Review of treatment performance at Hammarsdale Waste-water Works with special reference to alum dosing

DW de Haas*, GP Borain and DA Kerdachi
Umgeni Water, PO Box 9, Pietermaritzburg 3200, South Africa

Abstract

The treatment process at Hammarsdale Waste-water Works has been heavily influenced by the nature of the influent, which is largely of industrial origin, as well as by certain design features of the extended aeration 5-stage Bardenpho process present. In particular, dissolved phosphate, chemical oxygen demand (COD) and colour removal have proved problematic. Limitations of the activated sludge process have been seen as the underlying origin of these problems.

Change from a diffused to surface aeration system in 1987 to 1990 conferred greater stability on the biological process but did not prove adequate to produce enhanced phosphorus removal to the extent that the special phosphate standard (1 mg P/ℓ as dissolved orthophosphate) could be met. This paper examines the benefits at full scale of simultaneous precipitation using aluminium sulphate (alum) dosed into either the anaerobic zone or return activated sludge. Apart from producing consistent phosphorus removal to below 1 mg P/ℓ as dissolved orthophosphate, alum dosing at 150 mg/ℓ (relative to raw influent) has given significantly improved sludge settleability. COD and colour removal have not improved significantly (contrary to laboratory-scale tests), although the effect of sludge age in this respect was not investigated. Increased alum dosing (200 mg/ℓ) failed to produce statistically lower effluent COD or colour in a full-scale trial. This study highlighted the need for a more reliable sludge wasting/dewatering practice in order to improve control of sludge age. Theoretical predictions of sludge production were compared to Works data.

The unbiodegradable particulate fraction of the influent COD proved to be a critical unknown especially in view of the likely contribution of textile and chicken abattoir waste from local industries. Limited full-scale data suggest that the increase in sludge production due to alum is less than the 30% projected from laboratory trials.

Introduction

Chemical dosing as a means of supplementing activated sludge processes has become common practice in waste-water treatment. Yeoman et al. (1988) reviewed this practice for a number of plants in Europe, Canada and the United States of America, reporting that alum and iron salts are most widely used, with phosphorus removal being the prime motivation for adding chemicals. Metsch et al. (1985) compared pre- and simultaneous coagulation/precipitation effects at 2 different full-scale facilities and found that with both processes a total phosphorus effluent concentration of 1 mg P/ℓ can be expected, but that simultaneous precipitation gave a small saving in coagulant dosage. Both methods enhanced the removal of COD and BOD, with simultaneous precipitation giving improved stability to the activated sludge process (viz. improved phase separation in secondary clarifiers resulting in a lower effluent suspended solids content and a lower sludge volume index). On the other hand, pre-precipitation can give additional removal of suspended solids and COD in primary clarifiers, with resultant savings in plant operating or capital costs (along with the potential for increased biogas production by anaerobic digestion) and can be used to relieve oxygen demand at seasonally overloaded plants (Metsch et al., 1985).

The introduction of a special phosphate standard (< 1 mg P/ℓ dissolved orthophosphate) in certain catchments in South Africa, resulted in major municipalities such as Johannesburg adopting simultaneous precipitation in modified activated sludge processes as a means of supplementing biological phosphorus removal (Lötter, 1991). In the Umgeni Water area, the Umlaas River catchment upstream of Shongweni Dam is subject to the special phosphate standard. Hammarsdale Waste-water Works is situated in this catchment and based on hydrological data for 1976, during the dry season (winter) may contribute up to 12 to 19% of the flow into Shongweni Dam (Archibald and Warwick, 1980). Hammarsdale Works was designed as a 5-stage modified Bardenpho plant for biological nutrient removal but final effluent soluble reactive phosphate (SRP) concentrations averaged ca. 5 mg P/ℓ prior to alum dosing (Healey et al., 1989).

It is beyond the scope of this paper to consider possible reasons for the inability of this plant to meet the 1 mg P/ℓ standard by biological means alone. However, the nature of the influent waste water (over 90% of industrial origin with textile and poultry abattoir wastes as the major constituents) and the size of the anaerobic zone are probably of critical importance (Wentzel et al., 1991).

A permanent alum dosing system at Hammarsdale Works was commissioned in October 1989, with full-scale trials having been carried out in the period March 1988 to September 1989. Laboratory-scale experiments (Healey, 1987; Healey et al., 1989) had indicated that simultaneous precipitation with alum has the potential to give not only improved phosphate removal but also improved colour and COD removal, and possibly improved sludge settleability as well. Using fully aerobic bench-scale fill-and-draw reactors operated at a 4-d sludge age, Healey (1987) reported optimal colour and COD removal at alum dosages of 150 to 200 mg/ℓ. Good phosphate removal was recorded at these dosages (effluent SRP ranging 0,4 to 0,8 mg P/ℓ). Colour was reduced to 28 to 37°H (86°H in control reactor receiving no alum). (H denotes Hazen, where 1°H = 1 mg Pt/ℓ as defined by *Standard Methods,* 1985).

COD was reduced to 60 to 101 mg/ℓ (124 mg/ℓ in control reactor). Healey et al. (1989) also reported that residual alkalinity in the secondary effluent was sufficiently high (ca. 100 mg/ℓ as $CaCO_3$) not to warrant lime addition. Nevertheless, precautionary measures were taken including continuous pH monitoring and provision of a dry lime feeder at the head of works.

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*To whom all correspondence should be addressed.

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TABLE 1
WASTE-WATER CHARACTERISTICS FOR HAMMARSDALE WORKS. DATA FOR PERIOD JANUARY 1990 TO JUNE 1991. VALUES ARE AVERAGES IN mg/ℓ UNLESS OTHERWISE STATED, WITH 5TH PERCENTILE AND 95TH PERCENTILE VALUES RESPECTIVELY IN PARENTHESES

	Influent	**Effluent**
COD (as O_2)	1 263 (405; 2 153)	103 (72; 146)
BOD_5 (as O_2)	421 (27; 1 258)	5,8 (<1; 11,8)
TKN (as N)	44,9 (11,9; 120,7)	N.D.
TP (as P)	7,91 (1,71; 13,51)	0,96 (0,33; 2,55)
SRP (as P)	5,57 (0,85; 11,86)	0,67 (0,18; 2,44)
$NO_3^- + NO_2^-$(as N)	0,1 (0,0; 0,6)	0,5 (0,0; 1,3)
NH_3 (as N)	13,6 (3,3; 40,3)	3,7 (1,2; 10,0)
SS	300 (76; 646)	10,0 (2,0; 23,0)
Colour (°H)	356 (73; 806)	69 (50; 89)

N.D. - Not determined

Healey (1987) reported a 4 to 5% increase in mixed liquor suspended solids (MLSS) concentration due to alum dosing (at 150 to 200 mg/ℓ dosages) in the 4-d sludge age trials and estimated that the increase would be ca. 30% at a 30-d sludge age. Although Healey (1987) was unable to confirm these estimates in full-scale trials, increases in sludge production (by mass) of between 21% and 36% have been reported elsewhere for aluminium and iron salts (Schmidtke, 1985; Veldkamp, 1985).

In practice, alum was initially dosed at Hammarsdale Works at lower dosages (ca. 100 to 130 mg/ℓ) than the 150 to 200 mg/ℓ optimum found by Healey (1987). However, since June 1990, a target dosage rate of 150 mg/ℓ was applied at the anaerobic zones of 5 reactors, while the sixth reactor received a target dose of 200 mg/ℓ at the anaerobic zone in the period February to June 1991.

Comparisons in respect of the performance of the 6 reactors were rendered difficult prior to February 1991 since 4 were consecutively taken off-line for retrofitting of surface aerators. Hence, the period 21 February to 20 June 1991 offered the first meaningful opportunity for monitoring the effects of alum dosing at full scale. This paper presents the results of that monitoring period, and highlights differences between the laboratory and full-scale trials, especially in respect of sludge age and MLSS concentrations.

General process description

Hammarsdale Works was designed as a 5-stage modified Bardenpho plant with extended aeration (no primary clarification). The original design capacity was 27 Mℓ/d at an average influent COD of 750 mg/ℓ (6 identical Orbal reactors each of 4,5 Mℓ/d design capacity). However, the original diffused air system has been replaced by surface aeration. Despite a 25% increase in theoretical aeration capacity brought about by this, the high strength of the raw waste water (Table 1) has resulted in an actual treatment capacity of around 17 to 20 Mℓ/d (see **Results and Discussion**). The influent waste water is largely of industrial origin (see **Introduction**) but the COD fractions (Ekama et al., 1984) have not been accurately characterised. Apart from standard coarse screens, hydrosieve screens with 0,75 mm openings are used to improve removal of fibres, feathers and fatty deposits before biological treatment. No equalisation basin exists at the Works and raw sewage is delivered to the hydrosieve screens by a maximum of 3 lift pumps (18 Mℓ/d capacity each) at the head-of-works.

The total process volume is 32,64 Mℓ (equally divided into 6 reactors). The anaerobic mass fraction is 5,3%, while the primary and secondary anoxic mass fractions are 17,2 and 15,2% respectively. The total sludge age was designed to be 25 d (see **Results and Discussion**). The sludge recycle rate for each reactor is approximately 300 m^3/h (ratio approximately 4,5:1 relative to actual present raw inflow or 1,6:1 on design inflow). The mixed liquor recycle rate is approximately 1 030 m^3/h (5,5:1 on design inflow) but these pumps are presently not operated to save power. Denitrification is not impaired (Table 1) and the anoxic zones are stirred by submersible mixers at a mixing energy density of around 4 W/m^3 instead of the 10 W/m^3 recommended in the original design. Sludge settleability has always been poor at this plant. Primary chemical treatment of the Hammarsdale waste water (as opposed to simultaneous chemical precipitation in the activated sludge process, as described in this paper) had to be abandoned in the sixties due to poor sludge dewaterability and high chemical costs.

The biological sludge has always had a tendency to bulk with a predominance of filamentous micro-organisms observed microscopically. The normal SVI test fails since little or no settling occurs in a 1 ℓ measuring cylinder in 30 min. Dilute SVI (DSVI) results averaged 140 to 656 mℓ/g in the summer of 1987 and 160 to 1 710 mℓ/g in the winter of 1987 prior to the introduction of alum dosing but currently average ca. 140 mℓ/g throughout the year. The improved settleability due to alum has lowered average sludge blanket levels in the clarifiers and improved dewatering on the sludge drying beds, with a 43% decrease in capillary suction time having been recorded by Healey et al. (1989).

Tertiary treatment is in the form of a concrete maturation river with a retention time of 81 h at a flow rate of 12 Mℓ/d. The final leg of the maturation river has a chlorine contact chamber for disinfection.

Materials and methods

Data were retrieved from the Umgeni Water LIMS (Laboratory Information Management System) in the case of Head Office results and from the Hammarsdale Works Manager in the case of data from the Works Laboratory. The respective methods used by the two laboratories are given below. As a rule, weekday analyses are performed at Hammarsdale and weekly analyses at Head Office as an audit.

Soluble reactive phosphate (SRP)

Both Head Office and Hammarsdale Laboratories used the ammonium molybdate - ascorbic acid spectrophotometric method read at 880 nm. Whereas Head Offices used the automated method (No 424G, *Standard Methods*, 1985), Hammarsdale used the manual method No 424F, *Standard Methods*, 1985).

Ammonia

Head Office used the automated phenate method (No 417G, *Standard Methods*, 1985) without prior distillation, while Hammarsdale used distillation followed by the titrimetric method (Nos 417A and 417D, *Standard Methods*, 1985). The sample volume used in the latter was 250 mℓ.

Chemical oxygen demand (COD)

Head Office and Hammarsdale used the open reflux method, with the differences that Head Office used a microwave heating procedure (Slatter and Alborough, 1990) followed by automated potentiometric titration, whereas Hammarsdale used the conventional titrimetric method (508A, *Standard Methods*, 1985).

Colour

Both Head Office and Hammarsdale used a single wavelength spectrophotometric method (at 400 nm) based on potassium chloroplatinate standards (204A, *Standard Methods*, 1985) where 1°Hazen (°H) is equivalent 1 mg Pt/ℓ of the chloroplatinate ion.

Whereas Head Office used 2-point calibration at 5 and 10°H, Hammarsdale Laboratory calibrated the method over 5 points up to 130°H.

Dilute sludge volume index (DSVI)

This measurement was only carried out at Hammarsdale using 200 mℓ mixed liquor diluted to 1 000 mℓ in a 1 000 mℓ measuring cylinder. The sludge settled volume obtained after 30 min was related to suspended solids to obtain DSVI as for SVI (231C, *Standard Methods*, 1985).

Mixed liquor suspended solids (MLSS)

This measurement was only performed at Hammarsdale using a 50mℓ mixed liquor sample as per Method 209C (*Standard Methods*, 1985).

Apart from the above analyses, the following measurements taken at Hammarsdale Works are of importance here:

Raw sewage inflow and alum dosage rates

The flow rate is measured in a suitably constructed channel with a flume using an ultrasonic flow meter.

The sewage flows into a sump after flow measurement and is fed to the activated sludge reactors via a maximum of 3 lift pumps (each with a capacity of 18 Mℓ/d). The alum dosage rate is controlled via 3-speed positive displacement dosing pumps (one per activated sludge reactor), so that the speed is automatically set by the number of lift pumps in operation. The Works operator checks the flow rate each day by volume displacement from measuring cylinders which can be brought on-line. Small adjustments to the stroke length can be made to achieve the target dose rate. The average alum dosage rate is calculated daily from cumulative inflow and alum usage readings (the latter taken off calibrations on the sides of the alum storage tanks). The target alum dosage rates during the period February to June 1991 were: 200 mg/ℓ for Reactor 1 and 150 mg/ℓ for Reactors 2 through to 6 (dosage rates for aluminium sulphate, $Al_2(SO_4)_3.14\ H_2O$, relative to raw sewage).

This gives a target of 158 mg/ℓ for the 6 reactors overall. During July and August 1991, the target alum dose was 150 mg/ℓ for all 6 reactors. Alum is supplied by bulk road tanker as a 46% (m/m) solution of specific gravity 1,31 (± 0,02) kg/ℓ.

Sludge age

At present, thickened sludge (clarifier underflow) or mixed liquor is wasted by diverting a portion of the underflow recycle to a waste sludge sump. A separate pump coupled to level sensors in the sump transfers the sludge to a centrifuge or drying beds for dewatering. The total volume of sludge wasted is recorded daily from flow-meter readings on the sludge wasting line.

Comparatively little data were available on the solids content of the clarifier underflow. Regular monitoring of this variable has since been adopted, but for the purpose of sludge age calculations here, the degree of mixed liquor thickening in the clarifier had to be estimated.

Theoretically, assuming that no solids carry over into the secondary effluent, the degree of thickening cannot exceed 22% on average at present. This is based on 1,67 Mℓ/d average flow per reactor (10 Mℓ/d total for 6 reactors) and an underflow recycle rate of 300 m^3/h per reactor (recycle pump ratings). However, slightly higher (or lower) degrees of thickening may occur in practice since the inflow to the reactors is intermittent at a rate of 18 or 36 Mℓ/d depending on the number of lift pumps operating (3 lift pumps operating simultaneously is a very rare occurrence). During a trial in October 1990, the degree of thickening found from underflow and mixed liquor suspended solids measurements ranged from 2 to 52%, with the average of 32 positive observations being 25%. Of a total of 47 observations, 13 were negative (-0,44 to 22,87%), suggesting that at times the underflow recycle pumps may draw significant volumes of clarified liquid. Accordingly, sludge age was estimated here for 3 degrees of thickening, viz. none, 20% and 60%. The latter may be possible with an additional thickening step (unpublished data), and degrees between 20 and 60% may be possible in the clarifier with reduced underflow recycle ratios, depending on sludge settling characteristics.

Results and discussion

Flows and alum dosage rate

Figure 1 shows the actual inflow rate to the Works during the first 8 months of 1991. The weekly cycle of flows with minima

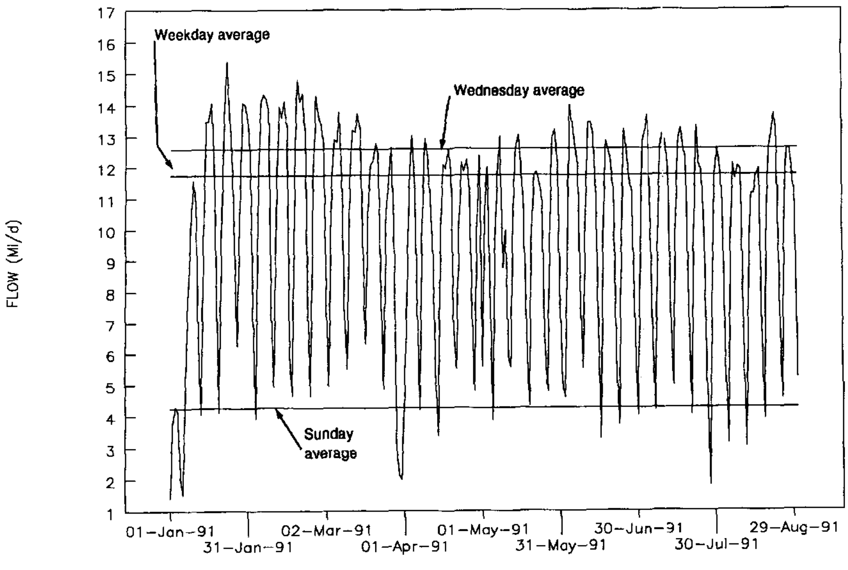


Figure 1
Record of inflow rate to Hammarsdale works in the period January to August 1991

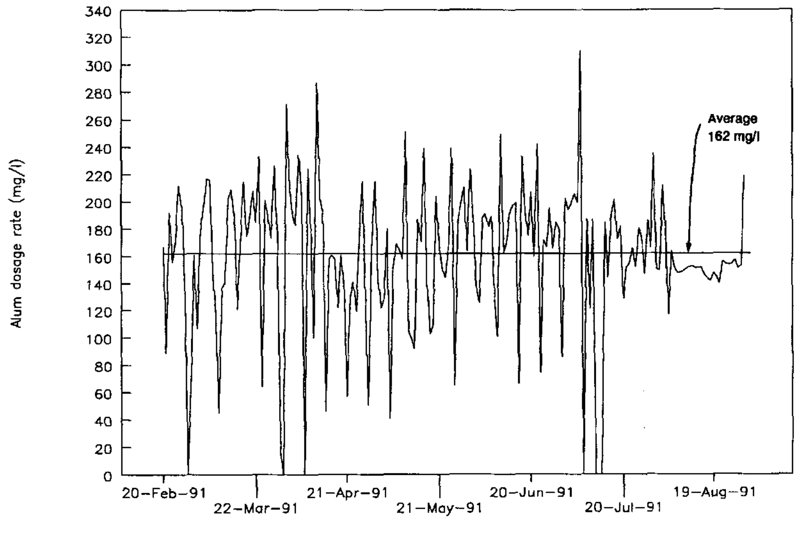


Figure 2
Record of alum dose rate at Hammarsdale Works based on actual consumption and inflow rate in the period 20 February 1991 to 31 August 1991

on Sundays, maxima in midweek and reduced flows over public holidays is typical of this Works with its large industrial effluent contribution. The 7-d average flow for the 8-month period was 9,85 Mℓ/d, while the workday average was 11,74 Mℓ/d. Little change in flows was noted over the 8-month period and similar observations have been made since 1986 (Twinch, 1991).

Figure 2 shows the actual daily alum dosage rate for the period of this study. It is evident that wide fluctuations were recorded. One reason for the periodic low dosage rates has been the operational practice of switching off the dosing system on Sundays (due to low inflow rates). Another reason for scatter in the observed daily dosage rate may be the potential error of ca. 10% which can be made in recording the volume of alum used off the sides of 20 m^3 tanks when daily consumption is around 2,6 m^3. Nevertheless, the actual average observed for the period of this study was 162 mg/ℓ (Fig. 2), which is very close to the target of 158 mg/ℓ (see **Materials and Methods**).

Secondary effluent quality

Figure 3 gives a comparison of the 6 secondary effluents during the study period using notched box-and-whisker plots.

Each box has as its top and bottom boundaries the upper and lower quartiles respectively. The width of the box is proportional to the number of observations. The notches of the box mark the 95% confidence of interval of the mean and the horizontal line in the notch is the mean. The whiskers extend to the limits of the range, while outliers are marked as points beyond the whiskers. Figure 3 shows that, on average, Reactor 1 (R1), which received 200 mg/ℓ, performed only slightly better with respect to COD and colour removal. In fact, the mean secondary effluent COD for R1 was not statistically different from that for the other reactors since the 95% confidence intervals of the means overlap.

R1 performed slightly worse than the other 5 reactors with respect to phosphate removal (Fig. 3). R1, R2 and R3 showed more scatter in the SRP data than the other 3 reactors but no reason for this was readily apparent. Nevertheless all 6 were well below the 1 mg P/ℓ limit: the 75th percentile was below 0,2 mg P/ℓ for R4 to R6 and below 0,6 mg P/ℓ for all reactors. These data support the finding by Healey (1987) that alum dosages around 150 mg/ℓ are sufficient to meet the special phosphate standard and that little or no improvement in final effluent SRP will be

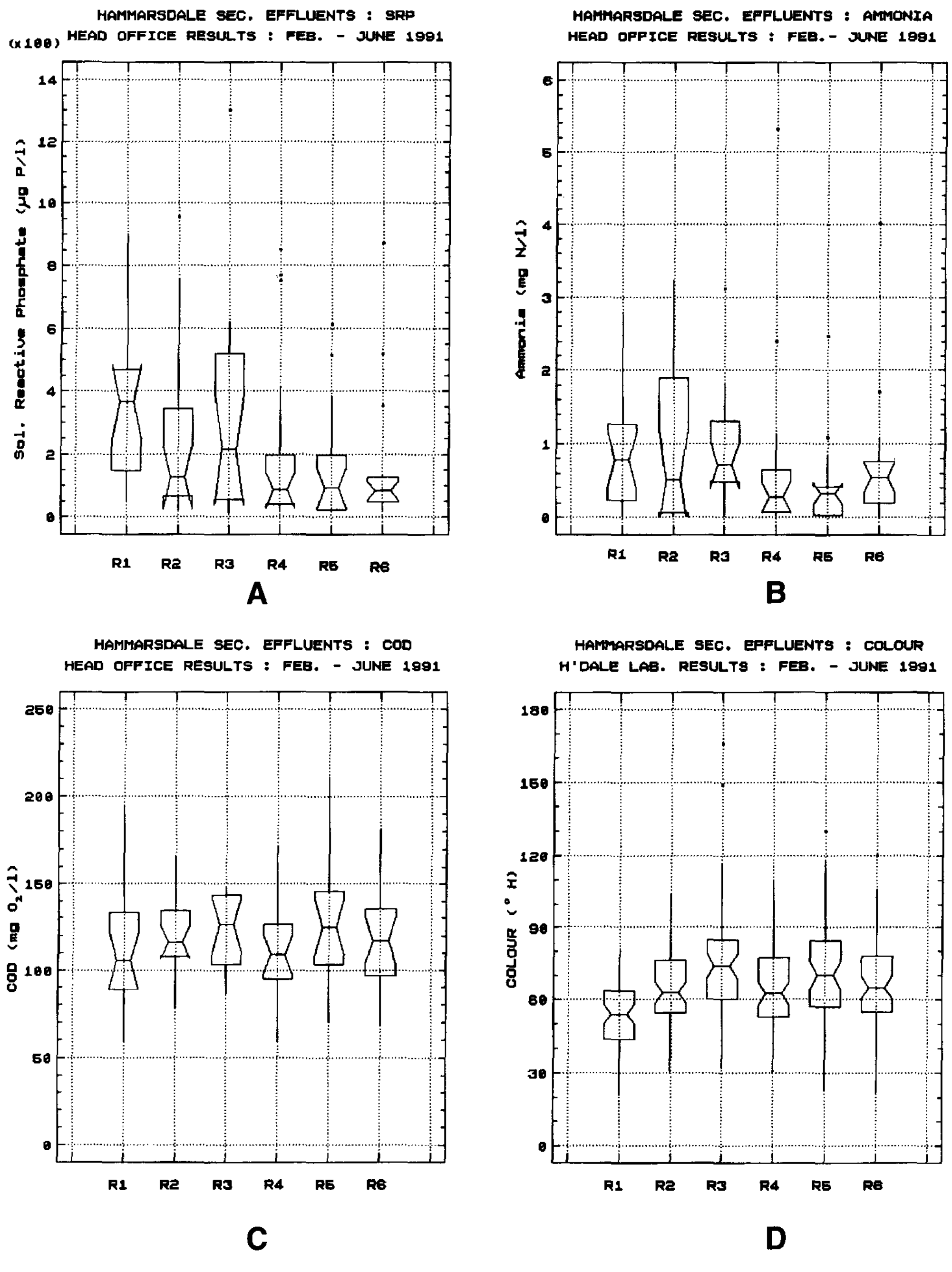


Figure 3

Notched box-and-whisker plots for secondary effluents at Hammarsdale Works in the period 20 February 1991 to 20 June 1991.
R1 to R6 denote Reactors 1 to 6 respectively.
A : Soluble reactive phosphate (n=65)
B : Ammonia (n=95)
C : COD (n=95)
D : Colour (n=60)
where n = Number of observations

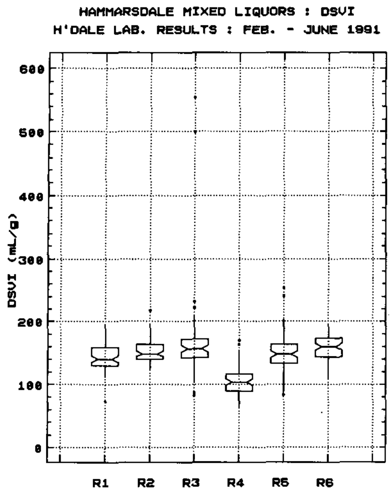
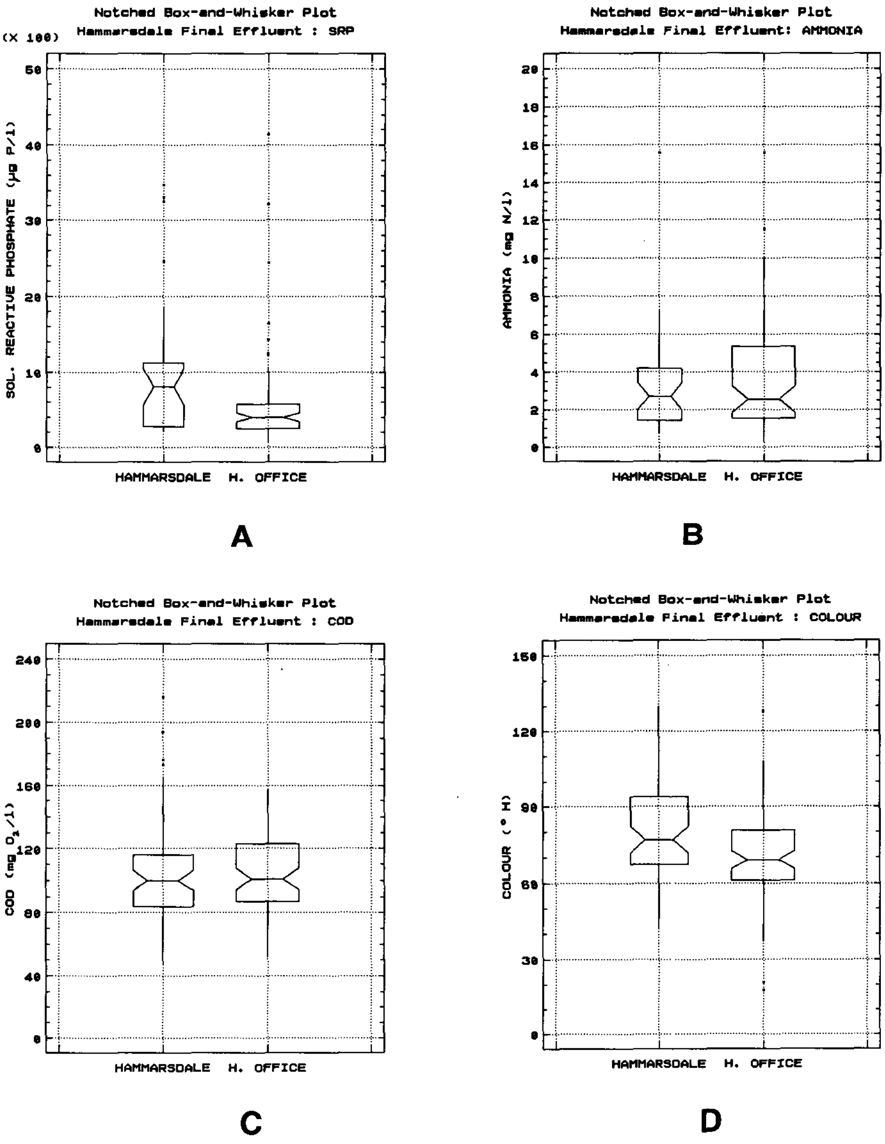


Figure 4
Notched box-and-whisker plots of mixed liquor DSVI for the six reactors (R1 to R6) at Hammarsdale in the period 20 February 1991 to 20 June 1991. Number of observations = 78



A

B

C

D

Figure 5
Notched box-and-whisker plots for final effluent from Hammarsdale Works in the period January 1990 to June 1991. n = Number of observations.

- *A : soluble reactive phosphate (n = 107)*
- *B : Ammonia (n = 115)*
- *C : COD (n = 144)*
- *D : Colour (n = 142)*

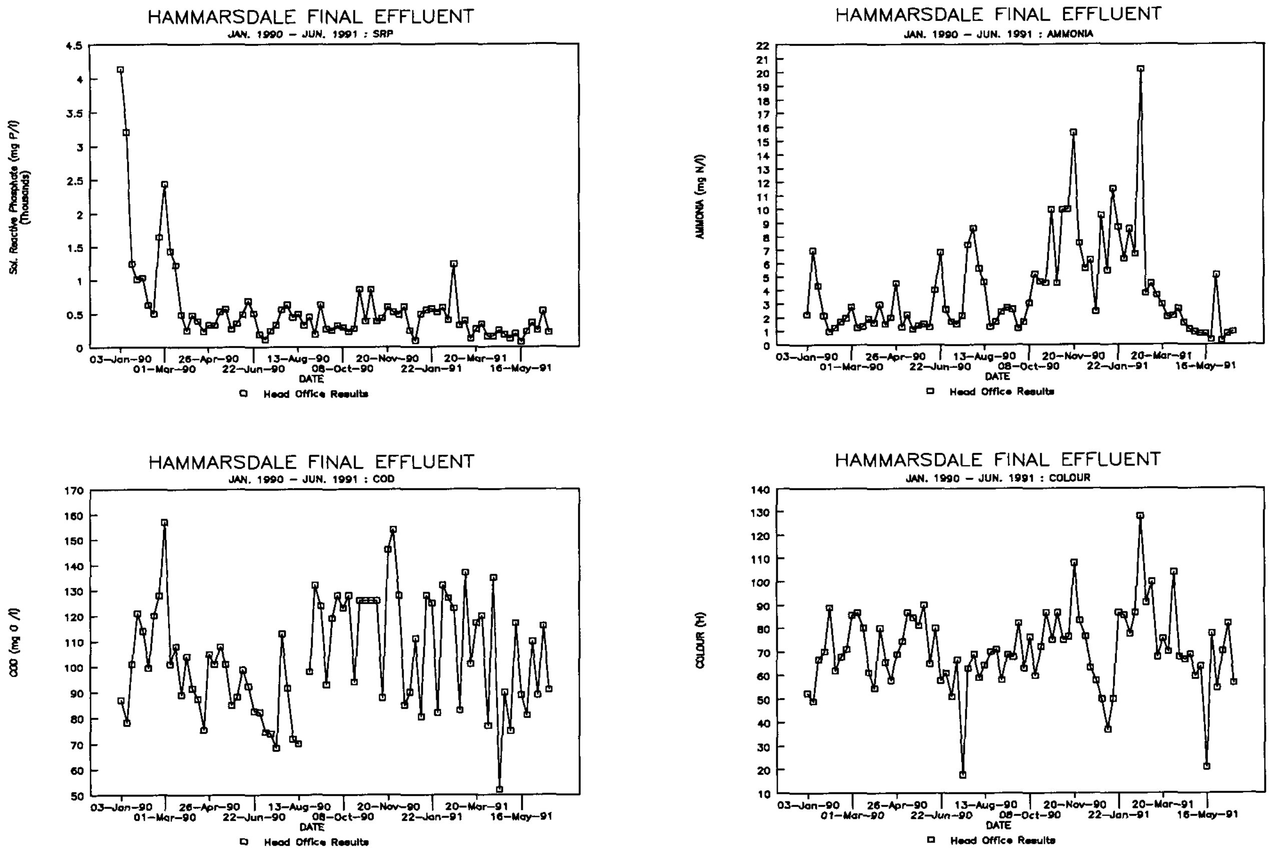


Figure 6
Record of final effluent quality at Hammarsdale Works in the period January 1990 to June 1991

observed at higher dosages.

R1 did not show statistically different secondary effluent ammonia concentrations (Fig. 3), although R4, R5 and R6 performed slightly better (as with phosphate). Again, no explanation is readily to hand for this observation since no obvious difference in aeration patterns could be found. These data suggest that alum at 200 mg/ℓ was not inhibitory toward nitrification at this Works.

Mixed Liquor DSVI

Figure 4 shows that little statistical difference in DSVI data for R1 relative to R2, R3, R5 and R6 could be found with R1 returning marginally lower readings. R4 was the notable exception, giving DSVI readings between 90 and 120 mg/ℓ, as opposed to 130 to 170 mg/ℓ for the other reactors. The reason for this difference is probably that alum was dosed into the return sludge line in R4, whereas it was dosed into the anaerobic zone in the other reactors. Improved mixing in the return sludge pumps may give maximum improvement in coagulation of suspended solids due to the alum.

Final effluent quality

Figure 5 shows that in the period January 1990 to June 1991, Hammarsdale final effluent complied with the 1 mg P/ℓ special phosphate standard with few exceptions, the 75th percentile being below 0,6 mg P/ℓ. The comparison between Head Office and Hammarsdale results is discussed below. Figure 6 shows the improvement in final effluent SRP since early 1990 when the permanent alum dosing system was in the process of being commissioned at a dosage rate of 100 mg/ℓ.

Similarly, Fig. 5 indicates that, for the same period, the final effluent complied with the 10 mg N/ℓ ammonia requirement (general standard) with very few exceptions. The 75th percentile was below 6 mg N/ℓ. Figure 6 shows that nitrification deteriorated in late 1990 to early 1991, probably due to under-aeration. Aerator timer settings were adjusted in late February 1991, and ammonia levels have since dropped.

From Fig. 5 it can also be seen that the final effluent COD usually ranged from ca. 85 mg/ℓ (25th percentile) to 125 mg/ℓ (75th percentile), indicating that alum treatment alone was insufficient to allow the 75 mg/ℓ COD limit (general standard) to be met under the operational conditions of the study period. Hence, the more optimistic predictions for COD removal from laboratory-scale work (see **Introduction**) have not materialised at full scale. It is possible that sludge age and MLSS concentrations are contributory factors in this regard. Another important factor may be that mixing intensity at the point of alum dosing (anaerobic zone) may be too low. At the time of

TABLE 2
COMPARISON OF HEAD OFFICE AND HAMMARSDALE LABORATORY RESULTS FOR FINAL AND SECONDARY EFFLUENT DETERMINANDS BY LINEAR REGRESSION. DATA FOR PERIOD JANUARY 1990 TO JUNE 1991. HEAD OFFICE RESULTS SERVED AS THE INDEPENDENT VARIABLE (x-axis) IN ALL CASES. RESULTS IN mg/ℓ UNLESS OTHERWISE STATED

Effluent	Determinand	n	R^2	X-coefficient	Intercept
Secondary	Ammonia (N)	95	0,2266	0,375	0,625
	SRP*	65	0,0002	-	-
	COD	95	0,0068	-	-
Final	Colour**	72	0,2354	0,560	41,1
	Ammonia (N)	47	0,7136	0,512	0,981
	SRP*	40	0,5257	0,856	323
	COD	74	0,2085	0,590	36,2

n : No. of observations
\- : Results ignored due to very weak correlation
* - Results in µg P/ℓ
** : Results in °H

TABLE 3
STANDARD DEVIATIONS OF DETERMINATIONS LISTED IN TABLE 1, ACCORDING TO HEAD OFFICE ANALYTICAL QUALITY CONTROL UP TO JUNE 1991

Determination	Standard concentration	Observed mean	Standard deviation
Colour	10,0°H	9,74	0,44
Ammonia	15,0 mg/ℓ	15,20	0,15
SRP	15,0 mg/ℓ	15,09	0,29
COD	400,0 mg/ℓ	387,5	13,5

TABLE 4
STANDARD DEVIATIONS OF DETERMINATIONS LISTED BY *STANDARD METHODS* (1985)

Determination and method	Method no.	Standard concentration	Standard deviation
Ammonia, Dist. + Titrimetry	417 A. and D	800 µg N/ℓ	28,6
		1 500 µg N/ℓ	21,6
Ammonia, Direct. Phenate	417 C	800 µg N/ℓ	15,8
		1 500 µg N/ℓ	26,0
SRP, Ascorbic acid	414 F. Manual	228 µg P/ℓ	3,0
	424 G. Autom.	340 µg P/ℓ	15,0
COD, Open reflux	508 A.	200 mg/ℓ	13

installation the large additional cost of installing flash mixers could not be justified. Hence the finding (see above) that the return sludge line appears to be a better point of dosing is significant. Figure 3C suggests that this modification may give an improvement in secondary effluent COD (compare R4 with others). Figure 6 shows little or no downward trend for COD in the period 1990/91.

Colour removal at full scale has also been disappointing. Figure 5 shows that the final effluent colour is generally 60 to 100°H, and occasionally as high as 130°H. Figure 6 shows that no long-term downward trend in colour was evident for 1990/91, the drop in colour during December resulting from closure of many dyehouses during the Christmas holidays. The general standard effectively requires the effluent to be free of colour. Since it is difficult to apply this standard in quantitative terms, a review of the general standard in respect of colour is urgently required. Even a standard of 70°H may not be sufficient to prevent the final effluent from appearing very opaque at a depth of one or more metres. From Umgeni Water records, the Darvill Sewage Works, which is an activated sludge process receiving largely domestic sewage from Pietermaritzburg, has a mean final effluent colour of 10°H (85th percentile 19°H). This effluent appears colourless in a 2 ℓ sample bottle whereas the Hammarsdale effluent has a light brown or pink hue in the same bottles. Clearly a review of the aesthetic quality of final effluents with respect to colour is needed.

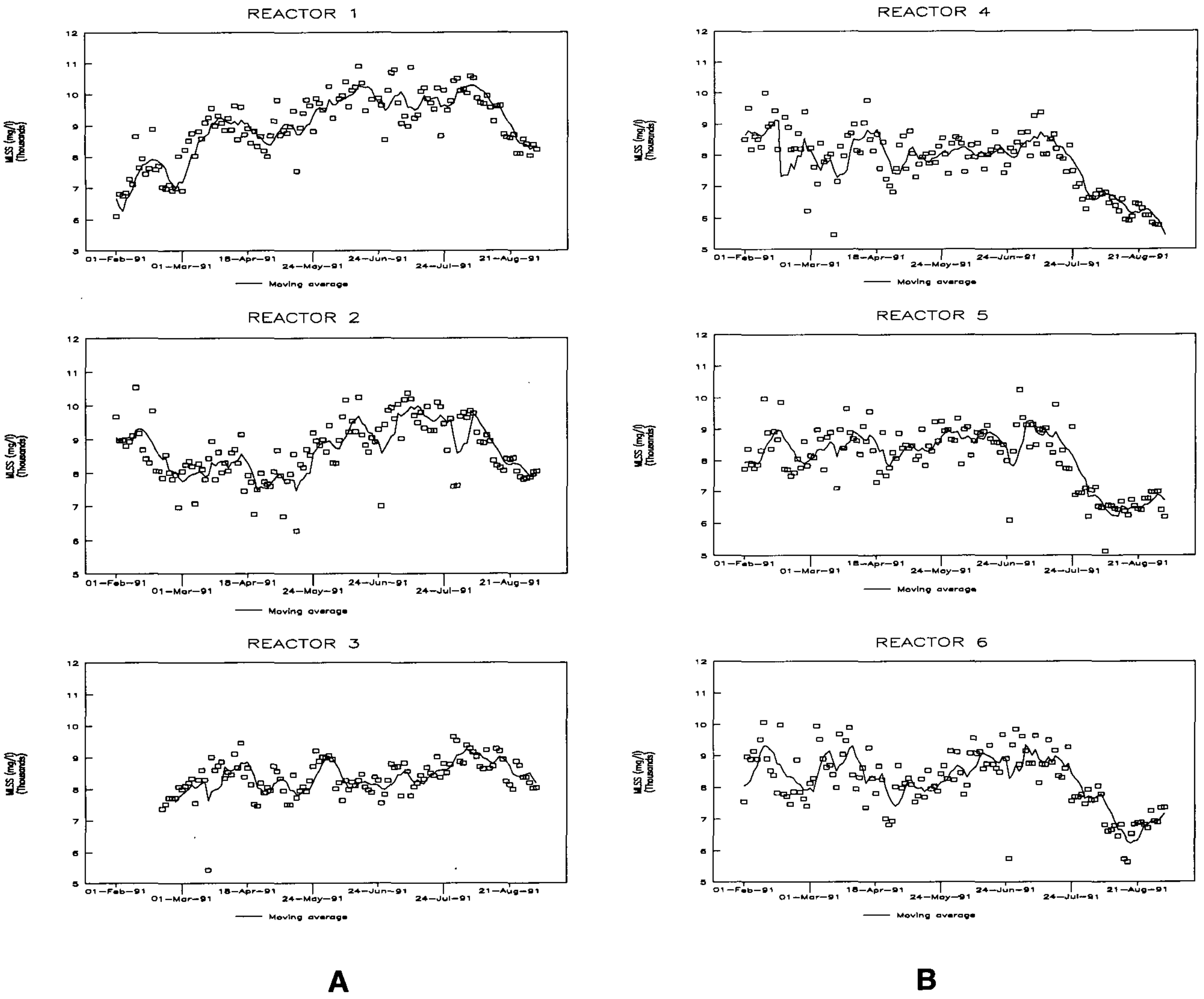


Figure 7
Record of mixed liquor suspended solids in Hammarsdale reactors in the period 20 February 1991 to 31 August 1991.
A 5-d moving average is indicated.
A : Reactors 1, 2 and 3
B : Reactors 4, 5 and 6

Comparison of Head Office and Hammarsdale Laboratory results

Figure 5 suggests that agreement between the results of the 2 laboratories was generally good, except for SRP and, to a lesser degree, colour. In the case of phosphate, increased attention has since been given to instrument calibration at Hammarsdale.

Head Office regularly undertakes quality control and inter-laboratory comparisons which have rendered satisfactory results. However, Head Office colour results were consistently lower than those of Hammarsdale. This is probably due to Head Office's calibration of the method at 5 and 10°H which is appropriate for clean water samples but not for coloured water/effluents. For coloured waste waters of varying hue, *Standard Methods* (1985) recommended the American Dye Manufacturers Institute (ADMI) Method as described by Allen et al. (1973). However, this method would require a dedicated scanning spectrophotometer. A preliminary investigation suggests that the absorbance measurement at 400 nm does correlate well with colour determined by the more elaborate ADMI method when applied to Hammarsdale final effluent (unpublished data), although the ADMI result is always higher when expressed in equivalent units (mg Pt/ℓ as chloroplatinate ion). This aspect is under further investigation.

Table 2 gives regression data comparing the 2 laboratories on the secondary and final effluent determinands considered in this study. This table suggests that for the sampling periods considered, correlation between the results of the 2 laboratories was generally weak. The best case was final effluent ammonia. The weak correlation for COD may be partly due to the standard

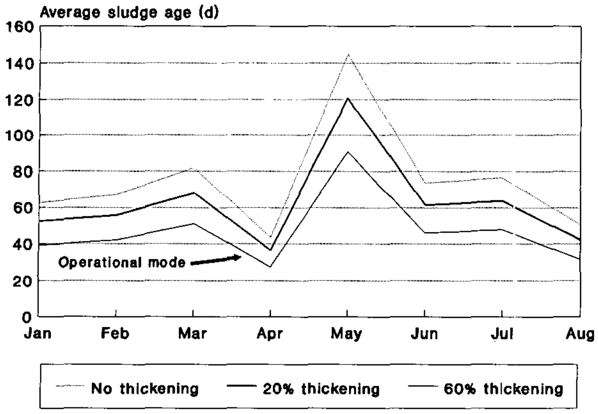


Fig. 8A: R1, R2, R3

A

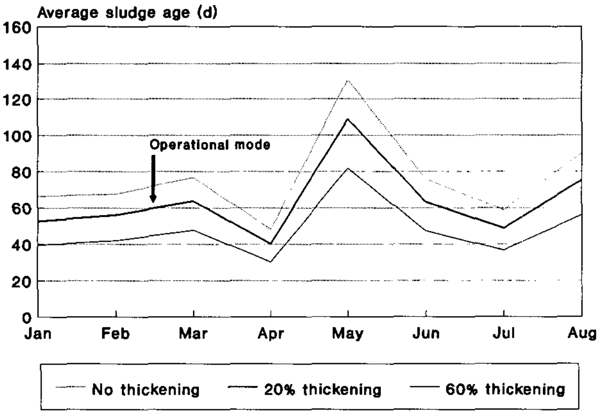


Fig. 8B: R4, R5, R6

B

Figure 8
Sludge age estimates for Hammarsdale Works (average of 6 reactors) in the period January to August 1991. Refer to text for details of thickening projections.
A : Reactors 1, 2 and 3
B : Reactors 4, 5 and 6

deviation of the method which is significant at concentrations of 80 to 120 mg/ℓ (Tables 2 and 3).

In general, improved correlation between Head Office and Hammarsdale results should be possible. In an attempt to achieve this, split sampling was introduced in June 1991.

Mixed liquor suspended solids and sludge age

Figures 7A and 7B show the MLSS concentration profiles for the 6 Hammarsdale reactors in the course of this study period. It is clear from these profiles that the observed MLSS concentrations vary significantly, which may be due to the limitations of grab sampling in the semi-circular aeration basin with only 2 of 4 surface aerators usually operating at a given time.

Examining trends, Figs. 8A and 8B suggest that MLSS concentrations averaged ca. 8 000 mg/ℓ in most cases, with a sideways trend in most cases but upwards in the case of R1, R2 and R6 from April to June. The high MLSS concentrations suggest long sludges and/or high influent organic loadings. Sludge wasting has had a history of problems at this Works, centering around difficulties with managing the sludge drying beds, of which only 15 out of the 21 originally designed were built. The centrifuge (intended for stand-by use particularly during periods of wet weather) has a high power demand, requires a polyelectrolyte dose of 4 to 7 kg/t dry solids (or R60 to R106/t dry solids) and produces a cake of approximately 7 to 10% dry solids as opposed to >20% dry solids without polyelectrolyte off the drying beds during fine weather.

Figures 8A and 8B show the average estimated sludge age for the Works in the first 8 months of 1991. As stated under **Materials and Methods**, it is likely that the degree of thickening in the clarifier averages ca. 20%. Unfortunately, during most of the period under consideration, clarifier underflow solids concentrations were not measured. During July thickened sludge was wasted from the clarifier underflow of Reactors 4, 5 and 6. The average degree of thickening achieved under close supervision during July (to avoid drawing supernatant) was 30%. This gave a reduction in sludge age to around 45 d (Fig. 8B) for July for these reactors. During August, attention was focused on wasting from Reactors 1, 2 and 3 in which the current civil construction makes wasting from clarifier underflow impossible. Hence, at the expense of an increase in sludge age in the other 3 reactors, that in Reactors 1, 2 and 3 was reduced to ca. 38 d (Figs. 8A and 8B). For the remainder of the year during which

TABLE 5
THEORETICAL SLUDGE PRODUCTION PER UNIT INFLUENT COD PER DAY AND STEADY-STATE MLSS CONCENTRATIONS AT TWO VALUES OF f_{up} AND FOUR SLUDGE AGES, WITHOUT ALUM DOSING AT HAMMARSDALE WORKS

f_{up}	R_s	$\frac{M(\Delta X_t)}{M(S_{ti})}$	X_{ti} (in mg/ℓ) at Q = 12 Mℓ/d	X_t(in mg/ℓ) at Q = 20 Mℓ/d
0,13	10	0,293	1 614	2 690
"	20	0,253	2 786	4 643
"	30	0,235	3 909	6 514
"	40	0,227	5 016	8 360
"	60	0,218	7 214	12 02 4
0,20	10	0,335	1 854	3 083
"	20	0,299	3 296	5 494
"	30	0,284	4 699	7 931
"	40	0,276	6 087	10 14 6
"	60	0,267	8 849	14 74 8

wasting of mixed liquor from Reactors 1, 2 and 3 and clarifier underflow from the other reactors was the dominant operational mode, the sludge age was generally in excess of 35 d (Figs. 8A and 8B). In theory it exceeded 80 d in May during which the centrifuge was hardly operated for management reasons.

The designers of Hammarsdale Works determined that at full load it should be operated at a sludge age of 25 d and a maximum of 5 000 mg/ℓ, on the basis of a sludge production of 0,65 kg solids per kg BOD applied (GF and J Inc., 1975). GF and J Inc. (1975) did not state whether the solids were measured as volatile or total suspended solids. However, the strength of the incoming sewage is now approximately twice that accepted by GF and J Inc. (1975) partly due to water-saving measures implemented by local industries during the drought years of 1981 to 1983. In particular, the COD is presently ca. 1 500 mg/ℓ whereas GF and J Inc. (1975) accepted 750 mg/ℓ. Moreover, the aeration capacity of the Works was uprated by 25% with the installation of surface aerators (Nozaic, 1988) and alum addition is expected to contribute additional sludge. It follows that a re-assessment of sludge production, sludge age and MLSS concentrations at this Works was necessary in order to streamline sludge wasting practices.

Prior to the introduction of alum dosing, biological excess phosphorus removal (BEPR) at Hammarsdale was limited. In 1987, for example, the influent total P averaged 9,5 (± 2,5) mg/ℓ while the effluent orthoP averaged 5 (± 1,2) mg/ℓ, giving a removal of 4 mg P/ℓ. The sludge had a low total P content of approximately 12 mg P/g VSS (very limited data).

Applying Eq. 7.6 of Ekama et al. (1984) (see **Appendix** **A** for assumptions), P-removal by incorporation in the sludge at a sludge age of 35 to 40 d is predicted to be 6,9 to 8,12 mg P/ℓ, with an excess phosphorus removal propensity factor (P_f) of about zero. This concurs with the observation by De Haas (1987, unpublished data) that the polyphosphate fraction of Hammarsdale sludge subjected to chemical fractionation (De Haas and Greben, 1991) was very small. It also concurs with the observation by Kerdachi (1987) that little or no phosphate release occurred when Hammarsdale mixed liquor was exposed to excess acetate in an anaerobic batch test. It is beyond the scope of this paper to detail the origins of the poor BEPR at Hammarsdale Works. Nevertheless, it appears that modelling sludge production at Hammarsdale as a non-BEPR system

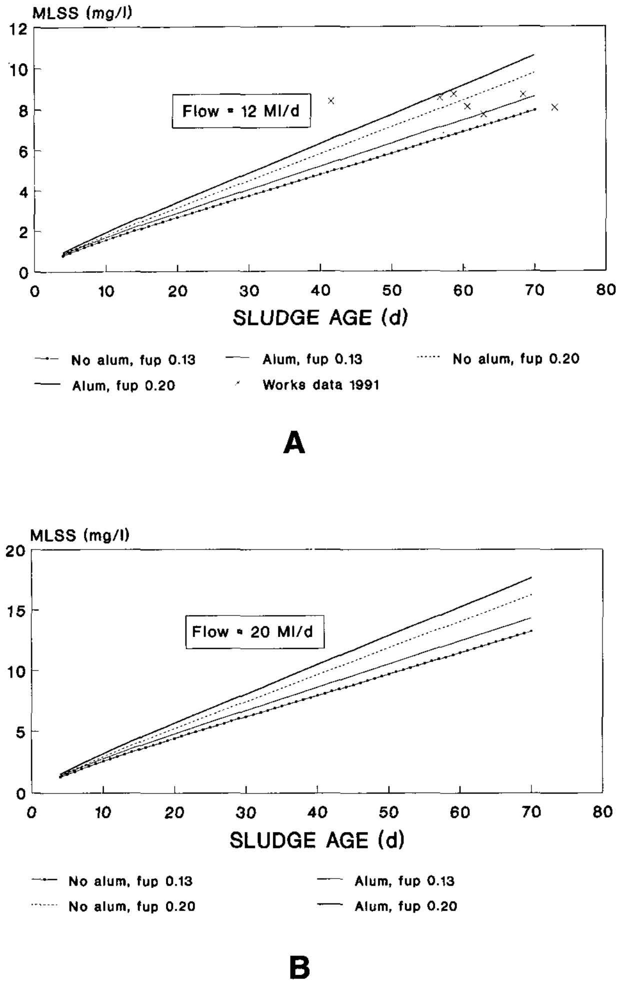


Figure 9
Theoretical and observed MLSS at Hammarsdale (average of 6 reactors). Works data for May neglected (see Figs. 7 and 8).
A: Flow = 12 Mℓ/d
B: Flow = 20 Mℓ/d

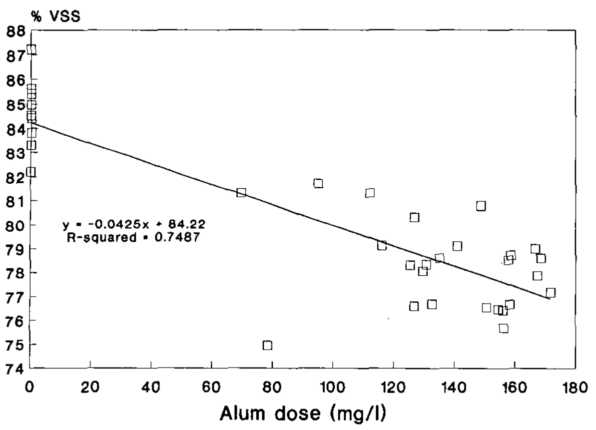


Figure 10
Effect of alum dose (based on influent flow) on %VSS observed at Hammarsdale Works for mixed liquors in the period October 1987 to January 1992

(Wentzel et al., 1990) is justified.

The steady-state activated sludge model of Ekama et al. (1984) was applied. The theoretical steady state MLSS in the system (X_t) was plotted as a function of sludge age along with the theoretical steady state MLSS in the presence of alum dosing at 162 mg/ℓ (X_{tal}). It was assumed that :-

$$X_{tal} = 1{,}089\ X_t$$

This assumption was based on VSS and alum dosing records from the Works in the period October 1987 to January 1992 (Fig. 10). These records suggested that in the absence of alum the VSS/MLSS ratio of the mixed liquor would be 0,84, while in the presence of alum dosed at 162 mg/ℓ the ratio would be 0,77. Assuming that alum does not contribute VSS, the increase in MLSS (or X_t) can thus be estimated at 8,9%.

The results are shown in Figs. 9A and 9B. Sludge production per unit influent COD load (without alum) is tabulated in Table 5. It should be clear from these data that small changes in $M(\Delta X_t)/M(S_{ti})$ with changing R_s or f_{up} give rise to significant changes in X_t. It is possible that f_{up} is higher than the 0,13 standard value for unsettled waste water (Ekama et al., 1984) due to the presence of high proportions of textile fibres and chicken feather fragments from industries in the catchment, and may be as high as 0,20. Comparing theoretical sludge production to the Works data for 1991 (Fig. 9A) suggests that the increased sludge production due to alum is not as high as 31% (Healey, 1987), on the assumption that f_{up} = 0,13. However, pilot-scale studies under controlled conditions would be needed to obtain more accurate operational data.

According to Nozaic (1988), the uprated surface aeration system at Hammarsdale has a maximum guaranteed oxygen transfer capacity of 203 kg/h per reactor and hence 1 218 kg/h (or 29 232 kg/d) for 6 reactors. This implies that, on a design basis, the Works has a maximum capacity of 20 Mℓ/d (average flow) at 1 500 COD/ℓ (present strength). However, the clarifiers are likely to become limiting before the aeration capacity does.

The clarifiers were designed by Geustyn et al. (1975) for an MLSS of 5 000 mg/ℓ at SVI ≤ 100 mℓ/g and a maximum flow of 27 Mℓ/d. From Table 5 (or Fig. 9B), assuming the worst case (f_{up} = 0,20, Q = 20 Mℓ/d and a 9% increase in sludge mass due to alum), the MLSS could approach 6 000 mg/ℓ to 8 650 mg/ℓ at a sludge age of 20 to 30 d, respectively. At present MLSS concentrations of 8 500 to 10 000 mg/ℓ (Figs. 7A and 7B), the clarifiers have given occasional carry-over of the sludge blanket when the daily average flow approached 15 Mℓ/d (unpublished data). It follows that there is a need to experimentally establish the capacity of the clarifiers. This could be done by disproportionately increasing the flow to one or more reactors.

To do this, close attention to sludge wasting will be necessary. It would be best to adjust the MLSS in the experimental and control reactors to approximately the theoretical concentration at the sludge age selected (e.g. 7 100 mg/ℓ for f_{up} = 0,13; Q = 20 Mℓ/d; R_s = 30 from Table 5). Once a new "steady-state" MLSS concentration has been achieved, the observed sludge fraction per unit influent COD (at the selected alum dosage rate) can be calculated using the observed 7-d or monthly average flow rate. However, for measuring clarifier performance, the weekday average or maximum flow rate will need to be related to sludge blanket levels and/or secondary effluent suspended solids (see above discussion of flow rate trends).

Theoretical calculations (**Appendix B**) from maximum solids loading, taking into account original design considerations (Geustyn et al., 1975) and practical sludge recycle limitations, suggest that the clarifiers will function with a maximum raw influent rate of 52 Mℓ/d at 6 511 mg/ℓ MLSS. On the basis of the same theory at the present MLSS concentration of ca. 8 500 mg/ℓ, the clarifiers would be expected to fail at more than 14 Mℓ/d inflow rate. The fact that the clarifiers have not failed at average daily flow rates of 12 Mℓ/d and MLSS concentrations as high as 10 000 mg/ℓ (Figs. 1 and 7A, B) implies that a more scientific model is needed to accurately predict clarifier performance. A more immediate indication of clarifier limitations can be obtained from the suggested trial in one reactor receiving disproportionately high inflows.

Finally, it should be noted that, theoretically, improved clarifier performance will be achieved at a sludge age of 25 d relative to 30 d or more, provided the DSVI remains constant (or improves). This follows from Figs. 9A and 9B or Table 5: a 15% reduction in MLSS, for example, at 25 d relative to 30 d will decrease solids loading on the clarifier by the same margin, but will require a 20% increase in mixed liquor wasted. Waste sludge thickening may provide the most cost-effective means of optimising treatment capacity.

Conclusions

- Simultaneous precipitation with alum at a dosage rate of 150 mg/ℓ has had a marked effect on phosphate removal at Hammarsdale Works, with the final effluent soluble reactive phosphate averaging 0,4 mg P/ℓ over an 18-month period. Inhibition of nitrification has not been observed up to 200 mg/ℓ alum. COD and colour removal as a result of alum dosing were not improved to the same extent at full scale as at laboratory scale. Uncertainty remains over the effect of mixed liquor solids on the coagulation properties of alum since the sludge age and MLSS concentrations observed at full-scale exceeded design targets.
- A full-scale trial over 4 months at average sludge ages of 35 to 65 d suggests that an increased alum dose of 200 mg/ℓ produces only a small improvement in colour and COD removal. However, it would be instructive to carry out a similar trial at lower sludge ages (20 to 30 d). The need to

closely monitor clarifier underflow solids concentration for accurate sludge age estimation was highlighted.

- Uncertainty surrounds the theoretical sludge production per unit influent load at this plant. This study has highlighted the need to experimentally determine the influent COD fractions, and especially the unbiodegradable particulate fraction (f_{up}). The contribution of alum to MLSS also needs to be more accurately determined.
- An increase in influent waste-water strength as well as the change from a diffused air to surface aeration system (with increased oxygen transfer capacity) has probably resulted in the clarifiers of the Hammarsdale system becoming limiting. Although sufficient aeration capacity may exist to treat a maximum of 20 Mℓ/d at present strength, clarifier performance must be tested at full scale under these conditions with close attention to sludge wasting. A safe operating limit for the clarifiers may be 17 Mℓ/d raw inflow, as opposed to 27 Mℓ/d in the original design.
- A comparison of analytical results from Works and Head Office laboratories for monitoring process performance has highlighted the need for the increased attention to instrument calibration as well as the need for sample splitting for audit purposes. Standard deviations of the methods should be taken into account when comparing results. Over the study period, the results of the 2 laboratories compare well for treated effluent COD and ammonia but closer attention to phosphate and colour determinations should be given.
- Future research should concentrate on:
  - Improved sludge wasting/dewatering techniques at full scale
  - Influent COD fraction characterisation
  - Improved techniques for colour removal (including pretreatment of dye waste concentrates)
  - Unbiodegradable effluent soluble COD characterisation and techniques for minimisation of major chemicals contributing to this fraction.

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Appendix A

List of symbols (refer to Ekama et al., 1984) and assumptions.

b_hT = endogenous mass loss rate for heterotrophic organisms at T°C (/d)
= 0,269/d at 24°C or 0,24/d at 20°C.
f = unbiodegradable fraction of active mass
= 0,20 mg VSS/mg VSS
f_{av} = active fraction of the sludge mass with respect to the volatile solids concentration
= 0,124 to 0,138 at R_s = 35 to 40 d; f_{up} = 0,20; and all other assumptions as per this Appendix.
f_{cv} = COD to VSS ratio of volatile sludge mass
= 1,48 mg COD/mg VSS
f_i = MLVSS to MLSS ratio of the mixed liquor
= 0,80 mg VSS/mg MLSS (0,69 mg VSS/mg MLSS with alum dosing)
f_p = phosphorus fraction of the inert MLVSS and endogenous MLVSS
= 0,012 mg P/mg VSS
f_{up} = unbiodegradable particulate COD fraction in the influent
= 0,13 to 0,20 (mg COD/mg COD) (see text).

f_{up} = unbiodegradable soluble COD fraction in the influent
= 0,08 (mg COD/mg COD) (see text).
M = prefix denoting mass of a variable
Q = 12 to 20 Mℓ/d (see text)
R_s = sludge age (d)
= 4 to 60 d (see text)
S_{ti} = influent total COD concentration
= 1 500 mg COD/ℓ
X_t = total sludge mass concentration in the absence of alum dosing
X_{tal} = total sludge mass concentration in the presence of alum dosing
Δ = prefix denoting change in parameter

Appendix B

Theoretical clarifier performance based on original design by Geustyn et al. (1975). Refer to Ekama et al. (1984) for theory.

Design criteria

$X_t = X_o$ = 5 000 mg/ℓ (MLSS in biological reactor)
Q_{max} = 54 Mℓ/d (maximum inflow rate)
S = 1 (Underflow recycle ratio)
Q_r = 27 Mℓ/d (Underflow recycle frow rate)

In practice the present recycle pumps having a rating (Q'_r) = 43,2 Mℓ/d in total for 6 pumps (1 per reactor) in continuous operation (300 m³/h each).

A by-pass for additional mixing of the anaerobic zone using the underflow recycle pump is not used since it has produced operational problems in the past.

$$\text{Hence, } M(X_o)_{max} = X_o(Q_{max} + Q'_r) \qquad \text{(Eq. 1)}$$
$$= 5\,000\,(54 + 43{,}2)$$
$$= 486\,000 \text{ kg/d}$$

Projections

At R_s = 30 d, f_{up} = 0,20, Q = 12 Mℓ/d
X_t = 4 699 mg/ℓ (Table 5)
and X_{tal} = 5 122 mg/ℓ = X_o

$$\text{From Eq. 1 } Q_{max} = \frac{M(X_o)_{max}}{X_o} - Q'_r$$
$$= \frac{486\,000}{5\,122} - 43{,}2$$
$$= 51{,}7 \text{ Mℓ/d}$$