# DO CONSTRUCTED WETLANDS CONTRIBUTE TO A BETTER RIVER WATER QUALITY?


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## Abstract
In many rural areas the agro- and natural ecosystems are intersected with a network of small watercourses to which the many anthropogenic discharges are a potential ecological threat. Constructed wetlands for wastewater treatment are often applied in these cases where no sewer system is present to transport the wastewater to a central treatment plant. In this paper, the impact of two reed bed systems located in the UK and Belgium is investigated by comparing the river water quality before and after the start-up of these reed beds, upstream and downstream of their discharge point and by comparing the effluent loads with the other pollutant loads that enter the respective watercourses.

Both constructed wetlands definitely proved to be capable of removing a great deal of pollutants, especially BOD and COD, but river water quality improvements were not always obvious from monitoring results alone. Dilution model studies were needed to reveal the positive effect exerted by the reed beds. The casestudies also convincingly demonstrated the need for an integrated approach. Constructed reed beds or small-scale wastewater treatment systems in general are quite useless if the watercourse receives several other untreated discharges. One small-scale wastewater treatment plant may seem to have only a minor effect but several of these works together can significantly contribute to the river water quality and avoid the exceedance of the self-purification capacity.



## Keywords
Reed beds, wastewater treatment, dilution model, river water quality


## Introduction
Constructed wetlands technology – commonly known as reed bed technology - emerged during the 1950s in Germany and has for many years been considered a marginal technology with limited applicability. Gradually however, experience with full-scale systems and innovative experimental set-ups led to sometimes radical

changes in design and operation and an ever-increasing application of this technology (Vymazal, 1998).

Reed beds are most often used for the treatment of domestic wastewater. Other applications concern the treatment of industrial wastewater like acid mine drainage or landfill leachate (Panswad & Chavalparit, 1997; Mays & Edwards, 2001), agricultural wastewater (Tanner *et al.*, 1995a, 1995b; Kern & Idler, 1999) and stormwaters (Wong & Somes, 1995; Carleton *et al.*, 2000). They are furthermore applied to strip nutrients from eutrophic surface waters before these are discharged into vulnerable nature reserves (Meuleman, 1999; DeBusk *et al.*, 2000; Newman & Lynch, 2000). Next to water quality improvement, they can also function as a faunal and floral development area, a recreational site, a hydrological buffer or a reservoir (Bays *et al.*, 2000).

Constructed wetlands can often be found in rural or remote areas where no sewer system is present and where people are thus (legally) obliged to treat their own wastewater. Low investment and maintenance costs, a low failure rate and an attractive view are certainly the most important factors that balance the choice between technical systems and reed beds in favour of the latter (Haberl *et al.*, 1995, Luederitz *et al*., 2001).

In many cases, the agro- and natural ecosystems in those rural and remote areas are intersected with many small brooks and watercourses to which the many anthropogenic discharges are a potential ecological threat. Not only point sources like untreated and treated wastewater need to be considered, but also the many diffuse sources of pollution.

This paper intends to investigate the impact of constructed wetlands on a small rural catchment area by comparing the river water quality before and after the start-up of a reed bed, upstream and downstream the discharge point of the reed bed and by comparing the effluent load of the constructed wetland with the other pollutant loads that enter the watercourse. Data from two different reed bed systems in Belgium and the United Kingdom will be used and elaborated by means of a simple dilution model study. As an introduction, some commonly applied emission and immission-based approaches will be reviewed.

## Emission and immission standards

Surface water is used for a wide range of applications: recreation, transport, potable water production and fishing but also for pollutant reduction via dilution and self-purification mechanisms. To harmonise all these uses, immission standards are a commonly applied tool. Effluent discharges will therefore have to meet certain quality demands, in order not to exceed these river water quality standards. In the following paragraphs, a non-exhaustive overview is given of some effluent standards and their relation to river water quality.

Belgium for example applies uniform effluent standards for reed beds (< 2.200 PE) that were based on Best Available Techniques, i.e. COD/BOD/SS of 250/50/60 $mg.L^{-1}$ respectively, with no nutrient restrictions at all. These effluent standards are even discarded if the temperature drops below 6 °C (VLAREM II, 1995). The carrying capacity of the watercourse is thus entirely neglected.

In The Netherlands, one makes use of mixed standards. Their territory has been split up in non-vulnerable, vulnerable and extremely vulnerable areas. For each area, the legislator provides a list of certified small-scale wastewater treatment systems that guarantee a minimum effluent quality. Effluent standards range from 750/250/70 $mg.L^{-1}$ for COD/BOD/SS in non-vulnerable areas to 100/20/30/30/2/2 $mg.L^{-1}$ for COD/BOD/SS/Ntot/$NH_4$-N/Ptot. In this way, the carrying capacity of the watercourse is partly taken into account.

A totally different approach can be found in the United Kingdom and the United States of America, where immission standards and case-specific water uses determine the appropriate effluent standards.
In the UK, all watercourses have been assigned one of five water quality classes, based on the desired ecological quality. The effluent standards are then calculated with a statistical Monte Carlo approach, so that the immission standards of the specified water quality class are not exceeded for more than 5% of the time. Inputs for this model are statistical distributions of the effluent and river loads (UK Environment Agency, 2000).

Effluent standards in the USA are set by means of Total Maximum Daily Loads (TMDL). A common procedure makes use of static models like QUAL2E with steady state conditions, i.e. steady values for flow rates and concentrations. The TMDL is then calculated as the maximum allowable effluent load for a constant low river flow rate (Shanahan *et al.*, 1998).

## Material and methods

### *Description of study sites*

Two horizontal subsurface-flow constructed wetlands were monitored: one reed bed at Saxby (Leicestershire, United Kingdom), operated by Severn Trent Water Ltd, and the other one at Zemst (Flemish Region, Belgium), operated by Aquafin n.v. Table 1 shows the basic design features of both natural wastewater treatment systems.

Table 1. Basic design features of the reed beds.

| Design feature | Saxby (UK) | Zemst (Belgium) |
|---|---|---|
| Design PE | 47 | 350 |
| Actual PE | 47 | 300 |
| Start-up year | 1998 | 2001 |
| Primary treatment | 16 m³ septic tank | 33 m³ septic tank |
| Number of reed beds | 2 in series | 2 in parallel |
| Dimensions of each bed (L x W x d) | 9.4m x 12.5m x 0.6m | 50m x 13m x 0.67m |
| Total planted area | 235 m² | 1300 m² |
| Plants | *Phragmites australis* | *Phragmites australis* |
| Matrix material | Pre-washed gravel 5-10 mm | Pre-washed gravel 5-10 mm |
| Discharged into | Eye | Kesterbeek |

Both systems differ on one crucial point. As there is no combined sewer overflow present in the sewer system at Saxby, the works has to accept and treat all flows. This is not the case at Zemst, where a combined sewer overflow (CSO) at the entrance of the works ensures that flows in excess of 6Q14 are discharged immediately into the receiving watercourse.

### *Assessment of treatment efficiencies*

During 2 weeks in August 2002, the influent and effluent of both reed beds at Saxby were monitored by means of automated samplers. The samplers were set to collect composite samples over 8 hours of the influent and both effluents of the two reed beds. Composite samples are preferred because they facilitate the application of mass balances. Samples were analysed at Severn Trent Laboratories for the common variables: COD, BOD, TOC, N, P etc. Simultaneously, meteorological data were collected on-site since they have a major impact on the water balance. Flow data were also registered on a 15 minutes base. Finally, during each visit to the reed beds, some grab samples were collected of the river Eye, before and after the discharge point to check if the final effluent has an influence on the river water quality.

A regular monitoring of the reed bed system at Zemst is carried out by Aquafin n.v. by collecting grab samples. Two additional high-detail measuring campaigns were carried out during September-October 2001 and March 2003. Eight-hour composite samples were collected by means of automated samplers and analysed with Nanocolor© test kits. Meteorological data were collected *a posteriori* from meteo bulletins. Flow data were registered on a daily base. Finally, some grab samples were collected of the brook Kesterbeek, before and after the discharge point to check if the final effluent has an influence on the river water quality.

As a quality check of this data, river water quality data of the Flemish and UK Environment Agencies were downloaded from their respective websites.

## Results

### *Summary of treatment efficiencies*

Since the focus of these various studies was on constructed wetlands, the primary treatment units were omitted from the monitoring campaigns. The average removal efficiencies shown in Table 2 should therefore be interpreted as the sole result of the reed bed removal processes, and not of primary treatment. Typical for reed beds is their high buffering capacity. A relatively large hydraulic residence time and several complementary processes efficiently smooth out influent peaks (data not shown). Only extreme influent loads can still be detected in the effluent.

Generally speaking, the treatment plant at Saxby exhibits a significantly better pollutant removal capability. Since both have a nearly equal planted area per Person Equivalent (PE), a different surface loading rate cannot be the cause. One possible explanation could be the difference in age and thus maturity of the beds. Several authors indeed noted that it takes at least 2 to 3 years for a constructed wetland to reach its optimal performance (Kadlec *et al.*, 2000). Another reason might be the different layout, i.e. beds in series versus parallel. Many studies have proven that hybrid systems consisting of multiple reed beds in series are more efficient (Cooper *et al.*, 1999; Vandaele *et al.*, 2000).

Table 2. Average ± stdev effluent concentrations and average concentration-based removal efficiencies (between brackets) of the reed beds at Saxby (UK) and Zemst (Belgium) during different periods. These data only consider the reed beds and not the primary treatment.

| Variable | Saxby August 2002 | Zemst Sept/Oct. 2001 | Zemst March 2003 |
|---|---|---|---|
| $BOD_{tot}$ (mg/L) | 2.1 ± 1.0 (97.1%) | <4 (81.4%)* | n.m. |
| $NH_4^+$ (mg N/L) | 5.7 ± 1.7 (73.8%) | 6.8 ± 0.9 (14.5%) | 9.8 ± 1.2 (22.1%) |
| $COD_{tot}$ (mg/L) | n.m. | 37.5 ± 7.4 (64.0%) | 33.5 ± 5.6 (64.3%) |
| SS (mg/L) | 17.1 ± 6.1 (46.1%) | 5.9 ± 1.0 (52.7%) | n.m. |
| $NO_2^- + NO_3^-$ (mg N/L) | 1.1 ± 1.4 (-25.3%) | 0.4 ± 0.1 (48.8%)* | 0.3 ± 0.1 (*-2.6%)* |
| Ortho-$PO_4^{3-}$ (mg P/L) | 2.7 ± 0.5 (59.6%) | 0.4 ± 0.1 (65.4%) | 2.0 ± 1.9 (29.1%) |
| $N_{tot}$ (mg N/L) | 8.3 ± 0.7 (63.8%) | 7.7 ± 0.8 (32.4%) * | n.m. |

n.m.: not measured
* data from the Flemish Environment Agency website

### *Evolution of the river water quality after construction of the reed beds*

Both Environment Agencies make use of a different strategy to assess river water quality. In Flanders, data from different sampling locations are treated separately, whereas in the UK, these data are aggregated into average concentrations for a certain river stretch. The latter approach renders the interpretation of the data somewhat difficult.

The discharge point of the constructed wetland at Saxby is located halfway along a 3.7 km long stretch of the river Eye called 'Garthorpe road bridge to confluence of Langham Brook'. Average water quality data for this river stretch are summarised in Table 3, indicating that no significant changes occurred after the construction of the reed bed in 1998. Nevertheless, the 90-percentile for BOD and the 10-percentile for DO slightly decreased, and as a result the chemical water quality class shifted from B to A, or from good to very good quality. An identical shift was noticed for the biological water quality, which is based on the presence and abundance of certain macro-invertebrates.

Table 3. Water quality data of the river Eye (stretch Garthorpe road bridge to confluence of Langham Brook). Data expressed as average ± stdev concentrations. Source: UK Environment Agency website.

| Years | BOD ($mg.L^{-1}$) | $NH_4^+$ ($mg N.L^{-1}$) | DO (%) | $NO_3^-$ ($mg N.L^{-1}$) | Ortho-$PO_4^{3-}$ ($mg P.L^{-1}$) |
|---|---|---|---|---|---|
| 1995-1996-1997 | 1.5 ± 0.82 | 0.07 ± 0.06 | 92.27 ± 16.36 | n.m. | n.m. |
| 1999-2000-2001 | 1.1 ± 0.76 | 0.05 ± 0.07 | 112.26 ± 19.05 | 13.08 ± 13.08 | 0.02 ± 0.33 |

Water quality data from the Kesterbeek, some 500 meters downstream of the constructed wetland, are summarised in Table 4. This location is known as site 356610 (Beekveldstraat) of the Flemish Environment Agency.

Table 4. Water quality data of the brook Kesterbeek (site 356610 – Beekveldstraat). Data expressed as average ± stdev concentrations. Source: Flemish Environment Agency website.

| Year | COD ($mg.L^{-1}$) | BOD ($mg.L^{-1}$) | SS ($mg.L^{-1}$) | $NH_4^+$ ($mg N.L^{-1}$) | DO (%) | $NO_3^-$ ($mg N.L^{-1}$) | Ptot ($mg P.L^{-1}$) |
|---|---|---|---|---|---|---|---|
| 2000 | 17.0 ± 7.1 | 3.8 ± 3.1 | 34.8 ± 13.0 | 3.0 ± 2.2 | 61.3 ± 14.1 | 1.5 ± 2.0 | 0.7 ± 0.3 |
| 2002 | 38.3 ± 26.5 | 5.0 ± 5.4 | 33.3 ± 6.2 | 4.8 ± 4.5 | 53.5 ± 27.4 | 1.1 ± 0.7 | 1.6 ± 1.4 |

Surprisingly enough, higher COD, BOD and $NH_4^+$ concentrations after the commissioning of the reed bed in 2001 seem to indicate an increase of organic pollution. The Belgian Biotic Index - also based on the presence and abundance of certain macro-invertebrates – remained at 5, indicating only an average water quality. Ammonium removal efficiencies of the reed beds are somewhat disappointing, so the effluent might contribute to the higher river ammonium levels. Removal efficiencies of COD and BOD are however satisfactory and the explanation thus had to be sought elsewhere. During rainstorms, the mixed sewer system at Zemst delivers considerable amounts of diluted wastewater to the wastewater treatment plant. Since the reed beds are incapable of handling this hydraulic load, the excess discharge is rerouted to the river via a combined sewer overflow. Untreated wastewater of 300 PE is thus discharged in the Kesterbeek and may cause the elevated COD and BOD concentrations. These CSO events are known to happen several times per year. In addition, it's not illogical to assume that the gathering of wastewater – although treated - at one single discharge location, shows other pollution patterns than the same amount of untreated wastewater being discharged at a number of different locations.

***River water quality before and after the discharge points***

Several grab samples of the river Eye at Saxby indicated that the difference in concentrations of total oxidised nitrogen, ammonium, orthophosphates and suspended solids before and after the discharge point was insignificant (data not shown). A similar conclusion can be drawn from grab samples of the brook Kesterbeek at Zemst, except for ammonium, in which case the effluent seems to have a negative impact on the water quality. Ammonium concentrations increase from $2.50 \pm 1.19$ to $5.17 \pm 4.61$ mg $N.L^{-1}$.This means that the reed bed effluent loads are insignificant compared to the river loads, except of course for ammonium. Indeed, during dry periods, the dilution rate at Zemst is estimated to be at least 5, whereas at Saxby, the dilution rate is estimated to be higher than 100.

***Wastewater loads compared to other loads***

Both wastewater treatment systems are situated in a rural area with intensive farming activities. Manure, drainage water and point sources from non-sewered houses and farms most likely deliver a considerable fraction of the pollution load to the watercourses.

The Kesterbeek at Zemst seems to receive a considerable load of non-treated domestic wastewater, since COD, BOD and ammonium concentrations upstream the reed bed are above the immission standards (Table 5). This assumption was qualitatively confirmed by a visual inspection of the upstream part of the Kesterbeek, which revealed several sewer pipes discharging directly in the brook. Surprisingly enough, despite the many drainage tubes, the nitrate levels are far below the immission standards whereas the phosphate levels are quite elevated. Anoxic, carbon-rich sediments might however induce denitrification and thus reduce nitrate levels. Anyway, enough nutrients are present to result in eutrophic conditions during the summer months.

For the river Eye at Saxby on the contrary, manure seems to be a major contributor, leading to elevated nitrate concentrations (Table 3). Indeed, during the sampling period, several adjacent farmers were in the process of fertilising their fields. Phosphate concentrations are on the contrary quite low and might thus limit eutrophication.

Table 5. Water quality data of the brook Kesterbeek (site 356620 – Grote Parijsstraat) compared with Flemish immission standards for basic water quality. Data expressed as average ± stdev concentrations. Source: Flemish Environment Agency website.

| | COD ($mg.L^{-1}$) | BOD ($mg.L^{-1}$) | SS ($mg.L^{-1}$) | $NH_4^+$ ($mg\ N.L^{-1}$) | $NO_3^-$ ($mg\ N.L^{-1}$) | Ptot ($mg\ P.L^{-1}$) |
|---|---|---|---|---|---|---|
| Data of 2002 | 41.8 ± 28.5 | 6.00 ± 6.00 | 27.0 ± 23.1 | 4.2 ± 3.5 | 1.0 ± 0.7 | 1.3 ± 0.7 |
| Absolute immission standards* | 30 | 6 | 50 | 5 | 10 | 1 |

* 90% of the samples should comply to this absolute limit. The 10% samples that exceed the standard may not deviate more than 50%.

***Dilution model***

To illustrate the various emission- and immission-based approaches, a dilution model was applied to calculate river water concentrations after the discharge point, based on effluent and river loads. Since no river flow rates have been measured, they were expressed as a certain multiple of the effluent flow rate. This assumption is based on the fact that both the wastewater and river flow rates are highly dependent on rainfall.

Mass balance: $Q_{river}.C_{river} + Q_{effluent}.C_{effluent} = Q_{after}.C_{after}$
and if $Q_{river} = D.Q_{effluent}$
then $D.C_{river} + C_{effluent} = (1+D).C_{after}$

Because the dilution rate at Saxby is very high, and the pollution load is only 47 PE, no dilution model is applied, since the effluent load will 'drown' in the river load. No adverse effects are to be expected, except maybe very locally around the discharge point.

At present, the wastewater treatment plant at Zemst receives the pollution load of about 300 PE. At 150 $liter.PE^{-1}.day^{-1}$, this means a total dry weather flow of 45 $m^3.day^{-1}$. The lowest estimated river flow rate based on flow velocities and cross-sectional areas is 216 $m^3.day^{-1}$, yielding a dilution factor of 4.8.

An example has been worked out for COD for 3 different situations. The immission concentration of COD before the discharge point was on average 41.8 $mg.L^{-1}$ in 2002 (Table 5). This concentration is already higher than the immission standard of 30 $mg.L^{-1}$, so every extra load will worsen the situation. Three different situations can now be distinguished :

1. The wastewater is discharged untreated;
2. A constructed wetland is present and operates near the effluent consent of 250 mg $COD.L^{-1}$;
3. A constructed wetland is present and operates at the measured efficiencies (Table 2), yielding an average effluent concentration of 35 mg $COD.L^{-1}$.

For these three situations, the immission calculated concentrations after the discharge point are 189.8, 77.7 and 40.6 mg $COD.L^{-1}$ respectively. Only for the last situation can a small improvement of the river water quality be noticed, since the effluent concentrations are lower than the immission concentrations before the discharge point.

A similar situation can be derived for BOD, since the immission concentration already matches the immission standard before the discharge point and no extra load can thus be allowed. The Kesterbeek can at that time only receive an extra amount of SS, without endangering the immission standard. Of course, one has also to take into account the selfpurification capacity of the river. Every watercourse is able to reduce a certain load of pollutants by a variety of mechanisms, so certainly for BOD, a small margin is available here.

**Discussion**

Do constructed wetlands contribute to a better river water quality? The answer is most definitely positive, although river water quality data do not always reveal this contribution. Relatively simple dilution models may be needed to point this out.

Constructed wetlands are certainly capable of removing a great deal of pollutants. They furthermore exert in most cases a strong peak shaving capacity, thus avoiding peak loads to be discharged into the receiving water courses. Ammonium removal seems to be the most critical variable, possibly due to a lack of oxygen for nitrifying micro-organisms. BOD and COD are generally very well removed because their particulate fraction is physically removed and because heterotrophic micro-organisms have a better affinity for oxygen.

At Saxby, the more extreme BOD and DO concentrations seem to have disappeared, leading to a shift in the water quality class from good to very good quality. This is most likely an effect of the pollution reduction and the buffering effect by the constructed wetland. The picture at Zemst is less clear, probably due to the polluting effect of CSO spills. Indeed, the dilution model indicates a slight decrease of the COD concentrations after the discharge point, whereas in reality one can notice a significant increase. Of course the effects of diffuse ongoing agricultural pollution also need to be taken into account.

Perhaps a new strategy should be adopted in order to avoid CSO spills. Aquafin n.v. has plans to temporary store excess rain water in a pond and to treat this water after the rain storm has passed. Another option would be to use the Severn Trent Water Ltd approach where wastewater is allowed on top of the bed surface when the flow rate exceeds the hydraulic treatment capacity. In this way, wastewater is not only temporary stored, but it is also partly treated because the reed beds function during that period as free-water-surface constructed wetlands (Green & Martin, 1996; Griffin & Pamplin, 1998).

Model outcomes of dilution studies confirm that immission standards are certainly to be preferred above emission standards to optimally protect the river. Similar conclusions are stated by Chave (2001) in his interpretation of the recent European

Water Framework Directive. Dilution studies however have the disadvantage of requiring a considerable amount of concentration and flow data or the adoption of several uncertain assumptions. This might limit the practical applicability. The Dutch system of mixed standards therefore seems an attractive compromise.

Fortunately, the vision of immission-based standards is gaining ground in Flanders. Ten so-called "good example small-scale sewage treatment plants" are currently being planned (start-up foreseen in early 2004), where - for a Flemish first time – optimal ecological quality of the watercourse together with habitat creation are aimed at.

Finally, the casestudies have convincingly demonstrated the need for an integrated approach. Constructed reed beds or small-scale wastewater treatment systems in general are quite useless if the watercourse receives several other untreated discharges. One small-scale wastewater treatment plant might be a drop in the ocean, but several of these works can significantly contribute to the river water quality and avoid the exceedance of the self-purification capacity.

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