Bulking control with chlorination in a nutrient removal activated sludge system*

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Abstract

This paper deals with control of bulking by chlorination in a laboratory-scale (15ℓ/d) biological nutrient removal system. Bulking was caused by filamentous organisms characteristic of nutrient removal systems, i.e. Type 0092, *Microthrix parvicella* and Type 0914. Over a continuous dosing period of 19 d, at 8 $mgCl_2/gMLSS.d$ the diluted sludge volume index (DSVI) decreased from 230 to 48 mℓ/g. Nitrification-denitrification continued essentially unaffected. The biological P removal initially decreased from its normal 20 mgP/ℓ (influent) to 14 mgP/ℓ but recovered during chlorination to 19 mgP/ℓ. Chlorination was terminated when overdosing became apparent and P removal declined precipitously to 12 mgP/ℓ. After chlorination termination, biological P removal recovered to its normal 20 mgP/ℓ in 5 d. Of the 3 filamentous organisms, Type 0914 was the most and *M. parvicella* the least susceptible to chlorination. Filamentous bulking in nutrient removal systems can be controlled by chlorination with a relatively minor loss of efficiency of biological N and P removal.

Introduction

Bulking, due to the growth of filamentous organisms, is a problem of considerable proportions in nutrient removal activated sludge plants – in a survey covering about three-quarters of these plants in South Africa, 75% had filament contents in the mixed liquor indicative of a bulking sludge, that is with diluted sludge volume index (DSVI) > 150 mℓ/g (Blackbeard *et al.*, 1987). The five main causative filaments were identified to be Type 0092, dominant in 82% of plants, Type 0675 in 45%, Type 0041 in 39%, *Microthrix parvicella* in 33% and Type 0914 in 33%. Proliferation of these organisms in the mixed liquor causes the sludge settleability to deteriorate significantly to DSVI's of 250 mℓ/g or higher.

The sludge settleability sets upper limits on the maximum overflow rate and biological reactor concentration above which the secondary settling tank cannot achieve satisfactory solid/liquid separation – the poorer the settleability the lower these limits. In South Africa settling tanks are usually designed to comply with the Institute for Water Pollution Control (IWPC) (SA Branch) criterion of 1 m/h maximum permissible overflow rate at peak wet weather flow. This criterion is satisfactory for sludge settleabilities better than 150 mℓ/g DSVI (or 100 mℓ/g stirred specific volume index) and a reactor concentration of 3,5 gMLSS/ℓ (Ekama and Marais, 1986).

As a plant approaches its design flow and COD load, the overflow rate and reactor concentration will be approaching the permissible limits. If the DSVI is greater than 150 mℓ/g, bulking problems are likely to commence, and the higher the DSVI above 150 mℓ/g the sooner these problems will be manifested. In the settling tank, bulking can cause excessive solids carry-over in the overflow and poor compactability of the sludge on the floor; the former leads to a poor effluent quality and the latter to large accumulations of solids in the settling tank which may lead to flotation of solids by denitrification and difficulties in achieving the required underflow concentrations, necessitating higher underflow recycles. Bulking also causes problems in the sludge handling operations by poorer thickening in the flotation (Bratby, 1977) or gravity thickening units and poorer dewaterability in belt presses and centrifuges (Osborn *et al.*, 1986; Pitman, 1987). Clearly, amelioration of bulking will greatly facilitate operation of the activated sludge system itself, and the subsequent sludge disposal systems.

Two approaches can be adopted for bulking control

- non-specific; and
- specific

With non-specific bulking control, the filamentous organisms, irrespective of type, are eliminated by killing these with the addition of a toxicant such as chlorine or hydrogen peroxide. With specific bulking control, the causes for the growth of the dominant filament types need to be identified. Jenkins *et al.* (1984) have identified a number of causes, i.e. septic influent, low DO (dissolved oxygen) concentration in the aeration basin, nutrient deficiency and low F/M, each of which may stimulate the growth of a particular group of filaments. By appropriate modification of the influent, plant configuration and/or operation, the relevant causes may be removed resulting in a decline in the filament content of the sludge. A manual on the causes and control of filamentous bulking has been compiled by Jenkins *et al.* (1984).

Non-specific control measures like chlorination can be applied to deal with a crisis situation until a specific control measure can be implemented. Sporadic chlorination also can be a permanent solution for cases where no specific control measures have been developed yet or where it proves to be economical. When a bulking problem develops in a plant, usually it requires immediate attention and dosing a toxicant yields the most rapid results. However, it should be remembered that as soon as dosing ceases, very likely the filaments will regrow because the causes for their growth have not been eliminated. If specific control measures can be found and implemented, these may take a long time to bring about a decline in filament content (2 to 3 sludge ages); also, a considerable degree of experimentation may be required to optimise the measure. During this period excessive bulking may need to be controlled by chlorination. Moreover, the specific measures should be considered effective only if regrowth does not occur. A possible outcome may be that the specific measure(s) are only partially effective in which event the frequencies of chlorination at least can be reduced. Consequently chlorination is an important bulking control measure.

Non-specific and specific measures for bulking control in nutrient removal activated sludge systems are currently being investigated at the University of Cape Town. In this paper implementation of non-specific control measures by chlorination, in a laboratory-scale modified UCT system, is reported in some detail. On specific bulking control measures some progress has

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also been made (Gabb *et al.*, 1987), discussed briefly by Blackbeard *et al.* (1987).

Background

Chlorination of activated sludge for bulking control has been implemented successfully for many years (Smith and Purdy, 1936; Tapleshay, 1945); more recently the method has been popularised by Jenkins and co-workers (Jenkins *et al.*, 1980; 1982; 1983; 1984). They tested a number of chlorine dosing points, i.e.

- into the return activated sludge flow;
- directly into the aeration basin;
- into a flow abstracted from and returned to the aeration basin; and
- into the outflow of the aeration basin to the secondary settling tank.

From these studies they identified four parameters that appear to influence the efficiency of chlorination of activated sludge:

- Overall mass dose rate, T_m(gCl_2/kgMLSS.d)

$$T_m = \frac{\text{mass of chlorine dosed per day}}{\text{MLSS mass in system; including settling tank if appreciable}} = M/V_pX_t$$

- Chlorine concentration at the dose point, C($mgCl_2/\ell$)

$$C = \frac{\text{mass of chlorine dosed per day}}{\text{flow rate past dose point}} = M/Q$$

- Local mass dose at the dose point, T (gCl_2/kgMLSS)

$$T = \frac{\text{mass of chlorine dosed per day}}{\text{MLSS mass flow rate past dose point}} = M/Q.X_Q = C/X_Q.$$

- Frequency of exposure of activated sludge to chlorine dose, F (/d)

$$F = \frac{\text{MLSS mass flow rate past dosing point}}{\text{MLSS mass in system}} = (QX_Q)/(V_pX_t) = T_m/T$$

Jenkins *et al.* (1984) list the magnitudes of these parameters that have resulted in successful bulking control with chlorination.

Neethling *et al.* (1985a) examined the relative importance of the four parameters. They concluded that there is a *limiting frequency* of exposure of the solids to chlorine, (F), below which it is not possible to prevent bulking by adding chlorine. The limiting frequency is dependent upon

- the difference in growth rates of the filaments and floc-formers (called the bulking potential);
- the relative amounts of filaments and floc-formers in the sludge; and
- relative survival of filaments and floc-formers when dosed with chlorine (called survival ratio).

Free chlorine and monochloramine (formed when chlorine is dosed to a sludge stream containing ammonia) reacted differently : With free chlorine, the survival ratio (assessed by OUR suppression) was dependent on the dose and MLSS concentration but independent of time, so that for this toxicant local mass dose (T) is an appropriate control parameter; with monochloramine, the survival ratio was dependent on the dose concentration and the contact time but independent of MLSS concentration so that for this toxicant, dose concentration (C) is an appropriate control parameter.

Neethling *et al.* (1985a) found that free chlorine reacts rapidly and stoichiometrically with nitrite so that free chlorine is not available for filamentous organism control until all the nitrite has been oxidised. Monochloramine however does not react with nitrite so that the efficacy of this toxicant is not reduced when nitrite is present. This observation is important for situations where nitrification or denitrification reactions are not complete resulting in the formation of nitrite. In these situations, one solution is to add ammonia upstream of the chlorine dosing point. Upon chlorine dosing, the ammonia reacts very rapidly with the chlorine to form monochloramine which does not react with nitrite. Monochloramine is formed when the ammonia to chlorine ratio is greater than 0,4 $mgNH_3 - N/mgCl_2$.

In pure culture studies on floc-forming and filamentous organisms isolated from activated sludge, Neethling *et al.* (1985a) could not establish, from survival ratios of these organisms (based on ATP concentration – see Neethling *et al.*, 1985b), whether the filamentous organisms were more sensitive to monochloramine than floc-forming organisms. However, there was some indication that the filamentous organisms associated with low F/M conditions (*M. parvicella*, Types 0041, 0675, 0092, 0803, 0961, 0581, 021N, and *Nocardia* spp.) were more resistant to monochloramine than those associated with low DO conditions (Type 1701, *S. natans*) (filament types in low F/M and DO groups taken from Jenkins *et al.*, 1984). They did not measure the resistance of filamentous and floc-forming organisms to free chlorine.

Criteria for successful bulking control with chlorination

Jenkins *et al.* (1983; 1984) set down several guidelines that need to be followed for successful bulking control with chlorination:

- Set target value for the sludge settleability (SVI, DSVI, SSVI) desired. When this target has been attained, *terminate chlorination.*
- Dose chlorine *only* when the target settleability is significantly and consistently exceeded.
- Dose only in *known and controlled* quantities.
- Dose only at a point of *excellent* mixing.
- Dose at a point where the chlorine demand of the stream is at a minimum, in particular watch out for nitrite in the dosing stream – it reduces free chlorine to chloride.
- Dose at a point where the recommended values of the chlorination parameters are met (discussed below).
- Regularly monitor settleability and effluent quality.

Chlorine dosage is based on the total mass dose rate T_m. The local concentration C, local mass dose T and the frequency of exposure F are considered in selecting a dose point. Chlorine mass dose rates (T_m) ranging from 1 to 15 gCl_2/kgMLSS.d are reported in the literature. Jenkins *et al.* (1983) recommend that where complete nitrification is required, mass dose rates greater than 5 gCl_2/kgMLSS.d should be used with caution until it has been demonstrated that higher rates do not adversely affect nitrification. Other recommendations are that the frequency of exposure (F) should be greater than 2,5/d and the local chlorine concentration (C) should not exceed 35 $mgCl_2/\ell$.

With chlorination it is generally good practice to start with a low mass dose rate (T_m) of say 2 to 3 gCl_2/kgMLSS.d, particularly

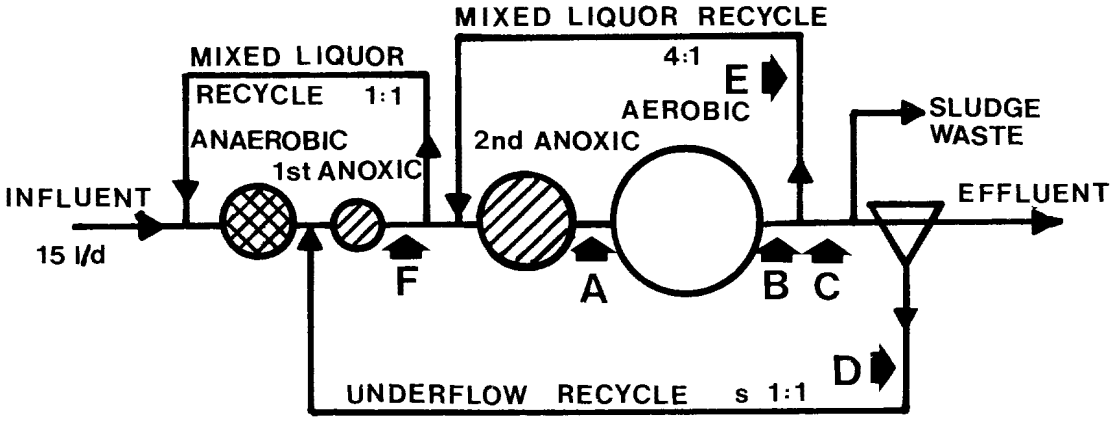

Figure 1
Configuration of modified UCT system for chlorination bulking control showing six possible chlorination dose points.

if there is no previous experience of chlorination at the plant. If this rate does not stabilise the settleability in about 3 to 4 d, then the rate should be increased slowly to 4 to 5 $gCl_2/kgMLSS.d$ for the next 3 to 4 d and 5 to 6 $gCl_2/kgMLSS.d$ thereafter. When, at a particular dose rate, the settleability begins to stabilise, then the rate should be slowly decreased, until, at the target settleability, the dosing rate is again low. Once the target settleability is reached, dosing should stop. Chlorination should be restarted only when the target settleability is significantly and consistently exceeded.

TABLE 1
DESIGN AND OPERATING PARAMETERS OF MODIFIED UCT SYSTEM IN CHLORINATION BULKING CONTROL (SEE FIG. 1 FOR SYSTEM CONFIGURATION).

Parameter	Value
Sludge age	21 d
Temperature	20°C
Influent : Mitchell's Plain raw sewage	
Flow	15 ℓ/d
COD concentration	1 000 mg/ℓ
Readily biodegradable COD concentration	210 mg/ℓ
TKN concentration	70-100 mgN/ℓ*
Total P concentration	30 mgP/ℓ**
Reactor volumes; mass fractions	
Anaerobic	6ℓ ; 0,16
1st Anoxic	2ℓ ; 0,10
2nd Anoxic	4ℓ ; 0,21
Aerobic	10ℓ ; 0,53
Unaerated mass fraction	0,47
Recycles	
Underflow 1 : 1	15 ℓ/d
Mixed liquor – Aerobic to 2nd Anoxic 4 : 1	60 ℓ/d
Mixed liquor – 1st Anoxic to Anaerobic 1 : 1	15 ℓ/d
VSS concentration in aerobic reactor	3 400 mg/ℓ
MLSS concentration in aerobic reactor	4 500 mg/ℓ
Mass MLSS in system	86 g

* *TKN/COD ratio differed between individual sewage batches.*
** *The influent was supplemented with 15 mgP/ℓ orthophosphate to raise the concentration to around 30 mgP/ℓ. This was necessary to ensure that the effluent P concentration always was high (>5 mgP/ℓ) so that the difference between influent and effluent P gives the system P removal capability in mgP/ℓ influent.*

System and sludge characteristics of nutrient removal pilot plant

The plant on which the chlorination bulking control study was undertaken was a laboratory-scale modified UCT system; the design and operating parameters are listed in Table 1 and a schematic layout of the configuration is shown in Fig. 1. In this system the sludge settleability progressively deteriorated over a period of about 1 month from a DSVI of 150 mℓ/g to over 200 mℓ/g (see Fig. 2). Microscopic examination indicated (see Table 2) that

- the overall filament abundance was abundant (5) to excessive (6) (after Jenkins *et al.*, 1984);
- a large number of polyphosphate accumulating organisms were present; and
- the dominant filamentous organisms were Types 0092 (ranked 1st), Type 0914 (2nd) and *M. parvicella* (3rd).

These 3 filaments are among the 5 most frequently dominant filaments in nutrient removal plants (Blackbeard *et al.*, 1987). The presence of large numbers of polyP accumulating organisms in the mixed liquor and the high biological P removal obtained (see Fig. 2), i.e. about 20 mgP/ℓ* for an influent readily biodegradable COD concentration (S_{bsi}) of around 200 mg/ℓ yielding a $\Delta P/S_{bsi}$ of 20/200 = 0,10 mgP/mgS_{bsi}, indicated that biological P removal was fully** active in the system. These conditions presented a worthwhile opportunity to investigate chlorination bulking control in a biological excess P removal system.

* *In this paper, phosphorus removal is reported as mgP/ℓ which is obtained from the difference between the influent and effluent P concentrations. Provided the effluent P concentration is greater than about 1 mgP/ℓ (which was the case in our experiments, see Table 1), the P removal in mgP/ℓ gives the system P removal capability. This method of reporting biological P removal performance is, in the opinion of the authors, superior to the percentage P removal method because it gives an indication of the actual mass concentration of P removed.*

** *The maximum biological P removal that can be attained is directly proportional to the influent readily biodegradable COD concentration, and a $\Delta P/S_{bsi}$ = 0,10 mgP per mg influent readily biodegradable COD reflects complete utilisation of the influent readily biodegradable COD for P removal. The lower the ratio $\Delta P/S_{bsi}$ below 0,10 mgP/mgS_{bsi}, the poorer the biological P removal below that attainable.*

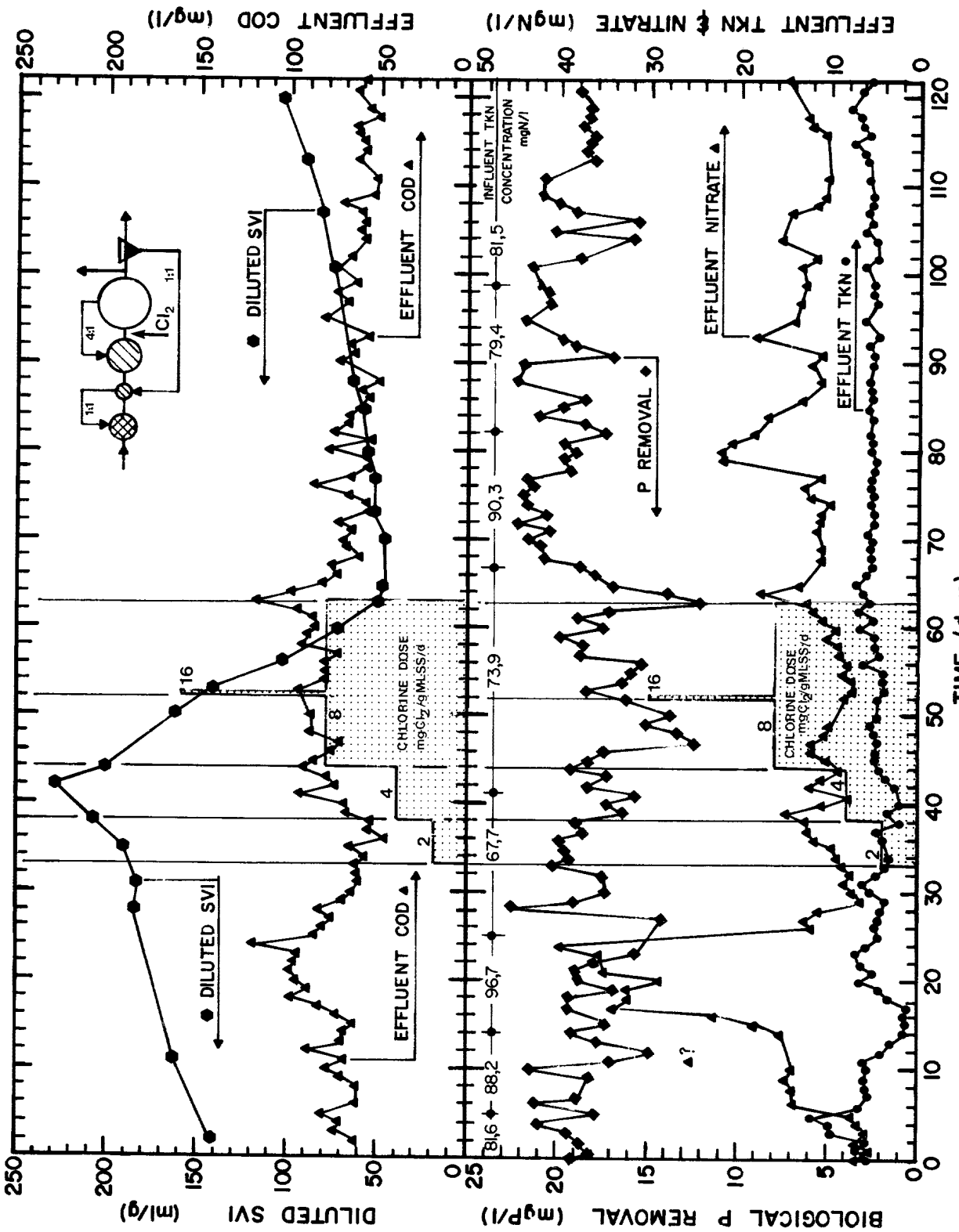

Figure 2

Diluted SVI and unfiltered effluent COD concentration (top) and biological P removal and effluent nitrate and TKN (unfiltered) (bottom) versus time in a modified UCT nutrient removal system at 20 °C and 21 d sludge age before, during and after a chlorination episode for filamentous bulking control. Chlorination period and dose rates are also shown.

System performance prior to chlorination

Daily data of effluent COD, TKN and nitrate concentrations (COD and TKN unfiltered), P removal (influent minus effluent P concentrations, unfiltered) and settleability in DSVI, measured in the system before, during and after the chlorination episode, are shown in Fig. 2. Other than causing a poor settleability, the excessive amount of filaments in the sludge did not adversely influence the biological COD, N and P removal of the system.

COD removal – effluent COD and suspended solids concentrations

The effluent COD concentration (unfiltered) varied between 60 and 100 mg/ℓ; the average for the period of about one sludge age before chlorination commenced, was about 80 mg/ℓ. During this period the DSVI increased from 150 mℓ/g to around 200 mℓ/g. As the DSVI increased, so the unfiltered effluent COD decreased, until 60 mg/ℓ was attained. Such improvement in unfiltered effluent COD is commonly observed during bulking episodes and arises through the entrapment of particles in the web-like floc structure formed by the filaments; generally filamentous bulking sludges have very good clarification characteristics giving very low effluent solids concentrations.

Nitrification/denitrification – effluent TKN and nitrate concentrations

Nitrification was complete and an effluent TKN (unfiltered) of about 5 mgN/ℓ was obtained. Denitrification reduced the nitrate generated by about 45 mgN/ℓ, the effluent nitrate concentration varying depending on the influent TKN concentration in the sewage batch being fed (see Fig 2). However, for a week before, and during the 3 weeks of chlorination, the influent TKN of the sewage batches stayed within a narrow range of 68 to 74 mgN/ℓ. Consequently, if significant increases in effluent nitrate concentration should be observed during chlorination, these could be attributed to the effect of chlorination. The average effluent nitrate concentration for the week before chlorination commenced was about 10 mgN/ℓ.

Biological P removal

The average P removal for the period of about one sludge age up to the time chlorination commenced was around 19 mgP/ℓ – this is only about 1 mgP/ℓ lower than that theoretically expected for the influent sewage characteristics and system parameters, indicating that biological P removal was progressing normally and in accordance with P removal behaviour observed in the past (Wentzel *et al.*, 1985).

Chlorination details and settleability

Six chlorination dose points were identified in the system (see Fig. 1) and the chlorination parameters, local mass dose, T ($mgCl_2/gMLSS$), local dose concentration, C($mgCl_2/ℓ$) and frequency of exposure, F(/d) at each of these points, for a total mass dose rate (T_m) of 2 $mgCl_2/gMLSS.d$, are listed in Table 3. The recommendations of Jenkins *et al.* (1984), i.e.

- that the local dose concentration C should not exceed 35 $mgCl_2/ℓ$, is met at all dose points even at very high total mass dose rates of 16 $mgCl_2/gMLSS.d$; and
- that the frequency of exposure, F, should > 2,5/d, is met only at points A, B and E.

Of these three points, the best are A and B, i.e. into the outflows of the second anoxic and aerobic reactors respectively (see Fig. 1), because these points have the highest frequency of exposure. At B the danger of chlorine reduction by nitrite is minimal because nitrification is very likely to be complete in the aerobic reactor. Low concentrations of nitrite can be generated during denitrification and therefore the presence of some nitrite at point A is possible. However, ammonia in excess of 10 mgN/ℓ is also present at A so that in all likelihood, if chlorine were dosed at A, monochloramine would form which is an effective toxicant that does not react with nitrite. Consequently there is little to choose between dosing at A or B, but A was selected because mixing was better there than at B.

Initially chlorine (appropriately diluted sodium hypochlorite with about 12% W/V available chlorine) was dosed at point A at 2 $mgCl_2/gMLSS.d$. The DSVI continued to increase so, after 4 d, the dose was doubled to 4 $mgCl_2/gMLSS.d$. This dose brought the DSVI under control – after 6 d the DSVI decreased slightly from 210 to 204 mℓ/g. In order to test the possible toxic effects of chlorine on biological N and P removal, the dose was doubled again to 8 $mgCl_2/gMLSS.d$ – target DSVI at which to terminate chlorination was not set because the objective of the experiment was to investigate the effect of a prolonged relatively high chlorine dose on biological P and N removal and the filaments causing bulking in nutrient removal systems. The dose of 8 $mgCl_2/gMLSS.d$ was maintained for 19 d. Midway during this period, an "accidental" overdose was administered for 15 h (equivalent to 4,7 x 15/24 = 3,0 exposures of the sludge mass) at the rate of 16 $mgCl_2/gMLSS.d$.

During the 19 d period the DSVI decreased from 204 to 51 mℓ/g. After 19 d, at 8 $mgCl_2/gMLSS.d$, the sludge was bleached to a light brown colour and a considerable quantity of floc debris accumulated as a foam on the reactor surface. These effects are signs of overdosing, i.e. too high a dose for too long a time. Such an overdose situation should not arise in practice on a full-scale plant because a target settleability will be set, which when reached, must prompt cessation of chlorination.

Effect of chlorination on filamentous organisms

The results of microscopic evaluation of the mixed liquor before, during and after the chlorination episode are set out in Table 2. From Table 2 it appears that of the 3 filamentous organisms in the sludge Type 0914 is the most susceptible to chlorination. At a dosage of 4 $mgCl_2/gMLSS.d$ this filamentous organism soon showed signs of decay and after 14 d of dosing at 8 $mgCl_2/gMLSS.d$, it had completely disappeared. During chlorination, Type 0914 became increasingly transparent and filled with dark granules while the ends were decaying. Type 0092 appeared slightly more resistant to chlorination than Type 0914. Although this filamentous organism also started decaying at a dose of 4 $mgCl_2/gMLSS.d$ it never completely disappeared even after the prolonged dose at 8 $mgCl_2/gMLSS.d$. During decay the ends of Type 0092 commenced to disintegrate and failed to Neisser stain. *Microthrix parvicella* appeared very resistant to chlorination; a chlorine dose of 4 $mgCl_2/gMLSS.d$ had very little effect. Even at a dose of 8 $mgCl_2/gMLSS.d$, it took 15 d before this filamentous organism showed significant decay but it did not disappear from the system. Neethling *et al.* (1985) also found *M. parvicella* to have a high resistance to chlorine.

During the chlorination episode, the overall filament abundance was reduced significantly, from excessive (6) to some (2); concomitantly the DSVI decreased from 230 to 48 mℓ/g. A week

TABLE 2
RESULTS OF MICROSCOPIC EVALUATION OF MIXED LIQUOR BEFORE, DURING AND AFTER CHLORINATION

Day (see Fig 2)	DSVI mℓ/g	Overall filament abundance*	Filament types rank and abundance*	Floc structure	Remarks
3, 11, 25 and 31	128 to 188	Increasing from very common (4) to excessive (6)	1) 0092 Ab 2) 0914 VC 3) Mp† C-VC 4) 0041 F 5) 0675 F	Open, irregular and diffuse, weak. Some bridging 70% < 150μ 100% < 500μ	PolyP clusters clearly visible Many protozoan species present Some free cells Inorganic and organic particles present
37 and 39	192 to 211	Abundant (5) to excessive (6)	1) 0092 Ex 2) 0914 VC 3) Mp C		Chlorination at 2 $mgCl_2$/gMLSS.d commenced day 33 Filaments healthy; chlorine no apparent effect Increased dose to 4 $mgCl_2$/gMLSS.d on day 38 and to 8 $mgCl_2$/gMLSS.d on day 44
45 and 50	204 to 153	Excessive (6) to abundant (5)	1) 0092 Ab 2) 0914 VC 3) Mp C		0092 disintegrating from free ends 40 to 50% affected 0914 becoming more transparent, but filled with dark granules. Ends beginning to disintegrate. Mp not affected very much Rotifera also affected
56	105	Very common (4)	1) 0092 Ab 2) Mp VC 3) 0914 S		0914 badly decayed 0092 decaying Mp beginning to decay
59	75	Very common (4)	1) 0092 VC 2) Mp C	Open, irregular and diffuse 80% < 150μ 100% < 500μ No bridging	Flocs fragmenting – signs of overdosing 0092 most (70%) have decayed ends which fail to Neisser stain 0914 disappeared Mp disintegrating – badly decayed Terminated chlorination on day 63
65	48	Some (2)	1) 0092 C 2) Mp S-C		Surface scum present from floc debris Many dead filaments and free flocs visible PolyP clusters not as darkly stained as usual and appears scattered in floc
75, 105 and 113	52 to 92	From some (2) to very common (4)	1) 0092 C-Ab 2) Mp C-Ab 3) 0914 S-C 4) 0675 F-C 5) 0041 N-F	Firm, irregular and diffuse, open 65% < 150μ 95% < 500μ 100% < 500μ Some bridging commencing	0092 and Mp regrowing 0914 reappearing 0675 and 0041 also becoming apparent PolyP clusters reformed and have usual appearance

* Ex = Excessive (6); Ab = Abundant (5); VC = very common (4); C = common (3); S = some (2); F = few (1); N = none (0). Qualitative scale after Jenkins *et al.* (1984).
† *Microthrix parvicella*

after cessation of chlorination, the DSVI again began to increase and after about 2½ sludge ages it reached 105 mℓ/g (Fig 2). Microscopic examination of the sludge indicated that the same three filaments had regrown (see Table 2) i.e. Type 0092 (1st), *M. parvicella* (2nd), and Type 0914 (3rd). Types 0675 (4th) and 0041 (5th) were also present in the sludge. These 5 filamentous organisms are the principal culprits causing bulking in nutrient removal plants (Blackbeard *et al.*, 1987). The reason for the fila-

ment regrowth is that the causes for their growth had not been eliminated. Clearly chlorination treats the symptoms and not the causes of bulking. Specific control measures seek to eliminate the causes.

Effect of chlorination on system performance (see Fig 2)

COD removal and effluent COD concentration

While the initial low dose of 2 $mgCl_2/gMLSS.d$ was administered, the effluent COD concentration (unfiltered) remained unchanged at about 60 mg/ℓ. When the dose was doubled to 4 $mgCl_2/gMLSS.d$, it increased to around 80 mg/ℓ and during the 8 $mgCl_2/gMLSS.d$ dose period, it varied between 80 and 90 mg/ℓ. At chlorination termination, it had increased to 120 mg/ℓ. The increases in effluent COD were mainly due to increases in effluent suspended solids, which cause the effluent to become more turbid. These increases arise from the chlorine destroying activated sludge floc material.

Sharp increases in effluent turbidity and decreases in settleability indicate chlorine overdose. When activated sludge has been overdosed, the effluent turns milky from all the floc debris escaping with the effluent. This happened on the last day of chlorination, reflected in the sharp increase in effluent COD, and was the reason for terminating chlorination on that day.

After termination of chlorination, the effluent COD concentration decreased from 120 mg/ℓ to around 70 mg/ℓ over a period of 5 d. Thereafter, it remained steady at between 60 and 70 mg/ℓ for the remainder of the experiment. The decrease was principally due to a decrease in effluent turbidity with sludge recovery from the chlorination episode. After about a week most of the floc debris had disappeared and the sludge began to lose its bleached light brown appearance.

Nitrification and effluent TKN concentration

During the initial low doses of 2 $mgCl_2/gMLSS.d$, the unfiltered effluent TKN concentration was below 4 mgN/ℓ and decreasing, indicating that nitrification was not affected by this dosage. When the dose was increased to 4 $mgCl_2/gMLSS.d$, the effluent TKN increased slowly to 5 mgN/ℓ. During the first half of the 8 $mgCl_2/gMLSS.d$ dose period, it remained at 5 mgN/ℓ and during the second half, increased steadily to 6,5 mgN/ℓ. These increases were principally due to increases in effluent turbidity indicating that nitrification *per se* was not affected by the chlorine dosages. Even during the 15 h "accidental" overdose of 16 $mgCl_2/gMLSS.d$, no perceptible increase in effluent TKN concentration took place. After chlorination was stopped, the unfiltered effluent TKN concentration decreased from 6,5 to 5,5 mgN/ℓ over a period of a week and remained at 5,5 mgN/ℓ. The nitrite concentration in the aerobic zone remained below 0,5 mgN/ℓ at all times during the experiment. The low effluent TKN and nitrite concentrations indicate that neither *Nitrosomonas* nor *Nitrobacter* were adversely affected by the chlorine dosages.

Denitrification and effluent nitrate concentration

Up to the time of the "accidental overdose", the effluent nitrate concentration varied between about 8 and 12 mgN/ℓ, the estimated denitrification ranging from 43 to 47 mgN/ℓ. There appears to be no correlation between the variation and the chlorine dose and consequently these variations have no assignable cause. However, after the "accidental overdose", there was a steady increase in effluent nitrate from 7 mgN/ℓ to 13 mgN/ℓ and on the last day of chlorination when overdosing had occurred, it was 18 mgN/ℓ, i.e. the denitrification decreased from 48 to 42 mgN/ℓ, and then on the last day of chlorination to 37 mgN/ℓ. After cessation of chlorination the effluent nitrate decreased from 18 mgN/ℓ to 10 mgN/ℓ over the "recovery" period of about 5 d, i.e. the denitrification recovered to 45 mgN/ℓ. These results indicate that towards the end of the chlorination episode, the denitrifying organisms were in distress to some degree. However, this distress was relatively minor, despite the prolonged high dosing, if one compares the denitrification achieved before and after chlorination. In practical application where a target DSVI is set, and the chlorine dosing is likely to be less severe than in this experiment, denitrification is unlikely to be affected.

Biological P removal

During the initial dose of 2 $mgCl_2/gMLSS.d$, the P removal remained unchanged between 19 and 20 mgP/ℓ. Upon increasing the dose to 4 $mgCl_2/gMLSS.d$, the P removal initially dropped to about 16 mgP/ℓ but increased again back to 19 mgP/ℓ after 6 d. When the dose was increased to 8 $mgCl_2/gMLSS.d$, a sudden drop in P removal to 12,5 mgP/ℓ took place, but over the 8 d up to the "accidental overdose" the P removal recovered again to 18,5 mgP/ℓ. The "accidental overdose" caused the removal to decrease again to about 15 mgP/ℓ but it again recovered to around 19 mgP/ℓ over 5 d. However, during the final two days of the chlorination episode, the P removal dropped precipitously to 12 mgP/ℓ. This decrease probably arose because of the prolonged dosing which caused an overdose condition on the polyphosphate accumulating organisms in the end. This overdose condition was detected microscopically because the polyP clusters did not stain as darkly as usual and appeared scattered in the floc during this time (see Table 3). The overdose also was manifested by a high effluent turbidity and much floc debris and scum. After cessation of chlorination, the P removal steadily recovered from 12 mgP/ℓ to around 20 to 21 mgP/ℓ over a period of 6 d, and remained at around the theoretically expected level of about 21 mgP/ℓ for the remainder of the experiment.

TABLE 3
CHLORINATION PARAMETERS FOR 6 POSSIBLE DOSE POINTS IN MODIFIED UCT SYSTEM (FIG. 1) FOR A TOTAL MASS DOSE OF 2 $mgCl_2/gMLSS.d$.

DOSE POINT	FLOW ℓ/d	MASS FLOW gMLSS/d	LOCAL MASS DOSE $mgCl_2$/gMLSS	LOCAL CONC. $mgCl_2/ℓ$	FREQUENCY /d
A,B	90	405	0,42	1,9	4,7
C	30	135	1,26	5,7	1,6
D	15	135	1,26	5,7	1,6
E	60	270	0,64	2,9	3,1
F	45	203	0,85	3,8	2,4

A – into flow between 2nd anoxic and aerobic reactors
B,C – into flow between aerobic reactor and settling tank before and after mixed liquor recycle take-off point
D – into underflow recycle
E – into mixed liquor recycle
F – into outflow of 1st anoxic reactor

Tracing the P release and uptake through the system during the chlorination episode indicated that at the times of reduced P removal, P release in the anaerobic reactor did not change, but that P uptake in the anoxic and/or aerobic reactors was reduced; P removal recovery following a dose increase or overdose of chlorine was associated with an improvement of P uptake in the anoxic and/or aerobic reactors. Apparently chlorination does not influence P release but temporarily inhibits the P uptake mechanism in the polyphosphate accumulating organisms from which they can recover provided the dose is not too high (< 8 $mgCl_2/gMLSS.d$) and not for too long a period. This result may have arisen from the fact that chlorine was dosed into the system at a point after the P release but before the P uptake. If the dose point had been after the P uptake but before the P release, e.g. into the clarifier underflow, a reduced release, and consequently also a reduced uptake, may have taken place. The influence of the dose point on the release and uptake mechanisms of the biological P removal is an aspect that will require monitoring in the application of chlorination of nutrient removal sludges.

Conclusions

- A filamentous bulking incident in a biological nutrient removal modified UCT activated sludge system, caused by excessive growth of filamentous organisms Type 0092, Type 0914 and *M. parvicella*, was successfully ameliorated by chlorination. These filamentous organisms are 3 of the 5 main ones causing bulking in nutrient removal plants – the other two are Types 0675 and 0041 (Blackbeard *et al.*, 1987).
- A total mass dose of 8 $mgCl_2/gMLLS.d$ was applied into the stream between the 2nd anoxic and aerobic reactors. The chlorine concentration at the dose point was 7,6 $mgCl_2/\ell$, the frequency of exposure 4,7/d and the local mass dose 1,7 $mgCl_2/gMLSS$.
- Following a lead-in period at overall mass dose rates of 2 and 4 $mgCl_2/gMLSS.d$, dosing at 8 $mgCl_2/gMLSS.d$ continued for 19 d, during which time the DSVI decreased from 230 to 48 $m\ell/g$. Dosing was terminated when the system manifested overdosing symptoms, e.g. high effluent turbidity. During dosing COD removal was essentially unchanged except when overdosing became apparent at the end of the dosing period, nitrification was unaffected and complete and denitrification was only marginally affected.
- Biological P removal initially was reduced when increasing the chlorine dose, but recovered in the following 4 to 5 d. The extent of the recovery depended on the magnitude of the dose increase. After 16 d of chlorination at 8 $mgCl_2/gMLSS.d$, P removal began to decline precipitously. On day 19, when chlorination ceased, the P removal had declined to 12 mgP/ℓ. After cessation of chlorination, P removal recovered back to its normal 21 mgP/ℓ in 5 d.
- Phosphorus release in the anaerobic zone was not affected by chlorination, but during periods of poor P removal, P uptake in the anoxic and/or aerobic reactors was reduced. Apparently for the particular dose point selected i.e. after the P release but before the P uptake, chlorine temporarily inhibits the P uptake mechanism in the polyphosphate accumulating organisms, from which they recover if the chlorine dose is neither to high (< 8 $mgCl_2/gMLSS.d$) nor of too long duration.
- Of the 3 filamentous organisms in the system, Type 0914 was the least and *M. parvicella* the most resistant to chlorination. The former completely disappeared from the system while the latter and Type 0092 were considerably reduced. Regrowth of Type 0092 and *M. parvicella* commenced and Type 0914 reappeared about a week after termination of chlorination.
- Filamentous bulking in biological nutrient removal systems can be controlled with chlorination with minor temporary loss in denitrification and biological P removal. The temporary loss of P removal can be overcome by in-plant chemical precipitation.

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