A treatment wetland used for polishing tertiary effluent from a sewage treatment plant: performance and processes

De nabehandeling van tertiair RWZI-effluent in een moerassysteem:
zuiveringsrendement en processen

(met een samenvatting in het Nederlands)

Proefschrift

ter verkrijging van de graad van doctor
aan de Universiteit Utrecht
op gezag van de Rector Magnificus, Prof. Dr. W.H. Gispen,
ingevolge het besluit van het College voor Promoties
in het openbaar te verdedigen
op maandag 8 september 2003
des ochtends te 10:30

door

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geboren op 22 maart 1967, te 's Gravenhage

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Summary and general conclusions

In this thesis, the performance of a wetland system used for polishing tertiary effluent from a sewage treatment plant (STP) was studied in detail. Constructed wetlands for wastewater treatment have proven to be an effective, low-cost and sustainable alternative for conventional wastewater treatment technologies (Moshiri 1993, Kadlec & Knight 1996, Vymazal *et al.* 1998). The removal of pollutants in these systems relies on a combination of physical, chemical and biological processes that naturally occur in wetlands and are associated with the vegetation, the sediment and their microbial communities (Howard-Williams 1985, Verhoeven & Van der Toorn 1990, Vymazal 2001). The numerous studies on the performance of treatment wetlands carried out during the last few decades have provided a wealth of quantitative information, which has been used to improve the pollutant removal capacity through design and operation measures. These studies largely dealt with municipal wastewater, sometimes combined with stormwater, that mostly had received primary or secondary pretreatment before supply to the wetlands (Moshiri 1993, Kadlec & Knight 1996, Vymazal *et al.* 1998). Only few constructed wetlands have been used to polish tertiary effluent from STP's (Knight *et al.* 1987, Jackson 1989, Kadlec & Knight 1996, Sundblad 1998). Due to advanced pretreatment, tertiary wastewater has only relatively low remaining COD and BOD levels and moderate N and P concentrations, but additional treatment may still be necessary before it can be discharged safely to surface waters that are sensitive to eutrophication. Surface-flow wetlands are commonly used for polishing this oxygen-poor wastewater; they process large quantities of wastewater, often at rather short hydraulic retention times (HRT).

The main aim of this study was to assess whether such a constructed system with a HRT of 2.4 days could adequately improve STP effluent quality with respect to N and P concentrations, COD, turbidity, faecal coliform densities and oxygen dynamics. The evaluation was based on monitoring of water quality and hydrology in different sections of the wetland system, and, for nutrients, also on studies of relevant removal processes associated with the vegetation and sediment. The effect of the HRT on the removal capacity for N, P and faecal coliforms, and on the rates of nutrient removal processes was studied in sections of the wetland, of which the inflow rate of the STP effluent had been adjusted independently. The most suitable HRT for obtaining sufficient improvement of the STP effluent quality in this wetland system to meet the design criteria was evaluated. Another objective was to interpret results of this study in the context of the general knowledge on the use of constructed wetlands for tertiary STP effluent polishing.

Description of the treatment wetland

The treatment wetland of this study was constructed on the island of Texel in the north-western part of the Netherlands (53°05' N, 4°47'E) in 1994 to polish the effluent of the STP 'Everstekoog' (up to 45,000 p.e.). In this low-loaded activated sludge plant, the wastewater, a mixture of mainly domestic sewage and stormwater, received tertiary treatment including chemical P removal with $FeSO_4$. The STP effluent quality was nevertheless still insufficient with respect to N, P, faecal coliforms and oxygen. Due to the small volume of the water bodies on the island, discharge of the STP effluent into surface water had a large impact on its quality and quantity. Low oxygen concentrations, similar to that of the STP effluent, had been observed in the surface waters at 1.5-2.0 km from the STP discharge point (Schreijer *et al.* 1997). A higher STP effluent quality was required to prevent detrimental effects on nature areas in contact with this water. Additional reduction of faecal coliforms in the STP effluent was also aimed for, because, in the future, the wetland outflow will be connected to a water course passing a residential area shortly after the discharge point. The objective for the wetland system used in this study was therefore to polish the STP effluent quality to the point that it resembled that of the receiving surface water.

The treatment wetland was a surface-flow system with a water surface of 1.3 ha, which was loaded with approximately 3,400 m^3 day^{-1} of STP effluent that passed the system in 2.4 days. The STP effluent was first pumped into a presettling basin, then divided over nine parallel ditches. The water from these ditches was collected in one discharge ditch, from which it flowed to the surface water of the island. The parallel ditches consisted of two serial sections with about the same surface area but different water depth, i.e. a shallow, front section (0.2 m) and a deeper, rear section (0.4 m). The front section of eight ditches contained either *Phragmites australis* or *Typha latifolia* and the second section contained submerged macrophytes (mainly *Elodea nuttallii*, *Potamogeton* spp. and *Ceratophyllum demersum*). One ditch without vascular macrophytes served as a control.

Performance of the wetland system at the design HRT

The functioning of the wetland system for the reduction of turbidity, COD, faecal coliforms, N, P, and for the oxygen dynamics in the through-flowing STP effluent was assessed over a year at the original design HRT of 2.4 days (hydraulic loading rate (HLR) of 25 cm day^{-1}) between April 1996 and March 1997 (chapter 5). The removal efficiencies of the pollutants in the wetland system as a whole and in the different wetland compartments were quantified from pollutant input and output concentrations, and from pollutant mass budgets of the water inputs and outputs. Pollutant removal efficiencies of treatment wetlands are mostly determined on the basis of the difference between the input and output concentrations of pollutants, but these estimates may generate considerable over- or underestimation of the actual removal efficiencies

(Howard-Williams 1985, Kadlec & Knight 1996, Moustafa *et al.* 1996). In our wetland, the two approaches did not result in clear and consistent differences in seasonal and annual pollutant removal efficiencies. This was related to the specific characteristics of the wetland, as the inputs and outputs of the water budgets other than the wetland inflows and outflows, i.e. precipitation, evapotranspiration and groundwater recharge, were small. Seasonal and occasional fluctuations of the pollutant inflow concentrations and STP inflow rates did not lead to systematic differences between the two approaches either. Thus, pollutant removal efficiencies in this wetland system were approximated by calculations from pollutant concentrations, but we considered the estimates based on mass budgets of the water fluxes to be more accurate.

Considering the high HLR to the wetland and the relatively low nutrient input concentrations (annual means of 5.15 and 0.79 mg l^{-1} for total N and total P, respectively), N removal rate was relatively high (26% of wetland mass input, 126 g N m^{-2} yr^{-1}), while the P removal rate (7%, 5.1 g P m^{-2} yr^{-1}) was low. Faecal coliforms removal in the wetland system was high during the growing season (95-100% of wetland mass input), but was less effective during the cold part of the year (79-91%). Turbidity of the surface water doubled during passage through the system, but the suspended solids changed composition, and were largely of wetland origin at the outlet. COD only increased slightly in the wetland. The oxygen concentration of the STP effluent, which was low at the inlet of the wetland, strongly increased during passage of the wetland with a characteristic diurnal shift throughout the year.

The presettling basin functioned well for the interception of occasional high organic N loads, and for organic and inorganic P associated with particles, resulting in N and P removal efficiencies of approximately 10%. The larger part of the reduction in faecal coliforms also occurred in this basin. The shallow, front sections of the parallel ditches, provided the greatest N removal in the wetland (18%), and were important for additional faecal coliform removal. The deeper, rear ditch sections were predominantly responsible for the strong enhancement of the oxygen dynamics in the STP effluent, due to the presence of submerged macrophytes, macro-algae and periphyton. A small net annual release of P and most of the increase in turbidity occurred in the parallel ditches. The presence of emergent macrophytes had a positive impact on the removal of faecal coliforms, which was greater in the *Phragmites* compared to the *Typha* stands. *Phragmites* stands also had the highest ammonium removal efficiencies, and the lowest increases in turbidity. The effects of the emergent macrophytes on pollutant removal in the front ditch sections were probably related to the amounts of plant surfaces available in the water for interception of pollutants and support of microbial activity, and to slower decomposition of dead standing *Phragmites* shoots.

Hence, the treatment of the wetland system resulted in STP effluent that resembled the quality of the receiving surface water more closely, but the performance was still insufficient for the removal of N and P and, during the autumn-winter period, also for faecal coliform removal.

Optimisation of the performance by enhancement of the HRT

The potential for enhancing the pollutant removal capacity of the treatment wetland by increasing the HRT of the water in the parallel ditches was assessed between April 1997 and March 1998 (chapter 6). The design of the wetland with nine parallel ditches, of which the inflow rate of the STP effluent could be adjusted independently, allowed us to simultaneously compare the pollutant removal efficiency at four HRT's (0.3, 0.8, 2.3 and 9.3 days). Two HRT's longer than the design HRT were introduced to test whether the removal efficiency of the ditches could be enhanced for N and P, and also for faecal coliforms during autumn-winter. The HRT even shorter than the design HRT provided the opportunity to examine whether the removal efficiency of faecal coliforms remained high during the growing season. Pollutant removal efficiencies of the ditches were estimated from pollutant mass budgets of the water inputs and outputs.

The removal capacity of the ditches for total N, ammonium, nitrate and faecal coliforms was considerably enhanced by the two longer HRT's than 0.8 days, resulting in substantially lower ditch output concentrations of these pollutants. The 0.3 day HRT was too short for satisfactory removal of faecal coliforms during spring-summer (only 46-73% of the annual mass input). A large part of the total removal of N and faecal coliforms in the ditches usually occurred in the front ditch sections, because reduced concentrations and mass input rates to the rear ditch sections logically resulted in lower removal efficiencies and mass removal rates. However, the rear ditch sections frequently played a more important role for N removal at the shorter HRT's, at times when removal efficiencies in the front sections were relatively low. Annual P removal in the ditches at all HRT's was still low, even when the HRT was increased up to 9.3 days. This was probably largely caused by the high P mass loading rate and HLR of 14 g P m^{-2} yr^{-1} and 3.1 cm day^{-1}, respectively. Substantial P removal in the ditches can only be achieved at HRT's of at least 15 days. Enhancement of the HRT resulted in increases of the turbidity and COD in the STP effluent during the growing season. Turbidity and COD levels in the ditch outputs were, however, still comparatively low even at the longest HRT (spring-summer averages of 9.62 ntu and 40.7 mg l^{-1}, respectively).

Phragmites stands showed higher seasonal removal efficiencies or lower relative releases for several pollutants compared to *Typha* stands, but the extent of this difference depended on the degree by which the removal efficiency was influenced by HRT. The generally moderate effects of vegetation type on pollutant removal were highest at intermediate removal efficiencies. With increasing HRT, the vegetation effect on ammonium and faecal coliform removal during autumn-winter became less clear, because the longer contact time at the longer HRT's, resulting in high removal efficiencies, probably compensated for the lower removal effectivity of the *Typha* stands.

Nutrient removal processes

The significance of relevant individual processes for N and P removal was determined for the wetland system as a whole and its compartments during the first year (chapter 5) and for the ditches with the HRT of 0.8 days and 9.3 days during the second year (chapter 6). The processes that give rise to the pollutant removal from wastewater have not often been quantified in treatment wetlands, although a better knowledge of the transformation and translocation processes of pollutants enables the improvement of the design and operation of wetlands for wastewater treatment (Tchobanoglous 1993). Direct measurements were used to quantify the annual nutrient input by atmospheric deposition and the annual nutrient outputs by groundwater recharge, harvesting emergent, submerged and floating plants, storage in the sediment, and for N, also denitrification. Total N and P removal in the wetland and its compartments by summation of the rates of these individually measured nutrient removal processes was also determined. Annual N and P removal efficiencies on the basis of these process measurements were often not in good agreement with the nutrient removal efficiencies calculated on the basis of the mass budgets of the water input and outputs (chapters 5 and 6). For N, addition of the measured removal processes usually explained at most 30% of the N removal in the wetland compartments as calculated from the mass budgets. This was probably largely due to an underestimation of the importance of denitrification by the measurements, which was related to the difficulties in determining the plant surface area for attachment of periphyton, the extrapolation of the denitrification measurements to the whole year, and the methods used (chapters 4 and 5). The estimates of the other processes were probably quite accurate, while two unmeasured processes in the N cycle, i.e. ammonia volatilisation and N fixation, were mostly rather insignificant in this wetland (chapters 5 and 6). Denitrification was therefore most likely the key process for N removal in this treatment wetland, as is the case in most wetlands (Howard-Williams 1985, Verhoeven & Van der Toorn 1990, Johnston 1991, Gumbricht 1993, Vymazal *et al.* 1998). Denitrification in the presettling basin was probably for a large part preceded by interception of incidental high organic N loadings to the wetland system through sedimentation, while the N deposited was then largely assumed to be gradually mineralised, nitrified and denitrified. At least a substantial part of the ammonium and organic N removed in the parallel ditches was probably also due to a sequence of these processes.

For P, often large discrepancies were observed between removal efficiencies based on summation of the process measurements and those based on the mass budgets of the water inputs and outputs, because the accuracy of the measurements and estimations of the low P process and mass removal rates in the wetland compartments was probably insufficient. The presettling basin, which functioned well for the sedimentation of P-rich sludge particles and organic matter, however, did show P removal which was for 79% accounted for by storage in the sediment. The most important processes for P dynamics in the ditches were the fluxes to or from the sludge layer, harvest of emergent macrophytes, and, during the second year, groundwater recharge.

The absolute N mass removal rates by the individual processes were usually lower in the ditches with the HRT of 9.3 days than those with the HRT of 0.8 days due to the lower N mass loading rates and N concentrations in the surface water. The relative importance of the removal through these processes increased by increasing the HRT, so that N removal efficiencies by these processes were enhanced. A similar HRT effect was observed for P removal by harvesting emergent macrophytes. The P mass removal rate through groundwater recharge was, however, only slightly affected by HRT, because mean annual P concentrations of the surface water in the ditches showed only small differences between the HRT's. An increase of the HRT had no or an even negative effect on absolute P removal by harvesting submerged and floating plants. This was caused by the higher ortho-phosphate concentrations of the surface water during the spring-summer period in the rear sections of the ditches with the longer HRT, leading to higher P concentrations in the harvested submerged and floating plants. The negative impact of the HRT on N and P removal through accumulation in the sediment was probably related to the hydraulic history of the ditches. A new equilibrium between the sediment and water therefore had to become established in the ditches with the longer HRT, before storage of nutrients in the sediment may occur.

Harvesting emergent macrophytes

Harvesting emergent macrophytes usually accounts for little nutrient removal in wetlands for wastewater treatment (Bavor *et al.* 1995, Vymazal 1999a,b, Obarska-Pempkowiak 1999). Vegetation harvesting may be more important in low-loaded treatment wetlands such as wetlands used for polishing wastewater that has already received tertiary treatment. To assess this possibility, the potential for nutrient removal through annual harvest of emergent macrophytes was quantified in our wetland system (chapter 2). Aboveground biomass and nutrient dynamics, and nutrient removal through annual harvest were studied in the *Phragmites australis* or *Typha latifolia* stands of the parallel ditches at the four different HRT's of 0.3, 0.8, 2.3 and 9.3 days, corresponding to N and P mass loading rates characteristic for a range of low to highly loaded treatment wetland systems (122 - 4190 g N m^{-2} yr^{-1} and 28.3 - 994 g P m^{-2} yr^{-1}). The vegetation was cut above the water level in October in two successive years.

Nutrient removal by harvest of the *Phragmites* and *Typha* shoots had little impact on nutrient removal at the three shortest HRT's, but harvesting reduced the mass inputs to the ditches with the longest HRT of 9.3 days by 7.0 - 10% and 4.5 - 9.2% for N and P, respectively. Hence, the annual nutrient removal by the harvest of emergent macrophyte shoots in temperate treatment wetlands is significant at N and P mass loading rates lower than approximately 120 g N m^{-2} yr^{-1} and 30 g P m^{-2} yr^{-1}, corresponding to a HRT of roughly 9 days in the ditches of this wetland system. The *Typha* stands yielded higher N and P removal efficiencies by the October harvest than the *Phragmites* stands. This was largely due to lower nutrient resorption efficiencies and lower reductions in shoot biomass between August and October in the *Typha* stands. The vigour of the *Phragmites* and *Typha* stands was not negatively affected by mowing the aboveground biomass in October rather than in winter as is common practice. This result indicates that optimisation of the nutrient removal by advancing the harvest from the winter to October is most likely feasible for wetlands in temperate climates. Nutrient removal by harvesting *Phragmites* shoots can probably be doubled without a reduction in vitality of the stands by advancing the harvest date to mid-September. This management strategy would yield approximately 30% more N removal and almost equal P removal than would result from harvesting *Typha* shoots in October. *Phragmites* may also be more preferable in treatment wetlands receiving very low rates of nutrient loading, because the vigour of *Typha* stands seemed to be more sensitive to a lower nutrient availability at N and P mass input rates lower than the range indicated.

Seasonal storage in periphyton

Few studies have determined the role of periphyton in surface-flow wetlands for nutrient removal from the wastewater, although large surface areas for periphyton attachment are provided by the plant shoots and sediment in the water column (Lakatos *et al.* 1982, Wetzel 1990, 1996, Eriksson & Weisner 1997, Lakatos *et al.* 1998, Richardson 1999). Temporal and spatial periphyton dynamics were therefore studied to examine the function of this ecosystem component for short-term storage of nutrients from the surface water in the treatment wetland (chapter 3). Further, N removal through denitrification in periphyton associated with macrophyte shoots was quantified and compared to that of the sediment and water (chapter 4).

The seasonal variation of periphyton biomass and nutrient content in the treatment wetland system was studied between April 1996 and February 1998 (chapter 3). Periphyton samples were collected from emergent macrophyte stands, submerged macrophyte stands and comparable situations without vascular macrophytes (control). These stands were in ditches with HRT's of 0.8 or 9.3 days. Seasonal N and P changes in periphyton standing stock associated with the plant shoots and the sediment in the *Phragmites* and *Typha* stands were less than 6% of the mass input rate at the 0.8 day HRT. At the longer HRT of 9.3 days, uptake in and release from periphyton in the stands amounted to 4-30% of the mass input rates of N and P. Periphyton associated with the sediment was much more important than that on plant shoots for the changes in nutrient content. Although the surface water may not have been the entire source or sink of nutrients which were taken up or released by the periphyton, temporal changes in periphyton biomass may affect nutrient dynamics in the surface water of wetlands substantially when annual mass input rates are below approximately 250 g N and 60 g P per m^2 wetland area, corresponding to a HRT of 5 days in the ditches of this wetland.

Light availability in the water column was probably the major factor regulating the seasonal dynamics of periphyton biomass, and N and P content. After a period with high periphyton living biomass and nutrient content during winter and spring, a strong attenuation in the water column by emergent macrophytes or submerged and floating macrophytes coincided with a decrease in periphyton during the growing season. After senescence and harvesting of the emergent macrophytes in autumn, light availability and periphyton biomass increased again in winter. Periphyton biomass in stands without vascular macrophytes was highest in summer. Periphyton chlorophyll-*a* content associated with the sediment (142 - 2006 mg m^{-2} substratum area) was always much higher than that attached to plant shoots in the same stands, despite the lower light conditions at the sediment surface. The difference was probably related to higher nutrient availability, less exposure to current and/or longer survival of the algae in the sediment. Maximum living algal biomass and nutrient content of periphyton were higher on *Phragmites* than on *Typha* shoots (chlorophyll-*a* content of 327 and 93.0 mg m^{-2}, respectively). The HRT in the ditches also influenced the periphyton biomass and nutrient content on *Phragmites* or *Typha* shoots, but through different processes. Periphyton nutrient contents on *Phragmites* shoots were higher at the shorter than at the longer HRT, which was probably due to the higher nutrient mass input rate at the shorter HRT enabling higher interception of nutrients by the dense *Phragmites* stands. On the other hand, the living algal biomass and nutrient content of periphyton on *Typha* shoots was favoured by the longer HRT. This was probably related to the lower current velocity preventing the attached algae from being washed away from the *Typha* shoots. The longer HRT also seemed to be beneficial to periphyton biomass associated with the sediment.

Denitrification in plant-associated periphyton and the sediment

Nitrate removal through denitrification in the sediment, the periphyton associated with plant shoots and the water was determined in the ditch with an 0.8 day HRT that had *Phragmites australis* in the front section and mainly *Elodea nuttallii* in the rear section (chapter 4). Denitrification measurements were made on five sampling dates between May 1997 and February 1998. The main factors that may control denitrification were also measured.

Denitrification appeared to be the predominant process for nitrate removal in this wetland system. The daily denitrification rates in periphyton on shoots of *Phragmites* (44.4-121 mg N m^{-2} stand area d^{-1}) and *Elodea* (14.8-33.1 mg N m^{-2} d^{-1}) were clearly higher than in the sediment (0.5-25.5 mg N m^{-2} d^{-1}) or the water (0.4-3.9 mg N m^{-2} d^{-1}). Seasonal variation in denitrification rates of periphyton on plant shoots correlated with the chlorophyll-*a* content of the periphyton communities as the algae in the periphyton provided for attachment surfaces and probably also organic compounds to the denitrifying bacteria. Decreases in periphyton biomass and denitrification rate in the *Phragmites* and *Elodea*-dominated stands during the growing season were related to enhanced shading by *Phragmites* shoots or a floating layer of macro-algae and *Lemna* spp., respectively. Light availability and the denitrification rate of periphyton increased again after the *Phragmites* shoots were cut in October. The lower denitrification rates of periphyton on *Elodea* than on *Phragmites* shoots was probably associated with the often lower nitrate availability in the *Elodea*-dominated stand. Denitrification in the upper sediment layer appeared to be limited by the nitrate availability, and denitrification in the water possibly by attachment area or organic carbon.

Surface-flow wetlands for polishing tertiary STP effluent: opportunities and limitations

This thesis dealt with a surface-flow treatment wetland, which was especially designed for polishing tertiary STP effluent. The simple approach to determine the removal capacity of pollutants in the wetland compartments on the basis of input and output concentrations usually approximated those quantified from the more complicated approach on the basis of mass budgets of the water inputs and outputs. Removal efficiencies of pollutants quantified from the mass budgets were still preferred, because such estimates were considered to be more accurate. The HRT and HLR were key design parameters that determined the degree of treatment efficiency of most pollutants in the parallel ditches of the wetland. The wetland system was ideal for studying the responses of pollutant removal to HRT, because it was possible to simultaneously vary HRT's. Detailed studies of several mechanisms controlling the nutrient removal capacity in the treatment wetland revealed the efficacy of harvesting emergent macrophytes for nutrient removal at longer HRT's, the considerable improvement of the nutrient removal through shoot harvest in October in stead of during the winter months, the major importance of periphyton for denitrification and the substantial temporary storage of nutrients in periphyton associated with the sediment at longer HRT's. Comparisons of the performance with that of other treatment wetlands showed that this surface-flow treatment wetland efficiently removed N and faecal coliforms from the STP effluent (Gearheart *et al.* 1989, Schierup *et al.* 1990, Knight *et al.* 1993, Kadlec & Knight 1996, Wittgren *et al.* 1996). The potential for P removal was low in this system. This was largely due to the high P mass loading rate (14 g P m^{-2} yr^{-1} in the ditches with the longest HRT) and the relatively low P input concentrations. Data from other wetlands indicate that high P removal efficiencies require P mass loading rates below approximately 10 g P m^{-2} yr^{-1} and HLR's below 10 cm day^{-1} (Schierup *et al.* 1990, Knight *et al.* 1993, Kadlec & Knight 1996). A low P adsorption capacity of the sediment and opposite seasonal P dynamics may also have contributed to the low P removal efficiency compared to that of other treatment wetlands.

The design and management of surface-flow wetlands for the treatment of tertiary STP effluent can be evaluated from results of this study, in which the treatment efficiency for pollutants was compared simultaneously for four different HRT's. The current water quality standards for the medium-sized STP (up to 45,000 person equivalents) on the island of Texel were rather similar to the EU standards for urban discharges to sensitive areas subject to eutrophication (Directive 91/271/EEC) for Kjeldahl N (15 mg l^{-1}, total N for the EU standard), total P (2 mg l^{-1}), TSS (30 mg l^{-1}) and BOD_5 (15 mg l^{-1}), while no COD standard was operative (125 mg l^{-1}) and an additional standard was effective for pH (6.5-8.5). A more stringent directive for water quality standards is being planned.

This study indicates that surface-flow wetlands can be very effective in removing total N, ammonium, nitrate and faecal coliforms from tertiary STP effluent at relatively short HRT's. A presettling basin with a HRT of 1.4 days and ditches with a HRT of 4 days were required to meet the future standard of ammonium (1 mg N l^{-1}) over an entire year. This HRT in the ditches corresponded to an N mass loading rate of 150 g N m^{-2} yr^{-1}. Kjeldahl N and total N concentrations of the wetland input already remained mostly below the current and future standard, respectively. More alternation of sections with emergent macrophytes and sections with submerged macrophytes promoting successively anoxic conditions for denitrification and oxic conditions for nitrification may further increase the N removal capacity in these wetlands, which may enable adequate N removal at even shorter HRT's (Gearheart 1996, Gerke *et al.* 2001). With the same HRT situation in the wetland system as for ammonium, the desired bathing water standard for faecal coliforms (10^3 cfu 100 ml^{-1}) was also met throughout the year, while a HRT of only 0.8 days in the ditches was sufficient for the spring-summer period.

Phosphorus removal in surface-flow wetlands supplied with STP effluent with relatively low P concentrations can only be achieved at very long HRT's. Annual P removal in the wetland system was still low when the HRT in the ditches was increased to 9.3 days (annual mean P output concentration of 1.41 mg l^{-1}). The HRT should probably be enhanced to at least 15 days to obtain substantial P removal in the ditches (Schierup *et al.* 1990, Knight *et al.* 1993, Kadlec & Knight 1996). This is not feasible in the treatment wetland investigated, because of the large land area required for realising such long HRT's. The use of subsurface-flow wetlands would reduce the land area needed for adequate P removal, but would probably still be considerable, despite the higher intrinsic P removal capacity of these wetlands and the opportunity to add P adsorbing compounds or sediments to the sediment matrix to enhance P removal (Verhoeven & Meuleman 1999, Brix *et al.* 2001). As a consequence, the future P standard of 1 mg l^{-1} can only be complied with additional chemical treatment in the

STP.

An extension of the HRT in the ditches to 4 days to sufficiently reduce ammonium and faecal coliform levels in the tertiary effluent from STP 'Everstekoog' would not affect the improvement of the oxygen dynamics in the ditches negatively (Schreijer *et al.* 2000). This would also not cause difficulties for COD, BOD and TSS, because they would remain well below their respective current and future standards at this HRT. The pH of all the ditch outputs was for a part of the day higher than the upper limit of the standard of 8.5. Such pH values well above 8.5 are, however, common for very productive natural surface water bodies with algae and submerged macrophytes (Wetzel 1983b) and the goal for the wetland to create STP effluent quality that resembles that of the receiving surface water is therefore met.

An increase in HRT implies a proportional increase in the land area needed for treatment wetlands, when the water depth is kept constant. In the wetland system used in this study, increasing HRT in the ditches from 0.8 to 4 days would result in the requirement of 2.5 times more land. In the Netherlands, such an extended wetland for STP effluent polishing is still feasible, but sufficient P removal at much longer HRT's would require too much land area. For other countries, the maximum HRT acceptable for such surface-flow treatment wetlands will rely on the daily flow of STP effluent, the water quality objectives, and the scarcity of land. Costs for energy requirements, operation and maintenance are usually relatively low in treatment wetlands compared to conventional treatment. Other benefits of treatment wetlands in relation to water quality improvement such as the buffering capacity at peak discharges or STP malfunction, and, on the other hand, disadvantages including less direct operational control and lower performance during the cold half-year in temperate climates should also be taken into account. In a densely populated country as the Netherlands, adequate polishing of tertiary STP effluent in surface-flow wetlands with similar goals as for the Everstekoog system will, for all the reasons mentioned, mainly be restricted to small to medium-sized STP's. The simultaneous use of these treatment wetlands for other wetland functions such as nature conservation, recreation and flood control, however, allows the use of relatively larger land areas (Claassen 1996, Veensta 1998, Ton 2000, Kampf *et al.* 2003a, b).