy of "no net wetland loss" by former U.S. President Bush and the increased environmental awareness, the interest in wetland values and wetland uses has accelerated.

This paper attempts to summarize the state-of-the-art of the uses of wetlands in water pollution control by reviewing the basics of the technology, the historical development, the performance expectations, and by identifying research needs. As evidenced by the great number of books and specialized conference proceedings (Godfrey *et al.*, 1985; Athie and Cerri, 1987; Reddy and Smith, 1987; Hammer, 1989; Cooper and Findlater, 1990; Etnier and Guterstam, 1991; Moshiri, 1993; Bavor and Mitchell, 1994) , the technology has developed so rapidly and in such a diverse manner during the last ten years as to make a complete review of the technology impossible within the scope of this paper. Therefore focus will be put on the use of free water surface and subsurface flow constructed wetlands for municipal wastewater treatment.

CONCEPTS

Constructed wetlands are wetlands intentionally created from nonwetland sites for the sole purpose of wastewater or stormwater treatment, whereas *created wetlands* are intentionally created from nonwetland sites to produce or replace natural habitat (Hammer, 1992). Until the late eighties the term *artificial wetlands* was used in the literature in place of constructed wetlands, but nowadays the latter is preferred by most wetland scientists. Constructed wetlands can be classified according to the life form of the dominating macrophyte in the wetland into (i) *free-floating macrophyte-based systems*, (ii) *emergent macrophyte-based systems*, and (iii) *submerged macrophyte-based systems* (Brix, 1993a). The development of constructed wetlands based on free-floating aquatic macrophytes (e.g. water hyacinths and duckweeds) has been stimulated by the desire to provide nutrient removal and upgrade the performance of conventional stabilization ponds, and a lot of work has been published about the design, performance and operation of these systems (Dinges, 1982; Reddy and DeBusk, 1987; Hancock and Buddhavarapu, 1993). The use of submerged macrophytes for wastewater treatment is still in the experimental stage (McNabb, 1976; Bishop and Eighmy, 1989; Gumbricht, 1993). Present-day knowledge suggest that their prime area of application will be as a final polishing step after primary and secondary treatment. Systems based on free-floating and submerged macrophytes will not be treated further in this paper.

Emergent macrophyte-based systems can be constructed with *free water surface flow, subsurface horizontal flow*, and *vertical (non saturated) flow*. Free water surface flow systems are flooded and expose the water surface in the systems to the atmosphere, whereas in the subsurface flow systems the water level is maintained below the surface of the medium placed in the beds. In systems with subsurface horizontal flow the medium is maintained water-saturated, whereas in vertical flow systems the medium is not saturated, because water is usually applied at timed intervals and allowed to percolate through the medium (similar to intermittent sand filters). All types of systems contain at least one species of rooted emergent aquatic macrophyte planted in some type of medium (usually soil, gravel, or sand). The pollutants are removed through a combination of physical, chemical, and biological processes including sedimentation, precipitation, adsorption to soil particles, assimilation by the plant tissue, and microbial transformations (Watson *et al.*, 1989; Brix, 1993a).

HISTORICAL DEVELOPMENT

The use of wetlands for improving water quality is not a new invention. As long as man has discharged sewage and other wastewaters, wetlands have more or less intentionally been involved in the cleaning of the water. Wastewater is usually discharged, directly or indirectly, into depressions in the landscape. If a wetland is not already present at the site, the discharge of water will very quickly lead to the formation of a wetland (Cooper and Boon, 1987). Even today the sewage from many single houses and farms in rural areas is disposed of in ditches or subsurface infiltration systems very close to the residences, often giving

DRAINAGE

The drainage of suburban houses is always giving trouble and is a matter about which most people seem utterly helpless. In districts where there is no sewerage system householders find that every day they have a large amount of dirty water to dispose of, and the difficulty is to know how to get rid of it. People who live on high ground throw it into an open drain and let it run away to the lower ground where it generates foul gases which breed disease. Others allow all their dirty water to run into the street where it flows along the gutters filling the air with foul odours and causing typhoid and kindred maladies. If people live near a creek or natural water course they send their drainage into that, thereby polluting it and turning one of the beauties of nature into a poisonous sewer which carries disease germs a long distance. Should people happen to live near a river or an arm of the sea they think that of course that is the proper place for getting rid of what they do not want. For the last 100 years or so, Sydney Harbour has been looked upon as a huge receptacle for the people of Sydney wherein to throw all their abominations, both solid and liquid.

Surely, after all, in spite of our boasted civilization, we are little better than the savages when our ways are so unclean. When you remonstrate with anyone he says, "Well what am I to do?". Very true, it must certainly go somewhere; but most people put it in the wrong place and they are really too lazy to take up the question for themselves and work at it, but expect the municipal council or the government to do all that is necessary and to relieve them of all responsibility in the matter. This tendency to lean upon others is a bad sign and the sooner we learn to think and act for ourselves and put our own shoulder to the wheel the better it will be for all concerned. If every householder disposed of his own drainage on his own premises as he might very easily do, the health of all of us would be much improved. Anyone who has a little ground about his house can dispose of his dirty water as follows:

Dig up a plot of ground thoroughly to a depth of from fifteen to eighteen inches. Cut a channel leading from kitchen and washhouse into the highest side of the plot and let all the dirty water drain into it. Plant the plot with plants that grow rapidly and require a great deal of water such as Arum Lilies, for instance. The dirty water will be all absorbed by the roots of the plants and a most luxuriant garden will be produced which will defy the hottest weather and will be always green and beautiful. By this means a curse will be transformed into a blessing.

The writer is acquainted with a gentleman living in Hornsby having a very large establishment who disposes of all his drainage in this way. He has seven channels leading to seven parts of his garden. Every day he changes the course of his drainage so that each channel is only used one day a week. He has found the scheme to work most successfully and raises luxuriant crops of vegetables even in the driest weather. Of course this scheme requires that the householder should have a certain amount of land, the more the better, but anyone with a fair sized back yard can carry it out. Twenty or thirty feet square properly worked would be enough for any ordinary family. The more sloping the land the better this scheme works.

Extract from an essay written by Nemo to the head of the Hornsby Literary Institute in 1904

rise to a typical wetland at the site of discharge. The functioning of these systems in relation to treatment of the wastewater is poorly documented, but it remains an acceptable solution in many areas. The term constructed wetland is a rather new invention even if the concept is very old. We know ancient Chinese and Egyptian cultures have been using wetlands for disposal of wastewater for many years. The oldest documentation of use of constructed wetlands I have been able to find was presented to me by Brian Mackney, NSW, Australia. He came across a handwritten note written in 1904 concerning the use of constructed wetlands (see above).

Much later, in 1953, Dr. Käthe Seidel in a report from the Max-Planck Institute discussed the possibility "to lessen the overfertilization, pollution and silting up of inland waters through appropriate plants so allowing the contaminated waters to be capable of supporting life once more" (Seidel *et al.*, 1978). She suggested for this purpose the common bulrush (*Schoenoplectus lacustris*), having observed in her research work that this species was capable of removing large quantities of organic and inorganic substances from contaminated water. In further experiments in the fifties Dr. Seidel showed that *Schoenoplectus* "improves and enriches the soil on which it grows in bacteria and humus and that it apparently exudes antibiotics". A range of bacteria (Coliforms, Salmonella and Enterococci) obviously disappeared from polluted water by passage through a vegetation of bulrushes (Seidel, 1964; Seidel, 1966). Experiments were also conducted with degradation of heavy metals and hydrocarbons (phenol and its derivatives) which showed that bulrushes and other higher plants were able to eliminate those from water (Seidel, 1966). In the sixties these promising laboratory scale observations were expanded to a number of full-scale trial systems treating the wastewaters from different industrial processes, river water for obtaining drinking water, road runoff and domestic sewage (Seidel *et al.*, 1978).

The pioneer work by Dr. Seidel resulted in the development of a system now known as the *Max-Planck-Institute-Process* or the *Krefeld System* (Seidel and Happel, 1981). This design consists basically of four to five stages in cascades, each with several basins laid out in parallel and planted with emergent macrophytes in gravel. The first two wetland stages consist of intermittently loaded parallel vertical flow beds with a top layer of sand planted with macrophytes followed by bottom layers of gravel. The following stages consist of horizontal flow cells containing sand or gravel with various species of emergent macrophytes. Performance of the systems is generally reported to be good (Haberl *et al.*, 1983; Boutin, 1987). However, operational difficulties have been experienced with clogging and ponding (Lienard *et al.*, 1990). Systems exist in France (Boutin, 1987; Lienard *et al.*, 1990), Austria (Haberl *et al.*, 1983), England (Burka and Lawrence, 1990), and in North America (Lakshman, 1979; Watson, 1992).

Based on Dr. Seidel's ideas, large scale treatment systems, now known as the *Lelystad Process*, were developed by the Ijsselmeerpolders Development Authority in Holland starting in 1967 (Jong, 1976). The first treatment facility was constructed to treat the wastewater from a camping site near Elburg accommodating up to 6000 people per day in the summer. The treatment system was a star-shaped free water surface flow wetland with an area of 1 ha and a water depth of 0.4 m (Jong, 1976). Because of problems with the maintenance of this design, the subsequent systems consisted of up to 400 m long shallow ditches that could be mechanically maintained (Kok, 1974). Since then numerous systems of this design have been constructed in Holland, some of them incorporating infiltration fields planted with reeds (Greiner and Jong, 1984).

The work of Dr. Seidel stimulated other institutions in Germany to be involved in the study of wetland treatment of wastewater (Seidel *et al.*, 1978). In the early sixties Dr. Seidel cooperated with Dr. R. Kickuth from the Institute für Bodenkunde at the University of Göttingen. Dr. Kickuth developed the concept of the *Root Zone Method* (German: Wurzelraumentsorgung) in the mid sixties (Kickuth, 1970; Kickuth, 1980; Kickuth, 1982). The Root Zone design typically consists of a rectangular bed planted with reeds (*Phragmites australis*) in selected soils (light clay or heavy top soil) that may include calcium and iron or aluminium additives to improve the soil structure and the precipitation capacity for phosphates. Water is flowing horizontally through the rhizosphere of the reeds as subsurface horizontal flow. During passage of the wastewater through the reed bed, organic matter is decomposed, nitrogen should be nitrified and subsequently denitrified, and phosphorus should be accumulated in the soil as a consequence of co-precipitation with calcium, iron and aluminium compounds. Inlet and outlet constructions at opposite ends of the bed distribute and collect the wastewater. The water level is typically maintained just below the surface. Performance claims for the design has not generally been attained and design values advocated by Dr. Kickuth and his representatives have generally been too optimistic (Brix, 1987a; Brix, 1987b; Brix and Schierup, 1989a). The primary failure has been Dr. Kickuth's predicted increase in soil permeability with time, resulting in flow predominantly occurring as surface flow over most of the beds (Brix and Schierup, 1989b). Also, the capacity of the reeds to transfer oxygen to the rhizosphere is generally considered to be much less than claimed by Dr Kickuth (Brix, 1990; Brix, 1993b).

In North America, observations of the assimilative capacity of natural wetlands led to the experimentation with different designs of constructed wetlands in the seventies (Spangler *et al.*, 1976; Wolverton, 1982). Most of the initial work was related to the use of natural wetlands for treatment of wastewater or as receivers for treated effluents (Nichols, 1983). However, it soon became obvious that application of wastewater to natural systems is likely to cause significant changes in species composition, community structure and function, and therefore the wetland's overall value. It was realized that constructed wetland systems have a much greater potential for application, because of the opportunity to optimize control over the treatment processes and because constructed wetlands do not interfere with the values of natural wetlands (Reed and Bastian, 1985).

The early European work influenced the development of the constructed wetlands technology in the United States. In the late sixties, research conducted at NASA's National Space Technology Laboratories in Mississippi led to the development of a "hybrid wastewater treatment system using anaerobic microorganisms and reed (*Phragmites communis*)" (Wolverton, 1982), and in 1976 the National Academy of Science published a book entitled *Making Aquatic Plants Useful: Some Perspectives for Developing Countries* (Anonymous, 1976), in which the European systems as well as the early systems developed by NASA were described. The gravel-based systems developed at NASA (Wolverton *et al.,* 1976) were further developed by Gersberg and co-workers, who found that systems planted with bulrushes were especially efficient in removing suspended solids, BOD, Coliform bacteria as well as nitrogen (Gersberg and Goldman, 1983; Gersberg *et al.,* 1984; Gersberg *et al.,* 1986; Gersberg *et al.,* 1989a; Gersberg *et al.,* 1989b). Different concepts of constructed wetlands design were developed in North America. At Brookhaven National Laboratory the *Marsh Pond Meadow* system was developed (Watson *et al.,* 1987; Conway and Murtha, 1989; Davido and Conway, 1989), a system consisting of a lateral-flow marsh planted with cattails (*Typha latifolia*) in a sand medium, a facultative pond, and a meadow planted with reed canary grass (*Phalaris arundinacea*). Other pioneering work was conducted in various States in North America (Spangler *et al.,* 1976; Watson, 1992; Bastian and Hammer, 1993). The promising results of these early projects resulted in the construction of other key projects in the 1980's, including the pilot and full-scale marshes at Arcata, California (Gearheart *et al.,* 1989), the pilot-scale marshes at Listowel, Ontario (Herskowitz *et al.,* 1987) and the Tennessee Valley Authority demonstration projects in Kentucky (Watson *et al.,* 1990).

PRESENT STATUS

Free water surface flow wetlands: The use of free water surface flow wetlands for wastewater treatment has developed very slowly in Europe since the ditch system at the Ijsselmeerpolders in Holland was constructed 25 years ago (Jong, 1976). In France, attempts were made to improve the performance of waste stabilization ponds by planting cattails (*Typha latifolia*) in successive ponds but with little success (Boutin *et al.,* 1987). Recently, a 22 ha free water surface flow wetland has been constructed in Sweden to reduce nitrogen in effluent from a 6 500 PE wastewater treatment plant before it is discharged into the Baltic Sea (Wittgren, H.B., personal communication 1994). There is a lot of interest in the potential for restoring wetlands that were previously drained and turned into agricultural land. A good example of this is to be found in Hungary, where a series of shallow wetlands have been restored on earlier drained agricultural land in order to create a buffering zone for improving the water quality of the main tributary to Lake Balaton (Brix and Schierup, 1989c).

In North America free water surface flow wetlands are the dominant type of wetland used for wastewater treatment. The total number of wetland treatment systems in North America is at least 200, of which about two-thirds are systems with free water surface flow (Knight *et al.,* 1993). About half of the free water surface flow systems are natural wetlands used for treatment of various types of wastewaters (Knight *et al.,* 1993). The size of the natural wetlands varies from less than 1 ha to larger than 1 000 ha, with about 50% being in the range of 10-100 ha (Fig. 1b). The constructed free water surface flow wetlands are generally smaller in size: approximate 60% are less than 10 ha. In general, the hydraulic loading rate is less for natural wetland than for constructed free water surface flow wetlands, although it is clear that no design consensus exists (Reed and Brown, 1991). Systems designed to treat effluents with very low levels of nitrogen and phosphorus (or for complete retention) generally have very low surface area specific loading rates, whereas systems designed to remove BOD and SS generally have somewhat higher loading rates (Reed and Brown, 1991). The depth of water in the systems ranges from 5 to 90 cm, although 30-40 cm is common. The most common pretreatments are facultative and aerated lagoons reflecting the fact that many of the systems have been constructed as polishing steps for an existing lagoon system (Reed and Brown, 1991).

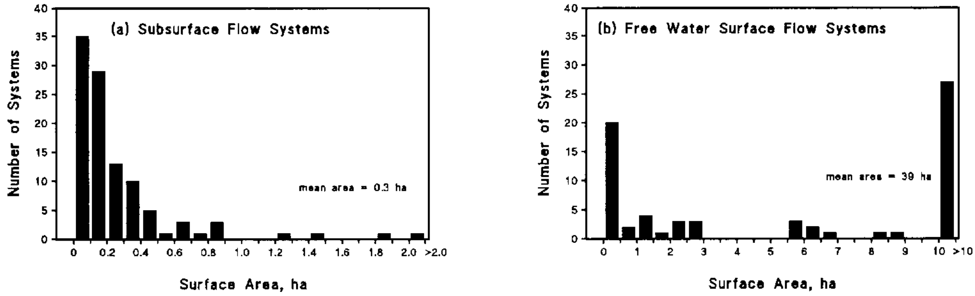

Fig. 1. Size distributions of (a) subsurface flow (n=104), and (b) free water surface flow (n=68) constructed wetlands

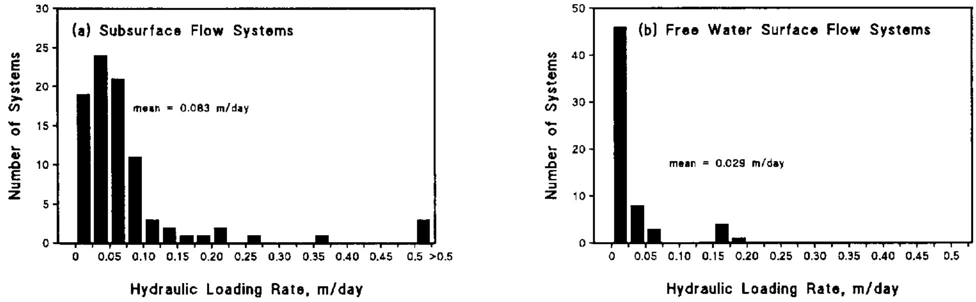

Fig. 2. Frequency distribution of hydraulic loading rate of (a) subsurface flow (n=89), and (b) free water surface flow (n=62) constructed wetlands

Subsurface flow wetlands: In Europe several hundred soil and gravel-based subsurface flow systems have been constructed. In each of the countries Denmark, Germany and United Kingdom about 200 systems are at present in operation, and the technology is still spreading at a fast rate, especially in some of the East-European countries. Most systems are planted with the Common Reed (*Phragmites australis*), but some systems include other species of wetland plants. The medium in the systems is soil in most of the Danish and German systems. It was believed that the growth of roots and rhizomes of the reeds would increase and stabilize the hydraulic conductivity. This has not occurred, and therefore nearly all of the soil-based systems are plagued with problems of surface runoff. In the UK and North America most systems are constructed with a gravel medium which secures subsurface flow. Problems with clogging of gravel media have occurred in some systems, mainly as a consequence of insufficient mechanical pretreatment of the wastewater. In Europe the systems tend to be aimed at providing secondary treatment for village-sized communities of up to approximately 1 000 PE, whereas in North America, they tend to be used for tertiary treatment from larger populations. In Australasia and South Africa subsurface flow systems are used for treatment of a wide variety of wastewaters (Bavor *et al.*, 1987; Davies and Hart, 1990; Wood, 1990; Oostrom and Russell, 1994). As opposed to the large surface areas and low hydraulic loading rates of free water surface flow systems, subsurface flow systems generally have small surface areas (<0.5 ha; Fig. 1a) and higher hydraulic loading rates (Fig. 2a).

TREATMENT PERFORMANCE

The data presented in Figs. 1-9 are based on data obtained from a database on North American treatment wetlands (Knight *et al.*, 1993; USEPA, 1993), data from the Byron Bay free water surface flow wetland systems in Australia (Andel *et al.*, 1993), data from UK (Coombes, 1990) and Danish subsurface flow

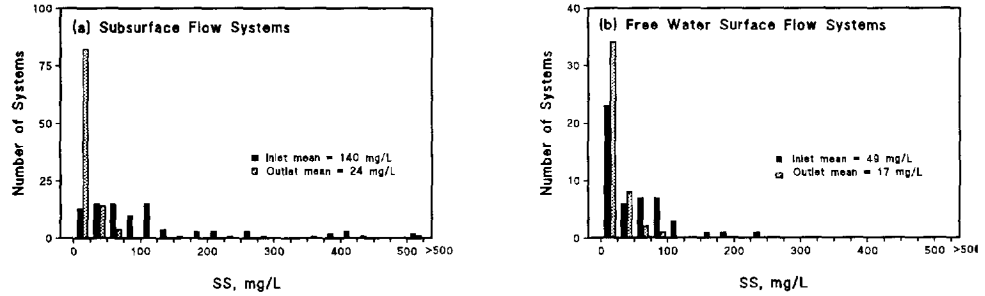

Fig. 3. Frequency distribution of inlet and outlet concentrations of SS in (a) subsurface flow (n=101), and (b) free water surface flow (n=49) constructed wetlands

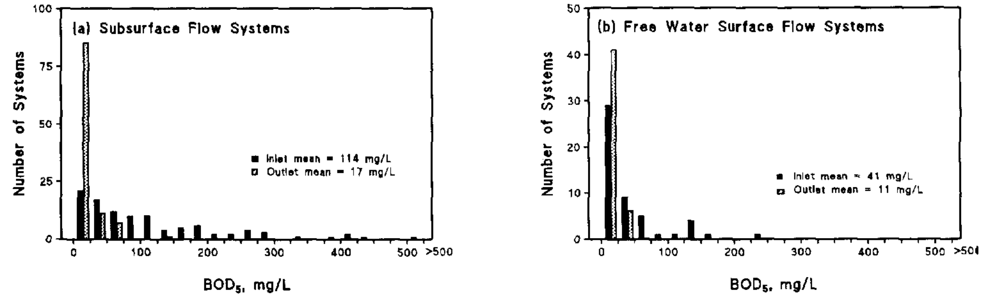

Fig. 4. Frequency distribution of inlet and outlet concentrations of BOD_5 in (a) subsurface flow (n=89), and (b) free water surface flow (n=51) constructed wetlands

systems (Schierup *et al.*, 1990). The graphs are based on performance data from a total of 104 subsurface flow systems and 70 free water surface flow systems. Due to the potential variability of data quality and validation for some of the systems, the results presented must be cautiously interpreted.

Suspended Solids: Suspended solids are generally efficiently removed in both types of constructed wetlands. The inlet concentrations of SS vary from very low levels (< 20 mg/L) for systems constructed for tertiary treatment, to moderate to high for systems constructed for secondary treatment (Fig. 3). Outlet concentrations are generally less than 20 mg/L and often less than 10 mg/L. Higher outlet concentrations are generally caused by planktonic production in open water areas of the systems.

Biochemical Oxygen Demand: The different applications of subsurface flow and free water surface flow wetlands (secondary versus tertiary treatment) are reflected in the inlet concentrations of BOD_5 (Fig. 4). Outlet concentrations of less than 20 mg/L are easily obtained in both system types and much lower levels can be reached. All wetlands, natural and constructed, possess a carbon cycle which produces low levels of BOD (1-3 mg/L) which defines the lower limit of BOD_5 that can be reached in the effluent.

Phosphorus: The principal goal of many of the free water surface flow wetland systems is phosphorus removal, whereas subsurface flow systems mainly are designed to reduce SS and BOD. This is reflected in the performance of the two types of systems (Fig. 5). Most free water surface flow systems produce effluents with < 1 mg/L of total phosphorus, while outlet concentrations from subsurface flow systems vary. Phosphorus removal in constructed wetlands occurs mainly as a consequence of adsorption, complexation, and precipitation reactions with aluminium, iron, calcium and clay particles, and by peat accretion (accumulation of organic matter). Of these, peat accretion is the most sustainable process.

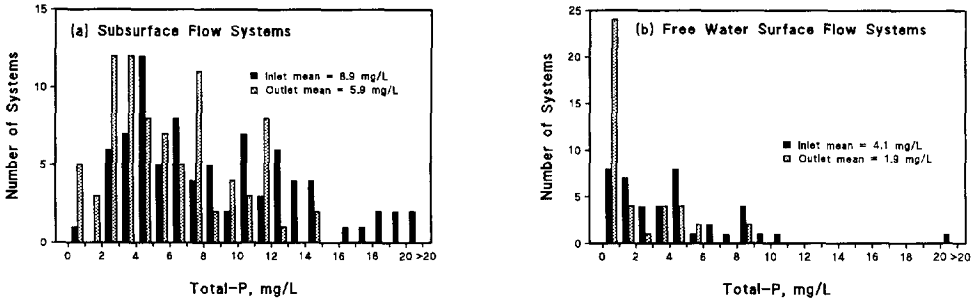

Fig. 5. Frequency distribution of inlet and outlet concentrations of total phosphorus in (a) subsurface flow (n=83), and (b) free water surface flow (n=42) constructed wetlands

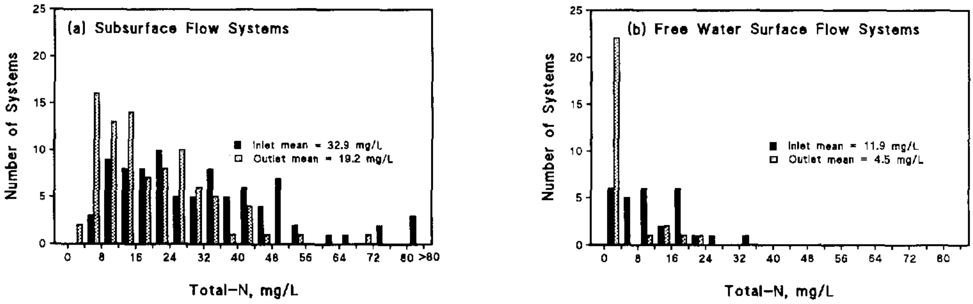

Fig. 6. Frequency distribution of inlet and outlet concentrations of total nitrogen in (a) subsurface flow (n=89), and (b) free water surface flow (n=28) constructed wetlands

Nitrogen: The major removal mechanism for nitrogen in constructed wetlands is nitrification-denitrification. The oxygen required for nitrification is delivered either directly from the atmosphere through the water or sediment surface, or by leakage from plant roots. Oxygenation is often the limiting step for nitrogen removal, and therefore the design of the wetland and the type and composition of the wastewater will influence nitrogen removal. Nitrogen is also taken up by the plants and incorporated into the biomass. The nitrogen removal in subsurface flow systems is generally about 30-40%; in free water surface flow systems, having lower loading rates, nitrogen removal is often >50% (Fig. 6).

REACTION RATE CONSTANTS

A large number of wetland systems have shown an exponential decrease in pollutant concentration level with distance through the wetland from inlet to outlet. This observation is consistent with a first order removal model, with the removal rate being proportional to the pollutant concentration. The removal can thus be described with first-order plug-flow kinetics. Combining the basic equation for the plug-flow model (Reed *et al.*, 1988) with the water mass balance, an exponential relation between inlet and outlet concentrations results:

$$C_{out} = C_{in}\exp[-k/HLR] \qquad (1)$$

where C_{out} = outlet pollutant concentration
C_{in} = inlet pollutant concentration
k = first-order rate constant (m/year)
HLR = hydraulic loading rate (m/year)

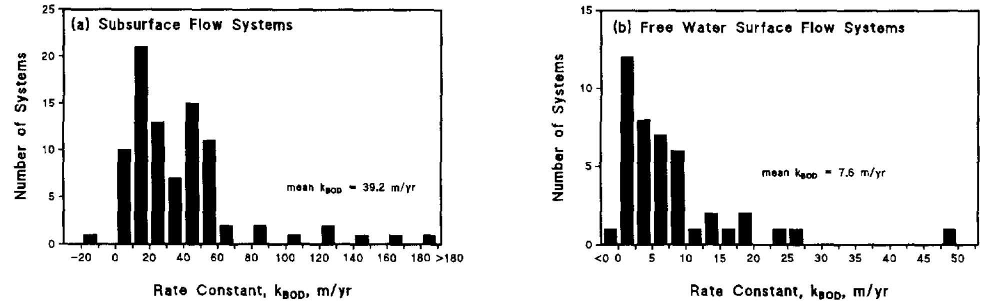

Fig. 7. Frequency distribution of removal rate constants for BOD_5 in (a) subsurface flow (n=88), and (b) free water surface flow (n=43) constructed wetlands

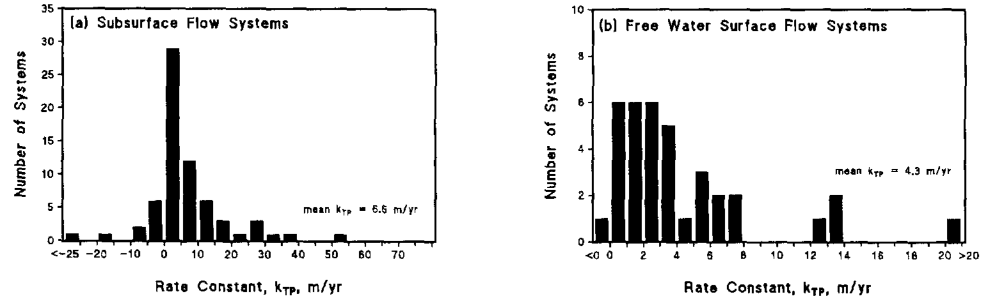

Fig. 8. Frequency distribution of removal rate constants for total phosphorus in (a) subsurface flow (n=67), and (b) free water surface flow (n=36) constructed wetlands

The rate constant, k, can be calculated from the following expression based on observed inlet and outlet pollutant concentrations and the hydraulic loading rate:

$$k = HLR(\ln C_{in} - \ln C_{out}) \qquad (2)$$

It should be noted that the use of ideal plug-flow characteristics assumes that dispersion in the reed bed is negligible. Furthermore, the rate constants are temperature dependent (Reed *et al.*, 1988). Thus, this empirical model should be used with great caution. Many studies indicate that the model can be used for BOD removal (Reed *et al.*, 1988; Brix *et al.*, 1989), and data also suggest that it can be used for total phosphorus with some confidence. However, it is questionable if the removal of nitrogen can be described by first-order kinetics.

The reaction rate constants presented in Figs. 7-9 are calculated based on mean inlet and outlet pollutant concentrations and mean hydraulic loading rates during the period of observation (from 1 to 8 years). Site specific differences and variability in loading rate, wastewater composition, etc., will inherently cause some variability in the calculated rate constants. Therefore, the results presented must be cautiously interpreted.

The mean rate constants for BOD removal, k_{BOD}, are approximately 5 times higher in subsurface flow constructed wetlands than in free water surface flow systems (Fig. 7). This probably partly reflects the greater surface area available for attached microbial growth in subsurface flow systems, partly the higher inlet concentrations of BOD_5 to the subsurface flow systems, although the last factor theoretically should not affect the rate constants. For total phosphorus the majority of systems of both types have rate constants below 5 m/year (Fig. 8) although the variability for subsurface flow systems is greater than for free water

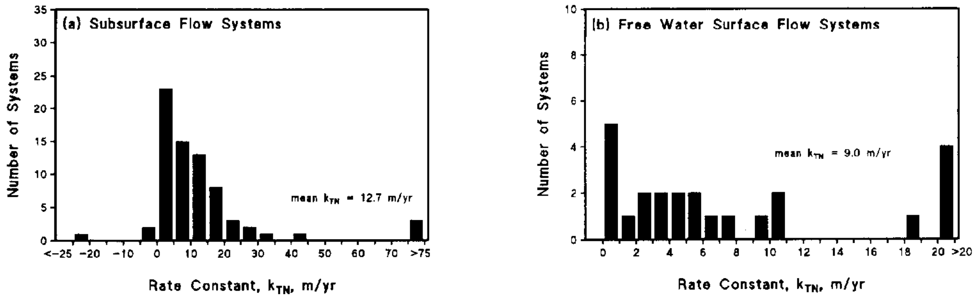

Fig. 9. Frequency distribution of removal rate constants for total nitrogen in (a) subsurface flow (n=72), and (b) free water surface flow (n=24) constructed wetlands

surface systems. The rate constant for total nitrogen, k_{TN}, varies considerably between systems (Fig. 9), probably as a function of the form of nitrogen (NH_4^+ versus NO_3^-) introduced into the wetlands, among others.

PERSPECTIVES

Different types of constructed wetlands are used to treat a wide variety of wastewaters all over the world. The climatic conditions, the size and design of the wetlands, the loading rates and regime, the plant species composition, and the type and composition of the wastewater vary considerably between sites. A database on North American constructed wetlands is presently being developed for the United States Environmental Protection Agency (Knight *et al.*, 1993), and local databases exists in other countries (Schierup *et al.*, 1990). In order to diminish the duplication of effort and to refine empirical wetland design approaches, all these data should be made available to engineers and scientist worldwide through a common database. Such a database would be a very useful tool and would minimise the risk of constructing malfunctioning wetlands. Design guidelines for both types of constructed wetlands have been published (Reed *et al.*, 1988; Steiner and Watson, 1993; WPCF Technical Practice Committee, 1990), but refinements are needed. It is necessary to study site-specific characteristics and performance data in great detail in order to be able to withdraw dimensioning criteria for use in future constructions.

Constructed wetlands with vertical flow have been in operation for decades in different places in Europe. Vertical flow systems have, however, not been applied so extensively, because vertical flow systems require more careful construction, media selection, etc., compared to other constructed wetlands designs. Several papers at recent international conferences have highlighted the promising performance of vertical flow systems (Cooper and Findlater, 1990; Bavor and Mitchell, 1994). The system designs used in different places are, however, so diverse that it is impossible to extract general design criteria from the data. The removal processes can be significantly intensified in vertical flow systems making the area use per PE less. A design consisting of several beds laid out in parallel with percolation flow and intermittent loading will increase soil oxygenation several-fold, compared to horizontal subsurface flow systems, stimulating sequential nitrification-denitrification and phosphorus adsorption (Brix and Schierup, 1990).

A new vertical flow system, PHYTOFILT, has recently been developed in Germany (W. Pietsch, personal communication, 1992). This system consists of a multi-layer bed with automatic pulse loading of the sewage onto the surface of the bed by a system of syphons. Differences in hydraulic conductivity between successive layers of sand in the filter are utilized for automatic aeration of the lower filter layer, which is connected to the system outlet by a syphon system. When water is drawn from the lower filter layer by the syphon, air is sucked into the layer from the atmosphere through an aeration drainage system and aeration pipes.

In Australia two different designs based on vertical up-flow of the wastewater have been developed. Results from pilot-scale experimental units have indicated that gravel-based vertical up-flow formats may significantly improve wastewater treatment through enhanced contact with the plant root-zone (Breen, 1990; Tanner, 1994). Large-scale up-flow format constructed wetland designs are still in development. Trial operational systems to treat primary settled sewage have been constructed in several places, and from the results obtained so far, these units show considerable promise. Operational problems have also been encountered, especially with clogging in the inlet zone, and improvements in design are currently under investigation. Phosphorus adsorption capacity might be enhanced by adding various iron and aluminium compounds or by using light expanded clay aggregates (LECA) as media in subsurface flow systems (Jenssen *et al.*, 1991). A multi-stage system consisting of an aerobic pretreatment step, a constructed wetland N-removal unit, and a constructed wetland P-removal unit have been suggested in which P-removal occurs in the final step.

A lot of effort is being invested worldwide in refinement of the constructed wetland technology. The treatment capacity of subsurface flow systems can be improved by selecting vertical flow systems with intermittent loading, by proper media selection, and by introducing some of the principles used in conventional treatment technologies, e.g. water recycling. Further research is needed to help define and optimize engineering design criteria, not only for vertical flow systems, but for all types of constructed wetlands. Research is also needed to better define the long-term performance capabilities and operational problems of the systems. The present state of knowledge concerning the use of constructed wetlands is sufficient to apply constructed wetlands as a tool for improving water quality. The potential applications range from secondary treatment of municipal and various types of industrial wastewaters to polishing of tertiary treated waters and diffuse runoff from agricultural fields. In many situations constructed wetlands are the only available appropriate technology. It is, however, important to be aware of the limitations of the technology and to distinguish constructed wetlands from natural wetlands. Natural wetlands should not be exploited deliberately to treat wastewaters as the discharge of wastewater into wetland has proved to bring about considerable changes in the wetland ecosystem and also because the long-term consequences cannot be precisely predicted. Constructed wetlands are a much more attractive alternative.

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