Monitoring and modelling of free water surface constructed wetlands

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ABSTRACT

Integrated water management has encouraged the construction of small scale wastewater treatment plants to treat residual discharges. For this study, six free-water-surface constructed wetlands have been monitored from September 1998 till April 1999 to determine their operational efficiency. These natural systems have been constructed by the Flemish Land Authority (VLM) in Wontergem. Design loads vary between 100 and 500 PE. The constructed wetlands seemed to function properly, even in winter conditions with low temperatures and high precipitation rates. COD, BOD and SS effluent standards for small scale wastewater treatment plants were rarely exceeded. N-removal seemed limited during the coldest period but clearly functioned better at higher temperatures. The monitored wetlands showed large differences in P-removal and removal of bacteria.
In order to obtain a better insight in the operation of free-water-surface constructed wetlands, a new model was implemented in the WEST simulator (Hemmis NV, Kortrijk, Belgium), based on the biofilm model of Rauch et al. (1999). The model confirmed the role of biofilms in these natural systems and seemed capable to simulate both microbial processes and meteorological influences.

INTRODUCTION

Although the Flemish Authorities – represented by Aquafin NV – yearly invest more than 7 billion BEF (175 million Euro) for the development of new sewer systems and sewage plants and the optimisation of the existing infrastructure, the quality of groundwater and surface water remains unsatisfying throughout Flanders (De Pauw & Poelman, 1994).

The investments have longtime been focused on densely populated areas because of the bigger economical return. However, more and more attention is paid to the remaining untreated discharges in rural areas. Because of the failing country planning in the past, the costs to connect these remote discharges to a central wastewater treatment plant (cWWTP) are extremely high (6.000 BEF – 150 Euro per meter sewer). It is estimated that therefore about 15 % of Flanders' population (900.000 PE) will never be connected to a cWWTP (Geenens & Thoeye, 1999). This is important since most of these remote discharges have a high impact on the aquatic environment : most of the ecologically valuable and vulnerable water courses are situated in these rural areas (De Gueldre, 1997).

The construction of small scale wastewater treatment plants (SS-WWTP) close to the discharge point can be a valuable alternative. These systems typically treat discharges less than 2.200 PE (European Guideline 91/271/EEC). However, their scale varies from individual installations to installations treating the wastewater of an entire residential area. Highly technological systems as well as relatively simple natural systems have been studied and are commercially available.

This study focuses on the natural wastewater treatment systems and more specific on free water surface constructed wetlands (FWS-CW). In these systems, the wastewater flows horizontally through the reed beds. Micro-organisms appearing as biofilms on the reed plant surfaces and the bottom of the ditches are responsible for the purification processes.

MONITORING PROGRAMME

The Flemish Land Authorithy (VLM) provided the town of Wontergem (situated near Deinze, Belgium) with six FWS-CW to treat part of the wastewater produced within the re-allotment borders. Table 1 gives an overview of the location and some properties of the constructed wetlands.

Table 1. Location and properties of the FWS-CW in the re-allotment Wontergem.

LOCATION	TREATMENT ZONE	DESIGN LOAD	PLANTED AREA (M^2 / PE)	GROSS AREA (M^2/PE)
Goedstraat	village centre Wontergem	250 PE	3,9	15,6
Terdonckstraat	village centre Wontergem	500 PE	4,7	10,5
Groeneweg	village centre Wontergem	100 PE	4,3	14,4
Kapittelstraat	residential area Dentergem	100 PE	3,4	15,4
Houtstraat	residential area Oeselgem	100 PE	4,1	18,0
Kruisstraat	village centre Markegem	420 PE	5,1	11,7

Four FWS-CW are constructed as one long S-shaped ditch. The two others consist of three parallel lane ditches. The waterlevel is constantly kept at 0,5 meter. All reed beds are dug in a heavy clay soil which normally prevents groundwater pollution. No impermeable foil has thus been used. The ditches were planted with *Phragmites communis* with a density of 8 plants per square meter.

The wastewater exiting the sewer system passes gravitary through a concrete entrance structure with an overflow bar. The dry weather flow passes entirely through a coarse grid to a sedimentation pond. Larger rainweather flows are partially evacuated over the overflow bar and are discharged without treatment. After the sedimentation pond, the wastewater flows through the reed beds and is discharged in a rural watercourse.

The influent and effluent of these SS-WWTP have been sampled several times from september 1998 till april 1999. Furthermore, the constructed wetland Terdonckstraat has been the subject of an intensive 10-day measuring campaign during which daily samples were taken on several places in the reed bed. During this 10-day measuring campaign, flows were also measured in order to obtain information on the hydraulic residence time and to be able to calculate mass balances.

The standard measurements were : dissolved oxygen (DO), water temperature (T_w), pH, conductivity (EC), COD, BOD, SS, NH_4-N, NO_2-N, NO_3-N, ortho-phosphate (OP), total phosphate (TP) and chloride (Cl^-).

RESULTS OF THE MEASURING CAMPAIGN

Flemish legislation (VLAREM II, 1995) imposes more flexible effluent standards for SS-WWTP compared to the effluent standards of the cWWTP. Furthermore, only COD, BOD and SS (respectively 250/50/60 mg/l) are subjected to an effluent standard, nutrient levels are not considered.

Table 2 shows whether or not the effluent standards were met during the measuring campaign. Both cWWTP and SS-WWTP effluent standards are considered.

Table 2. Comparison of measured effluent concentrations and SS-WWTP and cWWTP effluent standards. The table shows the number of samples that meets the legal standards. (H=Houtstraat, Kr=Kruisstraat, Kp=Kapittelstraat, Gr=Groeneweg, Gd=Goedstraat,T1=Terdonckstraat-basic,T2=Terdonckstraat-intensive). Based on Rousseau (1999).

CZV	H	Kr	Kp	Gr	Gd	T1	T2
SS-WWTP	7 / 7	7 / 7	6 / 6	7 / 7	3 / 3	7 / 8	10 / 10
cWWTP	6 / 7	3 / 7	2 / 6	7 / 7	0 / 3	6 / 8	4 / 10

BZV	H	Kr	Kp	Gr	Gd	T1	T2
SS-WWTP	7 / 7	5 / 5	3 / 5	5 / 5	3 / 3	4 / 4	8 / 8
cWWTP	7 / 7	4 / 5	2 / 5	5 / 5	2 / 3	4 / 4	6 / 8

SS	H	Kr	Kp	Gr	Gd	T1	T2
SS-WWTP	6 / 7	6 / 7	2 / 6	7 / 7	3 / 3	8 / 8	10 / 10
cWWTP	5 / 7	6 / 7	2 / 6	7 / 7	2 / 3	8 / 8	9 / 10

From Table 2, it can be concluded that, in general, the more flexible SS-WWTP effluent standards as well as the more rigorous cWWTP effluent standards are met. Only the FWS-CW Kapittelstraat operates less well because of underdimensioning and overloading.

Table 3 summarizes the most important results of the intensive 10-day measuring campaign on the FWS-CW Terdonckstraat (from 30/3/99 till 8/4/99).

Table 3. Overview of the most important analysis results of the FWS-CW Terdonckstraat during the 10-day measuring campaign (30/03/99 till 8/4/99). Based on Rousseau (1999).

	Influent	**After presedimentation**	**Middle of reed bed**	**Effluent**	**Efficiency**
	$x \pm \sigma$	**$x \pm \sigma$**	**$x \pm \sigma$**	**$x \pm \sigma$**	**(%)**
COD (mg COD l^{-1})	260 ± 104	152 ± 24	124 ± 28	132 ± 32	49
BOD (mg BOD l^{-1})	56 ± 25	30 ± 13	22 ± 13	21 ± 10	63
SS (mg SS l^{-1})	46 ± 33	10 ± 5	39 ± 32	19 ± 12	59
NH_4-N (mg N l^{-1})	7,8 ± 3,0	5,8 ± 1,3	1,7 ± 1,1	2,8 ± 0,6	64
NO_3-N (mg N l^{-1})	7,15 ± 3,30	3,95 ± 2,48	0,46 ± 0,59	0,15 ± 0,18	98
Ortho-P (mg P l^{-1})	1,1 ± 0,3	0,8 ± 0,1	0,7 ± 0,1	1,0 ± 0,4	9
TP (mg P l^{-1})	1,34 ± 0,50	0,96 ± 0,12	0,72 ± 0,11	1,08 ± 0,39	19
DO (%)	25 ± 3	25 ± 9	19 ± 4	26 ± 4	
Tw (°C)	10,7 ± 0,7	11,1 ± 1,0	9,6 ± 1,0	9,2 ± 0,9	
EC (µS cm^{-1})	935 ± 122	914 ± 30	769 ± 70	798 ± 53	

SIMULATION MODEL IN WEST

Existing models of FWS-CW are generally based on a steady state, first-order removal rate and do not take into account the really fundamental processes that are responsible for this removal. Only the model of Polprasert *et al.* (1998) describes the biochemical processes responsible for COD-removal in more detail. This model is based on a steady state approach of the biofilms occuring on the reed stems and the bottom of the ditches.

Based on the model of Polprasert *et al.* (1998), a new model was developed in WEST (Hemmis NV, Kortrijk, Belgium), in order to obtain a better insight in the role of the biofilms for wastewater treatment in reed beds. WEST (Wastewater treatment plant Engine for Simulation and Training) is a new modelling and simulation environment in which diverse mathematical models can easily be implemented. The simulation of the biofilms was based on the model of Rauch *et al.* (1999).

According to Kadlec *et al.* (1983), the flow regime in FWS-CW is intermediate between plug flow and perfectly mixed. This was simulated by using the tanks-in-series approach. Furthermore, this approach was advantageous because the modular modelling approach of WEST allowed to flexibly add or remove mass streams between subsequent tanks. Hence, the possibility was created to simulate rainfall, evapotranspiration and the release of C,N and P from decaying dead plants and periphyton.

In each perfectly mixed tank, two biofilms were defined : one on the reed stems (bulk water layer) and one on the bottom (detritus layer). In this way, two zones with different oxygen concentrations could be created by imposing an additional oxygen transfer resistance between the bulk water layer and the detritus layer. It was furthermore assumed that the biofilm on the bottom wasn't influenced by the water flow. In other words, substrates are only supplied through mixing and diffusion. This results in the following mass balances :

biofilm on the reed stems : $$\frac{dM}{dt} = Q_{in}C_{in} - Q_{out}C_{out} + diffusion + reaction$$

biofilm on the bottom : $$\frac{dM}{dt} = diffusion + reaction$$

The simulated processes are based on the industry-standard Activated Sludge Model N° 1 (ASM1) of Henze *et al.* (1987) : heterotrophic growth, autotrophic growth, hydrolysis, ammonification, nitrification, denitrification, BOD-removal and oxygen consumption and supply. Because FWS-CW are strongly influenced by meteo conditions, most of the reactions were made temperature dependent.

SIMULATION RESULTS

The validation of the model was hampered by a lack of literature values for most parameters. Moreover, the data set obtained from the intensive measuring campaign in Wontergem wasn't extensive enough to allow accurate parameter estimation (Rousseau, 1999). Hence, most parameters were taken from the ASM1 and from biofilm models used for other situations (e.g. trickling filter, …). It is clear that this only allows for a rough approximation of reality.

Because of the difficulties encountered during the validation of the model, it doesn't seem appropriate to give simulation results and to discuss them in a quantitative way. But based on the trends found in the simulation results, it could be concluded that at least the model concept was acceptable. Comparison of simulation results with literature data showed an acceptable agreement. This confirms the important role of biofilms in natural SS-WWTP. The model also seemed able to simulate crucial meteorological influences in a simple way. However, validation of the model with an extensive dataset remains absolutely necessary before one can rely on the simulation results. Extension of the model with nutrient removal by plant uptake, P-removal and removal of pathogens can easily be done and will offer an even better approximation of reality.

DISCUSSION

All monitored constructed wetlands of the town of Wontergem seemed to function properly, especially when in view of the fact that most samples were taken during winter with low temperatures and very high precipitation rates. Only the FWS-CW Kapittelstraat functioned less well due to underdimensioning and overloading.

Some constructed wetlands showed an inhibited N-removal. However, when the results of the basic and the intensive measuring campaign on the FWS-CW Terdonckstraat are compared, it seems that a slightly higher temperature already results in improved nitrification and denitrification.

The more flexible SS-WWTP effluent standards for BOD, COD and SS are generally met. In some cases, effluent quality even complies with the more rigorous cWWTP effluent standards. Nutrient levels in the effluent fluctuate around the basic quality standard for surface waters.

In the FWS-CW of Wontergem, the planted area per PE is somewhat lower than what is generally proposed in literature as design standard. One may conclude that a bigger planted area could guarantee that the effluent standards are met. However, this improvement of the effluent quality should always be carefully balanced against the bigger investments required for a larger surface.

The only problem that was repeatedly encountered was the lack of control and maintenance of the reed beds. Blocked grids and sedimentation ponds which are silted up endanger the proper functioning of the systems whereas they are very simple to prevent. This results in a higher overflow frequency and thus a negative impact on the water quality of the small rural water coarses into which is discharged. Indeed, for the FWS-CW Terdonckstraat, a significant decrease in biological water quality was found (Rousseau, 1999).

Concerning the new model of a FWS-CW developed in WEST, it can be concluded that the model seems to be a good first approximation of reality. Simulation of COD/BOD-removal, N-removal and reaeration are certainly possible and the implementation of the meteorological influences can also be easily done. Simulation results seemed to correspond with literature data. However, validation of the model with an extensive data set remains absolutely necessary before one can rely on simulation results.

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