Uprating and Rescuing Small Wastewater Treatment Facilities by Adding Tertiary Treatment Reed Beds
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Uprating and rescuing small wastewater treatment facilities by adding tertiary treatment reed beds

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ABSTRACT: A water utility developed use of gravel-filled constructed reed beds operating in a subsurface flow mode to polish secondary effluent to meet demanding standards for 5-day biochemical oxygen demand (BOD_5) and total suspended solids. Results collected by the regulatory environmental agency (EA) for 43 sites completed before the end of 1993 are given. The average BOD_5 concentration was 1.9 mg/L. The benefit of effluent polishing is further demonstrated by influent and effluent data from two sites that have operated since June 1990 and September 1991, respectively. Environmental agency effluent quality data are also given for 39 sites at which reed beds either treat stormwater and secondary effluent together or have been installed as remedial treatment for works struggling to meet secondary treatment standards. The average BOD_5 concentration for these sites was 3.0 mg/L. Remedial, or treatment plant rescue, application is illustrated by four contrasting case studies where constructed reed beds brought facilities back into compliance. *Water Environ. Res.*, **70,** 1307 (1998).

KEYWORDS: small wastewater treatment facilities, tertiary treatment, reed beds.

Introduction

Small wastewater treatment facilities serving populations of fewer than 2 000 people present particular problems to the operating utility in a climate of strict regulation of performance and cost efficiency. Economic considerations require that such facilities not have continuous attendance by operators and force the utility to not only increase the length of intervals between facility visits but to decrease the time attending the factility during such visits. Such considerations can lead to selection of highly automated, monitored, and telemetered treatment systems or to robust and often underloaded low-energy-input systems. The choice is often determined as much by current trends or corporate image as by engineering or financial practicabilities. Both approaches can achieve the objective of secure compliance with relatively low labor cost.

Severn Trent Water, Ltd., a water and wastewater treatment utility serving approximately 8 million customers in the U.K., has steered a middle course in an important part of an asset management program. It has adopted an effective secondary treatment system with a status monitoring arrangement by using rotating biological contactors (RBCs), but has opted for use of constructed reed beds for tertiary treatment where the discharge permit conditions require compliance with 5-day biochemical oxygen demand (BOD_5) and total suspended solids (TSS) limits more stringent than 95th percentile values of 25 and 45 mg/L, respectively (Green and Upton, 1994). Before Severn Trent's development of this process for tertiary treatment, much of the interest in such wetlands in North America and Europe had been focused on secondary treatment (Watson et al., 1989). The most enthusiastic attempts at using subsurface flow (SF) in wetlands in Europe had been in Germany (Bucksteeg, 1990) and Denmark (Schierup et al., 1990). While gravel and rock were being used in North America for subsurface flow wetlands, soil was the preferred media in Europe and only 1 of 130 sites reviewed by Schierup et al. (1990) used gravel. These last authors noted the tendency to surface flow on most of the soil-filled beds but concluded that the beds mostly provided basic secondary treatment when loaded at rates of approximately 0.1 to 0.2 population equivalents/m^2 (pe/m^2) or 5 to 10 m^2/pe. Their work suggested low efficiencies when used for tertiary treatment, although this was judged from a small sample of 5 of 130 sites.

Shared experience by water professionals in the U.K., in collaboration with workers elsewhere in Europe, led to publication of design guidelines for Europe (Cooper, 1990). That shared experience enabled Severn Trent to look with confidence at the constructed reed bed system using *Phragmites australis*, first for secondary treatment for small communities (Green and Upton, 1993, and Upton and Griffin, 1990) and then for effluent polishing. Figure 1 illustrates the growth of sites at which Severn Trent has installed constructed reed beds. At the majority of these sites reed beds are used to polish effluent, and at others they are used either to meet demanding standards to ensure that relatively modest standards are securely met or to operate in a combined effluent polishing and storm overflow treatment mode (Green and Martin, 1996, and Green et al., 1995).

Uprating Effluent Quality

Development of subsurface flow wetlands has been partly empirical and partly the application of well-ordered theories about the processes involved. Most systems have been designed, or subsequently modeled, for BOD_5 removal. The main assumption is that BOD_5 removal can be described using first-order, plug-flow kinetics and the surface area required can be calculated after making allowance for porosity and effective depth of the bed affected by subsurface flow. In European design guidelines (Cooper, 1990), these expressions are simplified into the equation

$$Ah = \frac{Qd\,(\ln C_o - \ln C_t)}{K_{BOD}} \qquad (1)$$

Where

$Ah =$ area required, m^2;

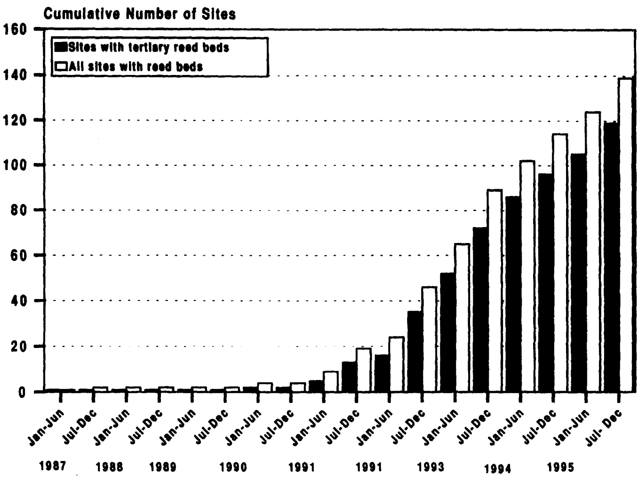

Figure 1—Increase in numbers of wastewater treatment facilities with constructed reed beds operated by Severn Trent Water.

$Qd =$ average flow, m^3/d;
$C_o =$ inlet concentration, mg/L;
$C_t =$ outlet concentration, mg/L; and
$K_{BOD} =$ a modified rate constant, m/d.

Cooper (1990) went on to propose using an empirical value of 0.1 m/d for K_{BOD}. This had been derived from U.K. and northern European experience, mostly with soil-based SF systems in secondary treatment applications.

Green and Upton (1994) used the design equation to derive a requirement of 1 m^2/pe for tertiary treatment applications to meet 95th percentile limits of 15 mg/L BOD_5 when the beds follow standard primary and secondary treatment in trickling filters or RBCs, which provided an effluent quality of 25 mg/L BOD_5 as a 95th percentile. The shape of the constructed reed bed is dictated by the need to conform to Darcy's law to maintain subsurface flow. Thus,

$$A_c = \frac{Q_s}{K_f(\frac{dH}{ds})} \qquad (2)$$

Where

$A_c =$ cross-sectional area, m^2;
$Q_s =$ average flow in, m^3/s;
$K_f =$ hydraulic conductivity, m/s; and
$dH/ds =$ slope of the bed, m/m.

Green and Upton (1994) established as an important condition that the hydraulic gradient be taken between the surface of the gravel at the inlet end to the depth of the collection drain at the outlet end rather than using the slope on the base of the bed.

Faced with significant asset renewal or total works replacement at large numbers of sites and considerable variation in the minutae of discharge-license conditions and average flow rates, Severn Trent adopted the simplification of using 1 m^2/pe to size the beds for tertiary treatment applications and 0.08 m/pe for the width of the inlet, thus typically resulting in beds 12.5 m long (Green, 1993). Compromises were made on sizing at some sites because of land availability or site conditions, and, in some instances, population growth predictions led to relatively generous areas being used. In all cases, the bed comprised excavations lined with an impermeable membrane, typically 0.75-mm, low-density polyethylene (LDPE) provided with a rock-filled inlet distribution zone and a similar collection zone, across the width of the bed at both the inlet and outlet, while the space between was filled with 5- to 10-mm washed gravel. The bed was laid with a base slope of 1% and a level surface and was planted with seed-grown plants of *P. australis* at a density of 4 plants/m^2. Effluent was distributed onto the inlet zone by riser pipes spaced at approximately 5-m centers or by simple fiberglass-reinforced plastic or concrete channels. The outlet collector comprised perforated or slotted drainage pipes connected to a chamber with a device for controlling the water level in the bed.

Performance

Figure 2 shows the BOD_5 data for 43 sites sampled by the environmental agency (EA), the quality regulator. All were standard applications of constructed reed beds where the secondary treatment system was expected to comply with permits of 25 mg/L BOD_5 and 45 mg/L TSS (and often 10 mg/L ammonia-N) but final effluent permits ranged from 20 mg/L BOD_5 and 40 mg/L TSS to 10 mg/L BOD_5, 15 mg/L TSS, and 5 mg/L ammonia-N. The median BOD_5 concentration was 1.8 mg/L and the average was 2.0 mg/L. The site with the highest average (4.9 mg/L) suffered from a breakdown of the secondary treatment system during the period. While Figure 1 gives a fair picture of the high quality of effluent from facilities uprated by tertiary treatment systems, it lacks a measure of the input to those systems. Figures 3 and 4 show the performance of two of the treatment facilities with relatively long-standing reed beds. Both of these were completed fairly early in the asset renewal program, and at both sites the existing trickling filters were retained and refurbished while at the majority of the newer sites (shown in Figure 2), trickling filters were replaced by RBCs.

Leek Wootton. The wastewater treatment facility serves two villages, Leek Wootton and Hill Wootton, with a design population equivalent of 1 150. Tertiary treatment comprises two constructed reed beds with a total area of 825 m^2. The area fell short of the planned 1 m^2/pe but made best use of available space. The beds were planted and commissioned in June 1990 and provided an immediate uprating in terms of BOD_5 and TSS removal. They have continued to provide high-quality effluent with no sign of decline over time. Reed beds also significantly improved the effluent in terms of ammonia-N, particularly after the first year of operation (Figure 3).

Ashby Folville. The wastewater treatment works serves a village with a design population equivalent of 860. The reed beds were completed in September 1991 in advance of the refurbishment of primary and secondary treatment at the site. They provided an important protection against permit failure during the reconstruction period, as witnessed by the relatively poor quality of the secondary effluent fed to the reed beds in 1991 and 1992 (Figure 4). As with Leek Wootton, improvements to BOD_5 and TSS were immediate and removal of ammonia-N improved after the first year of operation.

At Ashby Folville there is considerable infiltration to the sewerage system and flow is higher than the general design assumption of 200 L/pe. At both Leek Wootton and Ashby

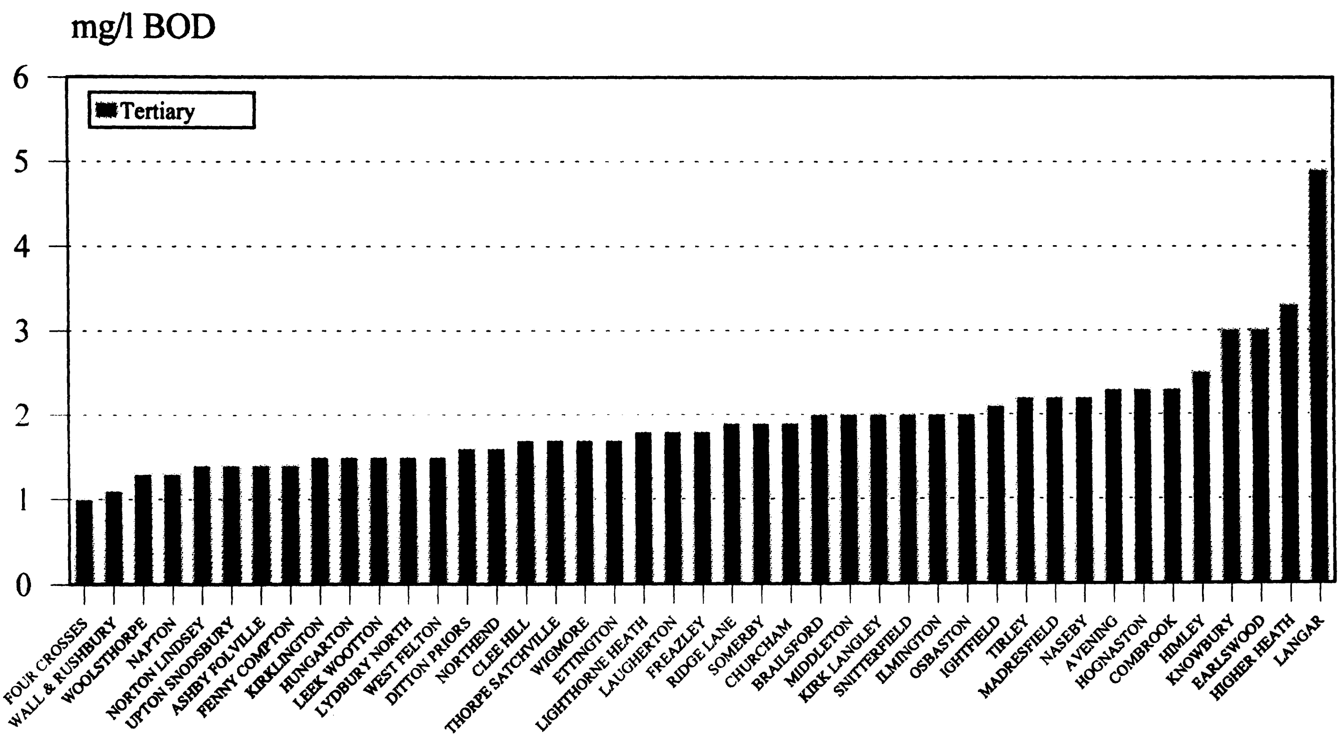

Figure 2—Average effluent BOD_5 concentrations for the period January–December 1995 for wastewater treatment facilities with tertiary treatment reed beds (environmental agency data).

Folville, reed beds comfortably exceed performance predicted by the design equation. This feature is shared by all of the tertiary treatment reed beds installed in Severn Trent. Green and Upton (1995) presented influent and effluent data for 12 sites; they showed calculated K_{BOD} values varying from 0.22 to 0.51 m/d and an average value of 0.36 m/d.

Based on performance of the systems, it would seem logical to revise the design assumption and thereby reduce area requirements per population equivalent to as low as 0.2 m^2 for tertiary treatment. While Severn Trent has taken account of the performance of its earliest reed beds, the design approach has remained conservative with 0.7 m^2/pe being adopted for purely tertiary treatment applications designed after 1993.

Reed Beds for Rescuing Small Treatment Facilities

Rescue can be broadly defined, from averting risk of occasional failure at an otherwise well-provided and -operated treatment facility to keeping the regulator at bay at sites having serious overloading problems or awaiting asset renewal.

Once operators of treatment facilities in Severn Trent's operational districts began to become familiar with the reed beds installed to uprate works, they began to see wider benefit. The U.K. regulators have sweeping power for prosecuting noncompliance with discharge permits. This has been reflected in Severn Trent not only by sharpened focus on asset renewal but also by tying compliance targets into bonus payments and, in extreme cases, disciplinary procedures. Given the opportunities for mishaps at unstaffed sites, the operators soon recognized the extra security given by tertiary reed beds and have promoted schemes for their installation.

Figure 5 shows BOD_5 data for 36 sites sampled by EA. Reed beds provided tertiary treatment at all of these sites. At 19 sites reed beds not only served to polish secondary effluent but also received stormwater from combined sewer overflows (CSOs) positioned at the inlet to the treatment works. These storm treatment systems have been described by Green and Martin (1996) and Green et al. (1995). At the remaining 17 sites, reed beds were installed because of perceived treatment problems or were provided in advance of more complete asset renewal.

For approximately 50% of the sites, values of effluent BOD_5 and TSS were indistinguishable from those shown in Figure 2. The median value was higher at 3.2 mg/L BOD_5, but the effluent quality overall represented a high standard of treatment for such a collection of small works and provided comfortable compliance with regulatory standards. Data collected before and after commissioning of the reed beds are shown in Figure 6 for three of the sites represented in Figure 5, together with data for a site in Severn Trent's area but not owned or managed by the water utility.

Luddington. At this site, a population of 1 260 is served by a wastewater treatment works comprising primary treatment followed by secondary treatment in a surface-aeration, activated-sludge plant. Plans were made to replace the entire works by the year 2000 with RBCs and storm reed beds. The existing works suffered from hydraulic overload in periods of heavy rain, giving the works an unsatisfactory performance rating, so the storm reed beds were provided in advance of the main scheme but were set up to receive all of the secondary effluent.

The beds were sized at 0.5 m^2/pe in line with Severn Trent's policy on storm reed beds (Green and Martin, 1996) for a design population of 1 334. Only one sample (out of 26) has failed to meet the discharge license limit since the reed bed was installed, and, on that occasion, the power failed at the site and the reed bed was bypassed. As shown in Figure 6a, the average BOD_5

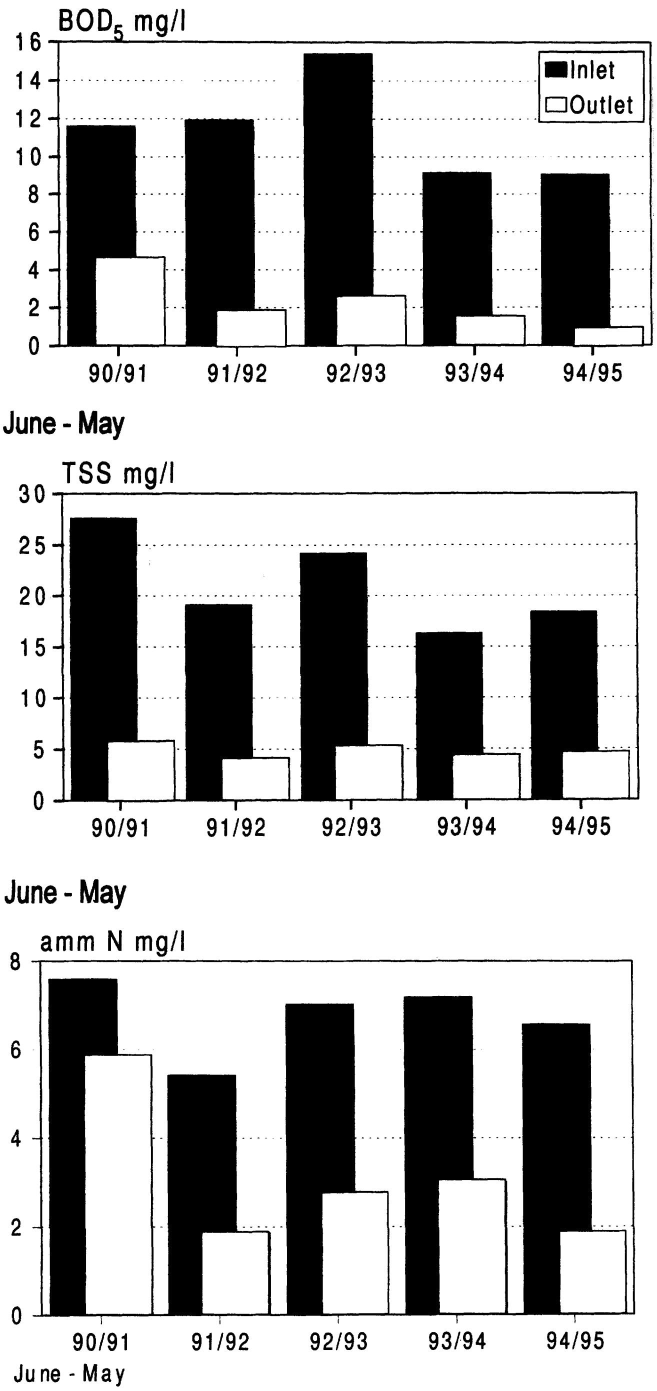

Figure 3—Performance of tertiary treatment reed beds at Leek Wootton; annual average results for BOD_5, TSS, and ammonia-N since commissioning of the beds.

for the period before commissioning of the reed bed was 9.9 mg/L. Since that date it was 4.4 mg/L.

Great Witley. At this site, treatment comprised an integral RBC, which was commissioned in 1980. Design loading was higher than currently accepted in Severn Trent and there was no provision for separation of storm flows. Because at the time the asset renewal program was being established the facility was operating well and was in good condition despite its loading and age, it was scheduled for replacement in the year 2009. A cluster of failed samples in 1993 (Figure 6b) changed its ranking and persuaded the operating district to install tertiary treatment reed beds for remedial purposes. These were fitted into the available space and only comprised 0.3 m^2/pe. The benefit was immediate and the average BOD_5 improved from 14.7 to 4.2 mg/L.

Little Wenlock. The wastewater treatment facility serves a population of 400. During the early part of 1993, the perfor-

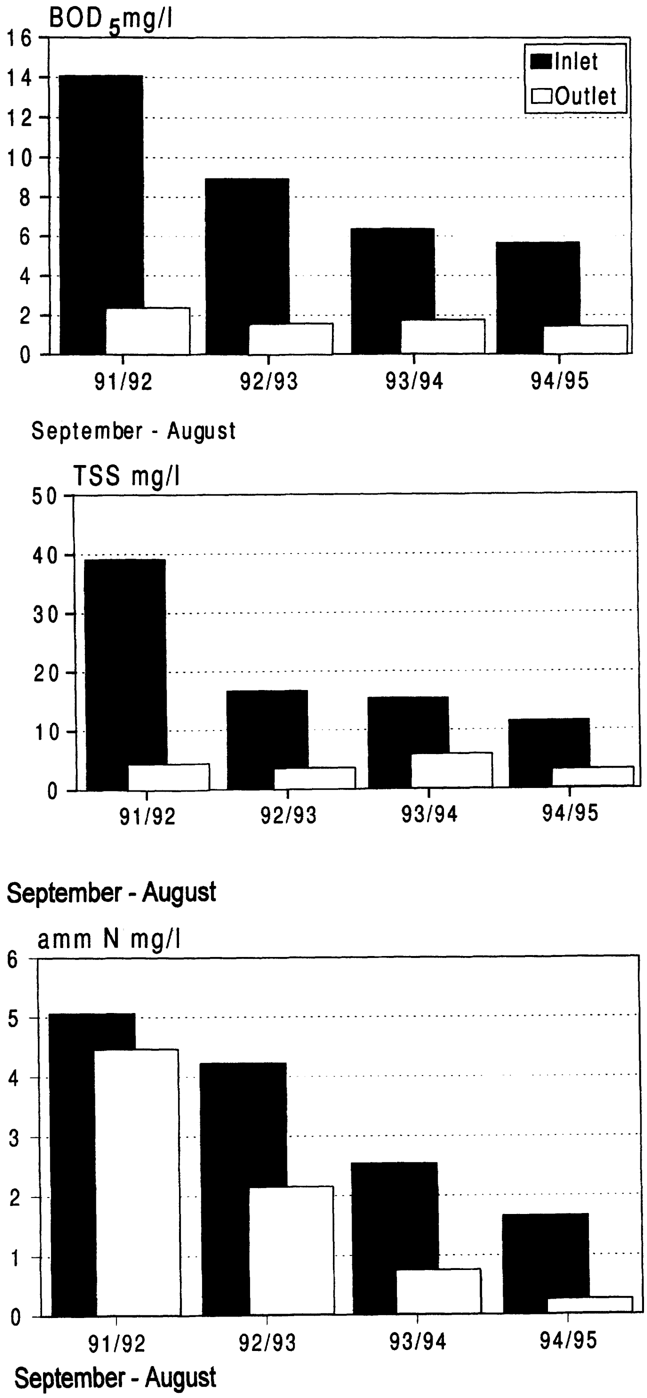

Figure 4—Performance of tertiary treatment reed beds at Ashby Folville; annual average results for BOD_5, TSS, and ammonia-N since commissioning of the beds.

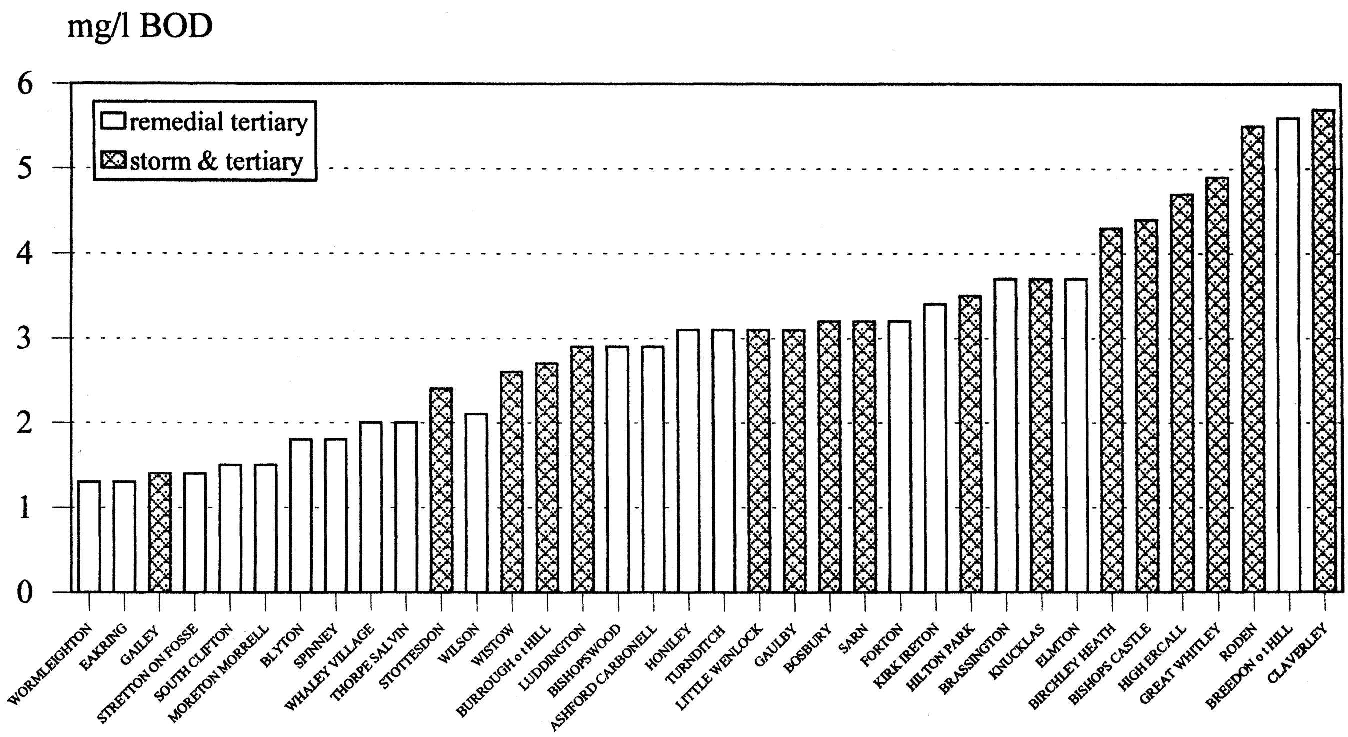

Figure 5—Average effluent BOD_5 concentration for the period January–December 1995 for wastewater treatment facilities with combined storm and tertiary, or remedial tertiary, reed beds (EA data).

mance of the works deteriorated and short-term remedial measures such as tankering and chemical treatment were considered. In May 1993 redundant sludge drying beds were converted to provide a single, gravel-filled reed bed providing approximately 0.13 m^2/pe. The benefits were seen immediately, but, at that loading, effluent-derived solids built up rapidly and began to clog the bed. In April 1995, the flow was diverted for 2 days while the mat of reeds was lifted off and the gravel was replaced. Many of the reeds were replanted and the bed was put back into use. In May 1996, the facility was replaced by a new works comprising RBCs and tertiary treatment reed beds.

Since the temporary reed beds were commissioned, no sample taken by the regulator failed to meet the discharge limits of 20 mg/L BOD_5 and 40 mg/L TSS. The average BOD_5 during the period before the reed bed was planted (as shown in Figure 6c) was 10.8 mg/L. The average BOD_5 since the reed bed was installed was 4.6 mg/L.

Tunstall Hall. This represents a different opportunity than the other three plant rescue examples. The wastewater treatment works serves an old country house converted to a residential home for the elderly. When Tunstall Hall was converted, an existing settlement tank was retained and a package treatment works comprising an enclosed recirculating filter with plastic media was installed for a population of 80. Despite having relaxed permit limits of 50 mg/L BOD_5 and 80 mg/L TSS, the treatment works consistently infringed those standards. A reed bed sized at approximately 0.7 m^2/pe was installed in February 1994. The benefit is shown in Figure 6d.

Because this application (which was carried out by a contractor used by Severn Trent for several small reed bed installations) was a step further than the Severn Trent works rescue applications, the Tunstall Hall facility was intensively surveyed over a 7-day period. The results of that survey are summarized in Table 1. The average flow rate during the survey was 12 m^3/d. Throughout the survey, the enclosed filter produced a well-oxidized effluent (average BOD_5 and ammonia-N of 33 mg/L and 5.0 mg/L, respectively) and removed 83% of the applied BOD_5 and 82% of the ammonia-N. Reed beds further improved the effluent, particularly in terms of BOD_5 and TSS. The average effluent quality of 51 mg/L chemical oxygen demand (COD), 7 mg/L TSS, 8.8 mg/L BOD_5, and 4.8 mg/L ammonia-N would compare favorably with conventionally designed small treatment works.

Discussion

Use of constructed reed beds in polishing good-quality secondary effluent to meet demanding standards has been well established. The performance demonstrated in Figure 2 challenges the assertion of Reed et al. (1995) that there is a lower limit to the design expectation of subsurface flow systems at approximately 2 to 5 mg/L BOD_5 because of the release of organic matter by plant breakdown. There has been no sign of such release in constructed reed beds used for tertiary treatment in this study. Green (1993) pointed out a limit to the removal of COD. Even where BOD concentrations were reduced to less than 1 mg/L, he found a residual COD of approximately 40 mg/L, which he attributed to metabolic byproducts such as humic and fulvic acids. Lower COD concentrations only were found in systems where the wastewater was diluted by rainfall or infiltration.

The design approach used by Severn Trent can be seen to be conservative and, given more precise flow and performance data

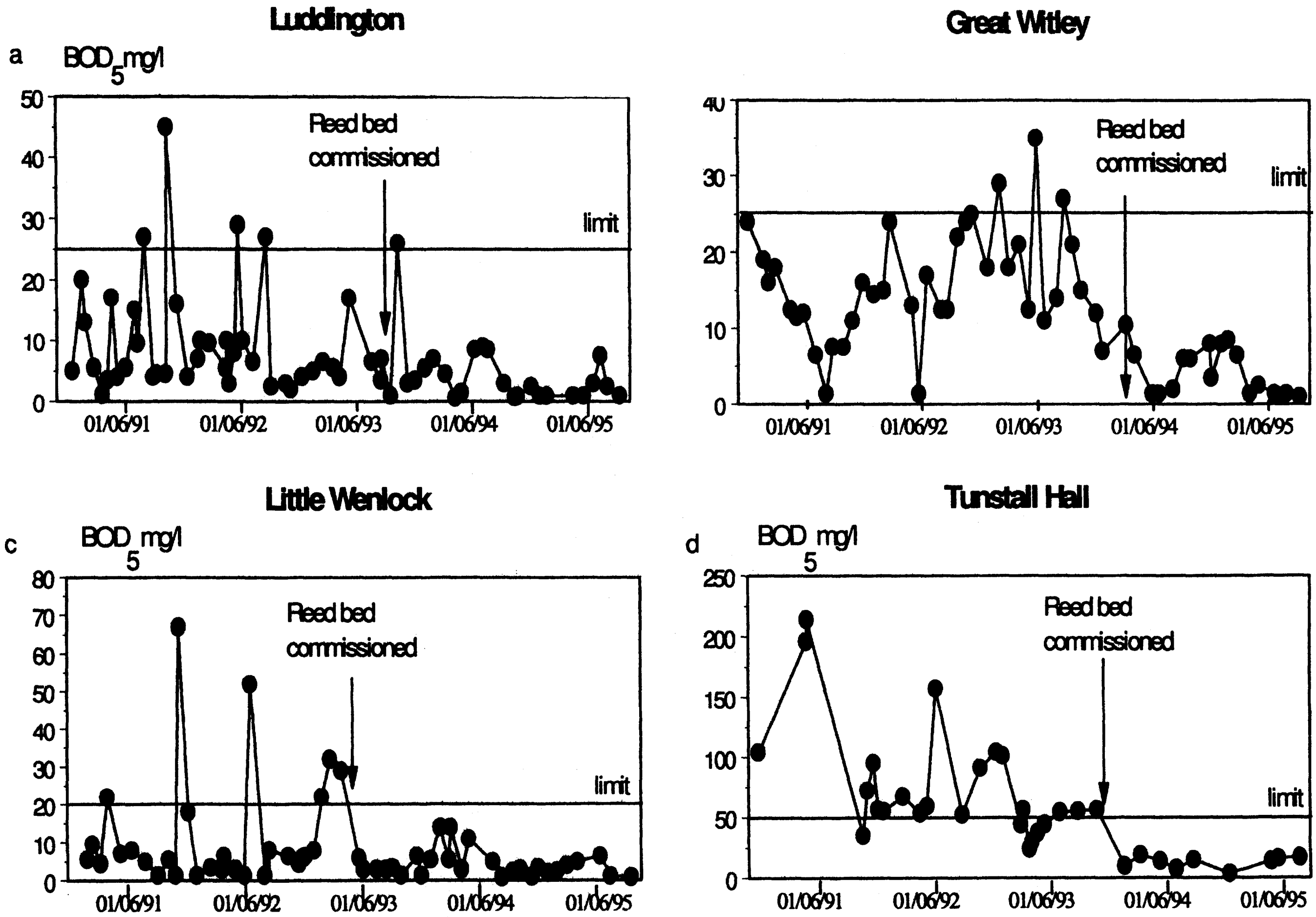

Figure 6—Effect of commissioning tertiary treatment reed beds at Luddington, Great Witley, Little Wenlock, and Tunstall Hall (EA data).

for small works, it should be possible to meet demanding BOD_5 and TSS standards with such tertiary reed beds sized at less than 0.7 m^2/pe. In the context of small works (populations of less than 2 000 to 3 000) where pressures to reduce operator attendance continue, it makes sense to provide a good safety margin. A further benefit achieved by relatively oversized tertiary beds is in the contribution these beds make to removal of ammoniacal nitrogen.

Plant rescue comes at two levels. The first of these is where it is sufficient to copy the tertiary treatment application and provide sufficient area to cope with periodic heavy loadings, as in combined storm and tertiary applications or in the Luddington example where secondary effluent has only periodic poor performance. The other application is where the beds are seen as short-term expedients and it is acceptable that they are renewed or abandoned in a few years. Such beds cannot be left alone

Table 1—Summary of survey carried out using composite samplers at Tunstall Hall wastewater treatment facility during the period August 9–17, 1995.

		BioPac effluent		Reed bed effluent	
	Influent, mg/L	mg/L	Stage removal, %	mg/L	Stage removal, %
COD[a]	560	115	75	51.2	56
BOD	197	33	83	8.8	73
SS[b]	74.7	38.4	49	7.0	82
Ammonia-N	27.7	5.0	82	4.8	6
Total nitrogen	0.25	0.92		0.15	

[a] COD = chemical oxygen demand.
[b] SS = suspended solids.

with the same confidence as those used for polishing reasonable quality secondary effluent. Applications like that at Tunstall Hall have yet to be proved in the long term, but if sufficient provision is made in the design to accommodate solids build up in the system, they should prove no more difficult to operate than effluent polishing beds. They offer the potential of a relatively cheap option for providing effluent that would comfortably meet commonly applied secondary treatment standards (such as 95th percentile BOD_5 of 25 mg/L).

Conclusions

Constructed reed beds operating with subsurface flow provide an effective means of achieving high-quality effluent in terms of BOD_5 and TSS when used to polish effluent from conventionally operated secondary treatment plants. There does not seem to be a lower limit to BOD_5 concentration beyond limitations of the accuracy of the analysis.

The design assumption used in Europe of a K_{BOD} of 0.1 m/d is conservative when applied to tertiary treatment. Removal of BOD_5, indicated by the examples of Leek Wootton and Ashby Folville, exceeds the design performance.

Overdesign offers the benefit of security against mishaps and added benefit in removal of ammoniacal nitrogen.

Medium- to long-term plant rescue can be applied at works with periodic performance lapses by using standardized sizes of 0.7 to 1.0 m^2/population equivalent. Much higher loadings can be used for short-term uses. Polishing poor-quality secondary effluent looks to be a promising application.

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