Removal of nutrients from combined sewer overflows and lake water in a vertical-flow constructed wetland system

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Abstract Lake Utterslev is situated in a densely built-up area of Copenhagen, and is heavily eutrophicated from combined sewer overflows. At the same time the lake suffers from lack of water. Therefore, a 5,000 m^2 vertical flow wetland system was constructed in 1998 to reduce the phosphorus discharge from combined sewer overflows without reducing the water supply to the lake. During dry periods the constructed wetland is used to remove phosphorus from the lake water. The system is designed as a 90 m diameter circular bed with a bed depth of c. 2 m. The system is isolated from the surroundings by a polyethylene membrane. The bed medium consists of a mixture of gravel and crushed marble, which has a high binding capacity for phosphorus. The bed is located within the natural littoral zone of the lake and is planted with common reed (*Phragmites australis*). The constructed wetland is intermittently loaded with combined sewer overflow water or lake water and, after percolation through the bed medium, the water is collected in a network of drainage pipes at the bottom of the bed and pumped to the lake. The fully automated loading cycle results in alternating wet and dry periods. During the initial two years of operation, the phosphorus removal for combined sewer overflows has been consistently high (94–99% of inflow concentrations). When loaded with lake water, the phosphorus removal has been high during summer (71–97%) and lower during winter (53–75%) partly because of lower inlet concentrations. Effluent phosphorus concentrations are consistently low (0.03–0.04 mg/L). Ammonium nitrogen is nitrified in the constructed wetland, and total suspended solids and COD are generally reduced to concentrations below 5 mg/L and 25 mg/L, respectively. The study documents that a subsurface flow constructed wetland system can be designed and operated to effectively remove phosphorus and other pollutants from combined sewer overflows and eutrophicated lake water.
Keywords Combined sewer overflow; constructed wetland; nitrogen; phosphorus; stormwater; urban runoff; vertical-flow system; water treatment

Water Science and Technology **Vol 44 No 11–12 pp 171–176**

Introduction

Lakes located in densely built-up areas have a high recreational value for the public. However, because of the intensive urban development and human activities in the catchment of the lakes, the water quality is often poor and reduces the recreational values. Discharge of uncontrolled urban stormwater and combined sewer overflows may be major contributors to the deterioration of the water quality. Stormwater runoff originates as runoff from parking lots, roads, roofs and other impervious surfaces, and as runoff across bare or vegetated soils. Combined sewer overflows occur during rain events when large amounts of rainwater are added to the normal domestic flows of the sewerage systems. Upgrading and extending the sewerage system in the catchment of the lakes may reduce these sources of pollution, but often this will also lead to an undesirable diversion of a major part of the freshwater source for the lakes. Another option is to clean the runoff water and the combined sewer overflows before discharge to the lake.

Lake Utterslev is an urban marsh system located in a densely built-up area about 10 km northwest of the city centre of Copenhagen. The marsh covers 91 ha and has a mean water depth of c. 1 metre. The marsh has at present no natural inflow, but water is pumped to the lakes through a channel at the west end of the marsh. In addition, the marsh receives urban runoff and combined sewer overflows. The residence time of the water in the lakes is three to thirteen months during summer. Until 1970 the lakes in Utterslev marsh received large discharges of untreated and poorly treated wastewater and, in spite of diversion and treatment of the sewage water, the lakes are heavily eutrophicated. The yearly mean phosphorus concentration of the lake water is 0.3–0.4 mg/L, and because of the large pool of nutrients accumulated in the sediments, release of phosphorus in the warm summer months periodically raises the concentrations of phosphorus in the lake water to more than 1 mg/L (Municipality of Copenhagen, 2000). Hence, there is no submerged aquatic vegetation in the lake, and water quality is generally poor because of algal blooms. The marsh is however a significant habitat for birds and other fauna, and has great recreational value for the public. Therefore, during recent decades large investments have been made in order to improve the environmental conditions in the marsh.

Constructed wetland systems have been successfully established to treat combined sewer overflows and urban stormwater (e.g. Shutes *et al*., 1997; Green *et al*., 1999; Scholes *et al*., 1999). In 1998 the Municipality of Copenhagen developed and constructed a wetland system to treat the combined sewer overflow before discharge into the marsh (Seehuusen and Gervin, 1999). This was done in order to reduce the loading of phosphorus in particular to the marsh, and at the same time retain the supply of water to the marsh. Besides treating combined sewer overflows, the constructed wetland is used to clean lake water in "dry" periods when there are no sewer overflows. This paper describes the system design and operational schemes and presents results from the initial two years of operation.

Location and design of the constructed wetland

The constructed wetland is located in the natural littoral zone of one of the lakes in an existing reed swamp (Figure 1). The system is designed as a 90 m diameter circular bed partly buried in the swamp and is separated from the rest of the swamp by a polyethylene membrane (Figure 2). The membrane is placed 3 m beneath the water level of the lake on the underlying clay layer. The two metre deep bed substrate consists of a mixture of gravel and crushed marble, which has a high binding capacity for phosphorus (Brix *et al*., 2001). The surface level of the bed medium is located one metre beneath the water level of the lake. The plant is surrounded by a dike of earth, and is planted with reeds (*Phragmites australis*). The surface area of the plant is 5,000 m^2, and the storage capacity for water in the system, including the void volume of the bed medium, is 6,500 m^3. The inlet-pipes are

Figure 1 Location of the circular constructed wetland system (CW) in Utterslev marsh

buried in a dike leading to the centre of the plant, from where the influent water is distributed over the surface of the bed (Figure 3). The system is intermittently loaded with combined sewer overflow water or lake water, and after percolation through the bed medium, the water is collected in a network of drainage pipes at the bottom of the bed and pumped to the lake.

A buried in-line retention basin built into the sewerage system is located immediately upstream of the constructed wetland system. The basin withholds the "first flush" of the combined sewer overflow, and therefore the water going into the wetland during overflow events is rather dilute. During periods with no overflow events, the system is used to clean lake water. The fully automated loading cycles result in alternating wet and dry periods.

Several built-in attributes of the system contribute to enhance the nutrient removal performance. The bed medium is relatively deep (2 m) and contains crushed marble, which has a high binding capacity for phosphorus (Brix *et al.*, 2001). The vertical-flow regimen secures a good contact between the water and bed medium, and the intermittent loading creates alternating wet and dry periods which increase oxidation of organic compounds and nitrification in the bed medium.

The routine operation of the system is automated via data acquisition and real time control. The control is based on flow transmitters measuring influent and effluent flow rates, and level transmitters placed in the retention basin and in the constructed wetland itself. Furthermore, on-line monitoring equipment is installed in the system to measure oxygen, temperature and pH in the inlet and the outlet water, in different depths of the free water on the surface of the bed during loading periods, as well as in different depths within the bed medium. Automatic samplers are installed at the inlet and outlet of the bed taking samples proportional to volume flow.

Treatment performance of the system

The initial period of operation has been a running-in period, where the focus has been to study the effects of residence time on removal performance. In the period from October 1998 to January 1999 only lake water with low contents of nutrients were treated in the system as there were no overflows from the sewer system until June 1999. In the period from October 1998 to the first of January 2000 a total of 125,000 m^3 of water were treated in the system (115,000 m^3 in 1999). The inflows consisted of c. 50 loadings of lake water (42 loadings in 1999), and 16 loadings of sewer overflows. The performance when treating lake water was tested by analysis of 24 in- and outlet samples. The performance when treating sewer overflows was tested by analysis of 12 inlet and 16 outlet samples. At two of the overflow events samples were taken of the outlet water after 3, 5 and 7 days, respectively, to

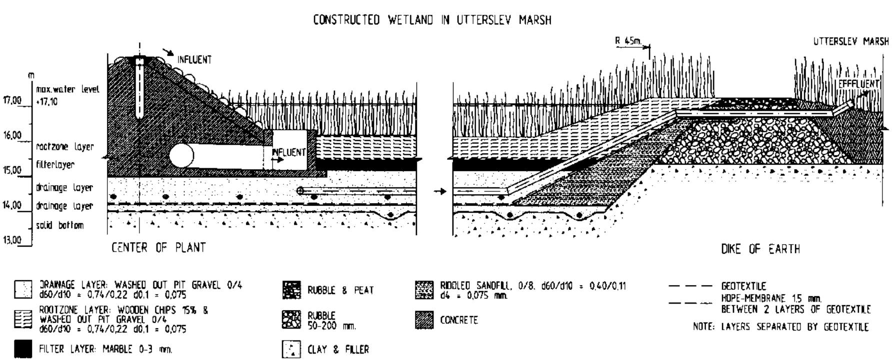

Figure 2 Cross-section through the circular constructed wetland system at Utterslev marsh

Figure 3 Photograph of the constructed wetland system at Utterslev marsh showing a boardwalk leading to the center of the circular bed

evaluate the effects of residence time. All samples were analysed using standard methods by a certified laboratory.

Phosphorus

Inlet concentrations of phosphorus in the lake water varied between 0.08 and 0.37 mg/L during winter, but were higher (0.12 to 0.78 mg/L) during summer because of release of phosphorus from the lake sediments during anoxic conditions in the lake. However, effluent concentrations from the constructed wetland system were consistently low (0.03–0.04 mg/L) resulting in high removal rates that were largely independent of inlet concentration (Table 1). Concentrations of phosphorus in the sewer overflows were higher (0.9 to 3.2 mg/L) than concentrations in lake water, but effluent concentrations were still low, and removal efficiencies greater than 97%. The retention times studied (3, 5 and 7 days) did not have any consistent effect on effluent phosphorus concentration. A total mass balance showed that 86 kg of phosphorus, corresponding to 96% of the loading, were removed by the constructed wetland system during 1999.

Nitrogen

The concentrations of nitrogen in the lake water were generally low and occurred nearly exclusively as organic nitrogen (Table 2). The total nitrogen content was reduced by c. 25% and some nitrification occurred in the system. The combined sewer overflows contained more nitrogen than lake water and mainly as organic-N and NH_4. This was effectively

Table 1 Average (±SD) inlet and outlet concentrations of total-phosphorus and percentage removal (% of inlet concentration) in the constructed wetland at Utterslev marsh when loaded with lake water or combined sewer overflows (Winter: November–May; summer: June–October)

		n	Inlet concentration (mg/L)	Outlet concentration (mg/L)	Removal (%)
Lake water	Winter	7	0.15 ± 0.10	0.048 ± 0.020	65 ± 8
	Summer	17	0.53 ± 0.18	0.032 ± 0.006	92 ± 6
Sewer overflow	Winter	2	1.27 ± 0.13	0.029 ± 0.005	98 ± 1
	Summer	10173 & 14	1.79 ± 0.83	0.041 ± 0.013	97 ± 1

Table 2 Average (±SD) inlet and outlet concentrations of total-nitrogen (Total-N), ammonium-nitrogen (NH_4-N) and nitrite + nitrate-nitrogen (NO_{2+3}-N) and percentage removal (% of inlet concentration) in the constructed wetland at Utterslev marsh when loaded with lake water or combined sewer overflows

		n	Inlet conc. (mg/L)	Outlet conc. (mg/L)	Removal (%)
Lake water	Total-N	21	1.64 ± 0.63	1.19 ± 0.55	25 ± 27
	NH_4-N	20	0.03 ± 0.05	0.03 ± 0.03	–
	NO_{2+3}-N	20	0.01 ± 0.02	0.83 ± 0.49	–
Sewer overflow	Total-N	16	7.26 ± 3.69	1.08 ± 0.65	81 ± 12
	NH_4-N	15	2.74 ± 0.79	0.02 ± 0.03	99 ± 1
	NO_{2+3}-N	15	0.58 ± 0.19	0.71 ± 0.71	–

removed in the system as a consequence of nitrification-denitrification processes (Table 2). The denitrification rate was higher when treating overflows compared to lake water, probably because of the higher nitrogen contents in the sewer overflow. However, the higher content of organic matter, and the degradability of the organic matter may also have affected the denitrification process. It was not possible to observe a significant relation between the residence time and the denitrification rate for any of the types of water. The effluent concentrations of ammonium were consistently low, and as a consequence of the nitrification process in the system some nitrate was present in the effluent.

COD and TSS

The COD (Chemical Oxygen Demand) concentrations in the lake water were very low in winter, but increased during summer as a consequence of the presence of algae (Table 3). This could also be seen in the contents of TSS (Total Suspended Solids), which varied between <5 mg/L during winter to 48 mg/L in August (yearly average 13 mg/L). The COD contents in the sewer overflows were consistently higher (up to 294 mg/L on one occasion) as were the contents of TSS (average 90 mg/L). Effluent concentrations of COD were generally low, but were higher during summer than during winter. Effluent concentrations of TSS were below the detection limit (5 mg/L) in 22 out of 24 samples.

Discussion

The present paper describes the initial experiences from the constructed wetland system. The initial year has been an experimental period to document performance and to experiment with loading practice, retention time, etc. Therefore, the constructed wetland system has not been loaded according to its expected capacity. In 1999 a total of 115,000 m^3 of water was treated in the constructed wetland, of which 38,000 m^3 was combined sewer overflows, and during summer (May to October) 75,000 m^3 of water was treated. A total of 86 kg of phosphorus was removed by the constructed wetland system of which two thirds were removed from the combined sewer overflows.

It is anticipated that the total capacity of the constructed wetland will be 180,000 m^3 per year, of which 135,000 m^3 will be treated during the summer period. The summer period is

Table 3 Average (±SD) inlet and outlet concentrations of COD and percentage removal (% of inlet concentration) in the constructed wetland at Utterslev marsh when loaded with lake water or combined sewer overflows (Winter: November–May; summer: June–October)

		n	Inlet conc. (mg/L)	Outlet conc. (mg/L)	Removal (%)
Lake water	Winter	2	9 ± 3	2 ± 1	68 ± 16
	Summer	12	59 ± 8	25 ± 12	58 ± 19
Sewer overflow	Winter	2	116 ± 20	11 ± 8	90 ± 8
	Summer	9 & 13	99 ± 77	27 ± 9	63 ± 23

relatively dry and therefore only a few sewer overflows are expected to occur. Therefore, the constructed wetland will mainly be treating lake water during summer. It is estimated that 105,000 m^3 out of the expected 135,000 m^3 treated during summer will be lake water. Hence, the constructed wetland will mainly be used to treat lake water when the phosphorus levels in the lake water are high as a consequence of release of phosphorus from the lake sediments. It is anticipated that in the future a total of 130 kg of phosphorus will be removed per year from sewer overflows and lake water.

The constructed wetland system clearly reduces the discharge of phosphorus and other pollutants contained in the sewer overflows to the Utterslev marsh. Furthermore, the constructed wetland removes phosphorus from the lake water when no overflows occur. Therefore, the establishment of the wetland no doubt contributes to improve the environmental conditions of Utterslev marsh. However, additional measures must be taken to restore the former environmental quality of the marsh. The heavily polluted sediments of the lakes, which release large amounts of phosphorus every summer, are of prime concern (Municipality of Copenhagen, 2000). However, a few minor combined sewer overflows and stormwater discharges located around Utterslev marsh also contribute in sustaining the poor water quality of the lakes.

The initial experiences with the constructed wetland at Utterslev marsh document that a constructed wetland can be designed and operated to effectively remove phosphorus and other pollutants from polluted water. The lifetime of the system is not known, but estimates based on the phosphorus sorption capacity of the bed medium of the constructed wetland indicate that the phosphorus removal can be sustained for several decades.

Acknowledgements

We thank Morten Seehuusen, construction engineer of the wetland system, Bent Petersen and Jørgen Kristensen, members of the construction project group, and Gert Jørgensen and Poul Erik Jøhncke, service staff of the wetland system. Jacob Harboe is thanked for preparing Figure 2 and Dr Brian K. Sorrell for linguistic improvements of the manuscript.

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