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# ADVANCED NITROGEN REMOVAL BY ROTATING BIOLOGICAL CONTACTORS, RECYCLE AND CONSTRUCTED WETLANDS

P. Griffin, P. Jennings and E. Bowman

*Severn Trent Water Ltd, Technology and Development, Avon House, St. Martins Road,*
*Coventry CV3 6PR, UK*

## ABSTRACT

The sewage treatment facility at Himley comprises Rotating Biological Contactors (RBCs) and subsurface flow constructed reed beds in series. A recycle facility returns RBC effluent to the influent flow. Effluent total nitrogen (TN) has always been low since commissioning and the reasons were investigated. Denitrification was observed to occur in the primary settlement tank. High hydraulic loadings in the RBC biozone deteriorated $BOD_5$ and TSS removal, but good nitrification was obtained. The relatively poor effluent from the RBC gave a carbon source allowing further denitrification through the reed beds. Ammonification caused an increase in ammoniacal nitrogen across the primary reed bed in summer. At this time strongly reducing conditions occurred within the reed beds which, in the absence of dissolved oxygen and oxidised nitrogen compounds, led to sulphate reduction and sulphide formation with odour generation. These problems were not observed at low winter temperature conditions. Effluent TN was always below 10 mg/l. © 1999 IAWQ Published by Elsevier Science Ltd. All rights reserved

## KEYWORDS

Reed bed; rotating biological contactor; subsurface flow wetland; nitrogen removal.

## INTRODUCTION

The removal of nitrogen compounds is taking on increased importance with regulators throughout Europe as the harmful effects of eutrophication become more apparent. Small sewage treatment works are not generally required to meet total nitrogen (TN) standards, but member states may set more restrictive standards to protect water quality and this is of particular consequence where endangered habitats are under threat by nutrient enrichment. In this context it may be noted that three quarters of river sites of special scientific interest (SSSIs) and many lake SSSIs in England suffer from excessive inputs of nutrients, mainly from sewage effluents. The intrinsically rural nature of SSSIs means that such pollution is associated with small sewage treatment works and as a consequence it is expected that certain small works may need to meet total nitrogen standards in the future. Severn Trent Water has over 1,000 sewage treatment works and about 72% fall into the small works category, generally considered to be less than 2,000 p.e. The use of constructed reed beds as a tertiary polishing stage to achieve high quality effluents in terms of TSS, $BOD_5$ and COD has been well established (Green and Upton, 1994; Cooper *et al.*, 1996). Such applications have also provided a small but significant improvement in the removal of ammoniacal nitrogen ($NH_4$-N) from partially to well nitrified secondary effluents (Green and Upton, 1995).

The oxygen limited conditions within subsurface horizontal flow constructed wetlands allow for some removal of Total Oxidised Nitrogen (TON). In general very large wetlands have been used for this purpose (Kadlec, 1996) but in Europe applications have been reported which combine conventional treatment and reed bed systems (Laber *et al.*, 1997). One problem is that there may be insufficient carbon to fuel the denitrification process, in which case dosing of an external carbon source may be required. As part of a major asset renewal program Severn Trent Water has installed constructed reed beds at over 160 wastewater treatment facilities. The standard solution adopted is for primary and secondary treatment in Rotating Biological Contactors (RBCs) (Upton *et al.*, 1995). At several of these installations high percentage removals of TN were observed even though this was not a target parameter. One of these sites was at Himley, in the West Midlands near Wolverhampton, where the design included a recycle facility to compensate for low night time flows and intermittent operation of the inlet pumping station. The site has been monitored since 1991. Figure 1 shows the site flow sheet.

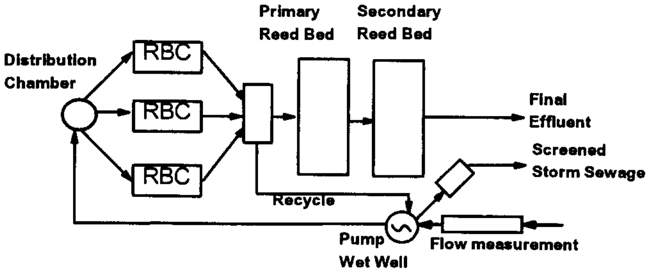

Figure 1. Himley process flow sheet.

The works is designed to treat a population of 720 with no industrial component. At present only 550 people are connected but infiltration is known to be high.

The sewerage system is short and all flows gravitate to the works where flow measurement is provided before pumping. Stormwater flows in excess of the installed pumping capacity overflow a weir and discharge through woven sack type screens directly to the watercourse. The influent is pumped to a distribution chamber where the flow is split equally between three integral RBCs each comprising a primary settlement tank (PST), biozone and final settlement tank. Two constructed reed beds are provided and advantage was taken of a sloping site to allow operation to be either in series or in parallel. The former mode has been used continuously since commissioning in August 1991. Initially the reed beds treated the effluent from the biofilter works and this continued until commissioning of the RBCs in December 1991 at which point the biofilters were demolished. The works design allows for an actuated valve to open in the reed bed feed chamber when influent flows drop below 2.5 l/s (216 $m^3/d$) and this recycle gravitates back to the influent pumping station. The nominal disc loading of the RBCs is 2.5 $g/m^2.d$. Primary and secondary settlement tanks are sized to provide treatment for 6 x Dry Weather Flow (DWF). Each reed bed has a surface area of 434 $m^2$. A permit has been issued requiring a DWF of 144 $m^3/d$ to meet a 95 percentile compliance with 20 mg/l $BOD_5$ (ATU), 30 mg/l TSS and 10 mg/l $NH_4$-N.

The design and construction of tertiary treatment reed beds within Severn Trent Water follows the concepts outlined by Cooper (1990) and have been described in detail by Green and Upton (1993, 1994). In brief, they comprise shallow low density polyethylene lined excavations sized at 0.7 $m^2$/p.e. and filled to an average depth of 0.6 m. with 5-10 mm pre-washed gravel. An inlet zone of larger stones contains distribution pipework, while perforated pipes in a similar outlet zone lead to a level control device. This is adjusted to maintain the water level at about 25-50 mm below the surface of the gravel matrix. The reed beds are usually 12.5 to 15 m long and of sufficient width to satisfy Darcys' law requirements for subsurface flow through the matrix during average flow conditions. The common reed, ***Phragmites australis***, is planted using pot grown seedlings and soon establishes a dense monoculture. The reeds at Himley have shown excellent growth, typically averaging 2 metres tall, with 100% cover. Hydraulic loadings on beds built to Severn Trent Water criteria are typically 0.29 m/d, which makes them relatively high rate when compared to European practice (Schierup *et al.*, 1990) and American practice (Watson *et al.*, 1989). The reason for the recycle was a perceived requirement to maintain both effluent quality from the RBC and the performance of the reed beds, but the consequences were not as anticipated with regard to both effluent quality from the RBC and the performance of the reed beds.

## METHODS

Routine samples taken since the plant was commissioned are spot samples of the reed bed influents and effluents. Effluent flows were measured using a portable ultrasonic flow meter over a V notch weir in the final effluent channel. During the surveys time proportional composite samples were taken using sampling machines. All $BOD_5$ tests had nitrification inhibited by the use of allyl thiourea. The redox potential measurements were performed on site. Dissolved oxygen and temperature measurements were also taken on site using an air calibrated YSI dissolved oxygen meter. Sulphide samples were fixed on site using sodium carbonate and zinc acetate. Hydrogen sulphide measurements in the atmosphere were performed using Draeger tubes. All chemical samples were refrigerated before analysis using standard methods at a NAMAS (National Accreditation of Measurement and Sampling) accredited laboratory.

## RESULTS

The performance of the Himley reed beds was monitored from commissioning in 1991/92 until 1994/95 by means of weekly spot samples of the RBC effluent and the two reed bed effluents. Since then monthly spot samples of final effluent have been taken. The data is presented in Figure 2.

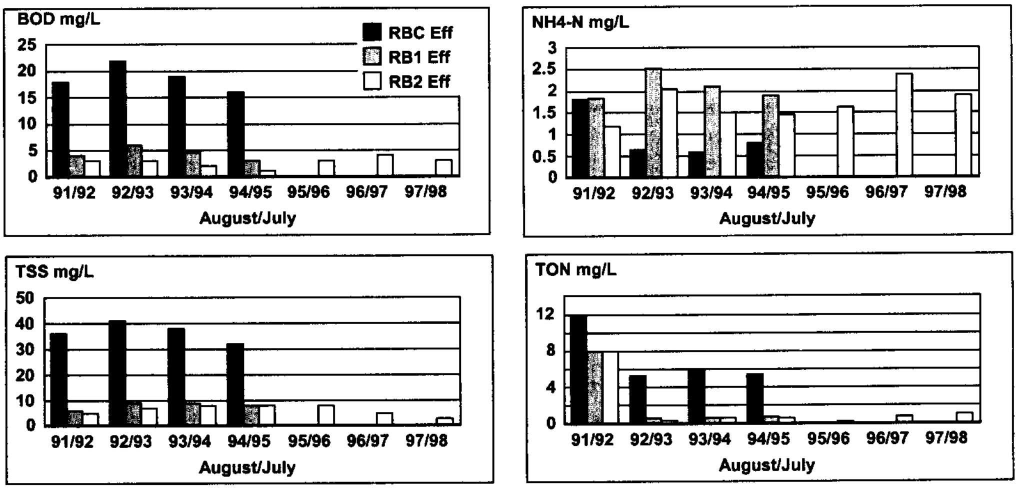

Figure 2. Annual average data for primary reed bed influent, primary reed bed effluent and secondary reed bed effluent since commissioning in 1991.

Three comprehensive surveys have been undertaken since 1994. Details of the average daily influent and recycle flows are provided in Table 1.

Table 1. Average and daily influent and recycle flows

| | Oct/Nov 1994 | May/June 1997 | Feb/Mar 1998 |
|---|---|---|---|
| Influent flow $m^3/d$ | 209 | 191 | 232 |
| Recycle flow $m^3/d$ | 424 | 210 | 161 |
| Flow through RBC $m^3/d$ | 633 | 401 | 393 |
| Temperature °C | 14-16 | 17-20 | 10-12 |

During the first survey it was noted that the influent flowmeter read much lower than the portable meter on the effluent and it was suspected that this caused the unusually high recycle volume. Tables 2,3 and 4 provide summary data. Missing determinands and samples mean that the nitrogen species do not always balance.

Table 2. Analytical data from survey (1) October/November 1994. Averages in mg/l. Number of samples and standard deviation in brackets below

| | BOD | TSS | TKN | NH4-N | TON | organic N | Total N |
|---|---|---|---|---|---|---|---|
| Crude Sewage | 274 | 250 | 33.5 | 18.8 | 0.3 | 12.8 | 31.9 |
| | (13,90) | (12,87) | (8,5.6) | (13,5.2) | (6,0) | (8,3.6) | (5,6) |
| Primary Sett. | 77 | 116 | 14.4 | 5.3 | 0.65 | 9.2 | 14.7 |
| Tank effluent | (14,16) | (13,26) | (8,1.2) | (14,1.1) | (8,0.7) | (8,1.0) | (5,1.3) |
| RBC Effluent | 19 | 36 | 5.5 | 0.6 | 5.7 | 5 | 11 |
| | (11,7.7) | (11,5) | (10,1.6) | (11,0.3) | (11,1.1) | (10,1.6) | (10,1.3) |
| Primary Reed | 3 | 6 | 3.4 | 2.3 | 0.74 | 1.1 | 4.1 |
| Bed Effluent | (11,1.8) | (11,5) | (11,0.5) | (11,0.6) | (11,1.0) | (11,0.55) | (11,0.9) |
| Secondary Reed | 2 | 8 | 2.8 | 1.9 | 0.37 | 0.9 | 3.17 |
| Bed Effluent | (13,0.3) | (13,7) | (13,0.8) | (13,0.6) | (13,0.2) | (13,0.4) | (13,0.8) |

Table 3. Analytical data from survey (2) May/June 1997. Averages in mg/l. Number of samples and standard deviation in brackets below

| | BOD | TSS | TKN | NH4-N | TON | organic N | Total N |
|---|---|---|---|---|---|---|---|
| Crude Sewage | 264 | 184 | 33.6 | 19.8 | 0.2 | 14.6 | 33.9 |
| | (6,107) | (8,99) | (7,9) | (8,5.8) | (8,0.05) | (7,6.2) | (7.9) |
| Primary Sett. | 75 | 77 | 21.5 | 10.3 | 0.2 | 11.2 | 21.7 |
| Tank effluent | (4,27) | (6,23) | (8,3) | (8,1.9) | (8,0.05) | (8,2.24) | (8.3) |
| RBC Effluent | 13 | 25 | 7.4 | 1.3 | 5.7 | 6.1 | 13.1 |
| | (8,4.4) | (9,8) | (9,0.6) | (9,0.4) | (9,1.1) | (9,0.6) | (9,1) |
| Primary Reed | 3 | 5 | 5.6 | 4.3 | 0.43 | 1.3 | 6.03 |
| Bed Effluent | (6,1) | (9,2.4) | (9,0.6) | (9,0.7) | (9,0.7) | (9,0.2) | (9,0.5) |
| Secondary Reed | 2 | 4.5 | 5.4 | 4.4 | 0.24 | 1 | 5.64 |
| Bed Effluent | (7,0.9) | (8,1.7) | (9,0.6) | (9,0.4) | (9,0.2) | (9,0.4) | (9,0.7) |

Table 4. Analytical data from survey (3) February/March 1998. Averages in mg/l. Number of samples and standard deviation in brackets below

| | BOD | TSS | TKN | NH4-N | TON | organic N | Total N |
|---|---|---|---|---|---|---|---|
| Crude Sewage | 191 | 219 | 25.2 | 17.8 | <0.2 | 7.4 | 25.4 |
| | (10,57) | (11,74) | (11,5.7) | (11,4.6) | (10,0) | (11,2.2) | (11,5.7) |
| Primary Sett. | 74 | 75 | 18.9 | 11.8 | <0.2 | 7.1 | 19 |
| Tank effluent | (10,26) | (10,11) | (10,2.5) | (10,2.1) | (10,0) | (10,3)) | (2.5,10) |
| RBC Effluent | 12 | 19 | 4.1 | 2.0 | 10.37 | 2.1 | 14.5 |
| | (11,4) | (11,7) | (11,0.9) | (11,0.7) | (11,1.4) | (10,0.8) | (11,1.7) |
| Primary Reed | 3 | 7 | 1.9 | 1.1 | 3.6 | 0.9 | 5.5 |
| Bed Effluent | (11,2) | (11,9.2) | (11,0.5) | (11,0.4) | (11,0.9) | (11,0.3) | (11,0.8) |
| Secondary Reed | 1 | 4 | 1.2 | 0.5 | 1.73 | 0.7 | 3.0 |
| Bed Effluent | (11,0.1) | (11,2) | (11,0.3) | (11,0.3) | (11,1.0) | (11,0.3) | (11,0.9) |

Results for the second and third surveys for pH, alkalinity, sulphide and sulphate are given in Table 5. Redox potential was measured at various points along the flow sheet during these two surveys. In the second survey each reed bed was divided into three sections along its length, and these are represented as primary RB (1), primary RB (2) etc., and similarly with the secondary reed bed. The results are given in Figure 3.

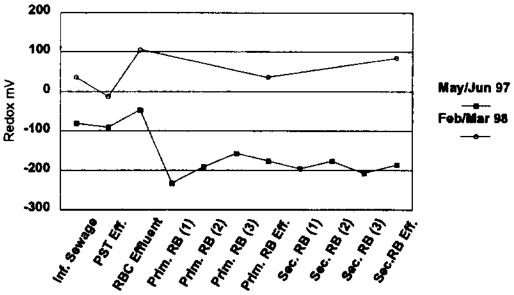

Figure 3. Redox potential (mV) for each process stage - Surveys 2 and 3.

Table 5. Results of survey 2 (May/June 1997) and survey 3 (February/March 1998) for pH, sulphate (as $SO_4$), sulphide (as S) and alkalinity (as $CaCO_3$). Averages in mg/l. Number of samples and standard deviations in brackets below

| | pH | | Sulphate | | Sulphide | | Alkalinity | |
|---|---|---|---|---|---|---|---|---|
| | Survey 2 | Survey 3 | Survey 2 | Survey 3 | Survey 2 | Survey 3 | Survey 2 | Survey 3 |
| Crude Sewage | 6.7 | 6.9 | 71 | 82 | | | 292 | 254 |
| | (7,0.2) | (11,0.2) | (7,11) | (10,9) | | | (8,31) | (11,18) |
| Primary Sett. | 6.8 | 7 | 77 | 76 | | | 271 | 245 |
| Tank effluent | (9,0.1) | (10,0.2) | (8,15) | (9,9) | | | (8,39) | (10,25) |
| RBC Effluent | 7.2 | 7.2 | 84 | 87 | 0.04 | 0.01 | 221 | 180 |
| | (9,0.1) | (11,0.2) | (9,9) | (10,8) | (2,0.01) | (2,0.01) | (9,34) | (11,18) |
| Primary Reed | 7 | 7 | 58 | 87 | 4.14 | 0.04 | 256 | 198 |
| Bed Effluent | (8,0.1) | (11,0.3) | (9,21) | (11,8) | (6,1.4) | (10,0.03) | (9,33) | (11,14) |
| Secondary Reed | 7.2 | 7.2 | 68 | 89 | 0.04 | 0.04 | 256 | 196 |
| Bed Effluent | (8,0.1) | (11,0.1) | (9,10) | (11,7) | (6,0.02) | (10,0.03) | (9,20) | (11,11) |

## DISCUSSION

The annual averages of routine samples taken weekly since commissioning show a poor quality RBC effluent in terms of $BOD_5$ and TSS, but excellent performance by the primary and secondary reed beds. $BOD_5$ and TSS in the secondary reed bed effluent were always below 5 mg/l $BOD_5$ and 10 mg/l TSS. $NH_4$-N in the RBC effluent has always been $< 2$ mg/l, but after the first year there is an obvious if small increase across the primary reed bed and a slight decrease across the secondary reed bed such that the final effluent $NH_4$-N never averaged more than 2.5 mg/l. After the first year the primary reed bed influent fell from an average of 12 mg/l TON to 5-6 mg/l TON, with the two reed beds reducing this to less than 1 mg/l. This performance has continued to the present day. The fall in primary reed bed influent TON coincided with commissioning of the RBCs. Investigation revealed that the recycle facility was in use, and the influent pumping station was operating for much of the day.

Recycle in RBCs has been used to reduce peak loading rates associated with intermittent operation of pumping stations, return nitrate to alleviate oxygen limiting conditions and displace oxygen demand from overloaded first stages to subsequent stages. There is no evidence that the performance of the primary settlement tank was affected by the 1:1 recycle in survey 2 with an average of 32% $BOD_5$ and 50% TSS being removed. Denitrification rates were measured in the primary settlement tank influent and the TON concentration fell from 4.5 to 2.18 mg/l within 55 minutes. Substrate limitation was then apparent with the concentration falling only 1.43 mg/l ( to 0.75 mg/l) over the next 130 minutes. Weston (1985) found no significant benefit associated with recycle. He further reported that for weak sewages where the $BOD_5$ entering the biozone was less than 75 mg/l, lower removal rates and reduced efficiencies resulted. This was attributed to low organic concentrations not being readily absorbed and assimilated by the biomass. Increasing hydraulic loading is also known to deteriorate performance by reducing the time for substrate utilisation particularly when retention times in the biozone drop below 60 minutes. However retention times in the biozones at Himley were invariably higher than this value. The effluent from the RBCs was poorer in the first survey when hydraulic loadings were higher, but the influent $BOD_5$ load to both works and biozone was higher as well. It seems that removal of particulate $BOD_5$ in the RBCs is the problem and some confirmation of this comes from a comparison of total and soluble $BOD_5$ in the secondary settlement tank effluent. Total $BOD_5$ was 32 mg/l while soluble $BOD_5$ was 8 mg/l. Disc loadings in all surveys were sufficiently low (ranging from 2.0 to 3.3 $gBOD_5/m^2.d$) as to allow good quality nitrification and were close to the design value of 2.5 g/m2.d. Removal of TN in the RBCs was respectively 61% and 65% in the autumn and summer surveys, reducing to 43% in the winter survey. An average reduction from 292 to 221 mg/l alkalinity as $CaCO_3$ occurred through primary and secondary treatment with alkalinity recovery from denitrification partially offsetting the losses from nitrification. With high quality nitrification the expected loss of alkalinity occurred, with 71 mg/l and 74 mg/l removed in surveys 2 and 3.

Hydraulically the individual reed beds were loaded at 0.44 m/d which is double the rate of 0.22 m/d that would be found with the more normal parallel operating mode. Taking the total reed bed area the Himley beds are loaded 24% lower than the 0.29 m/d typical of Severn Trent design reed beds and would now be considered oversized.

Average total Kjeldahl nitrogen (TKN) going onto the primary reed beds ranged from 4.1 mg/l to 7.4 mg/l, of which 0.6 mg/l to 2.0 mg/l was $NH_4$-N. Most of the TKN is organic nitrogen, the majority presumably in particulate form associated with the high TSS. High solids loadings have caused a layer of sludge 25-50 mm thick to collect on the inlet area of the primary reed bed and this is assumed to be providing the carbon source for further denitrification and also for sulphate reduction. The development of such a layer in the first year of operation accords well with the changes in $NH_4$-N and TON removal observed in year two. Redox potential in the summer survey dropped sharply in the inlet zone to -240 mV, with dissolved oxygen disappearing almost immediately. Ammonification of the organic nitrogen occurs at this point and the temperature dependence of this reaction is clearly seen with an increase in the concentration of $NH_4$-N from 1.1 mg/l at 10-12°C in survey 3, to 1.7 at 14-16°C in survey 1 and 3.0 mg/l at 17-20°C in survey 2, which is the summer survey.

It appears that the elevated summer temperatures allow removal of TON in the primary reed bed and increase bacterial activity such that redox potentials drop locally below the level needed for microbially mediated reduction of sulphate and organic sulphur compounds to sulphide. Conditions in the primary reed bed match those found optimal for sulphate removal elsewhere (Tyrrell *et al.*, 1997). Sulphate reduces by an average of 26 mg/l, and 4.14 mg/l sulphide is present in the effluent passing to the secondary reed bed. The increase of alkalinity from 221 to 256 mg/l as $CaCO_3$ observed across the primary reed bed is due to the alkalinity generated by denitrification and reduction of oxidised sulphur compounds. There was always a strong odour of hydrogen sulphide associated with the primary bed, particularly in the level control chamber where concentrations in the atmosphere ranging from 5 to 15 parts per million were measured. Not surprisingly white *Beggiatoa* growths were present at this point.

The contrast with the low sewage temperature conditions found in the third survey is considerable. The primary reed bed averages 3.6 mg/l TON in the effluent, redox potentials are always positive, no sulphate reduction occurs and sulphide is barely detectable in the effluent.

Returning to the summer conditions of survey 2, it is clear that the influent to the secondary reed bed is laden with sulphide, has a strongly negative redox potential and contains very low concentrations of $BOD_5$ and TSS. Therefore the presence of only a thin layer of sludge on the surface near the inlet is not unexpected and suggests a shortage of carbon for the denitrification and sulphate reduction reactions. There is however less than 1 mg/l TON to remove, so substrate limiting conditions must also apply. Both are probably implicated as only 0.19 mg/l TON is removed. The redox potential is fairly stable in the -200 to -150 mV range, while dissolved oxygen concentrations are zero throughout the bed. Clearly aeration from the free water surface is not sufficient to meet the oxygen demand from sulphide oxidation and bacterial respiration. Given the presence of sulphide and absence of oxygen, the lack of further $NH_4$-N removal by nitrification is explained. No change in alkalinity was observed across the secondary reed bed. That sulphide oxidation is occurring is apparent by the increase in sulphate by 10 mg/l across the secondary reed bed, while sulphide in the effluent falls to 0.04 mg/l. Loss to the atmosphere as hydrogen sulphide, or the possible storage of elemental or organic sulphur as found in Germany by Winter and Kickuth (1989a, b), are probable mechanisms. Burial as insoluble metallic sulphides is expected to be negligible since the siliceous gravels used have very low iron contents. It is possible that the most valuable function of the secondary reed beds is for the removal of sulphide from the effluent. With maximum oxygen deficit conditions in the secondary reed bed effluent, the re-aeration from falls in the level control chamber, measurement V notch and outfall pipe allow the final effluent entering the watercourse to contain 1.5 mg/l of dissolved oxygen.

Again, the contrast with the winter survey is marked. In the winter no sulphide is evident, less reducing conditions are found in the gravel matrix (indicated by the positive redox potentials in the effluent), a small amount of denitrification can occur and sulphate concentrations are unchanged. Considering all the surveys a respectable 83-90% removal of TN is found through the works.

The performance of Himley shows that recycle of secondary effluent can reduce TON and thus TN to low concentrations and that effluent polishing with constructed reed beds can ensure both low $BOD_5$ and TSS and further reduce TN concentrations. There is a balance between the benefit of TON removal and the potential disbenefits of hydrogen sulphide production and, as at Himley, the risk of increases in $NH_4$-N in the final effluent during the summer months. Himley has unintentionally provided a test bed for finding the balance. The summer survey suggests that the balance has been tipped too far and, whilst the effluent is well within its permit limits, it would fail to meet the 3 or 5 mg/l $NH_4$-N standards increasingly being imposed at other sites. A 1:1 recycle in the RBC should reduce TON concentration by about 50% to give a figure typically in the range 12 to 15 mg/l and tertiary treatment reed beds would reduce this to below 10 mg/l. A fully nitrified secondary effluent ( $NH_4$-N less than 1.0 mg/l ) could have a TKN concentration of 3 to 5 mg/l as a result of residual organic nitrogen. The reed beds are effective at removing much of this and can produce final TKN values in the region of 1 to 2 mg/l provided they are not compromised by undue accumulation of solids thereby developing a tendency towards anaerobic conditions.

Converting similar installations to the same mode of operation would be straightforward, but the RBC loading would need to be suitable to achieve full nitrification. If the work of Weston (1985) is correct a recycle rate suitable to lower the $BOD_5$ in the settled sewage to less than 75 mg/l would need to be provided. Extended operation of an uprated secondary settlement tank desludging pump linked to influent flow measurement might well suffice. A pump would probably be needed to lift the effluent from the first reed bed to the second reed bed. A logical addition to the process train would be to introduce an aeration facility to allow the stripping out of hydrogen sulphide and to increase dissolved oxygen concentrations passing to the watercourse. Positioning this between the primary and secondary beds may allow some further nitrification to occur.

## CONCLUSIONS

The flow sheet at Himley offers the possibility of achieving high quality standards with $BOD_5$, TSS and TN all below 10 mg/l. The $NH_4$-N in the effluent is satisfactory to ensure compliance with the permit, but appears to increase in the summer months, probably reflecting continuing accumulation of sludge with high organic nitrogen on the primary beds. This will need to be monitored since it impacts on both permit compliance and asset life. Some sulphate removal occurs through the reed beds in summer, but has no water quality advantage. The generation of hydrogen sulphide, particularly from the primary reed bed, would be of concern with regard to odour nuisance to operators and nearby properties, and also in confined chambers on health and safety grounds.

The process may have wider application but the benefits and disbenefits need to be carefully weighed and further optimisation work is needed.

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