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Constructed wetlands in Flanders: a performance analysis

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Abstract

During the last decade, the number of constructed wetlands in Flanders (Belgium) increased exponentially. Extensive data collection resulted in a database of 107 constructed wetlands that was used to evaluate certain trends and treatment performances. Design sizes vary between 1 and 2000 population equivalents (PE), with the majority of reed beds having a size smaller than 500 PE. Most reed beds are used as single treatment units, although they are sometimes also combined with other reed beds or even conventional systems. The main purpose is to treat domestic and dairy wastewater. Average removal efficiencies were lowest with free-water-surface (FWS) reed beds (chemical oxygen demand (COD), 61%; suspended solids (SS), 75%; total nitrogen (TN), 31% and total phosphorus (TP), 26%). The best overall performance was obtained with vertical flow (VF) wetlands (COD, 94%; SS, 98%; TN, 52%; TP, 70%), except for total nitrogen removal where combined reed bed systems even did better (COD, 91%; SS, 94%; TN, 65%; TP, 52%). Despite this considerable achievement in removal, the effluent nutrient concentrations of many systems remain too high and entail a tangible danger of eutrophication.

Keywords: Maintenance; Economics; Nutrient removal; *Phragmites australis*; Reed beds

1. Water quality management in Flanders

Flanders is the northern-most region of Belgium, located in between the North Sea, The Netherlands, France, Germany, and Belgium's Walloon Region. Its total surface area is 13,522 km^2, inhabited by nearly six million people (Administration of Planning and Statistics, 2003).

Since 1990, domestic wastewater collection and treatment in the Flemish region is mainly the responsibility of a single company, named Aquafin NV, with 51% of its shares owned by the Flemish government and 49% owned by various private investors (Aquafin NV, 2000). Wastewater treatment plants with a design capacity smaller than 2000 population equivalents (PE) may, however, also be planned and constructed by several government agencies, municipalities, and even private persons (if <20 PE).

Because the EU Directive 91/271 on Urban Wastewater obliged Member States to treat the

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wastewater of all agglomerations larger than 10,000 inhabitants before 31/12/1998 and because in 1990 only 30% of the domestic wastewaters in Flanders were being treated, it was decided to concentrate on the large scale projects in order to catch up as quickly as possible. Small-scale projects were not entirely neglected, but certainly had no priority.

This approach has undoubtedly been successful up till now. By 2002, 57% of all domestic wastewater was being treated, resulting in a significant load reduction of organic substances and nutrients into the Flemish surface waters (Aquafin, 2003a). Together with other emission reduction measures, this has generally resulted in a shift from extremely bad and very bad surface water quality towards a moderate water quality, as indicated by physico-chemical as well as biological variables. However, for the majority of the monitoring sites, the water quality still does not meet the standards and has in some cases even deteriorated (MIRA-T, 2002).

At the current levels of technology and investment rates, Aquafin NV estimates that up to 20% of the Flemish population will never be connected to a large-scale wastewater treatment plant and will have to treat its wastewater by means of small-scale or even individual treatment systems (Vandaele et al., 2000). One of the main reasons for this is the lack of town and country planning in the past, which has led to very dispersed location of housing and results in extremely high investment costs for connection to centralised sewer systems.

Several small-scale wastewater treatment techniques can be applied, of which constructed wetlands are amongst the most imaginative ones. A recent comparative study between mechanical and plant-based single-household systems revealed that the latter ones are more efficient in an economical as well as an ecological way (Rausch et al., 2000).

2. Effluent standards in Flanders

The effluent standards in Flanders for small-scale wastewater treatment systems (20–2000 PE) are not stringent: 250, 50 and 60 mg L^{-1} for COD, BOD and SS, respectively. No nutrient standards are imposed. Treatment systems with plants that are smaller than 500 PE are even dismissed from all effluent standards if the air temperature drops below 5 °C (VLAREM II, 1995). Systems with a capacity below 20 PE have similar standards. Table 1 compares the Flemish Environmental Legislation with a selection of effluent

Table 1
Effluent standards of different European countries for small-scale discharges into surface waters

Country	Remarks	COD (mg L^{-1})	BOD (mg L^{-1})	SS (mg L^{-1})	TN (mg L^{-1})	NH_4^+–N (mg L^{-1})	TP (mg L^{-1})	Reference
Flanders, Belgium		250[a]	60[a]	50[a]				VLAREM II (1995)
Germany		150	40					Börner et al. (1998)
The Netherlands	Class I	750	250	70				Debets (2000)
	Class II	150	30	30				
	Class III[a]	100	20	30	30	2		
	Class III[b]	100	20	30	30	2	2	
Austria		90	25			10[a]		Haberl et al. (1998)
Poland	<2000 m^3 day^{-1}	150	30	50	30	6	5	Kowalik and Obarska-Pempkowiak (1998), Kempa (2001)
Czech Republic	500–2000 PE[d]	125–180[c]	30–60[c]	35–70[c]				Czech Law No. 61/2003, chapter 24 (2003)
Sweden			10[b]		15		0.3–0.5	Linde and Alsbro (2000), Sundblad (1998)

[a] For plant-based systems only if $T > 5$ °C.
[b] Expressed as BOD_7.
[c] Mean–maximum value.
[d] Impact on the receiving water body may be taken into consideration and as a result discharge limits can be lower.

standards in some other European countries. One can clearly see that the Flemish effluent consents are the most relaxed ones, only exceeded by the Dutch standards for class I, which means the non-sensitive areas. It is clear that such standards do not offer real protection for a small water course into which the effluent is eventually discharged. The ‘good ecological quality’ as required in the European Water Framework Directive (Council of the European Communities, 2000) seems, therefore, a barely attainable goal in those, usually sensitive and biologically valuable, water courses.

Besides these non-stringent standards, there is, in practice, little or no control on whether or not the effluents comply and whether or not the treatment plants are operated and maintained properly, except for the constructed wetlands operated by Aquafin NV and a few other examples. This again greatly endangers surface water quality.

3. Experience with constructed wetland systems in Flanders

A first review on the use of constructed wetlands in Belgium was published by Cadelli et al. (1998), as part of a European treatment wetlands inventory (Vymazal et al., 1998). At that time, only two surface flow constructed wetlands and one combined system were described for the Flemish region. Since then, an exponential increase took place (Fig. 1a). The oldest constructed wetland is situated in Bokrijk. It is a vertical flow (VF) reed bed, dating from 1986 and still in operation, although it needed some major modifications due to excessive iron deposition in the drainage pipes and consequent clogging.

Unfortunately, only those treatment plants constructed by (semi-)governmental institutions are relatively well documented. Single-household systems, constructed wetlands on farms, etc. are usually not registered with the local authorities and can, therefore, only be traced by newspaper articles, newsletters from agricultural associations, internet searches, etc. An extensive search through this non-scientific and some regional scientific literature (a.o. Fornoville et al., 1998; Rousseau, 1999; VMM, 2001; AMINAL, 1998; AMINAL, 2002; Aquafin, 2003b; Duyck, 2003; VLM, 2003) resulted in a database on 107 wastewater treatment plants in which constructed wetland technology is being used. The distribution of the design sizes expressed as population equivalents is shown in Fig. 1b. One should be aware that these population equivalents, especially for small-scale systems, are derived from the actual number of people connected to it, and not from organic or hydraulic loading rates. Aquafin (2003c), for instance, found that one inhabitant in reality only produces about 40 g of BOD per day instead of the 54 g of BOD per day assumed during the design stage.

Many different types of constructed wetlands (CWs) are used in Flanders (Fig. 2), ranging from free-water-surface (FWS) over subsurface flow (SSF) to vertical flow CWs and all possible combinations. It is worth noting that the majority of these wetland systems are solely planted with common reed (*Phragmites australis* (Cav.) Trin. ex Steud.). Some ecologically oriented people, however, used their imagination to construct magnificent wetland systems in their backyard with

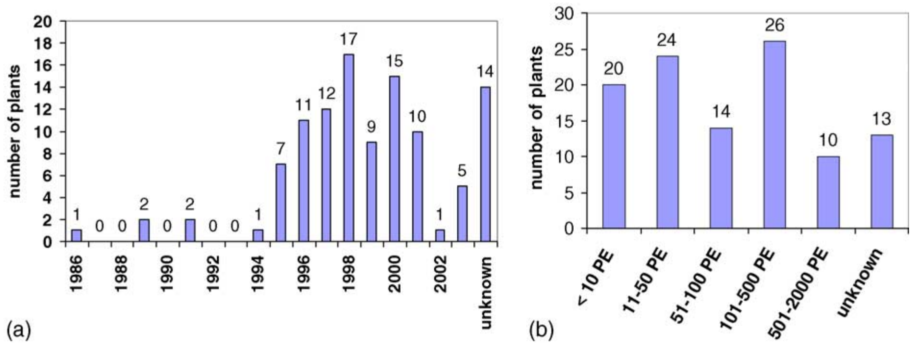

Fig. 1. (a) Number of constructed wetlands installed in Flanders since 1986; (b) distribution of design sizes of constructed wetlands in Flanders, expressed as population equivalents (PE).

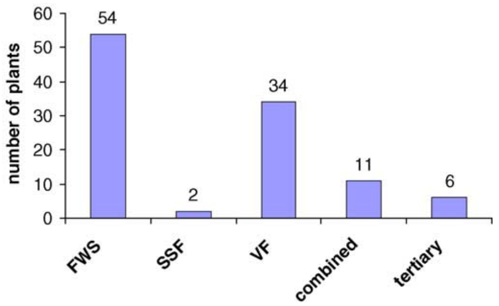

Fig. 2. Types of constructed wetlands installed in Flanders since 1986 (FWS, free-water-surface; SSF, horizontal subsurface flow; VF, vertical flow).

other species of helophytes and even hydrophytes and pleustophytes. Besides these constructed wetlands *pur sang*, which serve as secondary treatment systems, a number of tertiary treatment wetlands were also installed in which natural treatment systems are combined with more conventional ones to enhance the treatment efficiency and flexibility.

In the following sections, these different types of constructed wetlands will be further described in terms of design variables, investment costs, origin of wastewater, and operation and maintenance issues. Performance will be analysed through percentage reduction efficiency and a comparison of the effluent concentrations with the Flemish and Dutch Class IIIb standards (Table 1). This will allow the assessment of the suitability of the different systems to operate under non-stringent (Flemish standards) and stringent (Dutch standards) conditions.

3.1. Free-water-surface constructed wetlands

Nearly all free-water-surface constructed wetlands in the database (52 out of 54) were ordered by the Flemish Land Agency (VLM). Most of these fit within the framework of a re-allotment project and aim at improving the local water quality. VLM specifically seeks out clay bottoms with a low hydraulic conductivity so that no liner is needed. This approach significantly reduces the investment costs (J. Verboven, personal communication).

A typical lay-out starts with a concrete overflow structure allowing stormwater peak discharges to bypass the treatment plant. Wastewater that is not bypassed then flows through a course bar screen and enters a settling pond where the majority of particulate substances can be removed before the wastewater enters the reed bed. The reed bed is mostly a long, narrow channel and is planted with *P. australis*. Water levels are normally maintained at 40–50 cm (Rousseau et al., 1999).

The design size of the FWS constructed wetlands in the database varies from as little as 1 PE up to 2000 PE with an average surface area of about 7 m^2 PE^{-1} and an average investment cost of €392 PE^{-1}. Investment costs per PE clearly decrease as the design size of the treatment plant increases, with a marked transition at about 100 PE.

Fifteen free-water-surface CWs treat wastewater from a milking parlour, 34 receive domestic wastewater, three systems receive a mixture of the two previous types, one wetland treats the wastewater of a meat processing company and a last one treats wastewater of an eel farm.

Only few of those reed beds have been monitored in some detail. Fig. 3 shows cumulative frequency distributions of the influent and effluent concentrations for the variables chemical oxygen demand (COD), suspended solids (SS), total nitrogen (TN) and total phosphorus (TP). Data on flow rates are virtually non-existent and pollutant loads can thus not be calculated.

Several observations can be made from Fig. 3. Concerning COD, 100% resp. 98.7% of the effluent concentrations are in compliance with the 250 mg COD L^{-1} resp. 100 mg COD L^{-1}. Only 3% resp. 6% of the SS effluent concentrations do not comply with the 60 mg SS L^{-1} resp. 30 mg SS L^{-1} standard but these are probably due to extreme conditions or malfunctioning since the 80-percentile equals 13 mg SS L^{-1}. As mentioned in the introduction, there are no nutrient limitations for small-scale wastewater treatment plants in Flanders. Compared with the Dutch Class IIIb standards, however, 4% of the samples has concentrations above the 30 mg TN L^{-1} standard and 28% were observed to be above the 2 mg TP L^{-1} standard.

It is striking that 80% or more of the influent samples are already below the Flemish COD and SS standards. This is mainly due to the mixed nature of the sewer networks in Flanders and the resulting dilution by stormwater. It was also common practice in the previous decades to couple drainpipes and even ditches to the sewer system, which sometimes leads to extremely diluted wastewater.

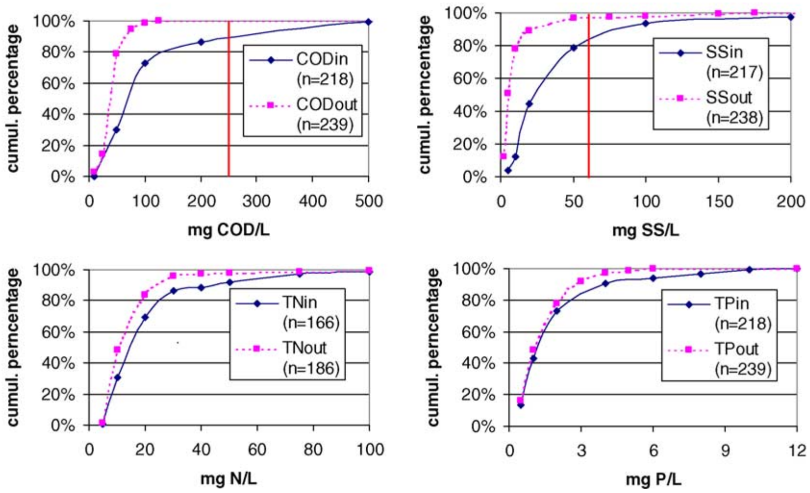

Fig. 3. Cumulative frequency distributions of the influent and effluent concentrations of 12 free-water-surface constructed wetlands in Flanders for the variables COD, SS, TN and TP. Vertical lines indicate Flemish effluent standards for small-scale wastewater treatment plants.

Fig. 3 seems to indicate that removal of COD and suspended solids is more efficient than removal of nitrogen and phosphorus. This is confirmed by the overall concentration-based removal efficiencies: 61% and 75% for COD and SS, respectively, versus 31% and 26% for TN and TP, respectively. The general performance is nevertheless quite low. A two-fold explanation is suggested. Low removal efficiencies are in most cases due to the stormwater and surface water discharges to the reed beds, which result in high hydraulic and low organic loading rates. Some other reed beds are on the contrary organically overloaded due to some local Small Medium Enterprises (SMEs) that produce high-strength wastewaters.

Operation and maintenance (O&M) problems are mainly related to the hydraulic constructions and to a lack of supervision. Misconceptions about the flow rates during the design phase have in some cases even caused a major part of the dry weather flow to disappear untreated over the overflow structure into the bypass. A raise of this structure is not always possible because this would cause a backflow into the sewer system and consequently inundations of the villages during severe rainstorms. A second O&M problem results from a lack of know-how. After construction, the responsibility is generally transferred from the Flemish Land Agency to the city council, which usually has no experience with wetlands. They also often adopt the misconception that ‘natural’ systems are able to manage themselves and not be looked after anymore. Unfortunately, clogged bar screens and completely filled settling ponds are therefore frequently observed (Rousseau et al., 1999).

3.2. *Vertical flow constructed wetlands*

Vertical flow constructed wetlands are fairly popular throughout Europe because of their reduced footprint and their good effluent quality (Haberl et al., 1995). These characteristics promoted an increasing use of VF CWs in Flanders as well (Fig. 2).

The design size of the 34 VF reed beds in the database varies from 4 up to 2000 PE with an average surface area of 3.8 m^2 PE^{-1} and an average investment cost of €507 PE^{-1}. Most reed beds (28 out of 34), however, have a surface area smaller than 80 m^2. The limited data (17 CWs) again show the economy of scale, i.e. the investment cost per PE decreases as the design size of the constructed wetland increases, although large variations are noted.

Loading of the beds is in most cases intermittent to optimise reaeration. Limited information could be found about the filter material but coarse sand seems to be most commonly applied. To enhance nutrient removal, the matrix material is sometimes mixed with one or more additions. Straw has in some cases been added as a carbon source to promote denitrification whereas iron and aluminum filings or lime are added to improve phosphorus removal.

Thirteen VF constructed wetlands exclusively treat domestic wastewater whereas 20 reed beds treat a mixture of domestic and dairy wastewater. One system is located on an experimental farm and treats domestic, horticultural and non-toxic laboratory wastewater.

Only seven VF reed beds have been monitored in some detail. Fig. 4 shows cumulative frequency distributions of the influent and effluent concentrations for the variables COD, SS, TN and TP.

More than 99% of the COD and more than 98% of the SS effluent concentrations are in compliance with the non-stringent Flemish consents (Fig. 4, Table 1). About 97% resp. 95% comply with the stringent Dutch Class IIIb demands for COD resp. SS. A few outliers are probably caused by system malfunctions or extreme conditions. When looking at the Dutch standards for effluent nutrient concentrations, one can observe that only 48% of the TN concentrations and 31% of the TP concentrations are sufficiently low.

Compared to the FWS constructed wetlands, one can see that the influent concentrations are generally higher. Some of the systems contributing to Fig. 4 receive indeed exclusively wastewater since they are single-household systems where the rainwater has been completely separated from the wastewater.

Overall concentration-based removal efficiencies are fairly good and equal 94% for COD, 98% for SS, 52% for TN and 70% for TP. Vertical flow constructed wetlands clearly perform better than the free-water-surface constructed wetlands.

Operational problems with VF systems are generally related to clogging phenomena. These are for some reed beds due to the mixed nature of the sewer networks. Hydraulic overloading and peak concentrations of suspended solids during storm events initiate rapid pore blockage. As a result, Aquafin NV, for instance, has abandoned this concept until new, separated sewer systems will be constructed. Some other treatment wetlands clearly receive organic loads that are significantly above the design load and are clogging due to an insufficient degradation capability on the one hand, and an excessive biofilm production on the other. Other common causes of clogging are the application of inadequate filter materials and an unequal distribution of wastewater on the bed surface.

3.3. Horizontal subsurface flow constructed wetlands

Horizontal subsurface flow or so-called root-zone constructed wetlands are less common as a one and only treatment step in Flanders. Due to the frequent clogging problems occuring in VF wetlands, however,

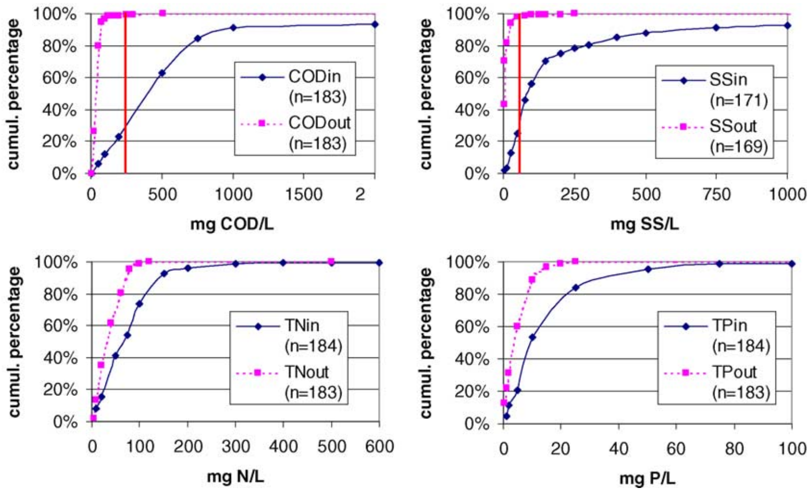

Fig. 4. Cumulative frequency distributions of the influent and effluent concentrations of seven vertical flow constructed wetlands in Flanders for the variables COD, SS, TN and TP. Vertical lines indicate Flemish effluent standards for small-scale wastewater treatment plants.

the focus is now more and more shifting towards this concept.

Two root-zone constructed wetlands could be traced and are included in the database. The treatment system at Hasselt-Kiewit was started up in 1999, has a design capacity of 152 PE and treats domestic wastewater on a surface area of 896 m^2. Since 2001, a 350 PE constructed wetland at Zemst-Kesterbeek treats domestic wastewater on a surface area of 1300 m^2. Due to eight parallel beds on the one hand, and some extra educational features on the other hand, the system at Hasselt-Kiewit is the most expensive one with an investment cost of €1636 PE^{-1}. The investment costs at Zemst-Kesterbeek were, however, much lower, i.e. €879 PE^{-1}.

The Zemst-Kesterbeek system comprises a multi-chambered primary settlement tank followed by two parallel beds. At Hasselt-Kiewit, a primary settlement ditch is followed by eight parallel beds. Contradictory to what is commonly recommended in the literature, all reed beds have a length/width ratio that is significantly higher than 1 and have a pulsed loading during dry weather conditions. Hasselt-Kiewit is a Flemish exception in the sense that more than one plant species is being used. Both reed beds are filled with washed gravel with a diameter of 5–10 mm.

Fig. 5 shows cumulative frequency distributions of the influent and effluent concentrations for the variables COD, SS, TN and TP. The graphs clearly demonstrate that all COD and SS effluent concentrations are below the Flemish standards for small-scale wastewater treatment plants and 95% resp. 93% are below the Dutch class IIIb standards. Ninety-three percent of the nitrogen effluent concentrations and 52% of the TP effluent concentrations comply with the Dutch class IIIb standards.

Overall concentration-based removal efficiencies equal 72% for COD, 86% for SS, 33% for TN and 48% for TP. The performance is in between the one of the vertical flow and the free-water-surface constructed wetlands.

Maintenance problems have occurred due to clogged inlet zones and resulting overland flow and are probably caused by the high length/width ratios. The inlet zones, therefore, become overloaded and the pores fill up with particulates.

3.4. Combined wetlands

Several researchers have proven that a combination of different reed beds not only offers more flexibility, but also provides significantly better effluent qualities (e.g. Cooper et al., 1999; Radoux et al., 2000; Gómez Cerezo et al., 2001). The most popular combination in Flanders consists of one or more parallel vertical flow reed beds followed by one or more horizontal

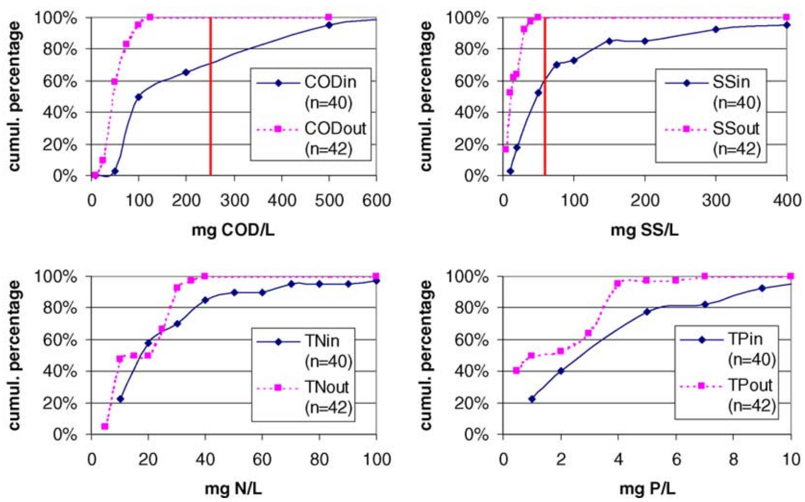

Fig. 5. Cumulative frequency distributions of the influent and effluent concentrations of two horizontal subsurface flow constructed wetlands in Flanders for the variables COD, SS, TN and TP. Vertical lines indicate Flemish effluent standards for small-scale wastewater treatment plants.

subsurface flow reed beds. This enhances nitrogen removal since VF wetlands stimulate nitrification and SSF wetlands consequently promote denitrification.

Eleven combined systems (Fig. 2) were identified and included in the database. Their design size varies from 5 up to 750 PE with an average surface area slightly exceeding 5 m^2 PE^{-1} and an average investment cost of €919 PE^{-1}. The same trend as for the other wetland types is noted, i.e. the investment costs per PE decrease as the design size increases, with a marked shift at capacities around 200 PE.

Nine of those combined wetland treatment systems are of the VF–SSF type, one is a FWS–VF combination and the last one consists of two SSF reed beds in series. Domestic wastewater is the sole source for nine systems, one treatment plant receives a mixture of domestic wastewater and rincing water from a horse stable and another one treats wastewater from a mink farm.

Cumulative frequency distributions of the influent and effluent concentrations for the variables COD, SS, TN, and TP can be found in Fig. 6. All COD effluent concentrations are amply below the Flemish 250 mg COD L^{-1} consent and more than 97% comply with the more stringent Dutch class IIIb standard. Suspended solids in the effluent reach a maximum concentration of 44 mg SS L^{-1} and thus no exceedances of the Flemish effluent standards have been noted, whereas only 8% of the concentrations exceed the Dutch 30 mg SS L^{-1} standard. Concerning nutrient effluent concentrations, only 47% of the TN and 41% of the TP concentrations comply with the Dutch class IIIb standard.

Overall reductions for COD, SS, TN and TP based on average influent and effluent concentrations equal 91%, 94%, 65% and 52%, respectively. Combined wetland treatment systems indeed seem to yield the highest nitrogen elimination by optimally using the strengths of each type of reed bed.

As can be expected, maintenance problems are identical to the VF and SSF systems and are mainly related to clogging issues, which already have been described in some detail in the previous sections.

3.5. Tertiary treatment wetlands

A combination of conventional and natural systems for wastewater treatment is also fairly popular in Flanders, with the conventional ones ensuring secondary treatment and the natural ones ensuring tertiary treatment. The addition of one or more constructed wetlands greatly enhances the capacity and flexibility of the treatment process.

Six small-scale wastewater treatment plants that make use of constructed wetlands for tertiary treatment are present in the database and are described in some detail in Table 2. Limited data on investment

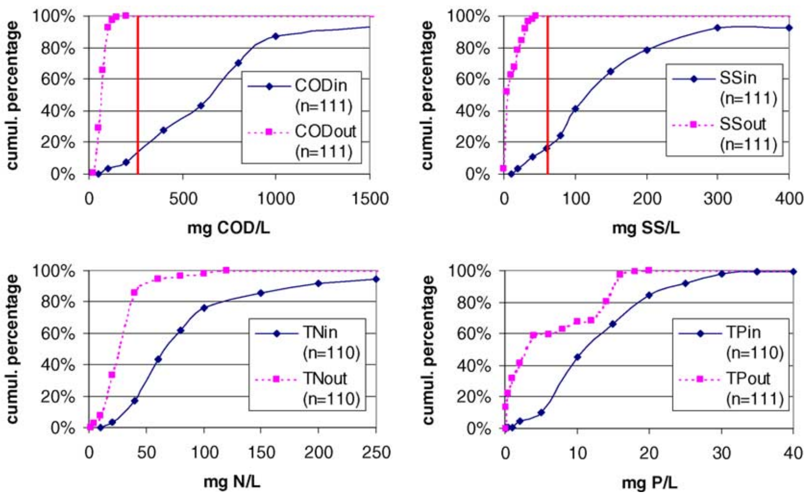

Fig. 6. Cumulative frequency distributions of the influent and effluent concentrations of six combined constructed wetlands in Flanders for the variables COD, SS, TN and TP. Vertical lines indicate Flemish effluent standards for small-scale wastewater treatment plants.

Table 2
Constructed wetlands as tertiary treatment systems in Flanders, Belgium

Site	Year	Design capacity (PE)	Area 'green' unit (m^2)	Waste water origin	Lay-out
Aalbeke	1997	500	500	Domestic	Two rotating biological contactors + one SSF CW
Sint-Maria-Lierde	2000	850	425	Domestic	Three rotating biological contactors + one SSF CW
Planckendael INCOMATS^{TM}	1995	150	174	Domestic Restaurant Animal cages	One activated sludge unit + three macrophyte beds + one SSF CW
Planckendael birdcage	n.g.	1–4	20	Animal cages	One rotating biological contactor + two SSF CWs
Tielt-Winge	1994	400	?	Domestic	One aerated lagoon + one duckweed pond
Lier	1995	30	100	Domestic	One woodfilter + one VF CW

costs show that the Planckendael INCOMATS^{TM} system is the most expensive one with an investment cost of €2809 PE^{-1}, followed by the RBC–SSF system at Aalbeke (€1389 PE^{-1}) and finally the RBC–SSF system in Sint-Maria-Lierde (€736 PE^{-1}). Investment costs of the Planckendael INCOMATS^{TM} system are, however, not fully representative, since the treatment plant is located in a zoological garden and major attention was paid to educational and visual aspects.

All six treatment plants are being monitored quite closely. Fig. 7 shows cumulative frequency distributions of the influent and effluent concentrations for the variables COD, SS, TN and TP. Except for one outlier, all COD and SS effluent concentrations are well below the Flemish standards. Compared with the Dutch class IIIb standard, only about 5% of the concentrations slightly exceed the required level. For the nutrients nitrogen and phosphorus, 87% of all TN and 65% of all TP effluent concentrations comply with the Dutch class IIIb standard.

Overall concentration-based removal efficiencies equal 82% for COD, 93% for SS, 49% for TN and 46% for TP. These are acceptable values but certainly not better ones than those of the previously described systems. One could therefore falsely conclude that extra energy inputs, a more controlled

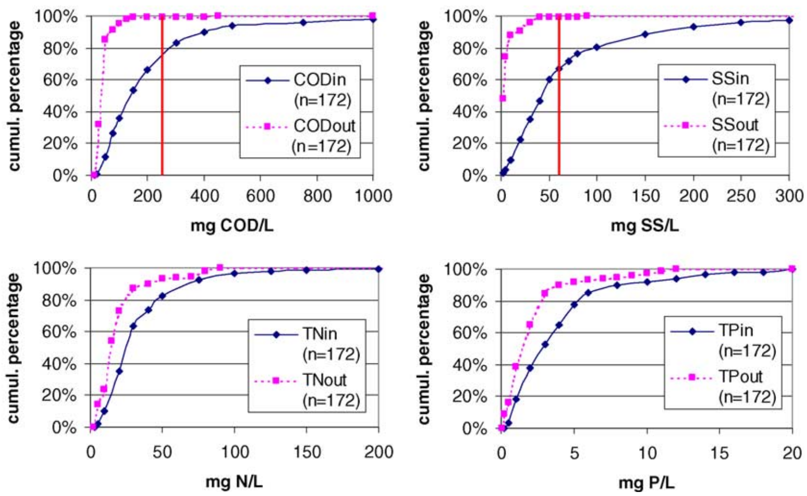

Fig. 7. Cumulative frequency distributions of the influent and effluent concentrations of six small-scale wastewater treatment systems with tertiary treatment wetlands in Flanders for the variables COD, SS, TN and TP. Vertical lines indicate Flemish effluent standards for small-scale wastewater treatment plants.

environment and a more labour-intensive maintenance not necessarily enhance treatment performance. Percentage reduction is, however, not always entirely representative, as indicated by the fact that the lowest average COD and SS effluent concentrations are produced by these combined technical–natural treatment plants.

4. Discussion

4.1. Organisation and legislation

Small-scale wastewater treatment remains a controversial issue in Flanders with continuing discussions about which government agency has which authority and consequent debates on the location of treatment plants, the choice of treatment technology and the organisation of maintenance and follow-up.

Two other weak points that can be identified are the non-stringent environmental legislation and the lack of enforcement. First of all, the effluent standards for small-scale wastewater treatment plants are too compliant and offer hardly any real protection for receiving, sensitive aquatic ecosystems. One is again referred to Table 1, which clearly demonstrates that the Flemish effluent consents are amongst the most relaxed ones. Fortunately, most constructed wetlands included in this study produce an effluent with a quality significantly better than the minimum required one. It nevertheless seems sensible to replace the current emission-based effluent consents with immission-based ones that take into account the carrying capacity of the receiving watercourse. Commonly known examples are the 'Total Maximum Daily Load' applied in the USA (Shanahan et al., 1998) or the 'Percentile Approach' applied in the United Kingdom (http://www.environment-agency.gov.uk).

Secondly, there is little sense in issuing effluent standards if they are not enforced. A central registration office should firstly compile a complete inventory of natural treatment systems and adequate monitoring arrangements should consequently be made to discontinue this lack of control. At the moment, there are also ongoing discussions about certification of certain single-household treatment systems which should guarantee at least a minimum level of performance (Maes, 2000).

4.2. Design and investment costs

Table 3 resumes average footprint, investment cost and design capacity of the different types of constructed wetlands.

Free-water-surface constructed wetlands clearly require the largest area whereas the tertiary treatment systems logically occupy the lowest area per PE. The footprints of all surveyed reed bed types are anyhow considerably smaller than the ones reported by Boller (1997), i.e. 7–12 m^2 PE^{-1}. The largest free-water-surface wetland in Flanders comprises a total area of 1.0 ha, which compares relatively insignificant to the median value of 40 odd ha reported by Kadlec (1995) for North-American wetlands. The treatment plant at Rillaar is the biggest one in Flanders, and consists of four parallel vertical flow wetlands, jointly occupying a surface area of 1.2 ha and treating the wastewater of some 2000 PE.

Average investment costs in Table 3 should be interpreted with great care because data quality is highly variable throughout the database, a problem that was also reported by others like Knight et al. (1993).

Table 3
Average footprint (in m^2 PE^{-1}), average investment costs (in € PE^{-1}) and average design capacity of the different types of constructed wetlands in Flanders, Belgium

	Average footprint (m^2 PE^{-1})	Average investment cost (€ PE^{-1})	Average design capacity (PE)
Free-water-surface CWs	7.0	392	201
Vertical flow CWs	3.8	507	158
Subsurface flow CWs	4.8	1258	251
Combined reed beds	5.0	919	272
Tertiary CWs	1.5[a]	1645[b]	386

[a] Area of 'green unit' only.
[b] Cost of full system.

Available data nevertheless indicate that FWS reed beds are the cheapest ones, which is entirely due to the ease of construction and the avoidance of lining. Subsurface flow constructed wetlands appear to be the most expensive 'green' technology, but the two available entries in the database should not be considered as fully representative. One ever-recurring fact is the economy of scale, i.e. the per capita cost decreases as the design size of the treatment plant increases. This characteristic seems to be common to all small-scale wastewater treatment plants as Boller (1997) describes a similar trend for reed beds as well as for rotating biological contactors, biofilters, stabilisation ponds etc. The same author also reports a dramatic increase of per capita costs for treatment plants below a size of about 200 PE, which is consistent with the findings of this study.

Vertical flow systems have the lowest average design capacity. This results from the fact that they are the most popular technology for single-household systems and dairy waste treatment, which are commonly discharges below 20 PE or even 10 PE. Treatment plants that combine technical and natural units exhibit the highest average design capacity as they seem to be more flexible and economically feasible for larger quantities of wastewater.

4.3. Systems assessment and operation

Influent concentrations of the free-water-surface constructed wetlands are the lowest ones compared to the other types of CWs, closely followed by the ones of SSF reed beds. This is mainly due to the fact that all FWS and SSF CWs receive wastewater of a mixed sewer system whereas at least some CWs of the other types receive undiluted wastewater. The lowest average COD and SS effluent concentrations are produced by technical systems with consequent tertiary treatment wetlands, most probably due to mechanical oxygen input and special sedimentation units. Hiley (1995) indeed reports that most wetlands are oxygen limited and that performance is enhanced if extra aeration is provided. The lowest nutrient concentrations were observed in the effluents of FWS constructed wetlands, which is, however, entirely due to the low influent concentrations.

Average removal efficiencies of FWS reed beds are the lowest ones (COD, 61%; SS, 75%; TN, 31% and TP, 26%). Several reasons can be given. Firstly, due to the diluted influent, the effluent concentrations can approach the background concentrations and further removal is thus hampered. Kadlec (1995), for instance, mentions background COD levels varying between 30 and 100 mg COD L^{-1}. A second possible reason suggested by Kadlec (1997) is the often noticed positive relation between loading rate and performance. In this case, the low influent loading rate would explain the low removal efficiencies. Finally, Verhoeven and Meuleman (1999) state that the low removal rate they observed is due to the fact that the most important processes involved occur in the sediment whereas the wastewater flows over the sediment. Dissolved nutrients thus have to transfer by diffusion, which is a fundamentally slow process.

The best overall performance was recorded for the vertical flow wetlands (COD, 94%; SS, 98%; TP, 70%), except for total nitrogen removal where the combined reed bed systems performed better (65%). Not considering a limited number of outliers, generally caused by extreme conditions or system malfunctions, all constructed wetlands produce an effluent with COD and SS concentrations considerably lower than the non-stringent Flemish or even stringent Dutch class IIIb standards for small-scale wastewater treatment plants. Nutrient limitations do not exist in Flanders but many treatment wetlands nevertheless demonstrate a significant removal of nitrogen (31–65%) and phosphorus (26–70%). These reductions are, however, in most cases not sufficient to produce an effluent that meets the demand of the Dutch class IIIb standards.

Operational problems are mainly related to clogging phenomena, a problem commonly acknowledged among wetland researchers (see e.g. Platzer and Mauch, 1997; Blazejewski and Murat-Blazejewska, 1997; Langergraber et al., 2002). Next to some design changes, it looks like this problem can only be dealt with through the construction of separate drainage systems for stormwaters and wastewaters.

Finally, maintenance really is a major issue, as evidenced by the many wetlands that are filled up to various degrees with solids, bar screens that are clogged and reed plants that are being outcompeted by a variety of weeds. Boller (1997) also reported that 'lack of trained operators is often claimed to be the major reason for malfunctioning of small plants'. Concurrent with the conclusions of Cooper et al. (1996) and others, the frequent misconception that natural treatment systems are a 'build-and-forget' solution and thus do not need any attention should be dealt with. Besides, local authorities should be better informed about the nature and frequency of required maintenance tasks and be convinced of their necessity for adequate performance.

5. Conclusions

The number of constructed wetlands in Flanders increased exponentially during the last decade and will most likely continue to since many small-scale discharges still await adequate treatment. The oldest reed bed dates from the year 1986 and is still in operation, although it needed some major modifications.

Design sizes vary between 1 and 2000 PE with the majority of constructed wetlands having a capacity smaller than 500 PE. Nearly all of them are planted with common reed (*P. australis*). Other plant species are presently rather an exception. Free-water-surface, vertical flow as well as subsurface flow reed beds are being used, usually as a single treatment unit, or sometimes combined with other reed beds or even conventional systems. The constructed wetlands mainly treat domestic and dairy wastewater although they are also used for treating wastewater from animal cages, horticulture, restaurants, etc.

Average removal efficiencies of FWS reed beds are the lowest ones, mainly due to the strongly diluted influent from the combined sewer systems and the limited contact with the soil or filter medium. The best overall performance was recorded for the vertical flow wetlands, except for total nitrogen removal where the combined reed bed systems performed better. This proves that a combination of different wetland types can optimise nitrogen removal. Despite the considerable nutrient removal observed for many wetlands, effluent concentrations of many systems remain relatively high and entail a tangible danger of eutrophication.

To stimulate and optimise constructed wetlands technology in the near future, more information should be readily available for owners about the nature and frequency of required maintenance tasks. It seems furthermore recommendable to replace the current, too compliant emission-based effluent standards with immission-based ones that take into account the local carrying capacity of the receiving watercourses. To evaluate and enforce the previous measures, adequate monitoring arrangements should be developed.

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