A review of the potential application of non-specific activated sludge bulking control

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Abstract

Filamentous bulking occurs in most biological nutrient removal activated sludge plants. The sludge mass becomes extremely voluminous, difficult to settle and has poor thickening and dewaterability properties. An analysis of the situation in six typical South African nutrient removal plants indicated that the cost of additional settling capacity, to accommodate the bulking sludge, amounts to 1,5 c/m^3 of sewage treated in 1991 replacement amortisation cost terms. The additional retention period in the secondary settlers promotes phosphate release and denitrification with subsequent sludge floating and carry-over into the effluent. The larger waste sludge volumes and poor dewaterability result in an additional cost of 0,9 to 3,7 c/m^3 in 1991 terms. Oxidants are effective as a non-specific bulking control measure and obviate the need for additional settling and sludge thickening and dewatering capacity. Chlorination will add about 5 cm/m^3 to the cost of sewage treatment, but also affects nutrient removal detrimentally. Hydrogen peroxide dosing will cost 10,5 c/m^3 of sewage treated and does not interfere with the nutrient removal processes. Ozonation costs about 3,3 c/m^3, does not disturb nutrient removal and can lead to an improvement in effluent quality. Since amortisation contributes the major fraction of ozonation costs, less than full utilisation of the capacity increases cost, e.g. if the equipment is only used 25% of the time, ozonation costs increase to 8,7 c/m^3 of sewage treated.

Introduction

Filamentous bulking is a problem in most biological nutrient removal activated sludge plants. According to a survey by Blackbeard et al. (1988), about three-quarters of these plants as operated in South Africa had diluted sludge volume indices (DSVI) > 150 mℓ/g. The total extended bacterial filament length in a gram of sludge can, under these circumstances, exceed 30 km (Lee et al., 1983). The filaments form weblike structures extending into the bulk liquid leading to a diffuse floc structure and bridging between the flocs (Ekama and Marais, 1984). The sludge mass becomes extremely voluminous and difficult to settle.

Sludge bulking can also have wider implications than difficult secondary settling. Low settleability may result in poor effluent quality due to a high solids carry-over from the secondary settlers. The high effluent solids can be ascribed to incomplete settling as well as anoxic conditions developing in the settler due to sludge accumulation. Denitrification occurs and the resulting nitrogen bubbles cause sludge particles to float. The poorly compacted sludge results in excessive waste sludge volumes usually with poor thickening properties with respect to gravity settling and dissolved air flotation (Bratby, 1977) and poor dewaterability in centrifuges and belt presses (Osborn et al., 1986).

Bulking is clearly a serious and costly problem and its prevention or amelioration is certainly worth investigating. Among the various possiblities, control of the growth of filamentous bacteria with chemicals, particularly the oxidants chlorine, hydrogen peroxide and ozone, looks feasible and attractive. This article is aimed at investigating the practical and cost implications of chemical bulking control.

Background

Bulking can be due to a variety of organisms, but in the case of biological nutrient removal plants bulking is mainly caused by 14 different filamentous bacteria (Eikelboom and Van Buÿsen, 1983). The five main filamentous bacteria dominating South African nutrient removal plants, according to a comprehensive survey by Blackbeard et al. (1988) are *Type 0092* - dominant in 82% of plants, *Type 0675, Type 0041, Microthrix parvicella* and *Type 0914*. The first four are classified by Jenkins et al. (1984) as typical in plants with a low food to micro-organism (F/M) ratio, while *0041* and *M. parvicella* are also associated with other nutrient deficiencies.

Blackbeard et al. (1988) suggest that *0914* should also be classified as a low F/M ratio organism. All these filaments are slow growers compared with floc-forming bacteria, but have the competitive edge under food or nutrient limiting conditions; probably due to their much larger surface to mass ratio through which they are more effectively able to absorb these substances essential for growth.

The growth of filamentous bacteria may, according to Lakay et al. (1988), be controlled by either:

- specific measures or
- non-specific measures.

Specific control measures are aimed at eliminating or circumventing the conditions which preferentially favour the growth of filaments. Chudoba et al. (1973) had some success with selector reactors ahead of the main plant where high F/M ratios ensure that floc-formers outgrow filaments. This approach is not practical in nutrient removal processes since selectors have no effect on bulking (Gabb et al., 1989). Some filaments, notably *M. parvicella* proliferate competitively under low dissolved oxygen concentrations and can be disadvantaged by increasing dissolved oxygen levels (Osborn et al., 1986; Barnard and Hoffmann, 1986). Some filaments, particularly *M. parvicella* and *Nocardia* concentrate in foam and actually cause the foam. Selective removal of foam (Jenkins et al., 1984; Hart, 1985; Pretorius and Laubscher, 1987) avoids foam build-up and could serve to keep the population of the particular filament at lower levels.

Non-specific bulking control involves the inhibition of the growth of filamentous organisms by the addition of chemicals, usually oxidants such as chlorine, hydrogen peroxide or ozone. It

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TABLE 1
SECONDARY SETTLER OVERFLOW RATES IN TYPICAL NUTRIENT REMOVAL PLANTS

Average dry weather design flow of plant (Mℓ/d)	Overflow rates (m/h) (wet weather)		
	Design	**Operating**	**Peak flow**
132	0,43	0,3	0,67
20	0,48	0,3	0,79
30	0,44	-	0,74
33	0,5	0,45	0,9
30	0,84	0,42	0,7
20	0,6	0,33	0,66
6	0,27	0,14	0,3
10	0,35	0,2	0,38
150	0,6	0,5	0,55
150	0,6	0,5	0,65
Total 581 Mean*	0,51	0,37	0,65

*Based on the weighted mean flow of the plants in the table

is possible that the filamentous organism is more exposed to the oxidative action of the oxidant than the typical floc-former due to its larger surface to mass ratio and due to the fact that it penetrates into the bulk of the liquid. However, the exact mechanism of oxidative bulking control is yet to be investigated and this is being researched at the University of Pretoria.

This report will compare the practical and cost implications of chlorine, hydrogen peroxide and ozone for the control of filamentous bulking, but firstly the cost implications of not using bulking control measures will be investigated.

The cost implications of unchecked bulking

Uncontrolled bulking will bring about additional capacity requirements at the design stage for both secondary settling and sludge thickening and dewatering.

Secondary settling

A DSVI of 150 mℓ/g implies that 1 g of sludge occupies 150 mℓ or that the mixed liquor suspended solids (MLSS) concentration which could still settle within 30 min is less than (1 000 mℓ/ℓ)/(150 mℓ/g) = 6,7 g/ℓ. This places a serious limitation on sludge management in nutrient removal activated sludge plants with secondary settling as the underflow concentration could be considerably higher. The underflow concentration from a settler operating at a typical 1:1 return flow ratio, for instance, needs to be twice as high as the inflow mixed liquor to avoid sludge build-up and eventual overflow. The MLSS should then be maintained at lower than 50% of 6,7 g/ℓ or at a value of less than 3,3 g/ℓ.

Sludge settleability often governs the permissible throughput and COD loading rate in an activated sludge plant as was demonstrated at the Northern Sewage Works in Johannesburg (Osborn et al., 1986). The highest overflow rate in a secondary settler is reached during peak wet weather flow conditions and the mean COD mass input determines the MLSS concentration. Ekama and Marais (1986) showed that the maximum permissible overflow rate in a secondary settler is 1 m/h for sludge with a MLSS of 3,5 g/ℓ and a DSVI of 150 mℓ/g. Should the DSVI increase to 200 mℓ/g either the overflow rate has to be reduced to 0,6 m/h to maintain the same MLSS or the MLSS has to be reduced to 2,4 g/ℓ to maintain an overflow rate of 1 m/h. The secondary settlers become a limitation to the plant capacity if they have been designed to the Institute for Water Pollution Control (now Water Institute of Southern Africa) criterion of 1 m/h overflow rate at peak wet weather flow. Major financial implications may result if new plants have to be built when the old plant could have served the purpose for several years longer - all because of sludge bulking. As a result, many plants have been built with reserve settling capacity.

A survey of most major nutrient removal plants in South Africa showed that virtually all had secondary settlers designed with peak dry weather overflow rates well below 1 m/h. Table 1 summarises some overflow rates in 10 typical plants in Pretoria, Johannesburg, Bellville, Kempton Park, Vereeniging, Port Elizabeth and Kimberley.

Most major nutrient removal plants therefore have been equipped with secondary settlers about 50% in excess of the capacity required for non-bulking sludge or more. This increases the risk of development of anoxic conditions which lead to the release of phosphates and denitrification and subsequent floating of sludge. The floating sludge is unsightly and contributes to the solids load in the effluent.

Settlers can certainly contribute significantly to the cost of an activated sludge plant. An attempt has been made to compile cost data in order to evaluate the cost implications of the use of additional settling capacity. One approach was through questionnaires sent to local authorities operating major nutrient removal plants and the other by using cost data presently in use by consultants and contractors. Table 2 summarises cost data as obtained from the questionnaires updated to 1991 values.

Total cost figures of more plants were obtained, but particulars on settler costs were limited to those in the tables. Not included in the figures was the proportional cost of establishment and services. Another attempt at establishing a cost figure for settlers was to use a rule of thumb figure of R150 per m^3 of settler volume (Pretorius, 1991) for the civil costs, adding the cost of mechanical equipment of R126 000 for a 30 m settler (Nel, 1991) plus VAT of R12 600 on mechanical equipment and a further c. 20% for establishment cost and services. A 30 m settler of 4 m

TABLE 2
COST DATA OF SOUTH AFRICAN SECONDARY SETTLERS

Plant			Settlers				
Capacity Mℓ/d	**Cost MR**	**Date completed**	**Number**	**Diameter m**	**Cost MR**	**Ratio***	**Unit cost 1991 MR****
132	26	1985/07	18	30	3,78	0,145	0,54
20	14	1989/04	3	27	0,82	0,06	0,39
30	49	1990/09	4	30	2,72	0,056	0,77
6	2,8	1986/03	2	24	0,39	0,14	0,45

MR = MegaRand or Million Rand
* Ratio of costs of secondary clarifiers to the whole plant
** Unit cost per settler (1991) of construction in million rand

TABLE 3
COST IMPLICATIONS OF EXCESSIVE SETTLING CAPACITY

Plant capacity (Mℓ/d)	Peak wet weather overflow rate (m/h)	Settlers	Possible alternative for 1 m/h	Capital savings (MR)	Savings (c/m³)
132	0,67	18 x 30 m	12 x 30 m	4,08	0,74
20	0,79	3 x 27 m	2 x 30 m	0,36	0,43
30	0,74	4 x 30 m	3 x 30 m	0,68	0,55
22,5	0,66	3 x 27 m	2 x 27 m	0,57	0,61
6	0,3	2 x 24 m	1 x 24 m	0,48	1,93
18	0,38	3 x 30 m	2 x 24 m	1,1	1,49

side-wall depth under average soil conditions would then cost R680 000. Similarly, a settler of 27 m diameter would cost R572 000 and a settler of 24 m diameter R475 000. These figures do not drastically differ from those in Table 2.

The ratio of the cost of settlers to total cost was variable depending to some extent on the loading rate. According to Bucksteeg (1971) the cost of secondary settling amounts to between 4 and 9 per cent of the total cost of activated sludge treatment plants. The higher ratios on the plants in Table 2 again confirm that the plants have a disproportionately large clarification capacity.

Possible savings, had smaller settling capacities been installed, have been calculated from the above cost figures and are shown in Table 3. The savings have been amortised over a period of 20 years at a discount rate (interest rate - inflation rate) of 6 % per annum and recalculated as a unit cost savings.

The mean savings in amortisation cost, based on throughput weighted values from Table 3, amount to 0,8 c/m³ and another 0,1 c/m³ in operating cost can be expected. The total mean savings that could be realised in present replacement value on the six plants in Table 3 if the settlers had been built with an overflow rate of 1 m/h, equal 0,9 c/m³.

Smaller or fewer settlers also have the benefit of reducing the retention time of sludge in the settlers, thereby limiting the opportunity for the sludge to become anoxic, releasing phosphate and to start floating due to nitrogen bubble formation. More readily settling sludge would also reduce waste sludge volumes and lead to a decrease in sludge treatment costs.

Sludge thickening and dewatering costs

Osborn et al. (1986) list comparative costs for dewatering of high and low DSVI sludges. According to their estimates, based on years of research at the Johannesburg City Council, the cost of dewatering a tonne of bulking sludge amounted to R87,30 against R42,80 for non-bulking sludge. Their estimate included capital amortisation at 6 % per annum. The costs, updated at an escalation rate of 17 % per annum, then amount to R192 per dry tonne of bulking sludge against R101 per dry tonne of non-bulking sludge. In order to quantify this cost effect of bulking as an integral part of sewage treatment, the sludge treatment costs have to be converted to unit costs of sewage treatment.

According to Ekama et al. (1984) sludge production relates to the COD of the influent in sewage according to a complex function of yield and decay rates strongly dependent on sludge age. A plot of this function can be used to determine that the sludge production from typical settled sewage at a sludge age of 20 d - common in nutrient removal plants - is 0,18 kg/kg COD and that of raw sewage 0,27 kg/kg. Typical COD concentrations in settled sewage range from 300 to 600 mg/ℓ and in raw sewage from 500 to 800 mg/ℓ (Ekama et al., 1984). These values, along with the sludge treatment costs, can be used to calculate the cost implications of sludge bulking as shown in Table 4.

On plants where land disposal is practised, treatment costs will not be so profoundly affected by the bulking problem and may cost as little as 0,1c/m³ more.

The total cost implication of bulking on sludge management equals the sum of the additional cost of settling capacity and of sludge thickening and dewatering, i.e. 1,0 to 3,7 c/m³.

Bulking control with chlorination

Chlorination has been used for bulking control for over half a century (Smith and Purdy, 1936) and has recently again been

TABLE 4
THE EFFECT OF BULKING ON SLUDGE TREATMENT COST

	Non-bulking sludge	Bulking sludge
COD of influent	300-800	300 - 800
Sludge production rate, kg/kg	0,18 - 0,27	0,18 - 0,27
Sludge production rate, /Mℓ	54 - 217	54 - 217
Sludge treatment cost, /tonne	R114	R245
Sludge treatment cost, /Mℓ	R6,16-R24,62	R13,23-R52,92
Additional costs /Mℓ	R7,07 - R28,30	
due to bulking /m^3	0,7c - 2,8c	

propagated and promoted by Jenkins and his co-workers (Jenkins et al., 1982 and 1984 and Neethling et al., 1985a). Although it is very effective in repressing the growth of filamentous organisms, it is not very selective (Neethling et al., 1985b) and it also affects the floc-forming organisms leading to effluent quality disturbances as below:

- interference with nitrification (Eisenhauer et al., 1976 and Thirion, 1982);
- increased turbidity and COD of the effluent (Smith and Purdy, 1936; Frenzel and Safert, 1971; Frenzel, 1977; Lakay et al., 1988); and
- reduced biological phosphate removal (Lakay et al., 1988).

Although it could be expected that chlorination should lead to organohalogens in the effluent this has not been observed, probably because of air stripping (Van Leeuwen and Van Rossum, 1990).

Chlorine dosages for bulking control ranged from 0,7 to 20 mg/ℓ based on plant sewage throughput rate in seven different activated sludge plants reviewed by Neethling (1984) or from 1 to 15 g/kg MLSS·d according to Jenkins et al. (1982). Neethling et al. (1985a) recommended that the chlorine dose rate should not exceed 35 mg/ℓ and that the frequency of exposure, i.e. MLSS flow rate past the chlorine dosing point divided by the MLSS in the system, should be larger than 2,5/d. Neethling et al. (1985b) found that the filaments associated with low dissolved oxygen concentrations such as *Type 1701* and *Sphaerotilus natans* had a lower resistance against chloramines than the filaments associated with low nutrient levels such as *Types 0092, 0041, 0675* and *M. parvicella.*

Lakay et al. (1988) found a chlorine dosage of 4 g/kg MLSS·d insufficient to alleviate bulking but a dosage of double that was effective, if disruptive to the delicate nutrient removal processes. Chlorine at 6 g/kg·d, which should have been sufficient, at a MLSS of 4 g/ℓ and a retention time of 16 h, would have required on influent rate-based dosage of 6 x 4 x 16/24 mg/ℓ, or 16 mg/ℓ. Gaseous chlorine currently cost about R3,20/kg. Capital costs, mainly a building to house the chlorination facilities, could add another 10c/kg. Chlorination would therefore add c. 5c/m^3 to the cost of sewage treatment. The work was conducted using Mitchell's Plain raw sewage with a COD of 1 000 mg/ℓ leading to a high MLSS value. The actual dosage here was 34 mg/ℓ at a cost of 11 c/m^3. In many cases it can be expected that the chlorine demand could be lower, although Neethling et al. (1985a) found that bulking control is more dependent on chlorine dose concentration than on the mass dose rate. It is further possible to lower the cost by only chlorinating until an acceptable DSVI has been reached and to resume chlorination only once the DSVI reaches excessive values again.

Bulking control with hydrogen peroxide

Hydrogen peroxide has been used for bulking control in conventional activated sludge processes with great success (Caropreso et al., 1974; FMC Corporation, 1976 and 1979). Dosages required are somewhat high making this choice costly; however, since hydrogen peroxide dissociates eventually to water and oxygen, it does not leave any toxic residuals. Bench-scale trials conducted at the University of Pretoria indicated that hydrogen peroxide, even in massive dosages of 100 g/kg MLSS·d did not affect the sensitive nutrient removal organisms. It was further found that high dosages were required for bulking control, i.e. 8 g/kg MLSS·d. It was observed during periods with *Types 0092* and *0041* dominating that such dosages of hydrogen peroxide could reduce the concentration of both organisms but that they remained the dominating filaments. The DSVI was lowered from over 200 mℓ/g to about 140 mℓ/g. Full-scale tests have been initiated at the Daspoort Sewage Works, Pretoria to investigate the use of hydrogen peroxide.

The cost implications of using hydrogen peroxide are as follows: the chemical is supplied as a 50 % solution at about R2,50 per kg, i.e. the H_2O_2 costs R5 per kg; capital costs are minimal; assuming an MLSS concentration of 4 g/ℓ, and a hydraulic retention time of 16 h, the influent rate-based dosage would be 8x4x16/24 mg/ℓ, or over 21 mg/ℓ as H_2O_2. This would imply a cost of 10,5 c/m^3.

Bulking control with ozone

Ozone is an alternative oxidant and disinfectant in many water and waste-water purification applications. More powerful than chlorine, ozone does not contribute to the salinity, nor does it normally form toxic residuals (Rice and Browning, 1981). Its benefits in bulking control (Van Leeuwen, 1988a) and the improvement of activated sludge effluent quality (Van Leeuwen, 1988b) have been demonstrated in nutrient removal activated sludge pilot-scale units. Nowhere has ozone ever been applied on full-scale bulking control, although the French hold a patent on this particular application. The Daspoort Sewage Works will be the first to use ozone bulking control on a full-scale experimental basis.

Pilot-scale work by Van Leeuwen (1988a) indicated that an ozone dosage of 2 g/kg MLSS·d could lower the DSVI from 180 to less than 100 mℓ/g within one sludge age without disturbing the nutrient removal processes. Nutrient removal processes were not disturbed, even at dosages of 30 g/kgMLSS·d.

Ozone has to be generated on site requiring expensive equipment. A cost analysis is only possible by calculating the cost on a certain basis such as 20 Mℓ/d, MLSS of 4g/ℓ and a retention time of 16h. The ozone demand would then be 2 x 4 x 16/24 mg/ℓ based on the influent rate, i.e. 5,3 mg/ℓ or 4,4 kg/h. Allowing for losses, ozone generators producing 5 kg/h would have to be purchased at about R1,5 million rand. Auxilliary equipment including compressors, pipes, diffusors and a building could increase the capital requirements up to R2,0 million. Depreciation of capital at a discount rate of 6 % per annum over 15 years would result in an annual amortisation cost of R130 800. The operating costs are mainly electricity, 20 kW.h/kg of ozone produced, i.e. 88 kW.h/h or 760 000 kW.h/a at 8c/kW.h which will amount to R60 800. Maintenance at 2,5% of the capitals and operation could add R50 000 to this figure. This comes to R241 600 annually, and treatment costs amount to just over 3,3 c/m^3.

The above cost analyses are based on the assumption that the ozone plant will be in use at full power for 24 h/d and 365 d/a. Since 54% of the costs are amortisation costs, the implication of using only half the capacity, for instance, will be that the unit treatment costs will increase to about 5,1 c/m^3 should the plant be operated, say only for three months per year, the unit costs will increase to 8,7 c/m^3 of sewage treated. However, with the quality benefits derived from ozonation, it is to be recommended that the ozone remain in use constantly. Alternatively, a single ozone plant could be built to serve two or more activated sludge units on modular plants.

Conclusions and recommendations

- Filamentous bulking sludge, if uncontrolled, requires additional settling and sludge thickening and dewatering capacity which can increase treatment costs by 1,0 to 3,7 c/m^3 but the additional sludge retention time in the clarifiers can cause anoxic conditions leading to phosphorus release, denitrification and floating sludge.
- Chlorine can ameliorate filamentous bulking but since this oxidant is not very specific, nutrient removal micro-organisms can also be affected. Chlorination costs about 5 c/m^3 of sewage treated, but up to 11 c/m^3 for strong sewage.
- Hydrogen peroxide can partially inhibit filamentous growths without disturbing nutrient removal processes at a cost of 10,5 c/m^3.
- Ozone can specifically inhibit filamentous growths without disturbing nutrient removal processes at a cost ranging from about 3,3 c/m^3 for continuous usage to 8,7 c/m^3 for 25% usage of equipment. An improvement in effluent quality is also possible.
- The use of oxidants obviates the need for additional clarification and sludge thickening capacity. This will not result in major savings on existing plants but the operational life of the plant before extensions are required, can be extended.
- Full-scale tests on bulking control with oxidants are necessary to establish operational procedures and more exact cost figures, and to ensure proper technology transfer.

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