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N. I. MARSHALL

OPTIMISATION AND EFFECTS OF COAGULANT TYPE, pH AND OZONATION ON CLARIFICATION FOR AUTOMATIC COAGULATION CONTROL

Supervised by: Dr SIMON PARSONS

Submitted 11th September 1998

This thesis is submitted in partial fulfilment of the requirements for the Degree of Master of Research

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ABSTRACT

Four phases of studies were carried out at Burham Water Supply Works in Kent. Firstly jar testing was used to compare and evaluate the performance of five coagulants. The coagulants tested were Polyaluminium Chlorides (PAC) from two suppliers, Aluminium Sulphate (Alum), Polyaluminium Silicate Sulphate (Pass 100) and Alba 18. Jar tests were carried out with coagulant alone and with non-ionic (LT20), weakly cationic (LT22s), and anionic (LT25) polymers. Secondly tests were also carried out at ambient and lower pH's, at various pre-ozone concentrations. Jar tests indicated PAC with LT20 polymer at a pre-ozone dose of 1.5 mg/l at pH 7.4 produced the highest water quality. Alum with LT20 was next, giving good and consistent settled water qualities. Pass 100 was circumspect and dependent upon the jar test procedure, but at optimum doses gave water qualities comparable to that of PAC. Alba 18 consistently produced poor settled water qualities.

For the third phase, PAC supplied by Industrial Alum Limited (INDA) and Water Treatment Solutions (WTS), Pass 100 and Alum were selected and tested on the clarifier. Alum and PAC (WTS) were tested at pH 7.5, pH 7.3 and ambient pH at pre-ozone concentrations 0.5, 1.0, 1.5 and 2.0 mg/l with various coagulant and polymer combinations. Pass 100 and PAC (INDA) were tested as describes but at a pre-ozone concentration of 1.5 mg/l. At optimum doses PAC (INDA) was found to perform best at a pre-ozone concentration of 1.5 mg/l at pH 7.5. PAC (WTS) was next, with similar results. Alum produced good and consistent water qualities. Pass 100 was affected by polymer addition and was out-performed by PAC and Alum coagulants.

The parameters taken into account were settled turbidity, residual aluminium, and removal of TOC, chlorophyll, phaeophytin, iron, manganese, and colour. If PAC with acid dosing can be shown to work full scale annually it would be economic to do so and to dose acid to achieve a pH of 7.5 when required.

Phase four involved the evaluation of an automatic coagulant control system that would automatically optimise the coagulant, acid and polyelectrolyte doses added to the water. This was evaluated using jar tests with PAC and Alum coagulants. The AC250 system indicated the potential to improve the quality of treated water whilst minimising the coagulant dose. In this case PAC would provide further coagulant savings, with consequent sludge savings.

ACKNOWLEDGEMENTS

Sincere thanks are due to Southern Water that enabled me to undertake this investigation. My thanks go to the Southern Water laboratory department for their invaluable contribution in handling and analysing vast numbers of sample bottles on a daily basis. In addition, I would like to express my gratitude for all the assistance I received from Mike and other operating staff at Burham.

Without Dr. Guy Standon and his excellent behind the scenes management in providing all the resources needed for both the practical work and write-up, this project would have not been possible. Thankyou for your generous assistance especially during intense and demanding periods.

Finally, many thanks go to Anthony Bracknell for his excellent management and tireless supervision of this project, whose advice, critical remarks and knowledge was of the highest value which contributed to the complete success of this project.

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LIST OF ABBREVIATIONS

Abbreviation	Description
Al^{3+}	The aqueous monomeric aluminium species $Al(OH)_3$
Al_{13}	The aqueous polymeric aluminium species $Al_{13}O_4(OH)_{24}^{7+}$
Alcan	Alcan Chemicals Europe Limited
Alum	Water treatment grade aluminium sulphate solution (8% Al_2O_3 by weight)
B.	Burham
DOC	Dissolved organic carbon
EM	Electrophoretic mobility
EOM	Extracellular organic matter
EPA	Environmental Protection Agency
Fe	Iron
GAC	Granular activated carbon
GF	Grid reference
H^0	Hazen (unit of colour measurement)
INDA	Industrial Alum Limited
IOM	Intracellular matter
LT20	Non-ionic polyelectrolyte
LT22s	High molecular weight weakly cationic polyelectrolyte
LT25	Anionic polyelectrolyte
M^{3+}	Aluminium or iron (III) metal ions
MGD	Million gallons per day
ml	Millilitres
MLD	Million litres per day

mg/l	Milligrams per litre
µg/l	Micrograms per litre
Mn	Manganese
M.V.	Mont Valerein
MRes	Master of Research
MW	Molecular weight
O_3	Ozone
nm	Nanometers
No.	Number of
NOM	Natural organic matter
NTU	Nephelometric turbidity units
PAC	Polyaluminium chloride
Pass 100	Polyaluminium silicate sulphate
PCV	Permissible Concentration or Value
Polymer	Polyelectrolyte
RGF	Rapid gravity filter
SCD	Streaming current detector
TOC	Total organic matter
WTS	Water Treatment Solutions Limited
WSW	Water supply works
W.W.	Weirwood
ZP	Zeta potential

EXECUTIVE SUMMARY

Burham water supply works (WSW) is a 73 million litres pre day (MLD) plant located six kilometres north of Maidstone, Kent, 400 meters south of Eccles Lake. Burham began operating in the early 1970's and currently operates at 50 MLD, supplying water to Gravesend and the Medway Towns.

Currently the works could be incurring higher operating costs than necessary, due to using non-optimal chemicals and excessive coagulant dosing by manual coagulant control that can be reduced by installing an automatic coagulation control system that would optimise the clarification process. Additionally, the most efficient pre-ozone dose required for the coagulation and removal of pesticides and metals is not known.

Currently Burham doses aluminium sulphate and polyaluminium chloride coagulants during summer (about May to November) and winter (November to May) respectively. Southern Water have funded this MRes project to identify the most effective coagulant at achieving the required duty annually at Burham. This involved the evaluation of acid dosing as a cost effective measure of reducing coagulant demand. Jar testing was used to select possible alternative coagulants and their performances at ranges of pH and pre-ozone concentrations. A pilot clarifier was operated to again evaluate the performances of the selected coagulants under these conditions.

The coagulants were Aluminium Sulphate (Alum), Polyaluminium Silicate Sulphate (Pass 100), Alba 18 and Polyaluminium Chloride (PAC) supplied by Water Treatment

Solutions Limited (WTS), and Industrial Alum Limited (INDA). Jar tests were carried out with coagulants alone and also with, non-ionic, weakly cationic, and anionic polymers. Tests were also carried out at ambient pH and pre-determined optimum pH, with artificially low pH values generated using sulphuric acid.

The coagulants selected from the jar tests for pilot plant trials were Aluminium Sulphate (Alum), Polyaluminium Silicate Sulphate (Pass 100), Alba 18 and Polyaluminium Chloride (PAC). Alum and PAC (WTS) were tested at pre-ozone concentrations of 0, 0.5, 1.0, 1.5 and 2.0 mg/l. Pass 100 and PAC (INDA) were tested at 1.5 mg/l, which, through the jar tests was the pre-determined optimum pre-ozone dose for coagulation. The testing regime for WTS PAC and Alum was divided into 3 phases. The first phase was with raw un-ozonated water, second with pre-ozonated water at 0.5, 1.0, 1.5 and 2.0 mg/l, and the third phase with acid dosing using pH 7.3 and 7.5. At each phase variations in polymer and coagulant dose were used.

Throughout the pilot clarifier trials the water samples were taken at nominal times of 8.00 and 14.00 During a sampling period water samples were taken at 30 minute intervals. The following determinants were analysed at the Southern Water Laboratories: Total organic carbon (TOC), dissolved orgainc carbon (DOC), colour, alkalinity, total hardness, total iron, total manganese, total aluminium, dissolved iron, dissolved manganese, dissolved aluminium, bromide, chlorophyll, phaeophytin, total algae, acid herbicides, urea herbicides and triazines.

Corresponding on-site measurements were taken every time water samples were taken from the pilot plant. The determinants were: turbidity, pH, temperature, and aluminium. Site determinants of aluminium were carried out using a Hach DR2010 portable spectrophotometer. Readings were ±30% of the laboratory results. Turbidity readings were ±10% of the laboratory readings.

Jar Test Results

Jar tests were carried out with Pass 100, Alum, Alba 18 and PAC (WTS & INDA) in parallel. Direct comparison of floc formation, settlement, and removal efficiencies were therefore possible at a given pre-ozone concentration.. In general, without polymer, the largest flocs of 2.25 mm (diameter), and highest removals were produced by Pass 100. PAC was next (1.5 mm) and then Alum (1.0 mm) Alba 18 consistently produced small flocs of 0.5 mm that did not settle, and was not considered for pilot plant trials as Burham has a sedimentation process.

The settling rates were in the same order as floc sizes, i.e. Pass 100 > PAC > Alum > Alba 18.

Settling rates, floc sizes and particle removals for PAC and Alum were increased by non-ionic LT20 polymer addition. Floc sizes for PAC were 2.25 mm and for Alum (1.5 mm). All flocs were able to settle within the 30 minute settlement period, although a large proportion of the total flocs formed settled within the first 15 minutes.

The settling and removal rates were as follows: PAC > Alum > Pass100 > Alba 18.

The addition of acid had no effect on floc sizes but increased settling and removal rates. PAC and Pass 100 flocs all settled within the first 15 minutes. A large proportion of Alum flocs settled within 15 minutes. Optimum doses with Pass 100, PAC and optimally increased removals.

The settled aluminium concentrations from the jar tests from all the coagulants showed the characteristic 'u' shape, with a minimum residual giving an indication of the optimum dose (with respect to aluminium residual). Pass 100 showed the most clearly defined optimum, with residuals increasing relatively quickly before and after the optimum coagulant dose. No significant difference in turbidity removals and aluminium residuals were observed between WTS and INDA PAC, and PAC gave good turbidity removals at and away from the optimum dose. Alum was next, and produced good removals at an optimum dose. Highest turbidity removals at a given coagulant, polymer and acid dose were produced at a pre-ozone concentration of 1.5 mg/l.

The tests with polymers showed that for Alum and PAC, the most effective flocculating aid was non-ionic LT20. LT25 anionic polymer showed to be the least effective flocculating aid, and gave the lowest removal rates throughout the coagulant/polymer combinations.

Pilot Trial Results

The literature on the effect of ozonation on coagulant performance indicates that ozone may in some cases improve coagulation by increasing natural organic matter removals (NOM) (measured by TOC and turbidity), or make it worse by decreasing NOM removals. The effect id dependant upon raw water characteristics, and coagulant type. The addition of pre-ozone on all coagulants pilot tested at Burham, enhanced and improved NOM removals at an economical optimum pre-ozone dose of 1.5 mg/l.

The following conclusions were drawn from the pilot trials:

1. When operating with pre-ozonated water, Alum and PAC produced scum but Pass 100 did not. The addition of pre-ozone at an optimum of 1.5 mg/l increased TOC and turbidity removals for PAC and Alum by 19% and 15% respectively.
2. The addition of LT20 polymer enhanced the removal of turbidity, TOC and metal removals.
3. An increase in TOC and turbidity removals directly resulted from a decrease in pH. Highest removals were observed at pH 7.5 for PAC, Pass100 and pH 7.3 for Alum.
4. pH is not significant in algal removal. The addition of pre-ozone at 1.5 mg/l greatly enhanced algal removals for all coagulants tested. With a combination of pre-ozone and clarification PAC (INDA) produced the highest removals.
5. Metal removal was not significantly effected by pH. The addition of pre-ozone at 1.5 mg/l improved iron removals by 59 % and 24 % and manganese removal by 49 % and 18 % for PAC and Alum respectively. This implied that manganese and iron are more amenable to removal by PAC than Alum.

6. The addition of pre-ozone produced lower aluminium residuals to an optimum pre-ozone dose of 1.5 mg/l for all coagulants.
7. Increasing the pre-ozone dose directly increased pesticide removal. Above a pre-ozone concentration of 1.5 mg/l the improvement in pesticide removal was very slight and uneconomic. For economic reasons a pre-ozone concentration of 1.5 mg/l was taken as optimum.
8. With pre-ozone (1.5 mg/l), PAC (INDA) performed best at optimum dose and pH with polymer, than Alum WTS PAC or Pass 100, when taking into account turbidity, residual aluminium, and removals in TOC, chlorophyll, phaeophytin, total iron, total manganese and colour.

The improved performance of Alum on the pilot clarifier could have been due to the high concentrations of algae present a the period of testing for Alum on the pilot The EOM secreted by the algae could have acted as a flocculating aid enhancing NOM removals by sorption coagulation mechanisms.

Comparison of Jar Test Results and Pilot Trial Results

Comparison of corresponding results from jar and pilot plant tests showed the turbidity removal results to be on average ±10%. The Hach spectrophotometer produced very different values in measuring aluminium concentrations than by the laboratory.

Improved actual performance with under-dosed coagulant could have been caused by the presence of the floc blanket. This enhances sorption coagulation mechanism by greatly

enhancing the chance of collisions between flocs and material still in suspension. This mechanism is not promoted by a simple jar test.

AC250 Evaluation.

The coagulant doses predicted by the AC250 were comparable with routine laboratory jar tests measurements performed during the trial period, except during periods of high pH, temperature and algae counts. The performance of the AC250 during this period illustrated the requirement for the 'Trim' factor present in more advanced systems (AC500 and AC1000 Aztec systems), which compensates for these factors.

These results imply that automatic coagulation control by an AC500 or AC1000 system has the potential to reduce the excessive coagulant dosing that currently occurs with manual coagulation control at Burham WSW.

Economic Conclusions

Based on the jar testing and pilot plant work, the following economic conclusions are shown in Table E.1

Table E.1 Cost Implications of Automatic Coagulation Control at Burham

Variable	Installation and Purchase Cost £	Saving £
PAC Replacing Alum	27450	14411
Acid Dosing	0	5719
Sulphuric Acid	1757	0
Filter Backwash	0	1000
Ac 1000	40000	
Total	69207	21130

The capital cost associated with purchase and installation is greater than the potential cost savings for one year. However, with the clarification process being continuously controlled by the AC 1000, the optimum dose for the coagulant will be continually dosed, saving on coagulant whilst decreasing the RGF's backwash frequencies. In addition to this, the cost of INDA PAC is £100. The minimum predicted payback time period is less than 2 years.

The reductions in sludge are given in Table E.2. The percentage reductions represent sludge reductions for PAC at ambient pH and PAC at optimum pH 7.5 compared to Alum at ambient pH. PAC and Alum sludge volumes were calculated at a pre-ozone concentration of 1.5 mg/l and an optimum coagulant dose of 3.5 mg/l with 0.06 mg/l polymer.

Table E.2 Sludge Volume Savings for PAC Compared to Alum at Optimum Coagulant Doses of 3.5 mg/l, Shown in Percentage Sludge Reductions at 2% Dry Solids at a Flow Rate of 50 Mld.

Coagulant	Sludge percentage (%) Reductions
Alum, ambient pH	100
PAC, ambient pH	33
PAC, pH 7.5	43

A further cost saving could be made with the reduction sludge volumes with use of PAC instead of Alum (33%) and PAC at an optimum pH of 7.5 (43%) during the months May to November.

1.0 INTRODUCTION

1.1 Location

The Burham Water Supply Works is part of Southern Water Services' River Medway Scheme, designed to ensure a clean and adequate supply of water to Gravesend and the Medway Towns. The Works is located six kilometres north of Maidstone, Kent (GR TQ7262). Burham began operating in the early 1970's. The design capacity is 73 million litres per day (16 million gallons), but the works currently operates at 50 million litres per day. It is operated by Southern Water and treats river water taken from Eccles Lake, which has been pumped from the River Medway at Springfield, near Maidstone.

1.1.2 Eccles Lake

This lake is situated approximately 400m north of the Burham Water Supply Works (GR TQ7360). It has a gross capacity of 545,000 cubic meters (120 million gallons), a surface area of 7.3 hectares and water enters the lake through tow 933mm diameter pre-stressed concrete pipelines situated at either end of the lake. This arrangement ensures regular circulation and blending of the lake waters and prevents stratification. Here materials carried down by the river such as clay, sand and plant matter settle. Dissolved gases escape naturally to the air and ammonia is removed by bacteria.

1.1.3 Raw Water Quality

The raw water quality entering the works does not fluctuate as suddenly as can be the case with river sources, due to buffering effect of the lake. This aids both works operation and studies carried out at the site. The water quality parameters or groups of parameters

that the works must be able to reduce are turbidity, colour, TOC, iron, manganese, aluminium, algae and pesticides. The water quality targets for leaving the treatment works are significantly below the legal limits *(The Water Quality (Water Supply) Regulations*, 1989), to allow for a margin of safety.

1.2 Treatment Process Operation

The original treatment process adopted at the works was pre-chlorination, clarification, rapid gravity filtration (RGF), pH correction and superchlorination followed by dechlorination. When the works was designed it incorporated certain features which, whilst providing potable water, were in part experimental. Following a series of trials on various aspects of the works, various modifications have been made. Pre-chlorination has been replaced with pre and inter-ozonation, and six granular activated carbon adsorbers (GAC's) installed. A systematic diagram of the treatment works is given in Figure 1.3.

The first stage of treatment begins with the addition of aluminium sulphate or polyaluminium chloride, followed by mixing, polymer addition and settlement in the clarifier tanks. There are a total of twelve clarifiers; two of the circular hopper type, four square bottomed and six square flat bottomed. All three tank designs are incorporated with sludge blanket weirs and concentrator pockets fitted with automatic sludge bleed arrangements

After clarification the water passes to a bank of eight variable decling rapid gravity filters designed to have a maximum operating head of 2400 mm and a maximum filtration rate of 5 mm/second. Following filtration ozone gas is injected into the tanks. The ozone is

generated from liquid oxygen is used to break down the pesticides contained within the water. The ozone residual is eliminated prior to the GAC's by dosing with sodium bisulphate.

These processes are able to remove adequately all contaminants except some pathogens that may still remain. These are removed by the final stage called sterilisation using chlorine. The entire treatment process is checked regularly by scientists. Samples are examined for chemical as well as bacteriological purity to ensure that the supply meets EC Directives and World Health Organisation Drinking Water Standards *(The Water Quality* (*Water Supply*) *Regulations*, 1989).

1.2.1 Waste Treatment and Disposal

The RGF's backwash water is piped into settling tanks. The clarified sludge is fed into one thickener. The supernatant liquors from both sets of tanks flow into the lagoon located at the south of the site. Sediment from the RGF washwater is fed into the thickener. Thickened sludge is dewatered, and the solids removed by container lorries to a landfill.

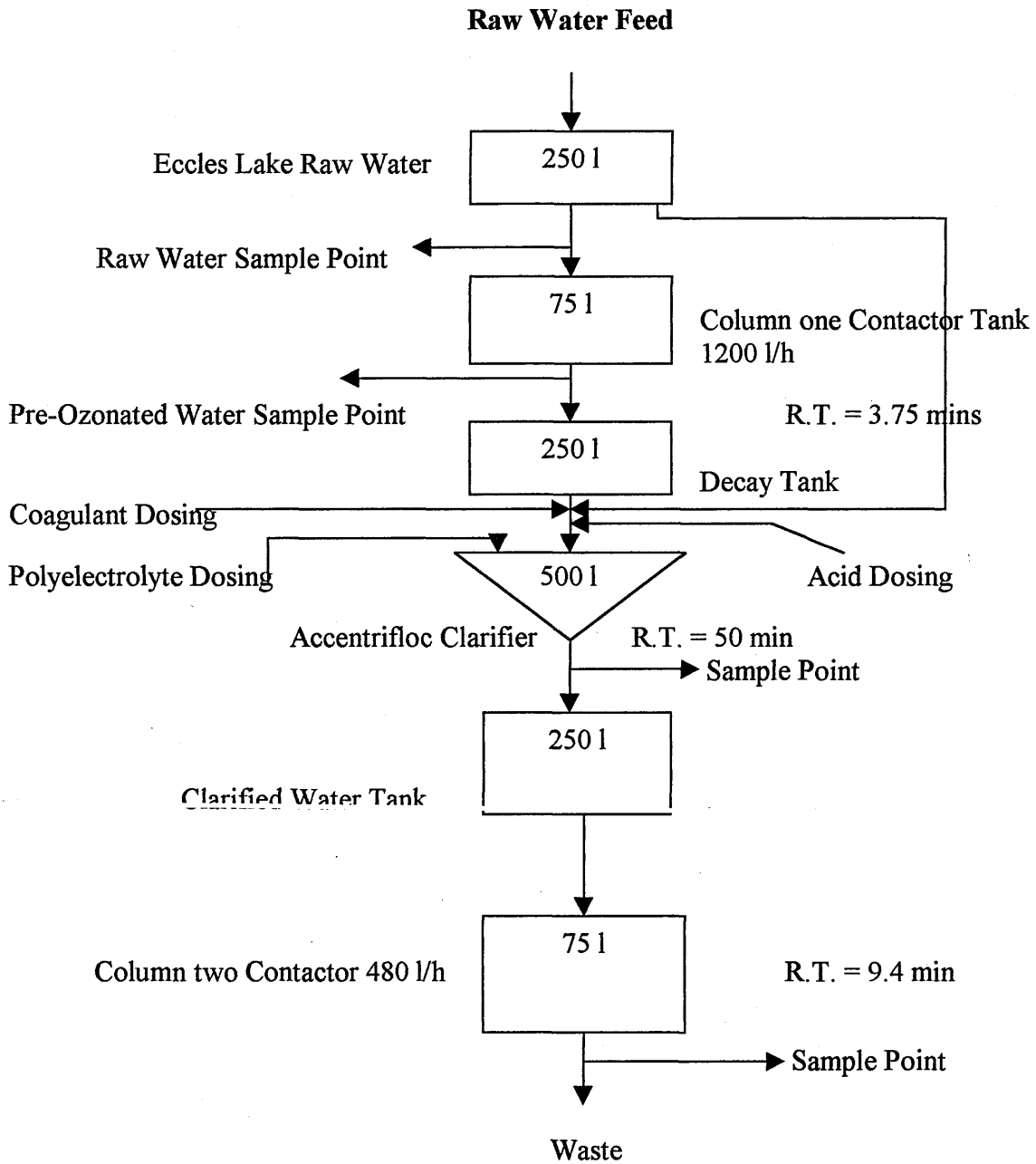
1.3 Current Problems at Site

The problems at Burham are in part due to excessive coagulant dosing by manual coagulant control that can be reduced by installing an automatic coagulation control system that would optimise the clarification process. The works could be incurring high operating effects due to using non-optimal chemicals and conditions for coagulation.

Additionally, the most efficient pre-ozone dose required for the coagulation and removal of pesticides and metals is not known.

1.3.1 Company Strategy and Approach

Southern Water have funded this MRes project to identify the most cost effective coagulant at achieving the required duty annually at Burham. This involved the evaluation of acid dosing as a cost effective measure of reducing coagulant demand. Jar testing was used to select possible alternative coagulants and their performances at ranges of pH and pre-ozone concentrations. A pilot clarifier was operated to again evaluate the performances of the selected coagulants under these conditions. The pilot clarifier set-up and pilot pre-ozonation column are shown in Plate 1 and 2 respectively.



Retention time = R.T.

Figure 1.3 A systematic Diagram of Burham Pilot Plant.

Plate 1. Pilot Clarifier with Un-Ozonated Water with Pass 100 at an Optimum Dose of 3.5 mg/l.

Plate 2. Ozonation Columns Mounted on Pilot Plant Clarifier.

2.0 LITERATURE SURVEY

2.1 Background

Aluminium based coagulants have been employed for water treatment since Roman times and today are the most widely used coagulant worldwide. During 1981, for example, The United States of America used more than 153000 tons of aluminium based coagulants for water and wastewater treatment (Faust, 1983). However, inspite of the increased usage of coagulants in water treatment the exact chemistry of coagulation is still not fully understood, but several important theories of coagulation have been proposed (Stumm & Morgan, 1962; Packham, 1965; O'Melia, 1972; Maier, 1974; Saunier *et al.*, 1983 Dental, & Gossett, 1987; Dentel, 1988; and Miller, 1995).

Coagulation itself is the physio-chemical alteration of the characteristics of turbidity enhancing the agglomeration of colloidal particles that can be subsequently removed. It occupies a central role in the treatment of potable water where it is required for the success of the sedimentation, filtration and disinfection processes.

The process of coagulation is achieved in stages. Firstly the coagulant is added to water and mixed thoroughly, destabilising the colloidal solids that would otherwise remain in suspension. Then the destabilised particles are aggregated together by a slow mixing stage, known as flocculation (O'Melia, 1972). The two mechanisms involved in particle growth are: 1) the adsorption of soluble positively charged metal hydroxide species either monomeric or polymeric in nature, resulting in charge neutralisation of colloidal material and. 2) at higher doses of coagulant, the formation of metal hydroxide precipitate by the hydrolysis of the coagulant which enmeshes and removes colloidal matter (Dentel, 1988). The mechanism that dominates is determined

by parameters such as pH, coagulant type and dose, ionic strength and the water source (Tobiason *et al.*, 1995).

The efficiency of the coagulation stage depends on different parameters including raw water quality, the chemistry of the coagulant, physical parameters of the process and the expected quality of the treated water. The most common and simplest form of measuring this efficiency is by measuring turbidity removal. Turbidity is a measure of the light transmitting properties of water, with respect to colloidal and residual matter (Sorg & Logsdon, 1980). Particulate matter in surface waters originates from both inorganic and organic biological sources. The composition of inorganic matter is mainly dependent upon local geology but mainly consists of clays and silts from land run-off, and manganese and iron particulates released due to microbial activity in the sediment floor. Organic matter is mainly derived from both the animal and plant kingdoms however, the presence of synthetic organic compounds such as pesticides are becoming more common and their subsequent removal more important (Stammeer & Wieczorek, 1996). The approximate extent to which these contaminants are removed by coagulation is commonly related to and measured by a reduction in turbidity.

2.2 Natural Organic Matter

Natural organic matter (NOM) is organic matter mainly originating from dead and decaying plant, fungal and algal detritus. Everton (1997) stated that the actual light scatter of different materials in the form of particles is a problem, as biological cells are not detected to the same extent as inorganic particles. Investigations by Everton showed that and an algal bloom exceeding 50000 cells/ml only increased turbidity by

several NTU's. Therefore the measurement of particulate matter is unreliable to be accurately measured by turbidity. The concentration of NOM present and therefore the effectiveness of coagulation need to be measured by other parameters that can be more accurately measured, for example, dissolved organic carbon (DOC) or total organic carbon (TOC).

2.2.1. Effects of Coagulation on NOM

Investigations by Edwards *et al.,* (1994) and Tobiason *et al.,* (1995) proposed that coagulants promote the conversion and removal of soluble NOM molecules into insoluble coagulant NOM reaction products by either the precipitation or sorption mechanisms of coagulation described in section 2.1. The tendency for NOM to precipitate is generally promoted by the presence of a low functional group content and a high molecular weight (MW). Therefore, conversely smaller MW NOM molecules that contain more functional groups are primarily removed by sorption onto the surface of suspended particles. But, in the presence of aluminium based coagulants both precipitation and sorption mechanisms can remove NOM.

However, investigations by Edwards *et al.,* (1992) reported that not all NOM is removed by the addition of coagulants. To explain this Edwards *et al.,* (1992 & 1994) suggested that non-sorbable NOM lacks functional groups necessary for adsorbing with hydroxide floc surfaces.

2.3. Coagulant Chemistry.

There are various reports proposing the chemical species formed in the processes of hydrolysis, complexation, polymerisation and precipitation. Jaing & Graham (1996)

and Tang & Luan (1995) have suggested that Al^{3+} ions in water hydrolyse to form the following monomeric: $Al(OH)_2^+$, $Al(OH)^{2+}$, $Al(OH)_3$ and $Al(OH)_4^-$; and polymeric species: $Al(OH)_2^{4+}$, $Al(OH)_4^{5+}$ and $Al_{13}O(OH)_{24}^{7+}$. Tang & Luan (1995) further proposes that these monomers hydrolyse to form small polymers or transform into precipitates, enhancing particle removal through charge neutralisation and then by adsorption onto hydroxide flocs.

Polymeric species ($Al_{13}O(OH)_{24}^{7+}$ or Al_{13}) are thought to be the most effective species for water treatment (Melia *et al.*,1989; Pouillot & Suty, 1992). The formation of this species may depend on a number of factors, for example mode of mixing and ionic strength, but the most important factor is the amount of base added and hence the degree of neutralisation (Kaeding *et al.*, 1992). Van Benschoten & Edzwald (1990) state that Al_{13} polymers are more refractory to hydrolysis and can persist in solution for an extended period of time as highly charged polymers before precipitating as $Al(OH)_3$ flocs, even in changing pH environments. This allows Al_{13} to be more effective in the removal of anionic particles by the charge neutralisation mechanism, and then by adsorption once precipitation has occurred. The use of polymeric coagulants such as polyaluminium chloride (PAC) is favoured for treating wastes over wider pH ranges and high levels of turbidity due to lower quantities of sludge produced to that of aluminium sulphate (alum) treatment.

2.3.1. Effects of pH on Coagulant Performance

The solubility and species speciation of metal coagulants is pH dependent (Van Benschoten *et al.,* (1992). Because pH dictates metal speciation and solubility the

optimum conditions for coagulation can be theatrically predicted for practical use to optimise the required coagulant demand for water treatment.

Investigations by Kaeding *et al.*, (1992) on varying pH and coagulant doses found that by reducing the pH by acid dosing prior to coagulant dosing, the optimum coagulant demand could be reduced. Furthermore, studies by Edwards and Benjamin (1992) also on varying pH and coagulant doses proposed that when the pH is below 6.25 the precipitation mechanism dominants. In this case the metal cationic species are present in sufficient monomeric and polymeric forms to neutralise the anionic sites on dissolved NOM molecules. The raising of the pH above 6.25 promotes NOM particle removal by sorption onto precipitated metal hydroxides.

2.3.2. Effects of polyelectrolytes on coagulation

The organic polymers used in water treatment consist of chained monomeric units, linked together in a linear or branched formation. The length of the polymer chain dictates the molecular weight of the polymer. Functional groups located along the chain can possess an anionic, cationic or non-ionic charge (Treweek & Morgan, 1979).

When a polymer molecule collides with colloidal particles, some of the functional groups on the polymer molecule adsorb onto the particle surfaces. Other branches of the polymer can adsorb other colloidal particles present, leading to floc formation (Narkis & Rebhun, 1975). Overdosing however, results in colloidal destabilisation due to the colloidal particles becoming surrounded by polymer to an extent that no functional groups are available for inter-particle bridging (Edzwald & Lawler, 1983).

Polyelectrolytes used in coagulation act as bridges between flocs promoting larger floc formation that is more resistant to floc shear.

2.4 Effects of algal and algomeric matter on coagulation

During growth, algae excrete polysaccarides and other polymeric matter referred to as extracellular organic matter (EOM). Fogg (1996) reported that between 7 and 50 percent of the total amount of carbon assimilated was released into the water in the form of EOM and that EOM can carry a negative charge, adding to the coagulant demand. However, studies by Paralker & Edzwald (1996) showed that EOM has flocculating properties. They suggest that if small amounts of EOM are present they can act as non-ionic or anionic polymeric coagulant aids, adsorbing and adjoining particles by promoting flocculation via sorption. But, as EOM concentrations rise, the tendency for EOM to form complexes with the metal coagulant ions increases, increasing coagulant demand (Hoyer *et al.*, 1987).

2.5 Metals Removal

Dissolved iron and manganese are commonly found in both surface and underground waters in their reduced form. Although they do not constitute a health hazard in concentrations normally encountered, settled iron and manganese can cause pipe damage and water colouration (Stoebner & Rollag, 1981). For these reasons, EEC directives concerning potable water fix guidance levels of 50 and 20μg/L for iron and manganese respectively, with maximum permissible levels of 200 and 50 μg/L (Reckhow *et al.*, 1991).

Manganese and iron removal by coagulation and sedimentation can only occur if the metals are present in their particulate form. Iron (II) and manganese (II), (VI) and (VII) compounds are soluble and not significantly removed by coagulation, whereas, insoluble M^{3+} hydroxides or hydrated oxide complexes (MnOOH) are removed by adsorption onto coagulant flocs.

In the presence of hydrophilic organic compounds such as humic acids, metals can exist in the form of metallic ion NOM complexes. In this case removal is achieved by the precipitation or sorption mechanisms of coagulation described in section 2.1.

McKnight *et al.,* (1993) showed that the oxidation of Mn with pre-ozone in raw water reduced Mn concentrations. Felix-Folho (1986) suggests that the addition of pre-ozone can oxidise the organic matter to release metal ions, which hydrolyse to the insoluble precipitates and induce coagulation.

2.6 Characteristics of ozone

The first documented use of ozone (O_3) in water treatment was in 1893 at Oushorn in the Netherlands for disinfection purposes (Smith & Moss, 1993). During the next 50 years, ozonation became increasingly popular throughout Europe, but mainly in France, where by 1945, 130 plants employed ozonation as a disinfection process. By 1988 there were a documented 1000 European water treatment plants employing ozonation for applications such as colour, taste and odour removal, organics (pesticides) removal, disinfection and microflocculation (Maier, 1974; Tobiason *et al.*, 1995).

Ozone is a powerful oxidant, capable of oxidising many organic and inorganic substances present in water. It is typically employed as a disinfectant, an oxidant and a pretreatment to enhancing the coagulation process (Edwards & Benjamin, 1991). Ozone reacts through two general pathways: the molecular pathway, by which it can react slowly but selectively and the free hydroxyl radical pathway, by which it can react less selectively but more rapidly (Hyde & Zabel, 1984).

2.6.1 Effects of Ozonation on Coagulation

There have been a number of reports published on the effects of preozonation on coagulation, flocculation and their affects on downstream processes. These claims have included reports of spontaneous coagulation of ozonated particles and particle flocculation during ozonation, prior to coagulation, known as microflocculation (Maier, 1974). Furthermore, this phenomenon has been reported to have caused a reduction in coagulant dosage required for good treatment and improved water quality (based on turbidity) following flocculation and sedimentation (Saunier *et al.*, 1983; Farvardin & Collins, 1988; Richard & Jacq, 1990; Edzwald & Peralker, 1992; Edwards *et al.*, 1994). Effects of ozonation on filtration have included increased filter run time, due to a lower rate of head loss and delayed turbidity time breakthrough (Prendeville, 1986; Tobiason *et al.*, 1992). Jekel (1994) summaries these effects as follows:

1. A direct aggregation of particles, measurable as a shift in the particle distribution to larger diameters and by increases or decreases in turbidity, as illustrated in fig 2.6.2.

2. Formation of colloidal or suspended particles from dissolved material, usually indicated by a turbidity increase and improved TOC/DOC removal afterwards.

3) Improved particle removal in filtration, thus less coagulant (up to 50% less) must be added and filter runs are subsequently extended.

4) Better settling rates of flocs.

5) Low ozone doses induce spontaneous interparticle flocculation of algal cells prior to coagulation by direct action on EOM

Reckhow *et al.,* (1986) and Edwards *et al.,* (1994) have proposed mechanisms responsible for the observed effects of ozonation on coagulation. They propose that when raw water containing NOM is ozonated, the carboxylic acidity of NOM increases, the average MW of NOM decreases, metastable organics that can polymerise are formed, metal-organic complexes are disrupted, releasing metal species (e.g. Fe, Mn), and IOM and EOM are released by algal lysis.

According to Edwards *et al.,* (1994) a decrease in MW reduces the tendency for NOM to precipitate (section 2.2.1.), reducing the coagulant demand, but also reducing the amount of NOM removed. Increasing the concentration of acidic functional groups, increases the charge density, increasing coagulant demand and NOM removal by sorption onto the surface of suspended particles. Studies by Edwards (1990) and Edwards & Benjamin (1992) concluded that the balance between these two factors determines the overall effect of ozonation on coagulant demand and removal efficiency (measured by turbidity).

La-Trobe Bateman (1997), illustrates the combined effects of ozone on NOM particle size, whilst taking into consideration acidity, ozonation and coagulant type, shown in Figure 2.1.

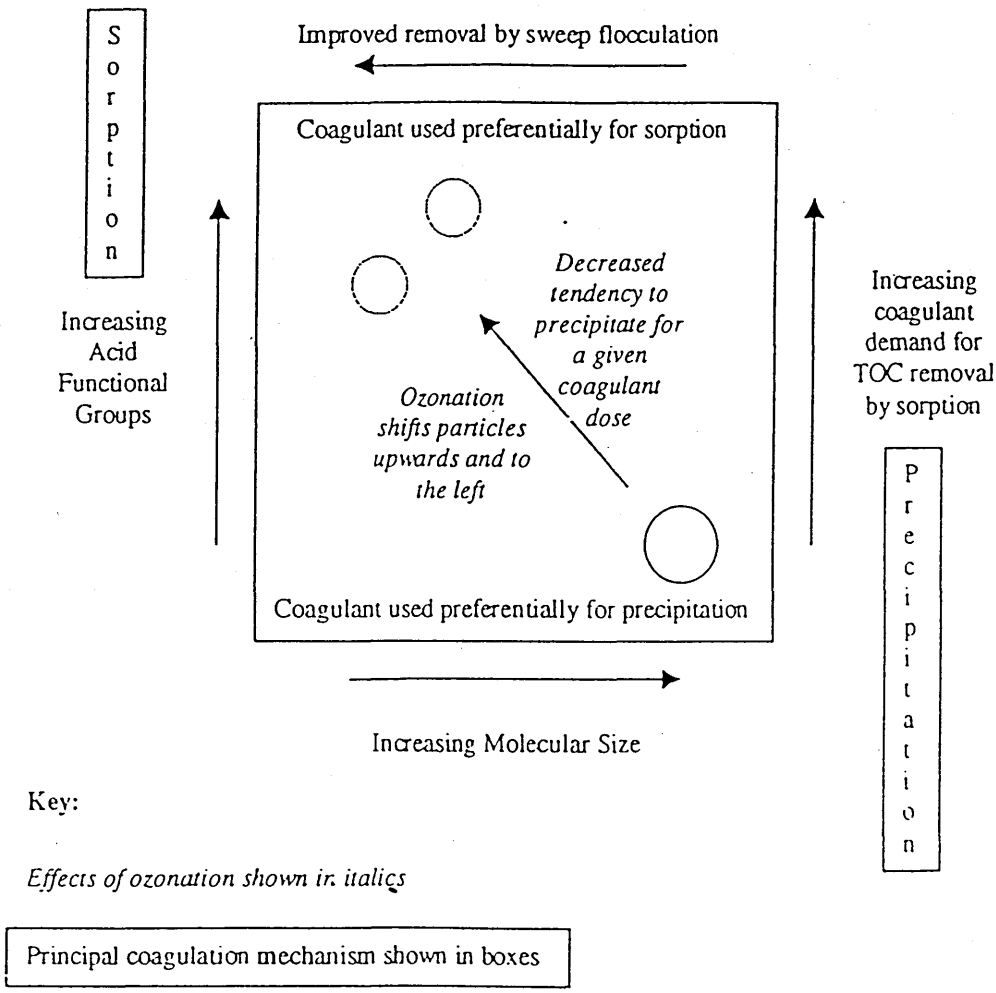


Figure 2.1 Summary of the Effect of Ozonation on Particle Size and Principal Coagulation Mechanisms (La Trobe-Bateman, 1997).

The square in Figure 2.1 represents the range of organic particle sizes (x-direction) and the acidic functional group density (y-direction) in terms of meq/g TOC (Flogstad & Ødegaard, 1985; La Trobe-Bateman, 1997). The effect of ozone is to break the particle into smaller particles increasing the concentration of acid functional groups. This transforms larger particles with relatively low charge densities, as shown from the bottom right, where the precipitation mechanism of coagulation predominates, to small relatively highly charged particles at the top left of the square where sorption mechanisms predominate.

Using Figure 2.1 and the effects of ozonation described in previous sections, it can be suggested that if a coagulant is added to unozonated water typically containing larger, less highly charged particles, some of the coagulant will precipitate out the NOM. Any excess will form hydroxide flocs and co-precipitate with the NOM-coagulant precipitates. Furthermore, if the same coagulant is added to ozonated water, predominately containing smaller, more highly charged particles, less of the coagulant will be used in precipitation, because there is less humic acid present, and more used in neutralising the acidic functional groups present on the smaller more highly charged particles formed by ozonation. The balance of these two therefore and the one that dominates, dictating the coagulant demand, are ultimately dependent upon how the particles change during ozonation.

2.6.2. Effects of Pre-ozonation on TOC Removal and Coagulant Demand

Various studies suggest that preozonation prior to coagulation and sedimentation can increase TOC removal rates and decrease the required coagulation demand (Farvardin & Collins, 1989; Chang & Singer 1991; Richard & Jacq, 1990). This is demonstrated

by the results of Richard & Jacq (1990) who studied the quality of clarified water with and without pre-ozonation for turbidity, TOC and dosage of coagulant (Figure 2.2). They reported that in general ozone increases turbidity with increasing ozone dosage (Maier 1974) and at an optimum dose improves the removal rate of organic matter in coagulation whilst reducing the required coagulant dose.

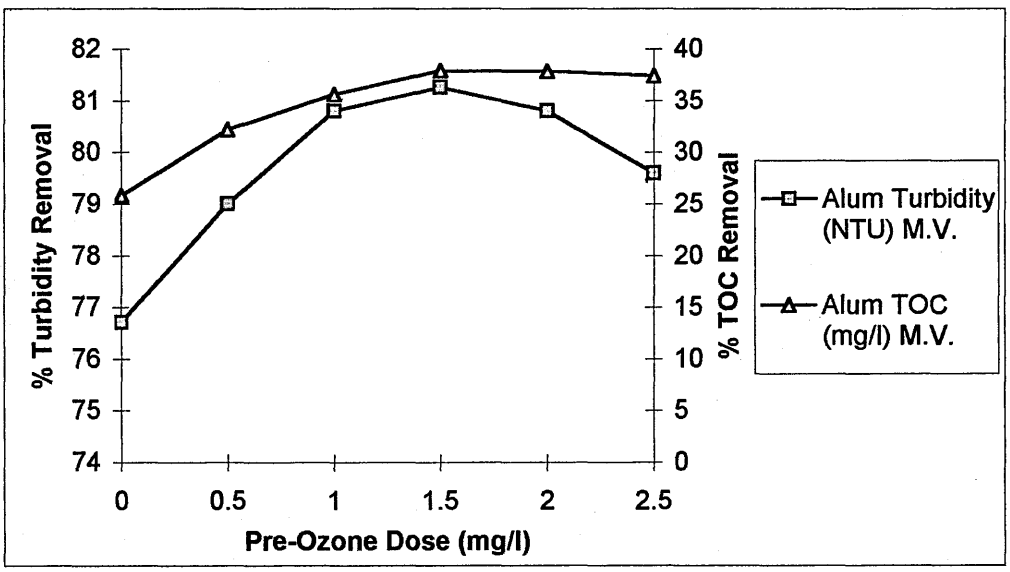


Figure 2.2 Determination of Pre-Ozonation Dose with Aluminium Sulphate at 2.4 mg/l as Al^{3+} (Richard & Jacq, 1990).

The amount of TOC removed for a given coagulant dose can be linked by various reports with the raw waters initial pH, alkalinity, hardness, metal, algal and TOC levels, and that the stability of particles against aggregation is decreased by increases in calcium (hardness) levels, but increases at low pHs. (Dowbiggin & Singer, 1989; Chang & Singer, 1991; Tobiason *et al.*, 1995).

Studies by Amy and Kraser (1995) on various American raw waters showed that waters that contained high TOC, low alkalinity, and low pHs achieved the highest TOC removal rates. They explained this by suggesting that at lower pHs, with low

calcium concentrations the precipitation mechanism dominates, and that under these conditions humic and fulvic acids become less dissociated and possess a reduced negative charge.

2.6.3. Effects of Pre-ozonation on Algae and Algomeric Matter

Algae are generally difficult to remove in conventional coagulation, sedimentation, and rapid filtration plants. The algae can pass through the sedimentation plant and filters providing problems to downstream processes. Investigations by Ginocchio (1981) noted that pre-ozonation increased the removal of algae by filtration prior to coagulation. At low ozone doses, ozone has shown to cause algal cells to secrete EOM, which aids coagulation, but at higher doses ozone affects the structure of EOM, having the effect of reducing the tendency for EOM to bind particles (Paralker & Edzwald, 1996). This is supported by the studies at Mont-Valerien in France in Table 2.1 (Richard and Dalga, 1993; La Trobe-Bateman, 1997), where Richard and Dalga (1993) concluded that the removal of algal cells by coagulation and sedimentation is enhanced with the use of an optimum pre-ozone dose.

Table 2.1 Remaining percentage of algal cells with increasing ozone doses using a fixed coagulant dose of 70mg/L at Mont-Valerien in France (Richard & Dalga, 1993).

Sampling point	Preozone dose (mg/l)			
	0	0.8	1.6	2.1
Raw	100	100	100	100
After Preozone	n/a	61.2	27.1	94.3
After Clarification	25	10.3	1.6	23.3

Ozone decreases molecular size and colloid charge and increases functional and acidic groups on the EOM. Edzwald & Paralker (1992) state that only 50% of EOM is still

present as high MW structures until 3mg/l of ozone is dosed where cell lysis and the release of IOM occurs. The dominant coagulation mechanism involved in algal removal is uncertain but will depend upon EOM type, species, pH and coagulant used.

2.6.4. Metal Removal

Ozone tends to be present in the ferrous (Fe^{2+}) state either in solution or as a complex with organic colour. Ferrous is rapidly oxidised by ozone to the ferric state (Fe^{3+}) which in turn hydrolyses and precipitates as ferric hydroxide ($Fe(OH)_3$). The precipitate can be removed in a clarifier or by filtration. (Paillard *et al.*, 1989).

Soluble salts of manganese are oxidised by ozone to the insoluble form, manganese dioxide, which can be removed in a clarifier or by filtration (McKnight *et al.*, 1993). However, if excess ozone is added the manganese can be oxidised to the water soluble permanganate which can give the water a pink colour (Paillard *et al.*, 1989). Reckhow *et al.,* (1991) states that in the presence of organic compounds ozone first disrupts the complex by oxidation, then the subsequent metal precipitates formed through oxidation are then removed by sedimentation and filtration processes achieving a high removal ratio, than just by coagulation alone.

2.6.5 Pesticide Removal

Comprehensive legislation governs the use of pesticides in the UK. These controls have set limits concerning potable water of 0.1μg/l for individual pesticides and 0.5 μg/l for total pesticides (Foster *et al.*, 1991). Atrazine and Simazine are the most commonly found herbicides in drinking water, due to their common application as a weed killer, and subsequent land run off. Ozone is capable of lysing the carbon-aromatic ringed bonds of these calicitrant compounds, resulting in the formation of

aliphatic and carboxycilic acids, ketones and aldehydes (Klein & Brown, 1982). The result of this makes some organics more amenable to adsorption onto GAC and BAC filters by adding oxygen to the compounds and increasing their polarity (Langlais *et al.*, 1991).

The presence of humic substances and bicarbonate ions has been reported by Xoing (1992) to reduce the rate at which pesticide degradation occurs. Meijers *et al.,* (1993), investigated pesticide removals at Menuse, Nieuwegein, Netherlands with pre-ozonation and stated that that as humic concentrations increase they consume the free hydroxyl radicals resulting in fewer radicals present for pesticide degradation. Bicarbonate ions were also found to inhibit the reactions of the hydroxyl radicals with pesticides during ozonation (Xoing, 1992). Consequently, the success of the coagulation process by removing a high percentage of the NOM present in the water, resulting in low turbidity values, can result in successful degradation of pesticides by interozonation and removal by adsorption.

2.7 Importance of Coagulant Control

As quality and environmental demands become ever more stringent, so the water industry finds itself dependent upon increasingly advanced technology to provide solutions and development (Dentel, 1988). One of these is the importance of quality monitoring and control development. The Environmental Protection Agency (EPA) cite improved clarification as one of the principal methods in improving water quality by optimising and controlling the coagulant dose at water treatment plants (Edzwald, 1986).

It is often the case at water treatment plants that an increase in the applied dose of coagulant yields an improvement in water quality. This leads to a tendency for plant operators to apply excessively high coagulant concentrations in order to be confident that the plant meets all water quality standards. However, the improvements in water quality may not justify the greater chemical costs incurred. Furthermore, it is possible that overdosing the water with coagulant may actually lead to a deterioration in final water quality.

Coagulant addition affects the economics of a water treatment plant in more ways than simply the cost associated with the purchase of the chemicals used. For example, the coagulation process affects the performance of the filtration stage downstream and as such may influence the filter run times and costs associated with backwashing. Similarly, the costs involved with sludge handling are dependent on the quantity and properties of sludge produced which in turn are affected by the coagulation process. Today in coagulation control, on line automatic coagulation control systems are used to instantly respond to changes in raw water characteristics, optimising the chemical

treatment dosages and actively reducing excessive chemical expenses, whilst still maintaining water quality.

2.7.1 Experimental Approaches

Bench-Scale studies

When a quick evaluation of coagulant products are required, bench-scale procedures are necessary. However, accuracy is sacrificed for the purpose of achieving rapid and rough comparisons. Jar tests are an example of bench-scale equipment and this method is a useful tool when comparing treated water characteristics such as turbidity when using two different products or doses, rather than to predict actual settled turbidity in a full scale facility.

Pilot scale studies

Pilot plant studies are usually performed when new process construction or significant upgrading of existing equipment is planned. Pilot-scale studies allow the optimisation of operational parameters, as well as design parameters, giving greater control over the influent and process conditions. Pilot-scale studies are therefore inherently better to bench-scale tests in predicting performance. However, more time and effort are required for pilot studies than for bench-scale work.

Jar Test Method

Szpak *et al.,* (1996) and Clark (1986) evaluated the conduct and uses of jar tests as the conventional laboratory method for assessing coagulation. They concluded that Jar testing is intended to simulate the coagulation, flocculation and sedimentation

processes, but state that a perfect simulation cannot be attained on a small scale as some phenomena, such as blanket formation and floc shearing are exclusive to full scale operations. Jar testing therefore, only serves as a guide towards plant performance.

Black *et al.,* (1957) remarks that the jar test is a simple test that can be adapted to meet requirements of individual applications but it does have limitations. For example, if final turbidity is the only parameter measured, it will provide information on the overall process but it will not allow an detailed understanding of the efficiency of each individual process involved. Furthermore Black *et al.,* (1957) adds that if a jar test yields a high turbidity, this only indicates that the applied dose was wrong without revealing whether it was too high or too low. Jar testing commonly tests above and below the optimum dose and can be used as a regular procedure to obtain the optimum dose. However, since the jar test is a labour and time consuming procedure, they are performed infrequently. Despite this, jar testing can be used to predict an optimum chemical dose and be used to predict the dose on the plant accordingly (Reed & Reece, 1984).

The standardisation of the jar test procedure have been proposed in the AWWA laboratory manual, *Simplified Procedures for Water Examination*, and by the ASTM manual: *Standard Practice for Coagulation and Flocculation Jar Test of Water.* However these reports themselves differ in aspects such as paddle speeds and stirring times. *Simplified Procedures for Water Examination* recommend that the jar test procedure should be altered and adapted to duplicate as closely as possible, the conditions on the full scale plant by altering aspects such as paddle location, paddle

speeds, stirring times, settling times, method of chemical addition and method of data collection.

Variations in jar tests

Various other characteristics maybe varied when attempting to reproduce the conditions of a plant. The type of container commonly used for jar tests are cylindrical, glass beakers (Kerri & Beard, 1987). Bratby (1980) recommends the use of a one litre sample volume to decrease the ratio of surface area to volume, the value of which would be minimal on a plant, allowing for greater accuracy of chemical dosing. Hudson & Wagner (1980) have proposed however, that the use of square plastic jars holds a number of advantages over normal glass beakers. They claimed that the use of square jars with a non-circular cross section provided intrinsic baffling and decreased conductivity of the container walls resulting in better temperature control. Dentel *et al.,* (1988) reported on the use of square plastic containers and glass circular containers and furthers this by stating that the optimum coagulant dose maybe over predicted with the use of circular beakers, and that the square geometry provides a better simulation of full scale conditions.

Temperature affects both the rate and extent of chemical reactions in coagulation. Van Benschoten *et al.,* (1992) reported on the differences in performance of coagulants in cold winter conditions, and stated that jar tests should also be carried out on coagulants at low temperatures to assess the coagulants performance.

Matijevic *et al.,* (1964) and O'Melia (1978) reported the method of coagulant and polyelectrolyte addition affects the final results obtained from a jar test. They claimed that polymer addition to jars should be continuous and not as a sudden aliquot with rapid mixing stopped when polymer addition is complete. However, studies by Dentel

(1987), showed that this was not the case and rapid mixing after polymer addition had little effect.

Other investigations by Amirtharajah & Mills (1982) and Cornwell & Bishop (1983), reported that, coagulation mechanisms are dependent upon local concentrations and mixing characteristics and suggested that it is beneficial to determine the method of chemical addition which best reproduces the coagulation behaviour at full scale.

Turbidity is the most commonly used parameter for evaluating the results of jar test but there are a number of other measurements which may be taken instead of, or in addition to turbidity. A visual examination of the size and appearance of floc formation and settlement behaviour are usually associated with the jar test procedure, in conjunction with other measurements. Studies by TeKippe & Ham (1970) reported a good correlation between floc size, settlability and turbidity removals. Dentel (1987) also showed that large floc sizes can mean overdosing with coagulants and poor turbidity removals. The use of visual performances in jar testing are therefore used as a guide to floc formation and settlement but cannot not provide definite results alone.

2.8 Continuous Dose Control

The continuous control of coagulant dosing requires a system which will respond to changes in conditions with an appropriate adjustment in the chemical rate. Such a system requires the monitoring of one or more parameters in order to establish basis for monitoring and adjustment.

The parameter which is monitored must be suitable for rapid measurement i.e. The time required for feedback/feedforward control must be less than the time scale of changes in conditions (Dentel & Kingery, 1988). For example, a continuous change in

flow rate requires a strategy to proportionally adjust the coagulant feed to constantly optimise the coagulation process.

Although the parameter measured for control purposes must be quantifiable, it is not necessary for it to yield a definite value. It may be acceptable if the reading is only relative to an arbitrary base value, as long as the relationship between the coagulant dose and the measured response is reproducible over the range of doses and process conditions. It is also conductive to implementation of a control algorithm if the relationship is linear (Everton, 1997).

2.8.1 Control Strategy

There are various basic approaches which can be adopted when implementing automatic dose control. Feedback control involves the adjustment of the coagulant requirement on the basis of either the treated water or dosed water quality. Systems which use the treated water quality as the basis for adjustment suffer from a long process delay time and so respond to changes a considerable time after they have occurred. Ratnaweera & Aasgaard (1994) reviewed coagulation dose control strategies and suggested that systems that used the treated water quality as the basis for adjustment suffered from a long process delay time in responding to changes in conditions, after the changes have occurred (ZP & SCD). Furthermore, systems in which the control is based on dosed water quality, have a faster response time but are often limited by the availability of accurate methods for the monitoring of dosed water.

Feed-forward control involves determination of the coagulant dose from measurements of the raw water quality. This method relies on the ability to accurately

relate the raw water characteristics to coagulant requirements which may only be achieved by extensive research work to develop a reliable model. Investigations by Everton (1997), propose that this method has the major advantage of responding to changes in the raw water quality before these changes have any impact on the treatment process. However if a feed-forward system control failure occurred, this system alone would not be able to respond to the subsequent water quality deterioration, and therefore more recently feed-forward systems have feedback systems installed, known as the 'Trim' factor (Everton, 1997). In this case, the quality of the dosed or final treated water as well as the raw water quality is monitored and the subsequent coagulant dose is increased or decreased in order to maintain optimum conditions for the coagulation process.

There are several parameters which are potentially suitable for use as a basis for continuous control. These include flow rate, particle charge, turbidity, pH and colour.

Plant Flow rate

A major cause of change in coagulant demand is the plant flow rate though the plant. A simple strategy is normally employed in such circumstances, where the coagulant feed rate is adjusted so that the coagulant dosage, or concentration, remains proportionally constant. This assumes that a constant concentration optimises coagulation. A substantial increase in the plant flow rate will cause reductions in the retention times of the treatment process which may require an increase in coagulant dose rather than just feed rate.

Particle Charge

Electrokinetic methods may be used to determine particle charge following coagulation and flocculation and include colloid titration, zeta potential (ZP) (electrophoretic mobility) and streaming current detectors (SCDs). These methods may be of use where the change in particle charge can be related to the degree of water treatment achieved (Dentel, 1991).

Zeta Potential

The use of ZP in coagulation control was reviewed by Neumann (1980) and found that ZP techniques yields rapid results and provides an effective means of coagulation control, especially as an addition to jar testing. The disadvantages are that this technique requires operator expertise and this system cannot optimise the coagulant dose directly, or indicate whether sufficient floc volume is available for flocculation. Letterman *et al.,* (1982) and Dental (1991) investigated the relationship between ZP techniques and turbidity removal. They demonstrated that when coagulant doses are high and EM indicates a high charge, good turbidity removals can be achieved. It is for this reason that some treatment plants utilise ZP techniques as a measure of determining coagulant doses.

Streaming current detectors

Streaming Current Detectors (SCDs) monitor charge on-line. Investigations from Dental (1995), and Geletti (1969) reported that SCDs detect changes in coagulant demand by providing an indication of particle charge which in theory is directly proportional to ZP. However, Dental (1995) demonstrated that the correlation between electrophoretic mobility (EM) and SCDs are often non-linear due to coverage of the

SCDs inner sensor surface by charged particles. Besides this a report by Elicker *et al.*, (1992) suggest that the rapidity of this measurement makes SCDs potentially useful for continuous dose control, optimising the coagulation process and reducing the amount of chemical required for treatment.

Turbidity

Turbidity measurements are commonly used for the monitoring of process performance. The use of turbidity for automatic control of coagulant dosing requires a reliable method for measuring turbidity on a continuous basis and the development of a control algorithm which could successfully use the signal. Culp & Culp (1974) reported that the use nephlometric instruments in measuring turbidity had complications. They noted that these problems were caused by the deposition and abrasion of organic matter on transparent surfaces in contact with the sample, and blockages at high turbidities. However Einsenlauer & Horn (1985) have shown through studies using a modified fibre optic technique, that these problems can be overcome with the use of a surface scatter turbidimeter. This technique was based upon a continuous flowing suspension, measured by light scatter, which successfully eliminated the problems associated with blockages and deposits.

The main problems associated with using turbidity as a parameter for continuos control is the provision of a control algorithm. Investigations by Dentel (1991) highlighted several situations where a 'set point' turbidity cannot be used for a number of reasons. Such a case could include, the receiving of a reading in excess of the set point where the response to increase or decrease the dose would not be known. Furthermore Dentel suggests that the main problems in using turbidity as a control

parameter is the time delay involved in obtaining a turbidity measurement. Reasons for this can be attributed to the fact that the chemically dosed water has to be flocculated, and then perhaps undergo sedimentation, before a measurement can be made (Gregory & Nelson, 1986). Everton (1997) however, proposed that turbidity measurements of the treated water could be used as a parameter for 'trimming' the dose predicted by a feedback system.

Colour

In the treatment of highly coloured moorland waters, colour measurement is the primary parameter used in the treatment process. 'True' colour, the colour due to dissolved species only, may be measured photometrically by determining the amount of light absorbed by the sample at an incident wavelength of 450nm and the Hazen colour scale. The colour due to dissolved species and suspended matter is known as 'apparent' colour. The problem associated with organic deposition or damage is avoided with the measurement of apparent colour due to the pre-filtration of the sample before measuring the colour parameter.

A study by Everton (1997) investigated the possiblity of correcting the colour reading for the effect of any turbidity present, and vice versa, by determining the optical densities at 425nm and 580nm. Everton, successfully showed that apparent colour could be corrected by turbidity if the optical density is known at each wavelength. Difficulties associated with measuring colour have been reported to be associated with damage and deposits of organic matter on the surfaces on the colour and turbidity monitor, and the time delays involved in generating a measurement value. Coagulant dose control can therefore be susceptible to these problems highlighted as some

automatic control systems (e.g. AC100) in practice, assume that high colour and turbidity readings require an increase in the coagulant dose (Gregory & Nelson, 1986; Dentel 1991).

More recently however, Everton (1997) has developed a on-line automatic coagulant control system that measures apparent colour, turbidity and pH and relates these parameters via a special calibration to the coagulant demand. This system is able to continuously, without time delay or organic matter deposition or damage interference, to monitor and immediately dose the required concentration of coagulant by using feedback, feedforward and algorithm control strategies. The actual details of how this is accomplished are however, to date unpublished.

3.0 OBJECTIVES

The principal objective of this work is to establish cost savings through coagulant dose optimisation using an optimised pre-ozone dose with optimised pH in conjunction with automatic coagulation control.

The proposed study will therefore involve the following aims:

1) Assess whether Polyaluminium Chloride, Pass 100, Alba 18 or Aluminium Sulphate could be dosed throughout the year, replacing Aluminium Sulphate during the moths May to November, based on dose, pre-ozone and pH optimisation.
2) Evaluate an AC250 automatic coagulant dose prediction system for its accuracy, consistency and reliability.
3) Demonstrate and target potential cost savings (chemicals, water, power resources, and sludge volumes) without compromising process performance.

The research plan consists of the following stages:

1) Jar testing of pH, temperature, pre-ozone, polyelectrolyte and chemical coagulant conditions and doses for optimum coagulation.
2) Evaluate other coagulants and polyelectrolytes and thus pre-ozone dose, pH polyelectrolyte doses and conditions.
3) Monitor, maintain and evaluate the AC250 automatic coagulant dose prediction system using jar tests on the pilot plant works.
4) Continue routine (back-up) full-scale jar testing throughout to manually set plant coagulant dose.

4.0 MATERIALS AND METHODS

4.1 Jar Test Procedure

The procedure adopted at Burham was based on that used by Southern Water for tests solely carried out at Burham. This procedure differed in some minor respects, to a conventional jar test procedure. The modifications provided an accurate prediction of the optimum dose and range for the full-scale plant.

4.2 Practical Details

Approximately, 8 litres of water was taken from the inlet pipe to the pilot plant raw water tank. Another 8 litres were taken from the outlet pipe of the pre-ozone column, and a further 8 litres from the full-scale pre-ozonation tank. The pipes were flushed for approximately ten minutes before a sample was taken.

One litre lots of sample were measured using a one litre measuring cylinder and placed in six one-litre beakers. A further 200 ml was placed into an additional 200 ml beaker and tested for raw determinants.

The stirrers were lowered into the beakers. The required dose of coagulant was added to each beaker then the stirrers were set to a speed of 250 rpm, and rapid mix continued for 5 minutes. The stirrer speed was then reduced to 25 rpm for a slow stir of 15 minutes. The required volumes of the coagulant were measured into six 5-ml syringes. The jar testing apparatus is shown in Plate 1.

If polyelectrolyte was being used as part of the test, it was added at the end of the rapid mix immediately before the stirrer speed was reduced to 20 rpm. If acid dosing was being used as a part of the test, it was added prior to coagulant.

The floc size in each jar was recorded at the start and at the end of the slow stir period. Floc sizes were estimated on a scale of A to F using the floc sizing chart in Appendix 1. After 15 minutes slow stirring, the stirrers were switched off and lifted out of the jars which, were allowed to stand for 20 minutes to mimic the sedimentation process.

4.2.1 Sampling and Analysis

Samples of settled water were drawn from each jar approximately 2cm below the surface using a 60 ml syringe with an attached 6 cm length of silicone rubber tubing. The syringe was rinsed between jars in deionised water.

Half the settled water volume was filtered through 90 mm diameter Whatman GFC (Glass fibre C 1.2 μm pore size) filter papers using a pump, a vacuum filtration flask and a Buchner 90 mm funnel. This test procedure was also carried out for the pilot clarifier trial analysis as it provided the closest approximentation to the effect of having sand filters down-stream of clarifiers.

Samples of settled and filtered water were analysed for pH, turbidity, colour, aluminium, iron and manganese. After two weeks this was reviewed. All these determinants were not required in order to select the best coagulant. Colour manganese and iron were only

qualitative measures, and were too variable to be used to differentiate coagulants. The analyses were therefore reduced to pH, turbidity and aluminium only.

4.2.2 pH correction

Prior to coagulant addition, sulphuric acid was used to adjust the ozonated water pH. Acid dosing tests were carried out pH ranges 6.8, 7.0, 7.2, 7.4, 7.6 and 8.0 at each pre-ozone concentration of 0.5, 1.0, 1.5 and 2.0 mg/l. After pH correction the same procedures as detailed in sections 4.2 and 4.2.1 were used in order to determine the optimum pH and optimum coagulant dose.

4.2.3 AC250 Analysis

Two coagulants were used. These were PAC and Alum with polyelectrolyte during the periods 17/03/98-17/04/98 and 29/04/98-09/06/98 respectively. Burham plant ozonated water was used in the same procedures detailed in section 4.2 and 4.2.1, in order to determine the optimum coagulant dose. The sampling time was noted and compared to the AC250 results printout.

4.2.4 Jar Test Schedule

1. Identify optimum aluminium dose for each coagulant.
2. Test each coagulant at each ozone concentration at optimum dose (-35%), optimum dose (-25%), optimum dose (-10%), optimum dose, optimum dose (+10%), optimum dose (+25%). Record floc formation, settling characteristics, turbidities and aluminium residuals.

3. Test Alum and PAC coagulants at their optimum doses and at –25% under-dose and +25% over-dose, with non-ionic (Magnafloc LT20), weakly cationic (Magnafloc LT22s), and anionic (Magnafloc LT25) polymers.
4. Find the optimum coagulation pH for each coagulant using pH's 6.8, 7.0, 7.2, 7.4, 7.6 and 8.0, and its optimum dose at a particular per-ozone concentration (0.5, 1.0, 1.5 and 2.0).

4.3 AC250 Design and Operation

The AC 250 is a combined three-stream colour/turbidity monitor and coagulant demand analyser. The monitor is a self-contained unit, which is either wall or bench mounted, as shown in Figure 4.1. Coagulant demand is prediction is achieved by on-line use of the Aztec-Everton coagulation control algorithm, which is calculated on raw (filtered) colour, raw (filtered) turbidity, raw turbidity and raw pH The pH and raw turbidity values are input as 4-20 mA signals from external meters.

The colour determination is based upon direct transmission of light through a sample in a 40 mm path length cell at the wavelength of 400 nm. The turbidity determination is carried out in the same cell (shown in Figure 4.2) by nephelometry with the detector at 90^0 to the incident light. Both the determinations are recognised and approved analytical methods. The dose signal can be either used directly by connection to a pump stroke positioner or pump frequency inverter, or for more defined control, be used by a PLC/SCADA pump control system.

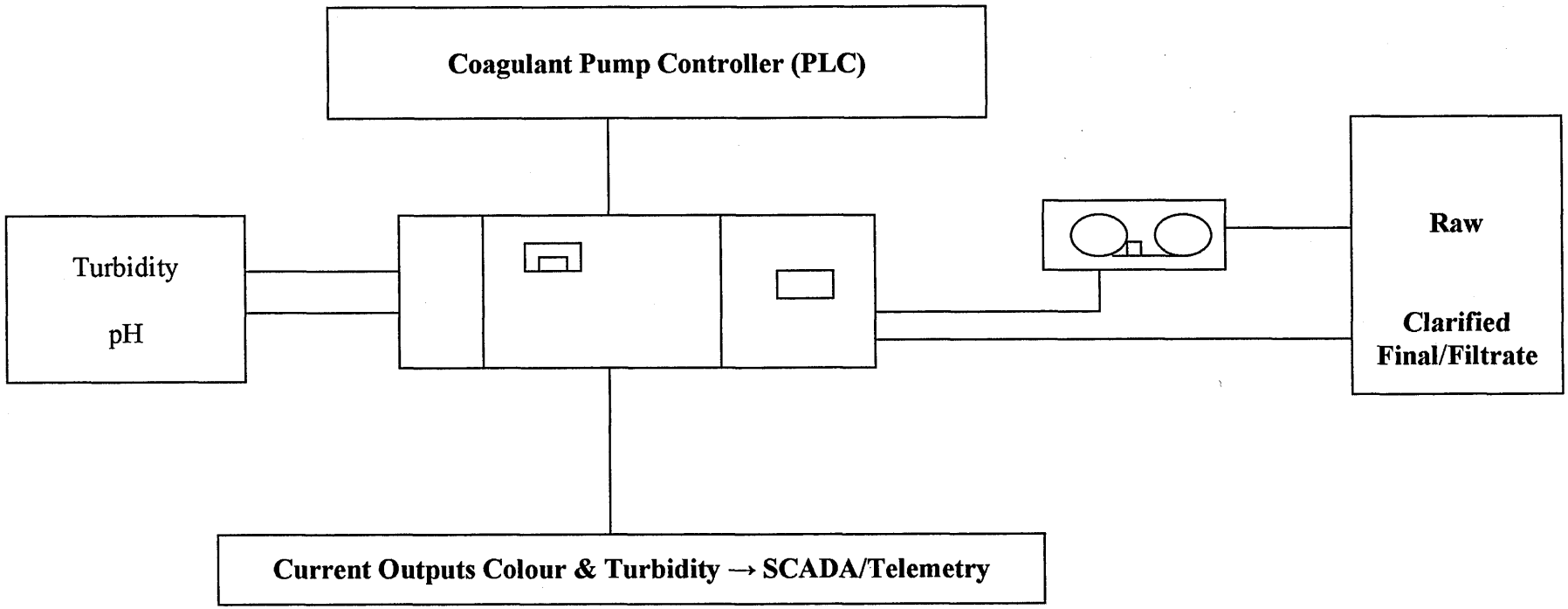
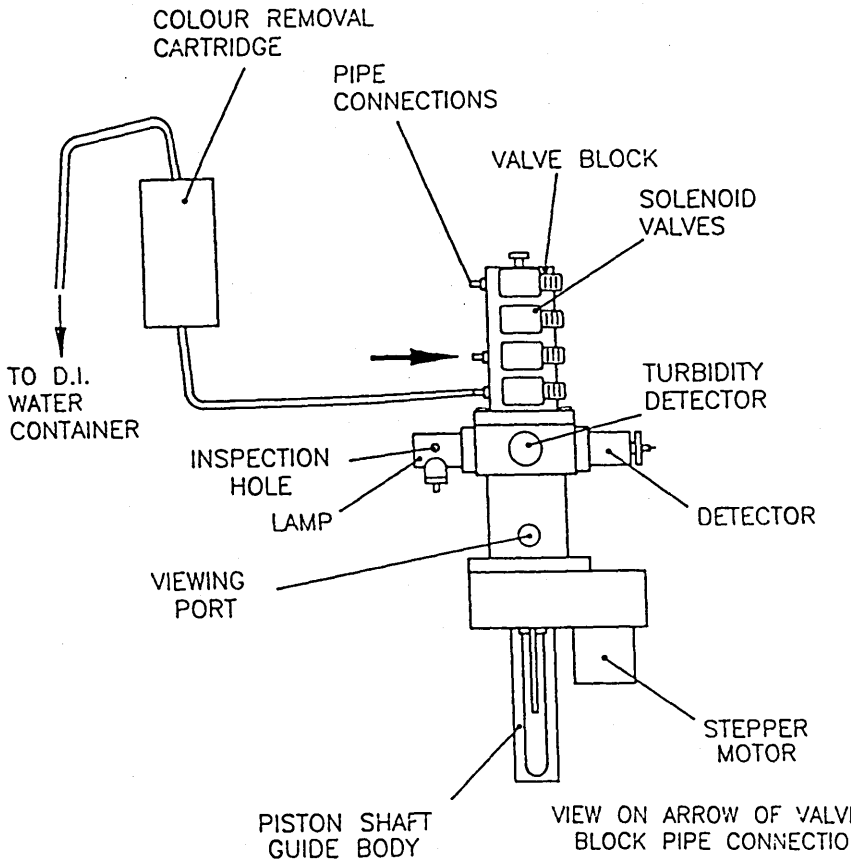


Figure 4.1 Aztec AC250 Automatic Coagulant Prediction System



VALVE No.	PIPE CONNECTIONS
1	D.I. WATER IN
2	BLOCK WASTE
3	D.I. WATER OUT
4	STREAM 1 SAMPLE
5	STREAM 2 SAMPLE
6	STREAM 3 SAMPLE
7	STREAM 4 SAMPLE
8	STREAM 5 SAMPLE
9	STREAM 6 SAMPLE
10	ALKALINE RINSE
11	TURBIDITY STANDARD
12	COLOUR STANDARD

Figure 4.2 AC 250 Sensor Head and Valve Block Pipe Connections.

The Aztec AC250 Coagulant Demand Analyser can be either upgraded to an AC500 or AC1000 Coagulation Control System. This allows either direct or indirect control of coagulant dosing pumps using the unique Aztec-Everton closed loop control algorithm known as the 'Trim Factor'.

4.3.1 Pilot Plant Design and Operation

The pilot plant at Burham is constructed inside a container on the main site located between the clarifiers and the main office building. The main designs and operating features of the pilot plant are described in the MSc thesis by La Trobe-Bateman (1997), a Cranfield University student using the same apparatus.

4.3.2 Ozone Production, Dose and Measurement

Pre-ozone production was by an air fed 'Labo' generator supplied and operated by Ozotech Ltd. of York Road Burgess Hill, West Sussex, RH15 9TU England. Operational procedures, measuring techniques and safety considerations for the unit are described in a MSc thesis by a Cranfield University student using the same apparatus in 1996 (Lea, 1996). The work area is shown in Plate 2.

4.3.3 Pre-Ozone Dose Selection

Pilot trials were carried out using WTS PAC and Alum with pre-ozonated water at 0.5, 1.0, 1.5 and 2.0 mg/l. The settled water quality results for Alum are given in Figure 4.3 below. Although settled turbidity and TOC concentrations were both lower with the

larger pre-ozone dose of 2.0 mg/l, the effect on settled aluminium was marginal, and for economic reasons, a pre-ozone dose of 1.5 mg/l was considered to be a more likely full scale operating dose than 2.0 mg/l, and was therefore chosen for the remaining pilot trials of Pass 100 and INDA PAC.

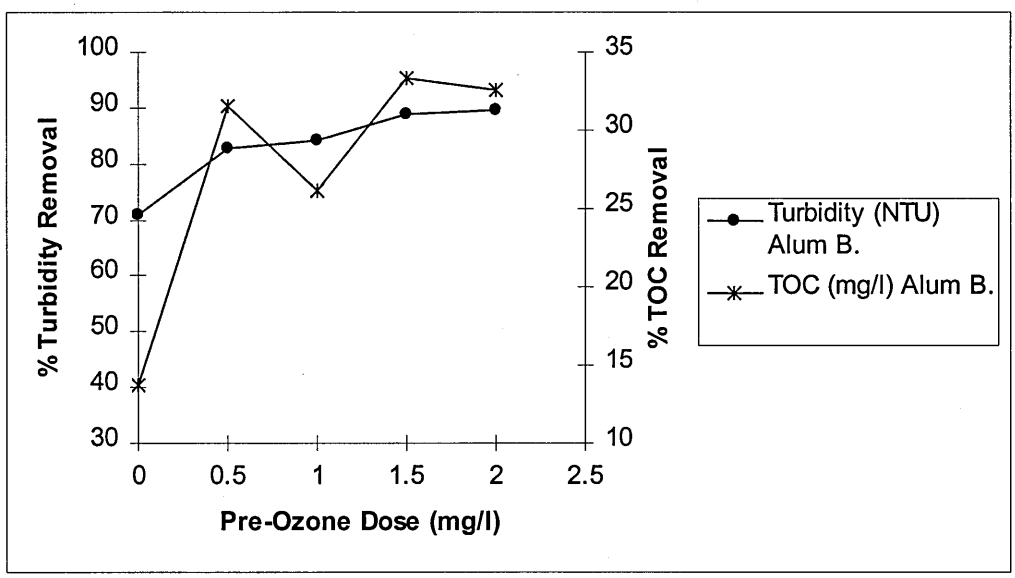


Figure 4.3 Effect of Pre-Ozone Dose on Settled Water Quality with Aluminium Sulphate During Pilot Trials

4.4 Pilot Plant Operation and Sampling

During the non-ozone trails raw water was fed into the 250 litre water header tank and pumped into the clarifier at 10.2 l/min. Clarified water ran to waste via the inter ozone tank, which had its drain valve open.

Raw water samples were taken from the ball valve outlet, and clarified water samples were taken 30 minutes later from the end of the clarifier outlet pipe.

During ozone trials, raw water was directly pumped in to the pre-ozone column at 20 l/min. The raw water sample was taken from a sample valve at the inlet to the column. Pre-ozonated water was allowed to overflow from the 250 l pre-ozonated water break tank and pumped on at 10.2 l/min to the clarifier. Pre-ozonated water samples were taken from a sample tap after the pre-ozone column. Samples were taken at nominal times of 8.00 and 14.00. During a sampling period water samples were taken at 30 minute intervals.

The samples were analysed for a wide range of water quality parameters at Southern Water Science Laboratories using in house methods based on the HMSO "Blue Book" methods. The following determinants were analysed: colour, total hardness, total iron, total manganese, total aluminium, dissolved iron, dissolved manganese, dissolved aluminium, urea herbicides, acid herbicides, triazine herbicides, total organic carbon, dissolved organic carbon, chlorophyll, phaeophytin, total algae, total dissolved solids and bromide.

4.4.1 Pilot Plant Schedule

The coagulants selected from the jar testing were Industrial Alum (INDA) polyaluminium chloride (PAC), Water Treatment Solutions (WTS) polyaluminium chloride (PAC), Alcan aluminium sulphate (Alum) and Alcan polyaluminium silicate sulphate (Pass 100). WTS PAC and Alum were each tested using raw and pre-ozonated water concentrations of 0.5, 1.0, 1.5 and 2.0 mg/l. Pass 100 and INDA PAC were tested at 1.5 mg/l.

The optimum dose was found by jar testing and selecting the dose above which produced the lowest aluminium residuals, highest turbidity removals, best floc formations and best settleability in the filtered and settled water.

The testing regime for WTS PAC and Alum was divided into 3 phases. The first phase was with raw un-ozonated water, second with pre-ozonated water at 0.5, 1.0, 1.5 and 2.0 mg/l, and the third phase with acid dosing using pH 7.3 and 7.5. At each phase variations in polymer and coagulant dose were used.

INDA PAC and Pass 100 were tested only at a pre-ozone concentration of 1.5 mg/l at ambient pH and the pH 7.3 and 7.5.

4.4.2 On-Site Analysis

Measurements were taken for settled and filtered water qualities for raw, pre-ozonated and clarified water. The following determinants were taken: turbidity, pH, temperature and aluminium residuals. Manganese and iron were measured for the first week of pilot operation. However, these determinants were not required in order to assess the performance of the coagulant. The wastes from the manganese assayed were treated as hazardous, and were taken from the site for safe disposal. In addition cyanide was released during the analysis, but safety precautions were taken.

4.5 On-Site Measurement Instruments and Accuracy

The following instruments were used for on site measurements:

pH	Ion sensitive field effect transistor type pH meter pH Boy 501 supplied by Camlab Ltd. Stated accuracy ±0.1 pH unit
Temperature	Organic filled thermometer. Accuracy ±0.1°C
Turbidity	Whatman portable turbidity meter model. This instrument gave variable readings, so the mean of six readings was recorded together with the standard deviation.

Other determinants were measured with a HACH DR2010 spectrophotometer using the methods given in the instrument manual. The reagents below were used:

Manganese	PAN method	0-0.700mg/l
Iron	Ferrover method	0-3.00 mg/l
Aluminium	Aluver 3 method	0-1.00 mg/l
Colour	Filter through 0.45 μm membrane filters and measure at 455 nm to give approximate values as mg/l PtCo APHA method.	

The accuracy of the HACH instrument is affected by interferences with the reagents by material apart from the analyte in the sample. For any given suite of tests on the same water, the interferences will be the same, and therefore it is acceptable to use the instrument for giving relative readings. The accuracy and performance of this instrument has been evaluated by La Trobe-Bateman (1997), a Cranfield University student in 1997.

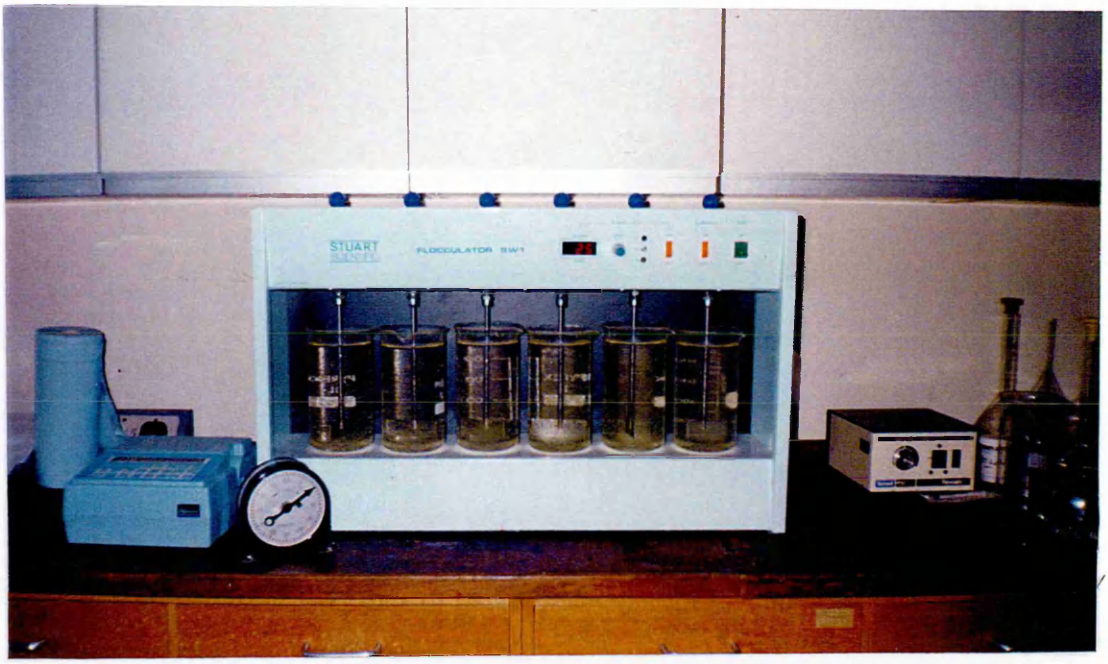


Plate 1. Jar Testing Apparatus: INDA PAC with LT20 at a Pre-Ozone Concentration of 1.5 mg/l.

Plate 2. Pilot Plant Clarifier and Container

5.0 RESULTS

The experiments carried out during this project and the aims and variables involved are listed in Table 5.1. Due to the time scale of the project, some experiments were run simultaneously. The raw water analysis for both jar tests and pilot trails are given in Appendicies 1 and 2. The results have been graphically summarised and normalised into percentage removals shown in Figures 5.1 to 5.19 and Tables 5.1 – 5.20.

Table 5.1 Summary of experiments carried out during this project.

Experiment	Total Days	Aim	Variables
Preozonation	46	To assess the impact of preozonation on raw water Fe and Mn oxidation coagulant performance and pesticide removal	Contact times constant at 3.7 5mins. Ozone doses of 0.5, 1.0,1.5 and 2.0mg/l applied.
Clarification with/ without Pre-ozonation and acid	62	To assess the impact of preozonation and acid dosing on coagulant performance	Residance time at 50 mins. Pre-ozone doses of 0.5, 1.0, 1.5 and 2.0mg/l applied. Coagulant, LT20 poly and acid dosed at a pre-determined optimum dose.
Polyaluminium chloride as a coagulant (WTS)	24	To assess the performance of of coagulant	Pre-ozone doses of 0.5, 1.0, 1.5 and 2.0mg/l applied. Coagulant, LT20 poly and acid dosed at pre-determined optimum and reduced doses.
Aluminium sulphate as a coagulant	19	To assess the performance of coagulant	Pre-ozone doses of 0.5, 1.0, 1.5 and 2.0mg/l applied. Coagulant, LT20poly and acid dosed at pre-determined optimum and reduced doses.
Polyaluminium chloride as a coagulant (INA)	9	To assess the performance of INA coagulant Vs WTS PAC coagulant	Pre-ozone dose of 1.5mg/l applied. Coagulant, LT20 poly and acid dosed at predetermined optimum and reduced doses.
Polyaluminium silicate sulphate	11	To assess the performance of coagulant	Pre-ozone dose of 1.5mg/l applied. Coagulant, LT20 poly and acid dosed at predetermined optimum and reduced doses.
AC250 and Plant performance	48	To assess the predictive performance of automatic coagulation control system.	Plant pre-ozonated and raw water with plant works coagulant.

5.2 Raw Water Quality

The raw water quality data for the duration of the practical work (i.e. 23/03/98 - 06/07/98) is summarised in Table 5.2.

Table 5.2 Summary of the Raw water data Collected for Burham treatment works 23/03/98 - 06/07/98.

Parameter	no. Samples	no. Results	Min. Value	Max. Value	Mean Value
Turbidity NTU	125	125	2.7	27	8
Colour Hazen^0	125	125	3.6	29	13.1
TOC (mg/l)	125	125	3.7	6.6	4.86
DOC (mg/l)	125	125	3.3	6.5	4.8
TDS (mg/l)	125	125	210	345	301
Total Al (mg/l)	125	125	0.004	1.02	0.183
Diss. Al (mg/l)	125	125	0.004	0.89	0.064
Total Fe (mg/l)	125	125	0.07	1.03	0.27
Diss. Fe (mg/l)	125	123	0.07	0.73	0.062
Total Mn (mg/l)	125	125	0.026	0.29	0.08
Diss. Mn (mg/l)	125	123	0.002	0.132	0.019
Hardness (mg/l) as $CaCO_3$	125	125	30	195	167
Total Acid Herbicides (ng/l)	605	545	10	190	25
Total Urons (ng/l)	484	428	10	625	262
Total Triazines (ng/l)	242	211	12	390	132
Bromide (mg/l)	125	125	0.079	0.128	0.108
Algae (no./ml)	125	122	1000	23000	5414

5.2.1 Pesticides in the raw water

The three most common pesticide groups occurring in Eccles Lake were sampled throughout this project. These are acid herbicides, urons and triazines. The fluctuations in pesticide counts shown in Table 5.2 reflect the concentrations of pesticide used by the local and farming communities at that particular period. Urons were the most common pesticide, having mean concentrations of 262 ng/l. From this group of urons, isoproturon was the most common. Other pesticides such as triazines were found to

fluctuate throughout the period of this project, often individually having concentrations above the permissible concentration or value (PCV) 100ng/l for an individual pesticide. Therefore it is clear that the removal of pesticides, in particular isoproturon by ozonation is necessary if the final water quality is to be within the PCV limits for that particular parameter.

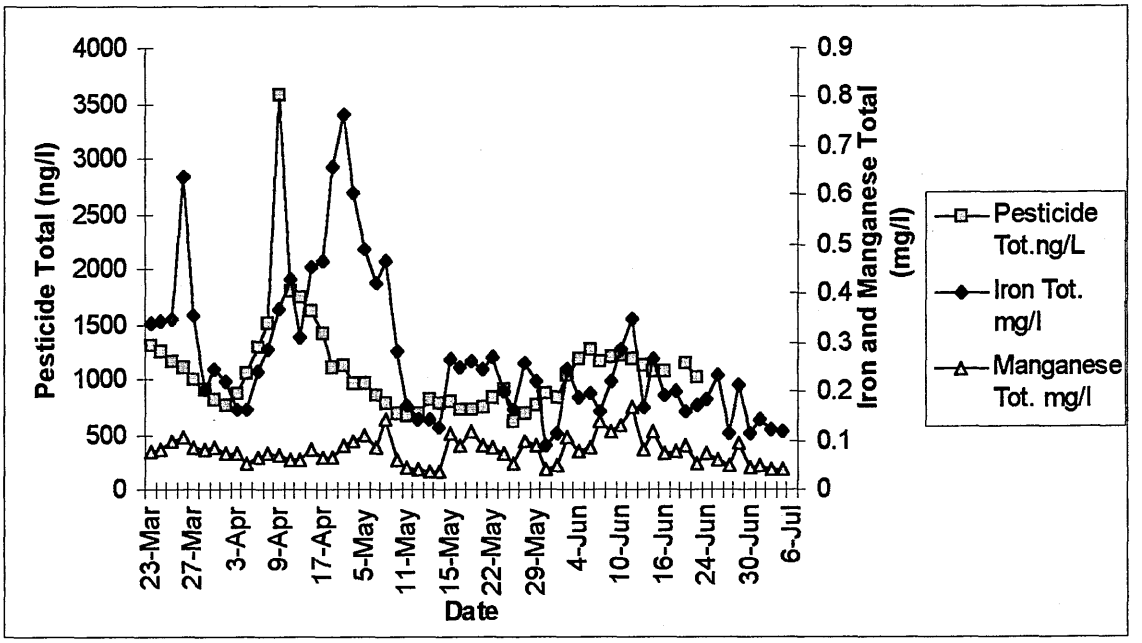


Figure 5.1 Mean Pesticide, Iron and Manganese Concentrations in the Raw Water During A period of 23.03.98 – 06.07.98.

5.2.2 Iron and manganese in the raw water

Only the metals iron and manganese have been monitored. The concentrations of Fe were highest in the months of March, April and May, during periods of heavy rainfall. High levels of TOC, turbidity and colour were monitored at the same period of time (Figure 5.2). This could mean that the ozone demand required to oxidise the metals may increase slightly during the spring months.

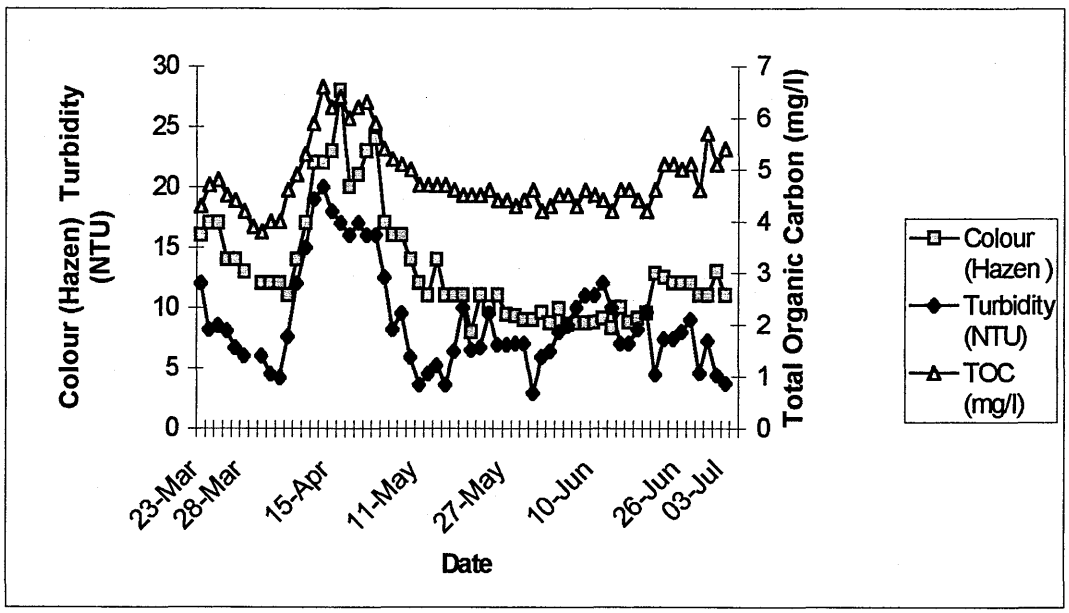


Figure 5.2 Mean Colour, Turbidity and TOC Concentrations in the Raw Water During A period of 23.03.98 – 06.07.98.

5.2.3 Other raw water parameters

Throughout the project, temperature and hardness remained relatively constant. The temperature is critical, as it influences the solubility of metals, and algal content in the raw water. During the period of 23/03/98 - 06/07/98 the temperature was relatively constant between 10-13 ^{0}C. Fluctuations in raw water colour, turbidity and pesticide concentrations that occurred in April (Figures 5.1 & 5.2), were matched by the rises in TOC concentrations. These fluctuations can be attributed to rain fall patterns, disturbing of the lakes sediment floor and crop spraying. However a rise in the concentration of algae as shown in Figure 5.3 showed no linear increase in turbidity readings (Figure 5.2), supporting the work by Everton (1997). The algal count pattern shows the greatest algal counts occurred during the warm summer months. During this period, counts of 1000 – 23000 cells/ml were measured, with peaks and smoothes associated with pH variations during dry, sunny periods and overcast, rainy conditions respectively. Therefore, the ozone demand required to sufficiently reduce the algal counts, would be increased during the summer months.

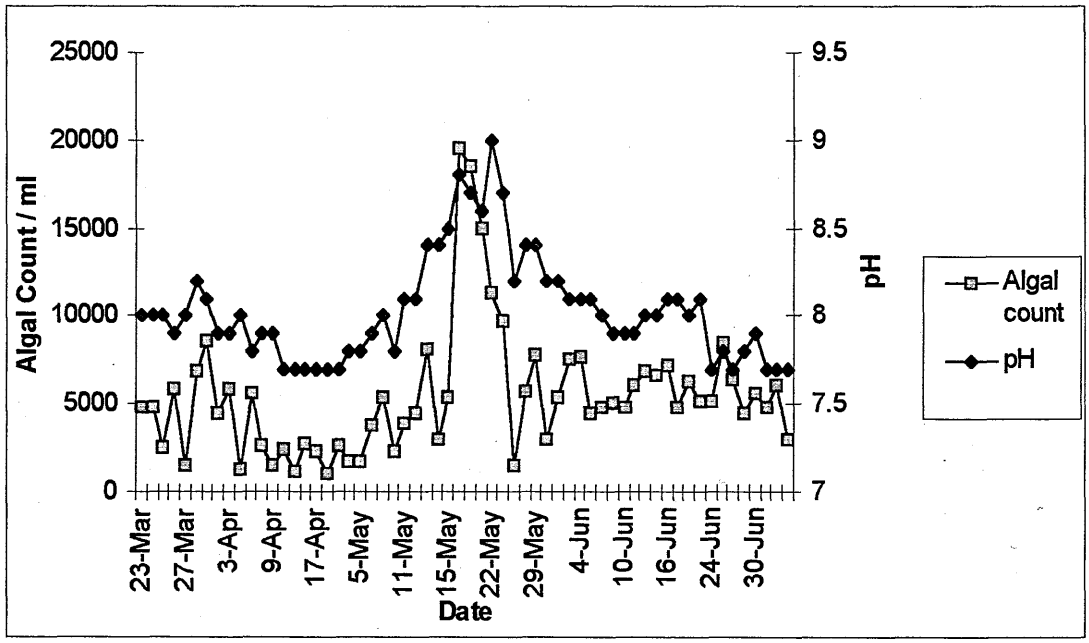


Figure 5.3 Relationship Between pH and Algal Count in the Raw Water During a Period of 23.03.98 – 06.07.98.

5.3 Phase 1: Jar Test Results

The results from the bench scale jar tests carried out during the period of 23/02/98 - 12/07/98 are documented in Appendix 1. The results have been normalised into percentage removals and are summarised into Tables 5.3 to 5.10, and Figures 5.4 to 5.13. The data has been entered into Microsoft Excel database, and manipulated into the relevant forms as shown in Appendix 1.

5.3.1 Jar Test Trends and Observations on Coagulant Flocculation and Settlement.

Tests were carried out on five coagulants (Alba 18, Pass 100, Alum and PAC (WTS & INA)), with and without polymer from which, further jar test trails were further carried out on four chosen coagulants. Tests were carried out both in series and in parallel. Direct comparisons of floc formation, settlement and removal rates were therefore possible and described below in general terms, all at the same ozone dose of 1.5 mg/l, and at ambient temperature (10 - 13 ^{0}C).

5.3.2 Floc Formation

In general, Pass100 produced the largest flocs of 2.25 mm (diameter) (refer to chart 5.1), in the quickest time. Both INDA and WTS PAC produced very comparable floc sizes of 1.5 mm in size, in relatively the same time. However, WTS PAC showed a more defined floc size to that of INDA PAC, which had generally a slightly more fluffy appearance. Alum slowly produced small floc sizes of 1.0 mm. Alba 18 consistently gave small flocs of 0.5 mm in size, which took the longest period of time to form, even at optimum doses. The floc sizes and the relative rate of formation can be placed in descending size order as follows:

Pass 100 (2.25 mm) > PAC (1.5 mm) > Alum (1.0 mm) > Alba 18 (0.75 mm).

5.3.3 Floc Settlement

Settlement of flocs occurred quickest with larger flocs. Pass 100 flocs settled within a 30-minute period, with the majority settling in the first 15 minutes. PAC was next, with most of the flocs settled within the first 15 minutes. Alum settled relatively slowly, and after 30 minutes all flocs had settled. Alba 18 flocs remained mainly uniformly dispersed in solution. After 30 minutes little settling had occurred.

5.3.4 Coagulant Performance

Jar tests were carried out with Pass 100, Alba 18, Alum and PAC (WTS & INDA), without polymer. Tests were carried out in parallel. Direct comparisons of turbidity removals and Aluminium residuals were therefore possible and described in general terms. The Jar tests were carried out at a pre-ozone concentration of 1.5 mg/l and at ambient temperature (10 – 13^{0}C). Pre-ozonated water quality: turbidity: 8.5 NTU, pH: 7.8, Al 0 mg/l.

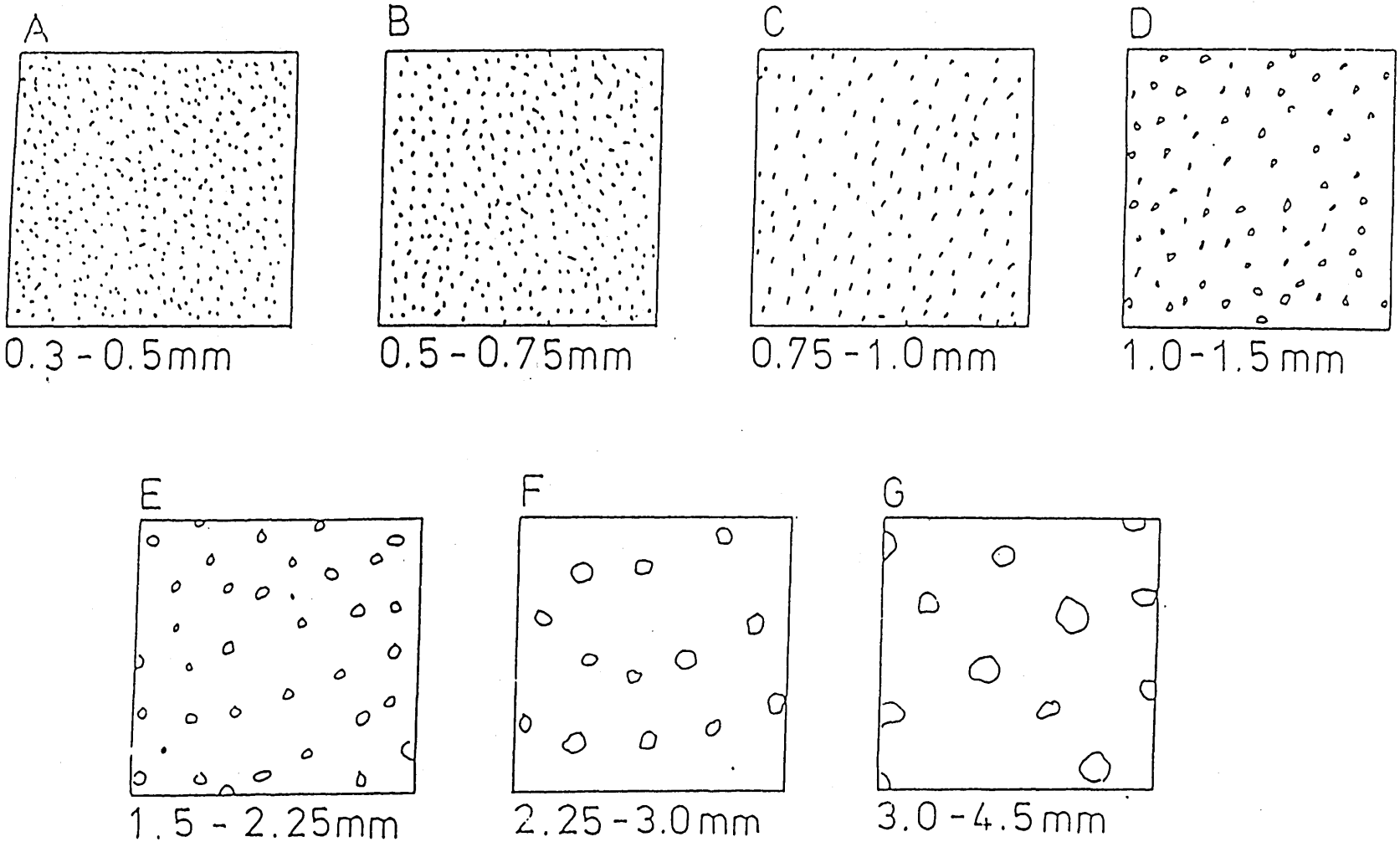


Chart 5.1 Floc Comparator for the Classification of Floc Produced in Coagulation Tests

Pass 100 produced the best percentage removal rates at an optimum dose of 3.5 mg/l. However over-dosing and under-dosing produced sharp increases in turbidity and aluminium residuals, as shown in Figure 5.4.

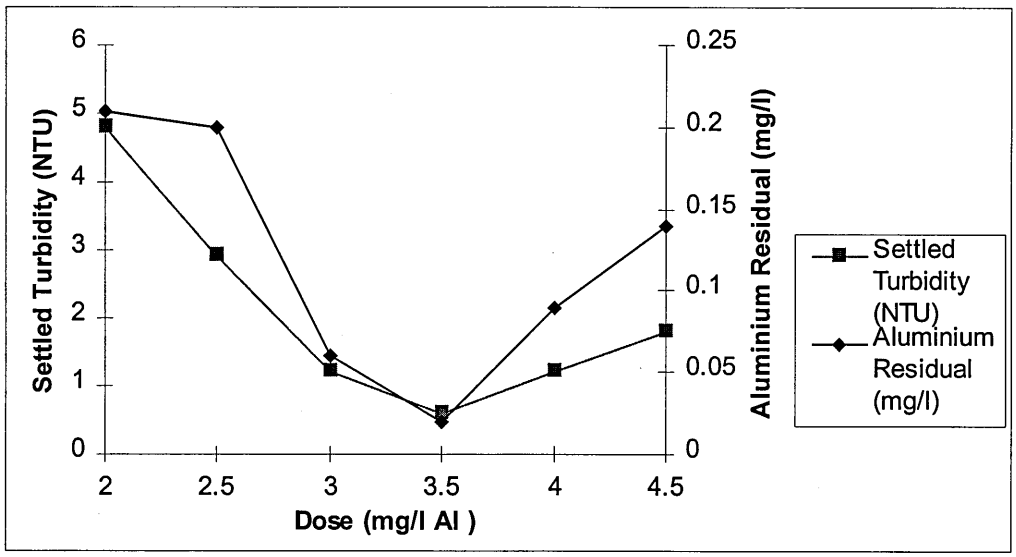


Figure 5.4 Jar Test: Pass 100 Settled Turbidity and Aluminium Residual

No significant difference was measured between settled aluminium residuals and turbidities for WTS PAC and INDA PAC (Figures 5.5 & 5.6). PAC produced high percentage removal rates for turbidity and low aluminium residuals at and away from the optimum dose of 3.5 mg/l.

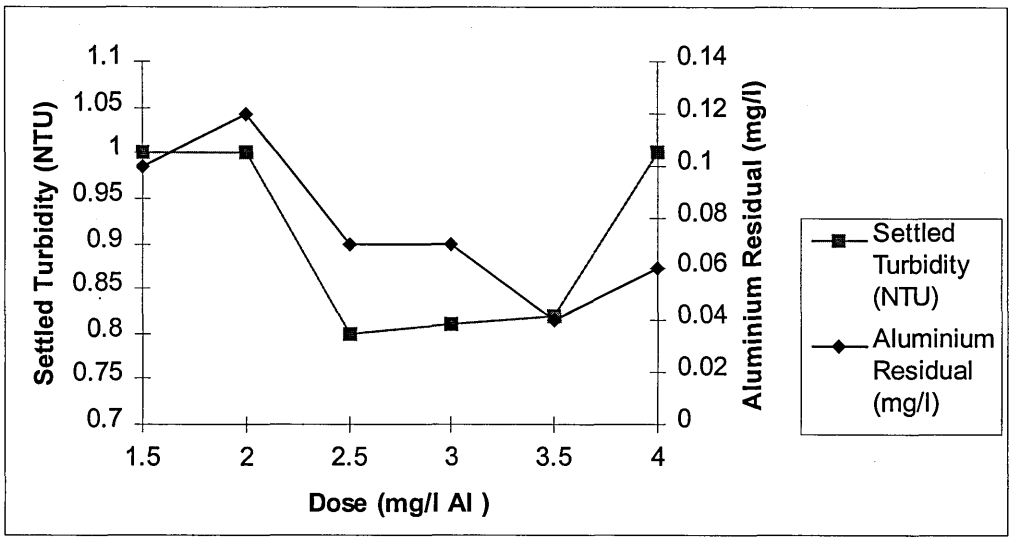


Figure 5.5 Jar Test WTS PAC Settled Turbidity and Aluminium Residual

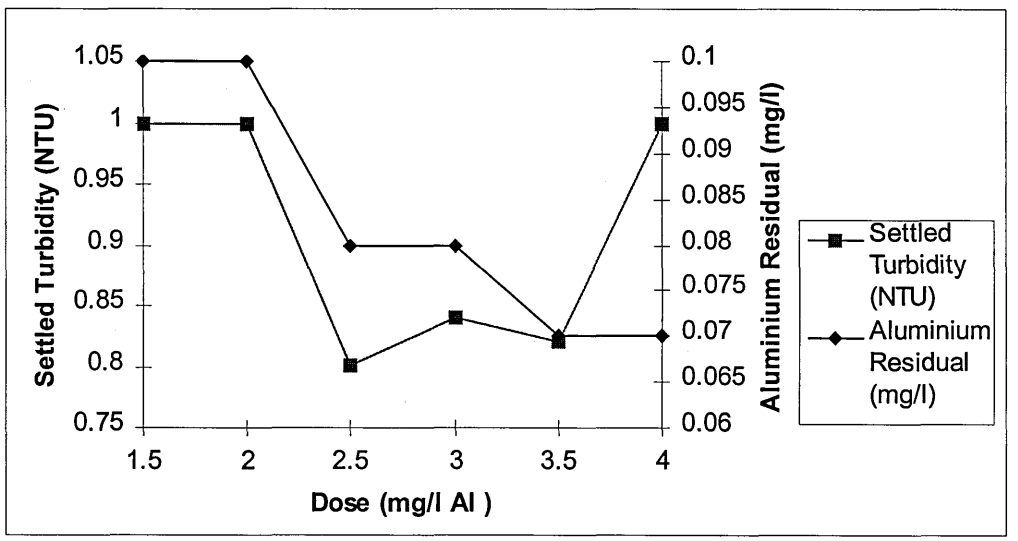


Figure 5.6 Jar Test INDA PAC Settled Turbidity and Aluminium Residual

The optimum dose for Alba 18 was often difficult to predict, due to poor floc floatation and poor settlement. However, Figure 5.7 Indicated that for Alba 18 the settled turbidities and aluminium residual concentrations were low and percentage removal rates high.

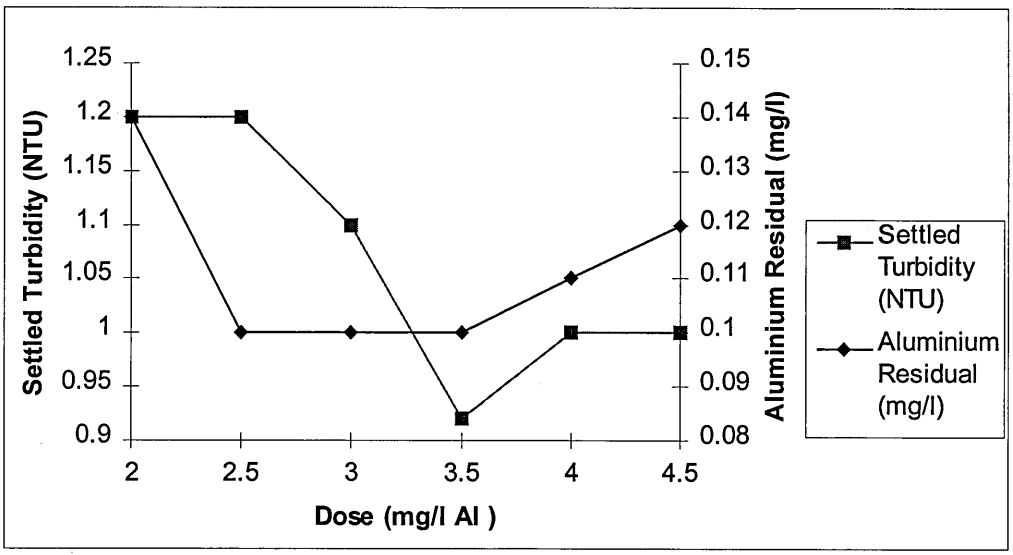


Figure 5.7 Jar Test: Alba 18 Settled Turbidity and Aluminium Residual

Alum produced good percentage removal rates for turbidity (0.85 NTU) at an optimum dose of 3.5 mg/l (Figure 5.8).

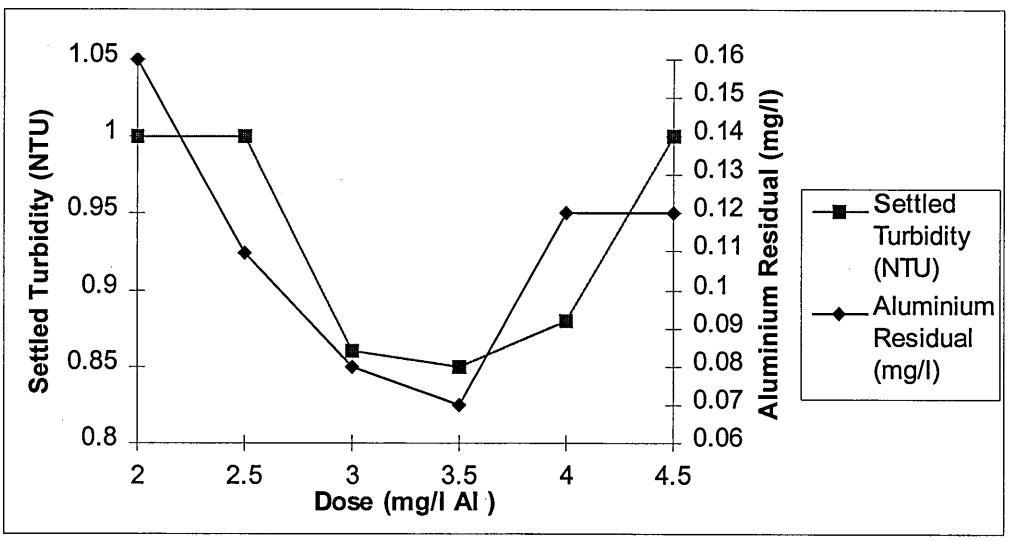


Figure 5.8 Jar Test: Alum Settled Turbidity and Aluminium Residual

Table 5.3 Settled Turbidities and Aluminium Residuals at Optimum Coagulant Doses for Pass 100, Alba 18, Alum and PAC (WTS & INDA) at 1.5 mg/l Pre-Ozone

Coagulant	Optimum Coagulant Dose (as Al)	Settled Turbidity (NTU)	Residual Aluminium (mg/l)
Pass 100	3.5	0.6	0.02
Alba 18	3.5	0.92	0.1
Alum	3.5	0.85	0.07
PAC (WTS)	3.5	0.82	0.04
PAC (INDA)	3.5	0.82	0.07

The best removals and lowest aluminium residuals were produced by the coagulants that produced the largest floc sizes and quickest settlement times. Larger flocs enhance particle removal by adsorption onto hydroxide flocs. The flocs that settle quickest will not be present in the supernatant drawn from the jar test. This is shown by Pass 100 producing the best settled water quality and Alba 18 the worst. The relative removal performances at optimum doses can be placed in descending order as follows:

Pass 100 > PAC > Alum > Alba 18

However, Pass 100 produced very high increases in turbidity and aluminium residuals when over-dosed and under-dosed. For practical reasons PAC gave the best removals at and away from the optimum coagulant dose of 3.5 mg/l (Figures 5.5 and 5.6), and was chosen as the optimum coagulant.

5.3.5 Polymer Addition

Jar tests were carried out on Pass 100, Alum, PAC (WTS & INDA) and Alba 18 with the addition of non-ionic LT20 polyelectrolyte. Polymer addition enhanced floc formation and settling rates when used with PAC and Alum. Floc sizes increased to 2.25 mm and

1.5 mm respectively (Chart 5.1). All the flocs settled within a 15 minute period for PAC and Alum.

The addition of LT20 non-ionic polymer had no effect on floc formation for Pass 100 and Alba 18. The floc sizes remained at 2.25 mm and 0.5 mm respectively in size. However it can it can be seen using Figures 5.9 & 5.10 that the addition of polymer increased settled turbidities and aluminium residuals for both Alba 18 and Pass 100.

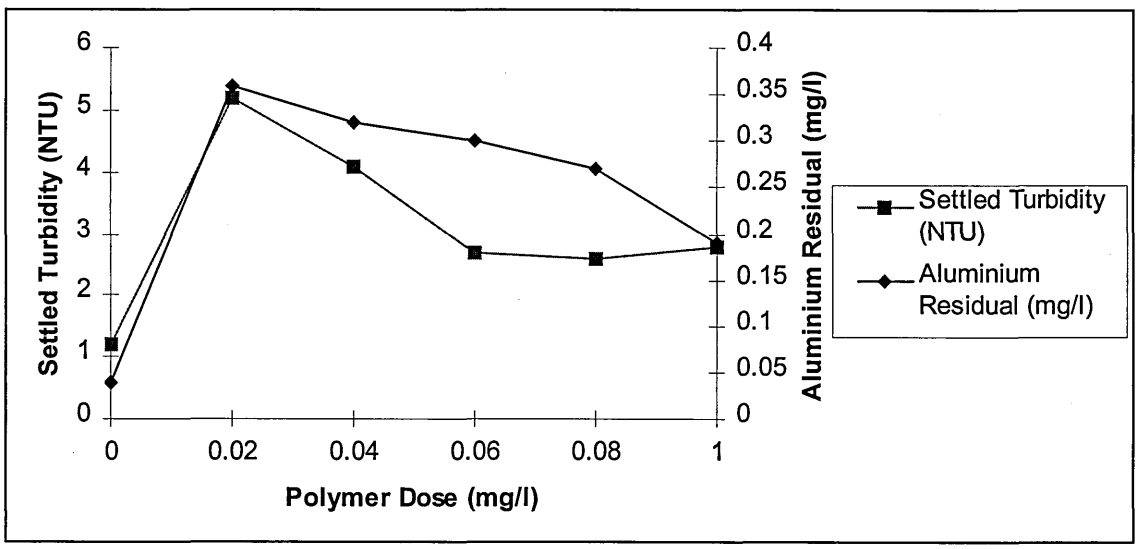


Figure 5.9 Jar Test: Pass 100 at Optimum Dose 3.5 mg/l and LT20, Settled Turbidity and Aluminium Residual

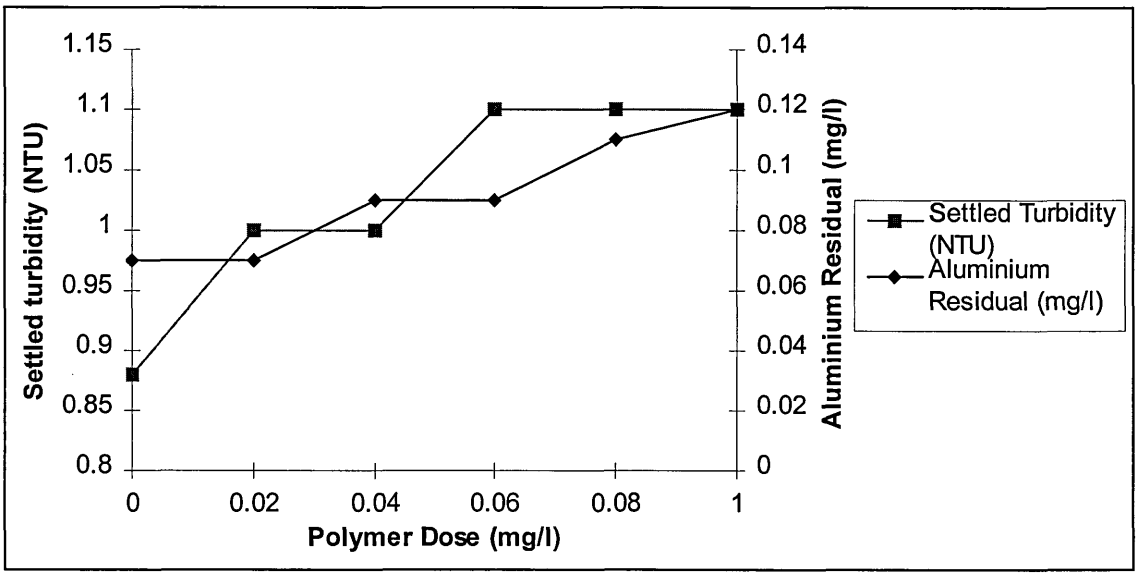


Figure 5.10 Jar Test: Alba 18 at Optimum Dose 3.5 mg/l and LT20, Settled Turbidity and Aluminium Residual

The addition of polymer to PAC, shown in Figures 5.11 and 5.12, improved turbidity removal by a further 0.2 NTU at an optimum polymer dose of 0.06 mg/l. No significant difference was identified between WTS and INDA PAC.

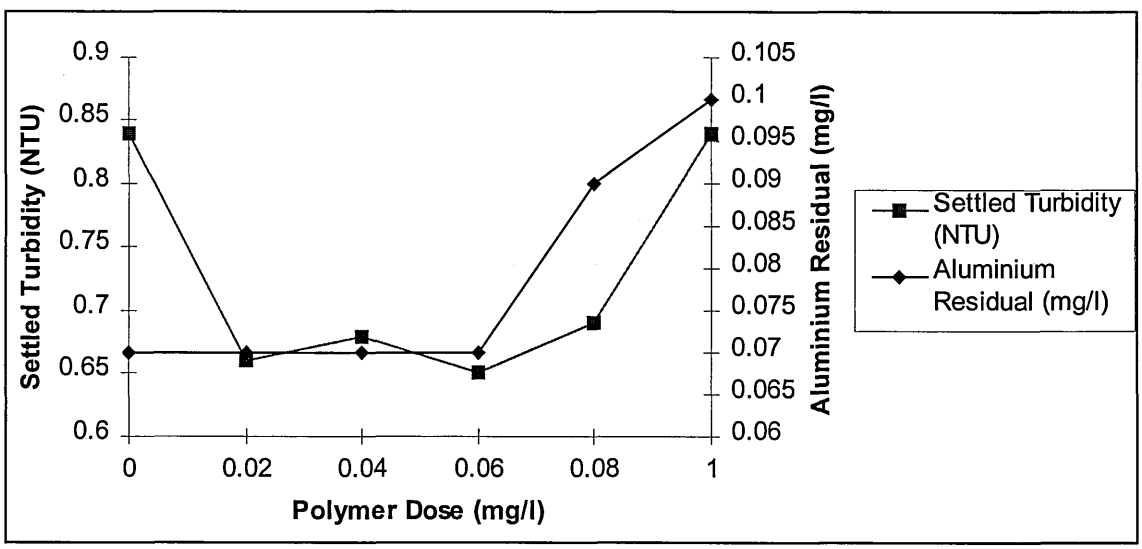


Figure 5.11 Jar Test: PAC (WTS) at Optimum Dose 3.5 mg/l and LT20, Settled Turbidity and Aluminium Residual

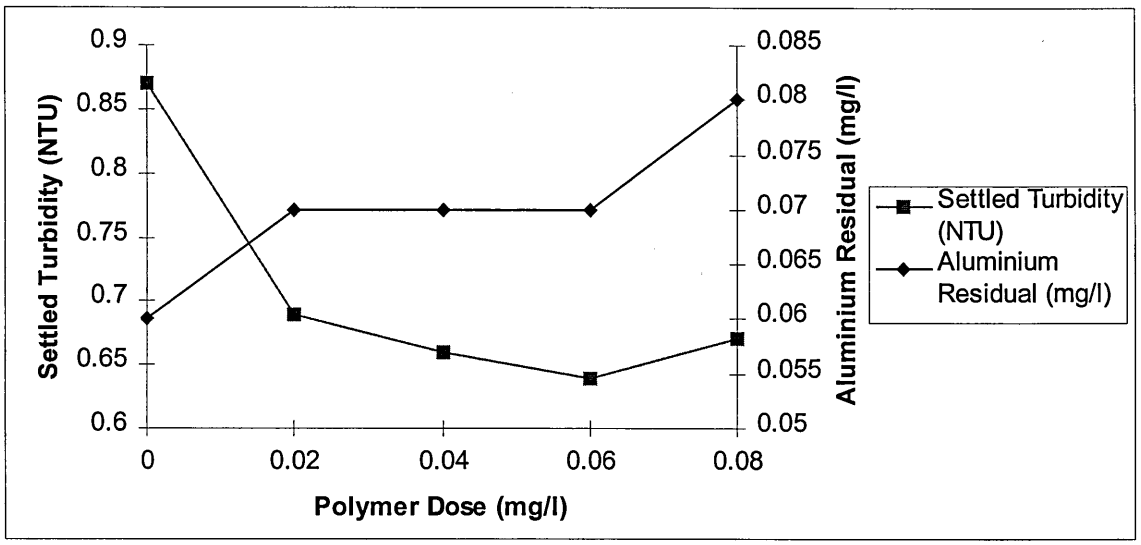


Figure 5.12 Jar Test: PAC (INDA) at Optimum Dose 3.5 mg/l and LT20, Settled Turbidity and Aluminium Residual

Alum also produced good removal rates at and away from the optimum dose. The addition of polymer to an optimum dose of 0.06 mg/l improved turbidity removal from 0.98 NTU to 0.7 NTU.

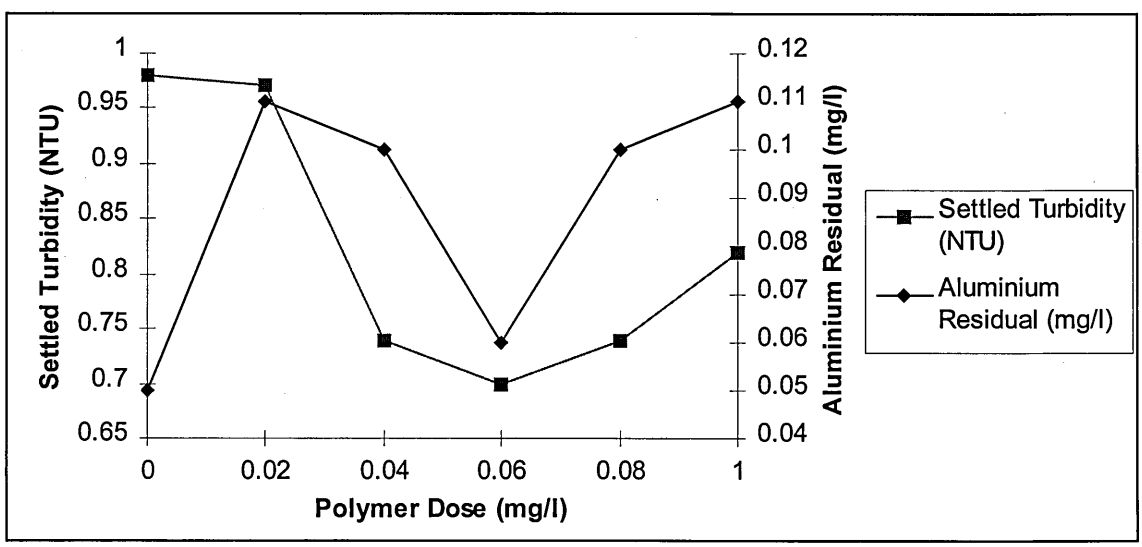


Figure 5.13 Jar Test: Alum at Optimum Dose 3.5 mg/l and LT20, Settled Turbidity and Aluminium Residual

The best removals were associated with PAC and Alum coagulants with the addition of 0.06 mg/l LT20 polymer (Table 5.4). The optimum coagulant dose however, remained as 3.5 mg/l. The floc sizes for PAC and Alum increased to 2.25 mm and 1.5 mm respectively enhancing removal by adsorption and quicker settling. This was not the case for Pass 100 and Alba 18. These pre-hydrolysed coagulants did not require LT20 polymer. At this stage Alba 18 was not considered further. Alba 18 showed poor floc formation, settlement and removal (Figures 5.7 & 5.10) and on the basis of these results could not be used as a coagulant at Burham prior to a sedimentation process.

Table 5.4 Settled Turbidities and Aluminium Residuals at Optimum Coagulant Doses for Pass 100, Alba 18, Alum and PAC (WTS & INDA) with LT20 polymer at a Pre-Ozone Concentration of 1.5 mg/l

Raw Water Quality: 10.5 NTU, pH 7.8, Al 0 mg/l				
Coagulant	Optimum Coagulant Dose (as Al)	Optimum Polymer Dose (mg/l)	Settled Turbidity (NTU)	Residual Aluminium (mg/l)
Pass 100	3.5	0	1.2	0.04
Alba 18	3.5	0	0.88	0.07
Alum	3.5	0.06	0.7	0.06
PAC (WTS)	3.5	0.06	0.65	0.07
PAC (INDA)	3.5	0.06	0.64	0.07

5.3.6 Coagulant Performance with Polymer Type and Dose

Two coagulants (Alum and PAC (INA)) were and subjected to further jar testing. Settled and filtered turbidities and aluminium residuals were measured to compare the polyelectrolyte, LT20, which is currently used at Burham against possible alternatives (LT22s and LT25). The test results are shown as percentage removals of settled turbidity,

as shown in Tables 5.5 & 5.6. The results of the tests involving LT20, LT22s and LT25 showed a high reduction of turbidity at and away from their optimum doses.

Table 5.5 Percentage settled turbidity removals of Alum with LT20, LT22s and LT25 Polyelectrolytes.

Raw Water Data: Turbidity = 6.4 NTU, pH = 8.0, Al = 0 mg/l				
PAC Dose (Opt. 3.5 mg/l Al^{3+})	Polymer	% Reduction (NTU) Polymer Dose (mg/l)		
		-25%	Optimum	25% +
25% +	LT20	n/a	94	n/a
Optimum		94	94	94
25% -		n/a	94	n/a
25% +	LT22s	n/a	89	n/a
Optimum		90	90	90
25% -		n/a	90	n/a
25% +	LT25	n/a	88	n/a
Optimum		88	88	88
25% -		n/a	88	n/a

Table 5.6 Percentage settled turbidity removals of PAC with LT20, LT22s and LT25 Polyelectrolytes.

Raw Water Data: Turbidity = 6.4 NTU, pH = 8.0, Al = 0 mg/l				
Alum Dose (Opt. 3.5 mg/l Al^{3+})	Polymer	% Reduction (NTU) Polymer Dose (mg/l)		
		-25%	Optimum	25% +
25% +	LT20	n/a	93	n/a
Optimum		93	94	93
25% -		n/a	93	n/a
25% +	LT22s	n/a	88	n/a
Optimum		85	90	89
25% -		n/a	88	n/a
25% +	LT25	n/a	86	n/a
Optimum		87	88	88
25% -		n/a	86	n/a

Non-ionic LT20 polymer is the current and correct polyelectrolyte to be used with Alum and PAC coagulants at Burham. It can be clearly seen using Tables 5.5 & 5.6 that LT20 produced the highest percentage removals above, below and at optimum polymer and

coagulant doses. The cationic LT22s polymer gave good turbidity removals but was out performed by LT20. LT25 anionic polymer showed to be the least effective coagulant aid, and gave the lowest removal rates throughout the coagulant/polymer combinations. The use of a polymer at Burham is necessary due to problems with floc shear. Burham is currently and correctly using the non-ionic LT20 polymer as a flocculating aid.

5.4 Phase 2: Coagulant Selection and Performance for Pilot Trails

Jar tests for Pass 100, Alum and PACl (WTS & INDA) performance were carried out at ambient temperature (10 – 13 ^{0}C), and at pre-ozone concentrations of 0.5, 1.0, 1.5 and 2.0 mg/l. Jar tests at each ozone concentration were carried out at pHs of 6.8, 7.0, 7.2, 7.4, 7.6 and 8.0. The jar tests were carried out to obtain the optimum doses and optimum pH for the coagulants Pass 100, Alum, and PAC (WTS & INDA), for pilot plant trials.

The tests that recorded the lowest measured values for settled and filtered aluminium residuals and turbidities, at optimum pH are summarised in Tables 5.7 to 5.10 below. Raw water data can be found in Appendix 2. The coagulant doses with the highest optimum pH, settled/filtered water turbidity removal rates and lowest aluminium residual were selected as the optimum and applied to pilot plant.

Table 5.7 Alum, Pass 100, and PAC (WTS & INDA) with 0.06 mg/l LT20 Polymer, at Optimum pH, Coagulant Dose and 0.5 mg/l Pre-Ozone.

Coagulant	Dose (mg/l)	pH	Turbidity (NTU)		Removal %		Aluminium (mg/l)		Removal %	
			Settled	Filtered	Settled	Filtered	Settled	Filtered	Settled	Filtered
Alum	3.5	7.2	0.44	0.38	88	90	0.06	0	- / -	- / -
Pass 100	4	7.6	1	1	92	93	0.08	0	- / -	- / -
PAC (WTS)	3.5	7.4	0.51	0.44	95	96	0.04	0	- / -	- / -
PAC (INDA)	3.5	7.6	0.48	0.46	95	96	0.07	0	- / -	- / -

Table 5.8 Alum, Pass 100, and PAC (WTS & INDA) with 0.06 mg/l LT20 Polymer, at Optimum pH, Coagulant Dose and 1.0 mg/l Pre-Ozone.

Coagulant	Dose (mg/l)	pH	Turbidity (NTU)		Removal %		Aluminium (mg/l)		Removal %	
			Settled	Filtered	Settled	Filtered	Settled	Filtered	Settled	Filtered
Alum	3.5	7.2	0.6	0.54	95	96	0	0	- / -	- / -
Pass 100	6	7.4	0.51	0.35	95	97	0	0	- / -	- / -
PAC (WTS)	3	7.4	0.62	0.53	95	96	0	0	- / -	- / -
PAC (INDA)	3	7.4	0.6	0.5	95	96	0	0	- / -	- / -

Table 5.9 Alum, Pass 100, and PAC (WTS & INDA) with 0.06 mg/l LT20 Polymer, at Optimum pH, Coagulant Dose and 1.5 mg/l Pre-Ozone.

Coagulant	Dose (mg/l)	pH	Turbidity (NTU)		Removal %		Aluminium (mg/l)		Removal %	
			Settled	Filtered	Settled	Filtered	Settled	Filtered	Settled	Filtered
Alum	3	7.2	1.1	0.97	92	93	0.02	0	- / -	- / -
Pass 100	4.5	7.2	0.6	0.51	95	96	0.07	0	- / -	- / -
PAC (WTS)	3	7.4	0.35	0.31	93	94	0	0	- / -	- / -
PAC (INDA)	3	7.4	0.37	0.31	93	94	0	0	- / -	- / -

Table 5.10 Alum, Pass 100, and PAC (WTS & INDA) with 0.06 mg/l LT20 Polymer, at Optimum pH, Coagulant Dose and 1.0 mg/l Pre-Ozone.

Coagulant	Dose (mg/l)	pH	Turbidity (NTU)		Removal %		Aluminium (mg/l)		Removal %	
			Settled	Filtered	Settled	Filtered	Settled	Filtered	Settled	Filtered
Alum	3	7.2	0.62	0.43	85	89	0.06	0	- / -	- / -
Pass 100	3.5	7.6	1	0.82	92	93	0.09	0	- / -	- / -
PAC (WTS)	2.5	7.4	0.6	0.33	88	96	0	0	- / -	- / -
PAC (INDA)	2.5	7.4	0.6	0.34	88	96	0	0	- / -	- / -

The results of the jar tests show that both Pass 100 and PACl produced the highest turbidity removal rates throughout. PAC produced the lowest settled aluminium residuals and pass 100 produced the highest settled aluminium residuals. Both PAC and Pass 100 produced the best filtrate qualities, which would consequently reduce the solid loads on the RGF's and backwash frequencies. Optimum percentage removal of turbidity was recorded at pre-ozone concentrations of 1.0 and 1.5 mg/l. Significantly however, it can be seen using Table 5.8 that the lowest turbidity removal rates were not observed at an ozone dose of 2.0 mg/l of ozone, the pre-ozone concentration currently used at Burham.

5.5 Acid Dosing

Acid dosing with a pH of 7.4 and 7.6, enhanced flocculation, increased floc size and settling rates and solid removals for PAC, Pass 100 and Alum. As the pH decreased below the optimum for a given coagulant, as expected the removals, floc sizes and settlement rates consistently and proportionally. Based on these results, pH 7.3 and 7.5 were chosen for the acid trials on the pilot plant clarifier, as pH 7.3 and 7.5 can be measured more accurately by the full-scale pH meters.

5.6 Phase 3: Combined Effect of Pre-Ozonation and Clarification on TOC and Turbidity Removal on Pilot Plant Clarifier

Burham currently operates with pre-ozone due to the presence of high concentrations of pesticides. Burham will continue to operate with pre-ozonation. The coagulant doses predicted by the jar tests were applied to the pilot plant. Pilot plant testing of Alum, Pass 100, and PAC (WTS & INDA) at pre-ozone concentrations of 0.5, 1.0, 1.5 and 2.0 mg/l is required to find the effect of pre-ozonation on coagulant dose and performance.

TOC and turbidity removal across the pilot clarifier for both Alum and PAC is shown in Figure 5.14 below. Raw water data for pilot plant clarifier can be found in Appendix 2.

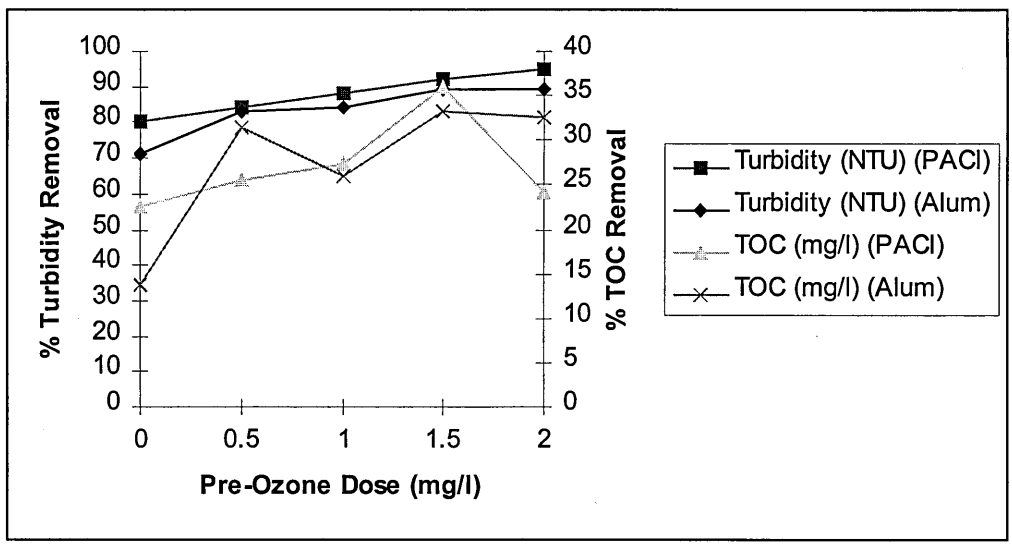


Figure 5.14 TOC and Turbidity Percentage Removals by Aluminium Sulphate and PAC at Optimum Dose of 3.5 mg/l, at Pre-Ozone Concentrations of 0, 0.5, 1.0, 1.5, and 2.0 mg/l for the Pilot Clarifier Trials.

The use of pre-ozone treatment combined with coagulation treatment improved TOC and turbidity removal as the pre-ozone concentration increased. The optimum TOC removals were obtained at a pre-ozone dose of 1.5 mg/l with an optimum Alum dose of 3.5 mg/l. No significance in turbidity and TOC removal occurred beyond 1.5 mg/l. For economic and performance reasons, it was therefore preferable to adopt a pre-ozone dose of 1.5 mg/l for the remainder of the tests.

Table 5.11 Summary of TOC and Turbidity Reduction by Alum, PAC, and Pass 100 at Optimum Coagulant Doses of 3.5 mg/l with a Pre-Ozone Concentration of 1.5 mg/l.

Coagulant	Dose (mg/l) as Al	% TOC Removal	% Settled Turbidity Removal
Alum	3.5	33 (18)	89 (54)
PAC (WTS)	3.5	36 (17)	92 (67)
PAC (INDA)	3.5	25	90
Pass 100	3.5	17	89

(The results in brackets show the percentage removals with unozonated water).

With and without pre-ozonation, no significant difference occurred between Alum and PAC in TOC removal. With and without pre-ozonation, PAC showed higher turbidity removals than Alum. The addition of pre-ozone at 1.5 mg/l increased TOC and turbidity removals for Alum by 15 % and 35 % receptively, and PAC by 19 % and 25 %. Unozonated tests on Pass 100 and INDA PAC were not carried out due to time constraints. However, the results for Pass 100 and INDA PAC in Table 5.11 show the same results as in the jar test results in Table 5.9. Tables 5.11 and 5.9 show that for the same dose, higher turbidity removals occurred with the use of pre-hydrolysed coagulants.

5.6.1 Polymer Effect on Coagulant Performance

Pilot plant trials were carried out on non-ionic LT20 polyelectrolyte to investigate if the addition of polymer improves solids removal at a given coagulant dose, at ambient pH and temperature.

As previously stated in section 5.3.6 Burham has problems with floc shear and the use of polymer on the full-scale plant is required. The effects of polymer on coagulant performance with (0.06 mg/l) and without polymer addition on each coagulant tested at optimum 3.5 mg/l (as Al^{3+}) on a number of typical determinants, are summarised below in Table 5.12 as percentage removed.

Table 5.12 Effects of Polyelectrolyte Addition on Coagulant Performance at a Pre-Ozone Concentration of 1.5 mg/l on Pilot Plant Clarifier.

Parameter (% Removal)	PAC		WTS		PAC		INDA		PASS 100		Alum	
	No LT20		Opt. LT20		No LT20		Opt. LT20		No LT20	Opt. LT20	No LT20	Opt. LT20
TOC	19		31		19		25		17	19	36	39
Settled Turbidity	61		93		93		94		89	83	63	87
Chlorophyll a	85		64		85		65		90	42	80	71
Colour	83		71		89		53		78	52	85	82
DOC	20		32		19		25		16	21	64	40
Iron	17		68		32		93		75	85	79	93
Manganese	41		48		79		85		64	83	60	81
Pesticide	77		79		65		61		42	50	71	60

By determining the optimal dose for Alum, Pass 100, and PAC (WTS & INDA), insight into the following effects of polymer addition can be gained:

1. The addition of LT20 polymer improved the removal of turbidity, TOC, DOC, iron and manganese for PAC (WTS and INDA).
2. Alum with LT20 produced the highest TOC (39%), colour (82% and DOC (40%) removals, contradictive to the jar test results in section 5.3.4, where PAC produced the highest removal rates.
3. The addition of LT20 to Pass 100, had no significant effect in improving removals for TOC, DOC, manganese and iron, but decreased turbidity, chlorophyll and colour removals.
4. The addition of LT20 decreased colour and chlorophyll removals for all 4 coagulants.
5. No significant difference was observed between WTS and INDA PAC for TOC, settled turbidity, chlorophyll and colour removals. However INDA PAC produced 93 % and 85 % removals for iron and manganese, higher than that for WTS PAC, of 68 % and 48 % respectively.
6. The variety of effects arising from polymer addition, indicate that it is vital to optimise the polymer and coagulant doses, since the performance of the coagulants are dependent upon the exact dose applied.

The effect of having a sub-optimal coagulant dose on final water quality has been investigated on the pilot clarifier with pre-ozonated water at a dose of 1.5 mg/l with 0.06 mg/l LT20. A number of typical determinants were measured to investigate whether the optimum coagulant dose is reduced with the addition of polymer, at ambient pH and temperature.

Table 5.13 Effects of Coagulant Dose Reduction and Performance at Optimum (3.5 mg/l as Al^{3+}) and Sub-Optimum (2.8 mg/l as Al^{3+}) Concentrations with LT20 Polyelectrolyte (0.06 mg/l) at a Pre-ozone Dose of 1.5mg/l.

	PAC	WTS	PAC	INDA	PASS 100		Alum	
Parameter	-25	Opt.	-25	Opt.	-25	Opt.	-25	Opt.
TOC	49	30	28	25	20	19	25	38
Settled Turbidity	90	93	90	94	77	83	60	87
Chlorophyll a	92	64	96	64	89	42	87	70
Colour	90	71	38	53	46	52	27	82
DOC	50	32	26	25	17	21	25	39
Iron	83	68	90	93	82	85	73	93
Manganese	50	48	84	85	92	83	70	81
Pesticide	50	79	72	61	52	50	61	59

PAC (WTS & INDA) removals increased with a sub-optimum PAC coagulant dose of 2.8 mg/l. This indicates the optimum PAC coagulant dose with LT20 is lower than the coagulant dose indicated by the jar tests in Table 5.4 This suggests the addition of LT20 polymer improved solids removal by adsorption onto hydroxide flocs.

This was not the case for Alum. A reduction in coagulant dose resulted in a reduction in removals. This suggests that the addition of polymer did not compensate for the reduction in coagulant dose and that there was not sufficient coagulant present at the sub-optimum dose to neutralise the colloidal anionic charge present in the water. No significant difference in TOC, DOC and metal removals occurred with a sub-optimal Pass 100 coagulant dose, as expected, and observed with the jar tests results in Tables 5.3 and 5.4.

5.7 Effect of pH on Coagulant Performance

Whilst there are differences between coagulant performances, the effects of pH on Al solubility are similar. A reduction in pH was investigated on Pass 100, Alum and PAC (WTS & INDA) at optimum coagulant doses of 3.5 mg/l with polymer (0.06mg/l) to find out if coagulant performance improves at lower optimum pHs, as indicated by the jar tests in section 5.4, Table 5.9.

Table 5.14 Effects of Acid Dosing to pH 7.5 on Coagulant Performance at Optimum (3.5 mg/l as Al^{3+}) and Sub-Optimum (2.8 mg/l as Al^{3+}) Concentrations at a Pre-Ozone Dose of 1.5 mg/l.

	PAC	WTS	PAC	INDA	PASS 100		Alum	
Parameter	-25%	Opt.	-25%	Opt.	-25%	Opt.	25%	Opt.
TOC	26	36	21	25	27	23	No Data	31
Settled Turbidity	81	92	88	84	86	78	85	87
Chlorophyll a	82	90	94	94	91	81	53	87
Colour	78	83	72	84	49	37	69	81
DOC	27	40	23	24	17	24	4	25
Iron	80	81	84	88	85	82	60	90
Manganese	90	53	72	71	68	68	49	69
Pesticide	48	58	55	56	42	42	63	41

Table 5.15 Effects of Acid Dosing to pH 7.3 on Coagulant Performance at Optimum (3.5 mg/l as Al^{3+}) and Sub-Optimum (2.8 mg/l as Al^{3+}) at a Pre-Ozone Dose of 1.5 mg/l.

	PAC	WTS	PAC	INDA	PASS 100		Alum	
Parameter	-25%	Opt.	-25%	Opt.	-25%	Opt.	25%	Opt.
TOC	29	21	17	21	17	19	18	29
Settled Turbidity	85	94	80	82	39	79	89	91
Chlorophyll a	94	86	73	90	76	92	96	88
Colour	90	81	88	79	70	77	90	92
DOC	31	19	12	21	16	18	20	30
Iron	76	74	75	76	77	88	79	90
Manganese	45	53	63	72	58	73	80	73
Pesticide	54	53	55	24	38	52	57	73

An increase in percentage solid removals directly resulted from a decrease in pH. PAC, Pass 100 and Alum produced the highest removals at their optimum coagulant doses of 3.5 mg/l. Optimum removals were observed at pH 7.5 for PAC and Pass 100 and at a lower pH of pH 7.3 for Alum, as observed in the jar tests in section 5.4. PAC produced the highest removals and best filtrate qualities. WTS PAC produced slightly greater TOC removals than INDA. However, no significant difference was observed with the reminding parameter removals shown in Table 5.12. Pass 100 removals at the optimum dose of 3.5 mg/l and at pH 7.5 were improved with the addition of acid, but was out-performed by PAC and Alum.

The addition of acid was to investigate whether solids removal was improved. In general this was not the case for Pass 100 and Alum. However For, with WTS PAC a further 6 % reduction in TOC, 8 % in DOC, 13 % in iron, and a 5% reduction in manganese was measured.

Table 5.16 Effects of Acid Dosing on Coagulant Performance at Optimum (3.5 mg/l) Dose with 0.06 mg/l Polymer at a Pre-Ozone Concentration of 1.5 mg/l from Table 5.14 and 5.15.

	Parameter (Percentage Removed)					
Coagulant and pH	TOC	Settled Turbidity	Colour	DOC	Iron	Manganese
PAC (WTS) (Ambient pH)	30	93	71	32	68	48
PAC (INDA) (Ambient pH)	25	94	53	25	93	85
Pass 100 (Ambient pH)	19	83	52	21	85	83
Alum (Ambient pH)	38	87	82	39	93	81
PAC (WTS) (Optimum pH)	36	92	83	40	81	53
PAC (INDA) (Optimum pH)	25	84	84	24	88	71
Pass 100 (Optimum pH)	23	78	37	24	82	68
Alum (Optimum pH)	29	91	92	30	90	73

5.7.1 Algal Removal

The effects of pre-ozonation and clarification on algal removal were investigated to find the optimum coagulant for algal removal. Algal removal was measured directly from algal count data and indirectly from chlorophyll and phaeophytin data. The percentage removals of each of the four coagulants tested at optimum doses at ambient and optimum pH on the pilot clarifier are given in Table 5.17. The numbers shown in the brackets refer to percentage removals without pre-ozonation where available.

Table 5.17 Algal Removal by Alum, Pass 100, and PAC (WTS & INDA) at Optimum Doses (3.5 mg/l) and Ambient and Optimum pH with polymer (0.06 mg/l), at a Pre-Ozone Concentration of 1.5 mg/l

Coagulant	Dose (mg/l as Al^{3+})	pH	% Algal Reduction	% Chlorophyll Reduction	% Phaeophytin Reduction
Alum	3.5	8.2	93 (47)	71 (49)	94 (70)
PAC WTS	3.5	8	61 (*)	64 (12)	no data (43)
PAC INDA	3.5	8.1	79	94	93
Pass 100	3.5	8.2	73	77	94
Alum	3.5	7.3	93	88	93
PAC WTS	3.5	7.5	*	81	78
PAC INDA	3.5	7.5	79	95	94
Pass 100	3.5	7.5	83	81	88

Note: - * means the concentration was below detection limits. Exact calculations of removals were not possible.

The pH is not significant in algal removal. The addition of pre-ozone at 1.5 mg/l greatly enhanced algal removals for all the coagulants tested. The effect of pre-ozone had its own effect on algal removal, in addition to coagulant removal. With pre-ozone, Alum produced the highest algal removals of 93 % compared to 79 % by INDA PAC and 73 % and 79% by Pass 100.

5.7.2 Effect of Pass 100, Alum and PAC (WTS & INDA) On Iron and Manganese Removal and Coagulant Residual

Iron and manganese concentrations are subject to seasonal fluctuations (Figure 5.1). PCV limits are 200 and 50 μg/l respectively, therefore Pass 100, Alum and PAC (WTS & INDA) were investigated to find the coagulant and pH that produced the highest metal removals. The figures in brackets in Table 5.16 represent the data without pre-ozone.

Table 5.18 Residual Aluminium and Iron and Manganese Removal by Alum, Pass 100 and PAC (WTS & INDA) Coagulants with Polymer (0.06 mg/l), at Optimum Doses (3.5 mg/l) and Ambient and Optimum pH with 1.5 mg/l Pre-Ozonated Water

Coagulant	Dose (mg/l as Al^{3+})	pH	% Total Iron Reduction	% Total Manganese Reduction	Aluminium Residual (mg/l)
Alum	3.5	8.2	94 (70)	82 (64)	0.5 (0.8)
PAC WTS	3.5	8	69 (10)	52 (3)	1.2 (1.6)
PAC INDA	3.5	8.1	93	85	0.5
Pass 100	3.5	8.2	87	78	0.6
Alum	3.5	7.3	90	73	0.6
PAC WTS	3.5	7.5	80	51	1
PAC INDA	3.5	7.5	88	73	0.6
Pass 100	3.5	7.5	83	62	0.9

Metal removals for each coagulant were not significantly effected by pH (Table 5.18). The addition of pre-ozone however, has significantly improved metal removal. For PAC (WTS) and Alum ozone has improved iron removal by 59% and 24%, manganese removal by 49 % and 18 % respectively. This implies that manganese and iron are more amenable to removal by PAC than Alum.

INDA PAC showed greater reduction in iron and manganese concentrations by 8 and 22 % to that of WTS PAC at pH 7.5. Reasons for this remain unclear.

PAC WTS produced a higher quantity of scum, which could have increased the aluminium residual concentration by carry over, producing the high residuals of 1 and 1.2 mg/l.

5.8 Effect of Pre-Ozonation at 0.5, 1.0, 1.5 and 2.0 mg/l On Pesticide Removal

The use of pre-ozonation at Burham is primarily due to the presence of pesticides in the raw water (Figure 5.1). Different pre-ozone concentrations of 0.5, 1.0, 1.5 and 2.0 mg/l were dosed to investigate which pre-ozone concentration produced the highest pesticide removals. The percentage removals for three main groups of pesticides tested during this project at 0.5, 1.0, 1.5 and 2.0 mg/l pre-ozone concentrations are shown in Figure 5.15.

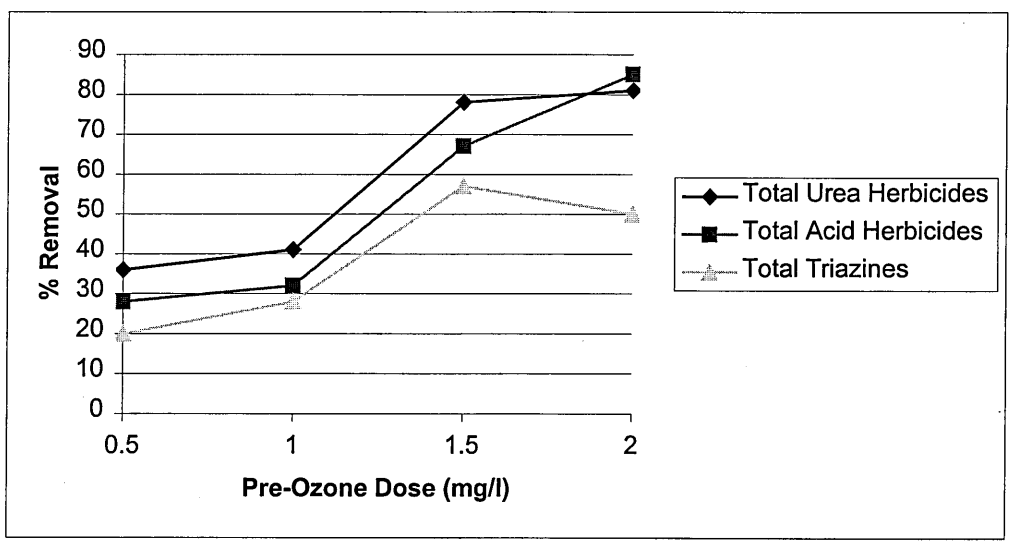


Figure 5.15 Effect of Pre-Ozone Doses 0.5, 1.0, 1.5 and 2.0 mg/l on the Removal of Total Urea Herbicides, Total Acid Herbicides and Total Triazines

Pesticide removals increased with increasing pre-ozone concentrations. Total urea herbicides are more susceptible to ozonation than total acid herbicides and total triazines. The highest pesticide removals occurred at a pre-ozone dose of 2.0 mg/l. However, the total pesticide removal after 1.5 mg/l was only slightly greater than at 2.0 mg/l, and the optimum pre-ozone dose was economically taken as 1.5 mg.l. Despite this, Figure 5.15 demonstrated that pre-ozonation alone was sufficient to remove approximately 70 % (1.5 mg/l pre-ozone dose) of total pesticides.

5.9 Pass 100, Alum, and PAC (WTS & INDA) Performance Rankings

The performance of each coagulant was compared using the same dosing conditions to summarise and obtain an optimum coagulant to be used on Burham full scale plant. The scores shown in Tables 5.19 and 5.20 represent the performance of the coagulant in the removal of the particular parameter. The scores are scaled 1 to 5 to summarise not only in terms of one being better than the other, but also the size of the difference. 1 represents very poor removal and 5 high removal.

Table 5.19 Rankings Given to WTS PAC, INDA WTS, Pass 100 and Alum based on Relevant Water Quality Parameters Under Optimum, Sub-Optimum and pH Conditions.

	WTS PAC			INDA PAC			PASS 100			ALUM		
	Opt. pH 8.0+	Opt. pH 7.5	Under Dose	Opt. pH 8.0+	Opt. pH 7.5	Under Dose	Opt. pH 8.0+	Opt. pH 7.5	Under Dose	Opt. PH 8.0+	Opt. pH 7.5	Under Dose
Parameter	Score	Score	Score	Score	Score	Score	Score	Score	Score	Score	Score	Score
TOC	3	4	3	2	2	2	1	2	3	4	4	1
Turbidity	4	4	3	4	3	4	3	2	4	3	3	3
Colour	3	4	3	3	4	4	2	1	2	3	3	4
Algae	1	3	2	2	3	3	2	3	2	3	3	3
Chlorophyll	1	3	2	4	5	4	3	3	2	2	2	3
Phaeophytin	4	3	4	3	3	3	4	3	4	4	4	3
Total Iron	3	3	3	3	3	3	3	3	3	4	4	3
Total Mn	2	2	2	3	3	3	3	2	3	3	3	3
Residual Al	1	1	2	2	2	2	2	1	3	2	2	3

An overall measure of the best performing coagulant was obtained by entering the above data into a spreadsheet, shown in Appendix 2. The spreadsheet gives rankings from 1 - 4 and removal performances from 1 – 5. The final scores from Table 5.19 are present in Table 5.20.

Table 5.20 Summary of Alum, Pass 100 and PAC (WTS & INDA) Total Score From Table 5.19 at Ambient pH, Optimum pH and at –25% Sub-Optimum Coagulant Dose at Optimum pH.

Coagulant	Ambient pH	Optimum pH	-25% Sub-Optimum Coagulant Dose at Optimum pH	Total
WTS PAC	22	27	24	73
INDA PAC	26	28	32	86
Pass 100	23	23	26	72
Alum	28	28	26	82
Total	99	106	108	

Acid dosing prior to coagulant addition indicated INDA PAC and Alum as the coagulants with the highest overall removals. A reduction in the coagulant dose to a –25% sub-optimum dose, with INDA PAC produced the highest score (32). INDA PAC produced the highest total scores (86) indicating that acid dosing at Burham should use the coagulant INDA PAC.

5.10 Comparison of Jar Test Results with Pilot Clarifier Results

The jar test procedure at Burham is different than a conventional jar test procedure, as described in section 4.0. The jar test procedure used solely at Burham has been modified to provide a more accurate jar test procedure that produces an optimum coagulant dose for the full-scale plant. Data from the pilot clarifier and from a subsequent jar test is shown in Figure 5.16 to evaluate the accuracy of the Burham jar test procedure.

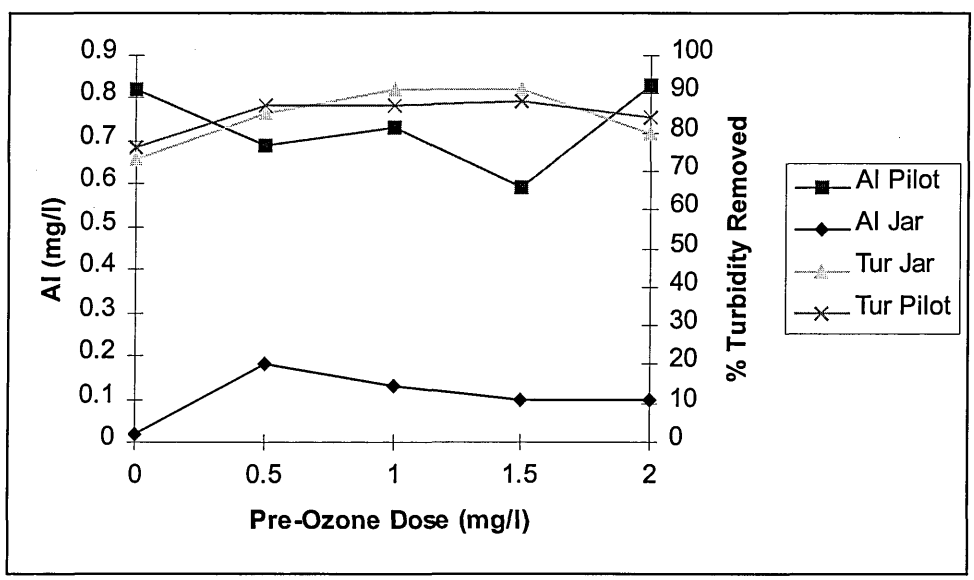


Figure 5.16 Comparison of Jar Test and Pilot Clarifier Settled Water Quality

Turbidity removals from the pilot clarifier and jar tests were within ±1%. The highest turbidity removals occurred at a pre-ozone concentration of 1.5 mg/l. The aluminium

residuals in Figure 5.16 from the clarifier and jar tests produced very different results. This was due to the different procedure for testing aluminium concentrations between jar tests and pilot clarifier.

5.11 Phase 4: Coagulant Dose Prediction

In order to assess the prediction of the coagulant dose by the AC 250, the jar testing procedure described in Section 4.0 was followed, initially using raw water samples and then from pre-ozonated water from Burham WTW. The AC250 uses the plant pH meter and an in-built turbidimeter and colourimeter with a unique algorithm to predict an optimum coagulant dose. The turbidity and pH measurements were monitored by laboratory means and plotted in Figures 5.17 and 5.18 Respectively with the coagulant dosed on the plant with the AC250 data to assess the accuracy of the AC250 turbidimeter and plant pH meter.

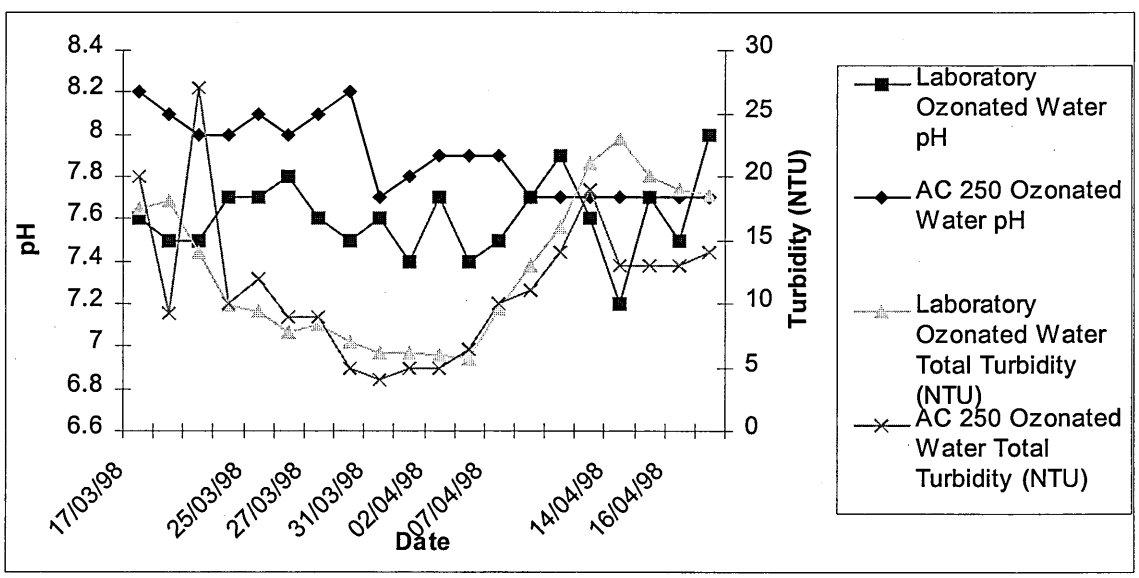


Figure 5.17 pH and Turbidity Measurements for WTS PAC by Laboratory and AC 250 During 17/03/98 – 17/04/98.

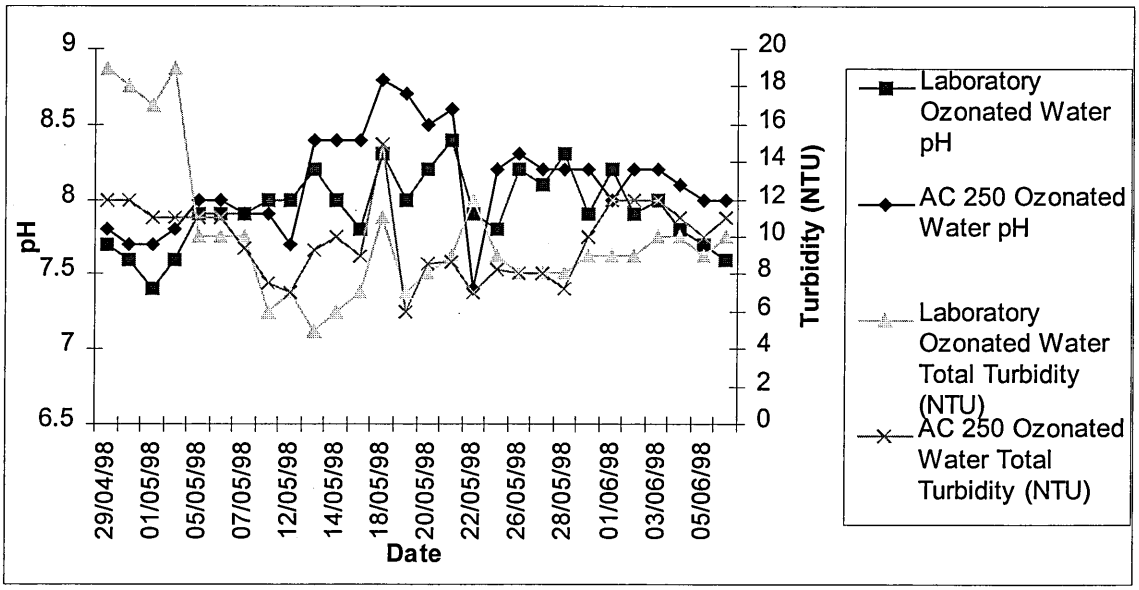


Figure 5.18 pH and Turbidity Measurements for Alum by Laboratory and AC 250 During 29/04/98 – 09/06/98.

The tests show that the AC 250 system values produced by the monitors were comparable with routine laboratory turbidity measurements performed during the trial periods for PAC and Alum. However, significant differences in pH readings were observed throughout the period of testing which could be attributed to the calibration of the instruments used.

5.12 On-Line Trial of Aztec AC250 Coagulant Dose Prediction System

The predicted optimum coagulant doses for PAC (17/03/98 – 17/04/98) and Alum (29/04/98 – 09/06/98) from jar tests and AC250 are shown in Figure 5.19.

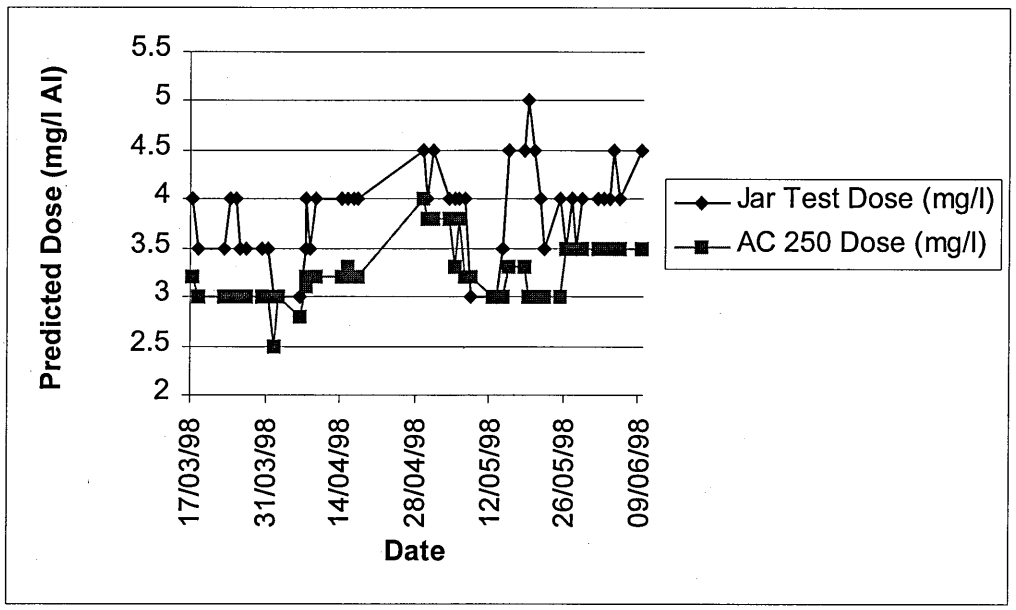


Figure 5.19. Jar Test and AC250 Optimum Predicted doses for PAC and Alum During a Period 17/03/98 – 09/06/98

The coagulant doses predicted by the AC250 were in general, lower than the routine laboratory jar test measurements except during periods of high pH, algal counts and temperature. Under these conditions the coagulant doses provided by the AC 250 were found to be insufficient to maintain sludge blanket stability in the sedimentation tanks and plant performance was compromised. The performance of the AC250 system during this period illustrated the requirement for the 'Trim' factor present in the more advanced AC 500 and AC 1000 Aztec systems, which compensate for these factors. These results imply that the AC250 coagulant prediction system is unreliable in predicting the optimum coagulant dose.

6.0 DISCUSSION

The laboratory investigations have been extensive and have produced a considerable quantity of results. The objectives of this project were to optimise the clarification process and evaluate automatic coagulation control as described in section 3.0. The following reviews the findings of this and other similar investigations carried out with these perspectives. The raw water qualities for Burham, Weirwood, Mont Valerien and Menuse can be found in Appendix 3. The following compares the findings of the reports from Burham, Weirwood, Mont Valerien and Menuse and with the literature the writer attempts to explain the different mechanisms of ozonation and coagulation involved.

6.1 Effects of Pre-Ozonation on Clarification.

The dosing of metal-ion coagulants or polyelectrolytes can promote the removal of dissolved organic matter under suitable conditions (optimum coagulant dose and optimum pH dose) Tobiason *et al.,* (1994). The effects of pre-ozonation ahead of coagulant dosing have been reported in numerous papers (Jekel, 1993, 1994 & 1998; Ma *et al.*, 1997; Edwards & Benjamin, 1991 & 1992) in relation to enhancing coagulant performance in particle and NOM removal. A frequent observation is that pre-ozonation can increase reductions in turbidity or particle counts, relative to the system without pre-ozonation (Jekel, 1983). Studies by Richard & Jacq (1990) at Mont Valerien and by Lea (1996) and La Trobe-Bateman (1997) at Weirwood in Figures 6.1 and 6.2 demonstrate the effects of pre-ozonation on clarification using Alum at optimum 3.5 mg/l, shown as turbidity and TOC removals on three different waters: the River Seine at Mont Valerien; Eccles Lake, Burham; and Weirwood Reservoir at Weirwood.

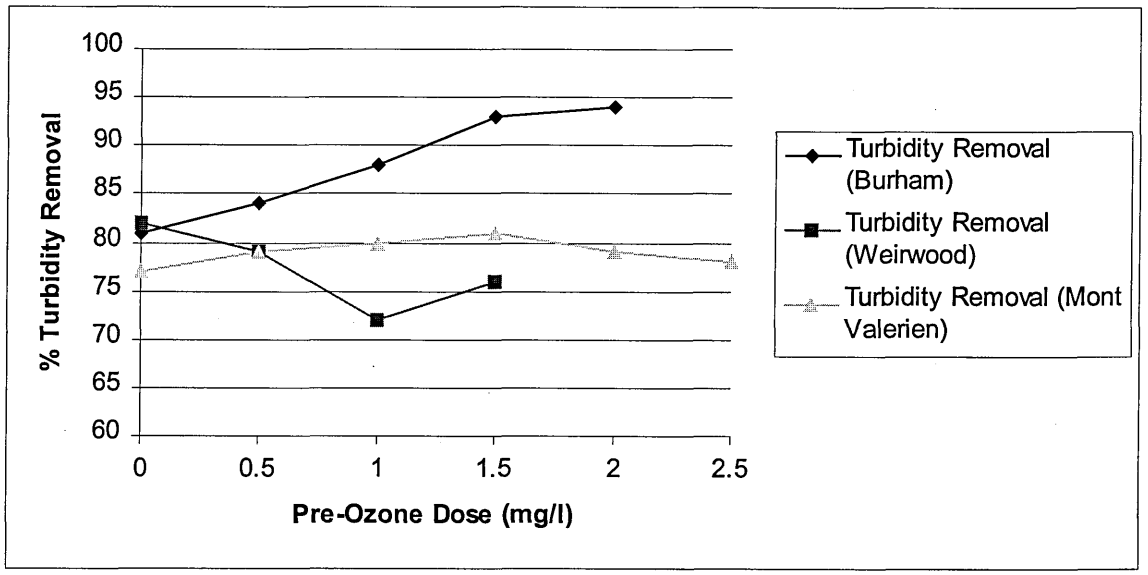


Figure 6.2 Turbidity Removals Across the Clarifier For Alum at an Optimum Dose of 3.5 mg/l with Literature Data in Section 2.6.2 From Mont Valerien and Weirwood.

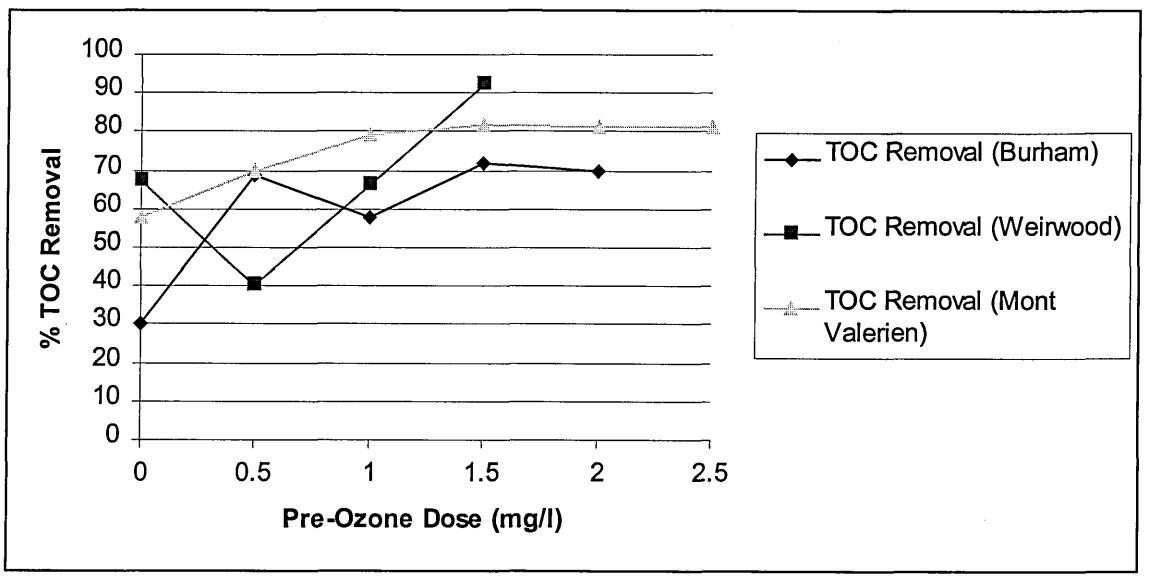


Figure 6.2 TOC Removals Across the Clarifier For Alum at an Optimum Dose of 3.5 mg/l with Literature Data in Section 2.6.2 From Mont Valerien and Weirwood

The effects of pre-ozonation on coagulation produced the following effects:

1. Pre-ozonation increased turbidity removals at Burham and Mont Valerien, where turbidity removals were greatest at 1.5 mg/l, the optimum pre-ozone dose.
2. Pre-ozonatin decreased turbidity removals at Weirwood.
3. Pre-ozonation improved TOC removals at Burham Mont Valerien and Weirwood. Maximum removals occurred at a pre-ozone dose of 1.5 mg/l.

The different observations and effects of pre-ozone on clarification shown in Figures 6.1 and 6.2 cannot be interpreted by a basic mechanism. The literature suggests that the effects of ozone are numerous, and that there are cases where the addition of pre-ozonation prior to clarification has both significantly increased and decreased particle removals.

The literature on ozone has included various descriptions for the effects of ozone, such as 'microflocculation' (Maier, 1974); 'ozone as a coagulant aid' (Saunier *et al.*,1983); and 'ozone induced particle destabilisation' (Edwards & Benjamin, 1992). The mechanisms responsible for the effects of ozone in coagulation/particle removal are based mostly on the presence of certain levels of dissolved organic matter (DOC) or of natural organic matter (NOM), for example algal cells (Jekel, 1998). Reckhow *et al* (1986) and Edwards *et al.,* (1994) have proposed mechanisms responsible for the observed effects of pre-ozonation on coagulation. They propose that when raw water containing NOM is ozonated, the carboxylic acidity of NOM increases, the average MW of NOM decreases,

metastable organic complexes are disrupted, releasing metal species (e.g. Fe, Mn), and IOM and EOM are released by algal lysis.. According to Edwards *et al.,* (1994) a decrease in MW reduces the tendency for NOM to precipitate (section 2.2.1), reducing the coagulant demand, but also reducing the amount of NOM removed. Increasing the concentration of acidic functional groups, increases the charge density, increasing coagulant demand and NOM removal by sorption onto the surface of suspended particles. Studies by Edwards (1990) and Edwards and Benjamin (1992) concluded that the balance of these two mechanisms and therefore the one that dominates is ultimately dependant upon how the particles change during ozonation.

When a coagulant is added it is consumed by either or both of the mechanisms. If a fixed amount is added, for example, to un-ozonised water, some of the coagulant will precipitate out the NOM. Any excess will form hydroxide flocs and co-precipitate with the NOM coagulant precipitates (Tobiason *et al.*, 1995). When the same coagulant is added to ozonised water less of it is used in direct precipitation of the humic acid, because there is less humic acid present, but more is used to neutralise the increased acid functional groups formed by ozonation. These two effects counteract each other, and the one that dominates depends on how the particles change during ozonation (Reckhow *et al.*, 1986; Edwards *et al.,* 1994).

The most likely effect pre-ozonation had at Burham and Mont Varerien was to fragment the particles present in the un-ozonised water. This would have had no effect on coagulant demand for precipitation, but would have produced an overall improvement in

NOM removal efficiency through removal by sweep flocculation and charge neutralisation. This is illustrated in Figure 2.1 (La-Trobe-Bateman, 1997), where smaller particles are removed more effectively by sweep flocculation, as indicated by the arrow at the top of Figure 2.1, and demonstrated as an increase in NOM removal at a give coagulant dose in Figures 6.1 & 6.2.

Conversely, results from Weirwood (Lea, 1996) showed an initial decrease in NOM removal (measured as TOC) with the addition of pre-ozone. The literature suggests that if ozonation only adds acid functional groups to the dissolved NOM (low ozone doses), then there will be a stoichiometric increase in the coagulant demand to precipitate the NOM and to neutralise the small particles with increased functional groups formed by ozonation (Edwards *et al.*, 1994). Without an improvement in removal by sweep flocculation, an increase in coagulant demand would be required to obtain the same water quality.

6.1.1 Effect of Pre-Ozonation on Algal Removal

A complex issue in pre-ozonation is the effect of ozone on algal cells and their dissolved products. Various reports describe the benefits of pre-ozonation prior to coagulation for the removal of algal cells. Investigations from Burham , Weirwood and Mont Valerien into the effects of increasing pre-ozone concentrations on algal removals are shown in Table 6.1. Due of the variation of the total algal count in the raw waters, the results are given as percentage of remaining algae compared to those found in the raw water.

Table 6.1 Remaining Percentage of Algae with Optimum Aluminium Sulphate Doses at Mont Valerien, Wierwood and Burham.

% Algal Removal											
Pre-Ozone	Mont Valerien				Weirwood		Burham				
Dose (mg/l)	0	0.8	1.6	2.1	0	1	0	0.5	1	1.5	2
After Pre-Ozone	N/A	39	73	6	N/A	90	N/A	33	41	74	34
After Clarification	75	90	98.4	77	69	83	46	85	90	93	91

Using the results obtained from the three different sites it can be seen that, in terms of percentage of algal removed, Mont Valerien, Wierwood and Burham show similar trends. As the pre-ozone dose increases the removal of algae increases until a maximum, optimum pre-ozone dose of 1.5 and 1.6 mg/l for Burham and Mont Valerien respectively. The addition of the coagulant Alum at an optimum dose of 3.5 mg/l, at Burham and Weirwood as shown in Table 6.2, enhanced this effect and improved the removal of algae, increasing removals up to an optimum pre-ozone concentration of 1.5 and 1.0 mg/l for Burham and Weirwood receptively.

Table 6.2 Algal Removal at Burham and Weirwood at Optimum Coagulant Dose

Coagulant	Dose as Al	% Algal Reduction	% Chlorophyll Reduction	% Phaephytin Reduction
Alum W.W.	3.5	84	93	89
PAC W.W.	3.5	88	90	88
Pass W.W.	3.5	86	87	84
Alum B.	3.5	93	71	94
PAC B.	3.5	79	94	93
Pass B.	3.5	73	77	94

Results show removals with pre-ozone (1.0 mg/l) Key: B. Burham; W.W. Weirwood.

Algal cells subjected to low ozone doses have been shown to secrete EOM, in the form of polysaccarides and other polymeric matter (Fogg, 1996). The EOM can carry a negative

charge, and if of sufficient MW can adsorb on and adjoin particles or other algal cells promoting flocculation via inter-particle flocculation (Paralker & Edwald, 1996). The addition of ozone at low doses subsequently did not increase the coagulant demand, but as shown in Table 6.1, enhanced algal removal. Bernhardt *et al.,* (1985) suggests the presence of EOM at optimum ozone doses acts as a flocculating aid. During Alum testing on the pilot clarifier, algal concentrations were very high (Figure 5.3) This would explain the very high turbidity and TOC removals obtained by Alum on the pilot clarifier. A more stable blanket, improved by the presence and flocculating properties of EOM, could have enhanced turbidity and TOC removals by sorption.

Edzwald & Paralker (1992), suggest that little algal lysis occurs at ozone doses up to 3 mg/l and the algae will be present as dead cells. At 2.1 and 2.0 mg/l of pre-ozone the algal count increased (Table 6.1). The literature suggests that as EOM concentrations rise, the tendency for EOM to form complexes with the metal coagulant ions increases, increasing coagulant demand. Hoyer *et al.,* (1987) further suggests that higher doses of ozone affects the structure of EOM by decreasing molecular size and colloid charges and increasing the functional and acidic groups on the EOM. This reduces the tendency for EOM to bind particles, reducing flocculation and algal removal whilst subsequently increasing the coagulant demand, as shown in Table 6.2 at a pre-ozone dose of 2.0 mg/l at Burham.

The dominant mechanism in algal removal is uncertain, but these investigations have shown it will depend upon EOM type, algal species dominating in the raw water, pH, coagulant used and ozone concentration.

6.2 Effect of Pre-Ozonation on Iron and Manganese Removal

Dissolved iron and manganese are commonly found in both surface and underground waters in their reduced form. Although they do not constitute a health hazard in concentrations normally encountered, settled iron and manganese can cause pipe damage and water colouration (Stoeber *et al.*, 1981). For these reasons, EEC directives concerning potable water fix maximum permissible levels of 200 and 50 µl for iron and manganese respectively (Reckhow *et al.*, 1991).

A study that compared oxidation of Mn with pre-ozone in raw water carried out by McKnight *et al.*, (1993) gave similar trends to those identified in this investigation. The raw water studied by McKnight *et al.*, (1993) can be found in Appendix 3. The results showed that metal removal increases almost linearly with increasing pre-ozone doses.

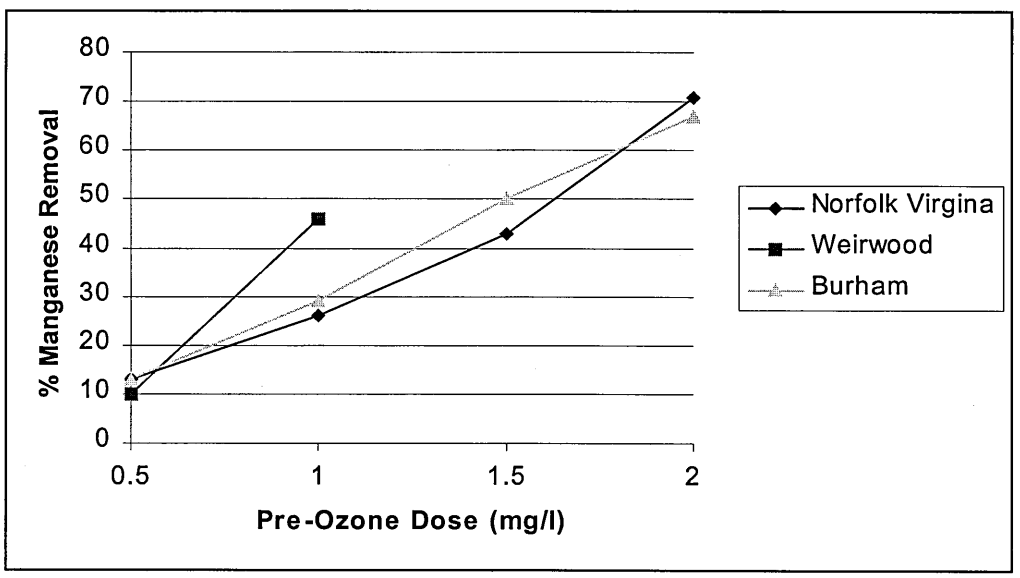


Figure 6.3 Manganese Removal after Raw Water Pre-Ozonation at Menuse, Weirwood and Burham.

6.2.1 Iron Removal

A reduction in dissolved iron at 0.5 and 1.0 mg/l and 0.5, 1.0, 1.5 and 2.0 mg/l pre-ozonation for Weirwood (Lea, 1996) and Burham is shown in Figure 6.4. At both sites iron removal increased in an almost linear fashion with increasing pre-ozone concentrations and was reduced to below the PCV level of 200 µl.

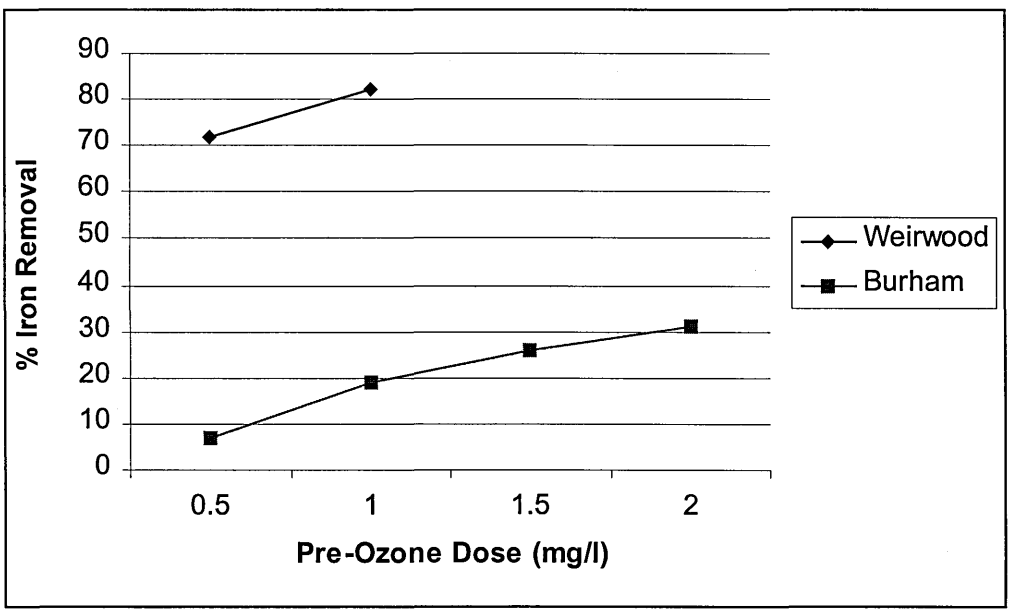


Figure 6.4 Iron Removal after Raw Water Pre-Ozonation at Weirwood and Burham.

The success of pre-ozonation for the removal of dissolved metals is dependant on raw water quality (Paillard *et al.*, 1989). Molecular ozone is more selective for metals than hydroxyl radicals (Abukhudair & Farooq, 1989). However, in low alkalinity conditions such as in Burham, Wierwood and Menuse, ozone acts mainly in the free radical pathway (Amy & Kraser, 1995). The humic and fulvic acids compete successfully for radicals, leaving the metals unaffected. Only when the ozone demand exerted by the organics is satisfied will the metals be oxidised. The dose of ozone required to satisfy this demand is

often uneconomic, as shown at a pre-ozone concentration of 2.0 mg/l where metal oxidation was greatest, however this pre-ozone dose has been shown to compromise the efficiency of coagulation.

6.2.2 Effect of Pre-Ozonation and Clarification on Manganese and Iron Removal

Iron and manganese can be present as organo-metal complexes of DOM as well as Fe^{2+}, Fe^{3+} or Mn^{2+}. The addition of pre-ozone can oxidise the organic matter to release the metal cations, which hydrolyse to the insoluble precipitates and induce coagulation, and oxidise the metal ions, which in turn precipitate (Felix-Filho, 1986). The role of clarification is the removal of the hydroxide precipitates formed. The coagulant that can most efficiently remove the hydroxide flocs is evaluated in Table 6.3.

Table 6.3 Comparison of Iron and Manganese Removal by Alum and PAC at 1.0 mg/l at Optimum Coagulant Doses of 3.5 mg/l at Burham and Weirwood.

Coagulant	% Total Fe Reduction (0 mg/l Pre-Ozone)	% Total Fe Reduction (1.0 mg/l Pre-Ozone)	% Total Mn Reduction (0 mg/l Pre-Ozone)	% Total Mn Reduction (1.0 mg/l Pre-Ozone)
Alum W.W.	86	92	23	71
PAC W.W.	95	87	92	72
Alum B.	69	87	66	70
PAC B.	74	75	53	58

Key: B. Burham; W.W. Weirwood.

With Pre-ozonation, Alum showed the highest metal removals at Burham. However, metal removals at Weirwood do not appear to be very consistent. For Alum at an optimum dose of 3.5 mg/l, 1.0mg/l of pre-ozone has enhanced both iron and manganese removal, but pre-ozonation with PAC decreased iron and manganese removals. One

explanation could be that during the period of testing for PAC the NOM concentration was high, resulting in reduced metal removal efficiencies, and a higher pre-ozone dose was required. The reason for improved Mn and Fe removal across the clarifier at Burham with pre-ozonation was due to the oxidation of the metals. The oxides, MnO_2 and $Fe(OH)_3$, are strongly adsorbed onto flocs, whereas Mn^{2+} and Fe^{2+} ions or organo-complexes of these ions, are not (Reckhow *et al.*, 1991).

Other investigations (Korathi, 1988; Paillard *et al.*, 1989) have also shown that iron is relatively easier to oxidise than manganese under a wider range of conditions. This is expected as the literature suggests that Fe is more susceptible to oxidation than manganese as the oxidation potential of iron is 0.77V, with manganese at 1.208V (Abukhudair & Farooq).

6.3 Pesticide Removal

Pesticides have been shown to be carcinogenic to human health. The presence of these complex organic compounds in surface waters has increased over the last 20 years (Mandle, 1992).

Ozonation remains and the main unit treatment process used at potable water treatment plants to facilitate in the degradation and removal of these compounds prior to adsorption onto GAC. Comprehensive legislation governs the use of pesticides in the U.K. The effectiveness of pesticide removal by pre-ozonation at Burham Weirwood and Menuse, was investigated and are shown in Figures 6.5 and 6.6.

Pesticide removals of three main groups of pesticides tested at Burham and Weirwood with increasing pre-ozone doses of 0.5, 1.0, 1.5 and 2.0 are shown in Figure 6.5. Pesticide removals increased as the pre-ozone dose increased. After a pre-ozone dose of 1.5 mg/l, the increase in pesticide removals was not economically significant and therefore the optimum pre-ozone dose for pesticide removal was 1.5 mg/l.

The main conclusion which can be made is that total urea herbicides are much more susceptible to ozonation than acid herbicides and triazines. Degradation of these pesticides by ozonation is probably mainly due to hydroxyl radical reactions during ozonation (Klein *et al.*, 1982) The result of this makes some organics more amenable to adsorption onto granular activated carbon (GAC), by adding oxygen to the compounds and increasing their polarity (Langlais *et al.*, 1991).

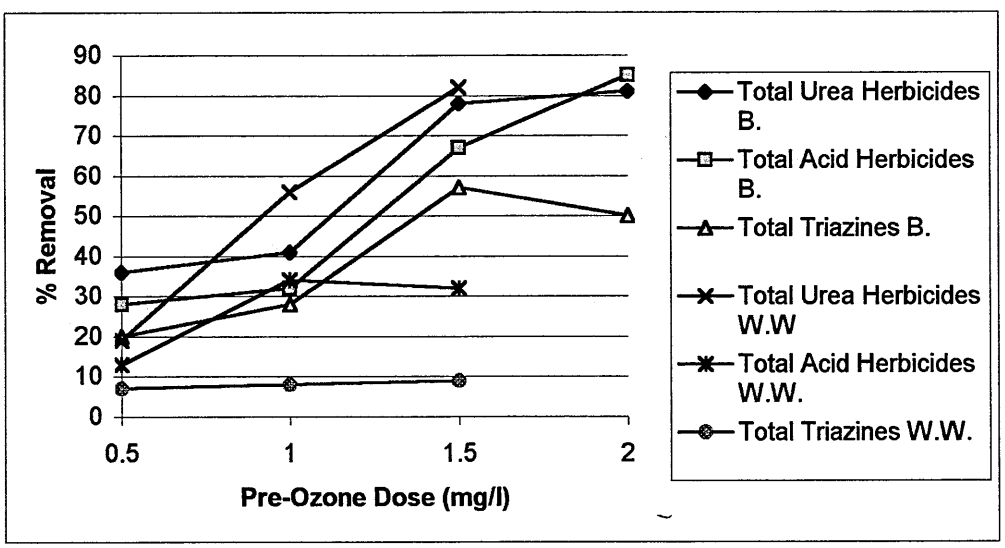


Figure 6.5 Effect of Pre-Ozonation at 0.5, 1.0, 1.5 and 2.0 mg/l on the Removal of Three Groups of Pesticides at Burham and Weirwood.

The effect of pre-ozonation on raw water from the river Meuse at Nieuwegein, the Netherlands (Meijers *et al.*, 1993) at 2.0 mg/l is shown in Figure 6.6 together with the corresponding data from Burham pilot plant.

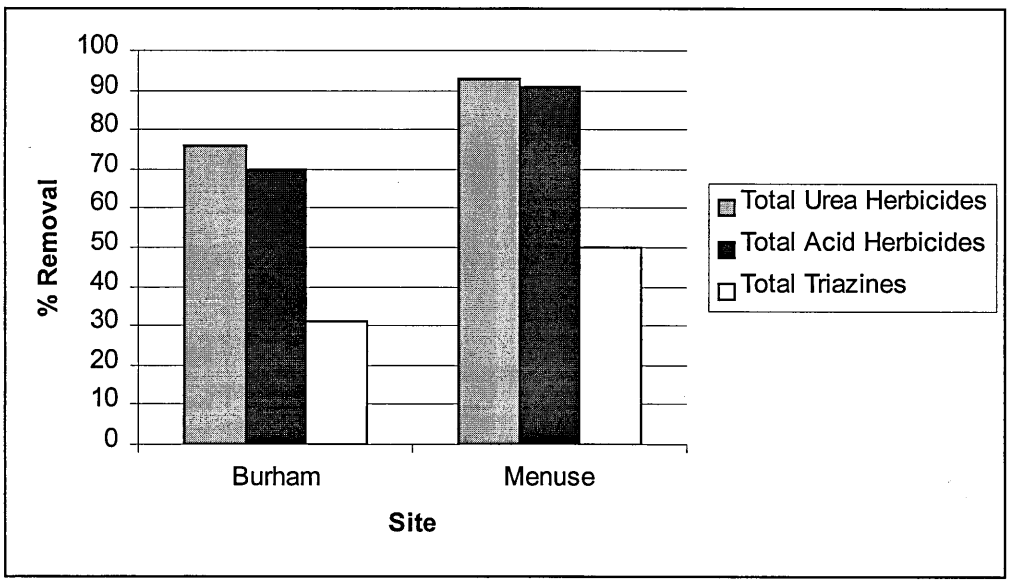


Figure 6.6 Effect of Pre-Ozonation on the Removal of Three Groups of Pesticides at Burham and Norfolk Menuse, Virginia.

It can be clearly seen using Figures 6.5 and 6.6 that total urea herbicides are much more susceptible to ozonation than acid herbicides and triazines. Degradation of these pesticides by ozonation is probably effected by NOM type present (Xoing, 1992). The presence of high concentrations of humic acids consume the free hydroxyl radicals resulting in fewer radicals present for pesticide degradation. Consequently the success of NOM pre-ozonation is reflected by a high removal percentage of pesticides.

6.4 The Use of Polyaluminium Chloride and Aluminium Sulphate in Coagulation.

An aim of this investigation to find the most efficient coagulant for Burham. Results in Section 5 showed that PAC was the most efficient coagulant at Burham. The following attempts to explain this phenomenon by using the results obtained at Burham and from a similar investigation carried out at Weirwood (La Trobe-Bateman 1997).

Optimum coagulant doses of 3.5 mg/l for Pass100, Alum and PAC (WTS) are shown in Table 6.4 using this data comparisons can be made between PAC and Alum removals.

Table 6.4 TOC and Colour Removals by PAC, Alum and Pass 100 in Pilot Trials at Burham and Wierwood at Optimum Coagulant Doses of 3.5 mg/l With and Without Pre-Ozonation (1.0 mg/l).

Coagulant	Dose (mg/l)	% TOC Removal	% Colour Removal
Alum B.	3.5	33 (18)	89 (54)
Pass 100 B.	3.5	17	89
PAC B. (WTS)	3.5	36 (17)	92 (67)
Alum W.W.	3.5	34 (36)	56 (64)
Pass 100 W.W.	3.5	35 (32)	63 (60)
PAC (WTS) W.W.	3.5	39 (35)	71 (51)

The results in brackets show the removals without pre-ozone. Results out of brackets show removals with pre-ozone (1.0 mg/l). Key: B. Burham; W.W. Weirwood.

The results show that without pre-ozone Alum removes TOC slightly better than PAC, as expected, and with pre-ozone, PAC removes TOC and colour better than Alum. The literature suggests that un-ozonated water predominately contains large relatively low charged particles that are removed in coagulation by precipitation (Jekel, 1994). Al^{3+} ions in water hydrolyse to form mainly monomeric species that rapidly hydrolyse and

precipitate (Tang & Luan, 1995). PAC polymeric species are more refractory to hydrolysis and persist in Al_{13} form for a longer period of time before precipitating. Therefore Alum can be more effective in the removal of low charged, high MW particles than pre-hydrolysed coagulants (Melia *et al.*, 1989; Van Benschoten & Edzwald, 1990).

The literature suggests that pre-hydrolysed coagulants are more effective in the removal of anionic particles (Van Benschoten & Edzwald, 1990). Ozonation appears to transform the NOM present in the raw water into species, which are more amenable to removal by the highly charged polymeric species produced by pre-hydrolysed coagulants, than by monomeric species produced by Alum. The high MW polymeric species produced by PAC could act as a flocculating aid forming a filamentous floc that would provide the charge neutralisation and adsorption required to more efficiently remove these particles. This supports the observations by Pouillot and Suty (1992), that the beneficial effects of polymeric species include the production of larger flocs for a given coagulant dose that improve removal by sorption. This also supports the jar test results in section 5.3.1 & 5.5.1 where PAC consistently produced larger flocs and higher removal rates than Alum. However, this was not the case for Pass100. Pass 100 was less effective than Alum at Burham but it out-performed Alum at Wierwood. Explanations for this remain unclear as the coagulation chemistry for Pass 100 remains unpublished.

6.4.1 Effects of pH on Coagulant Performance

The solubility and species speciation of metal coagulants is pH dependant (Benschoten *et al.*, 1992). Because pH dictates metal speciation and solubility the optimum conditions for coagulation were investigated for use at Burham to optimise the required coagulant demand for water treatment.

The mechanisms of coagulation involve a number of chemical factors including hydrolysing and polymerising tendencies, the adsorbivity of such aluminium hydroxide species, the solubility of each of these species and total aluminium solubility as a function of pH (Dental & Gosset, 1987). The differences that occur between PAC and Alum at the same dose at Burham are illustrated by the results of a jar test in Figure 6.7. to evaluate the effectiveness of PAC and Alum at the same coagulant dose of 3.5 mg/l in 1.5 mg/l pre-ozonated water. The raw water data can be found in Appendix 3.

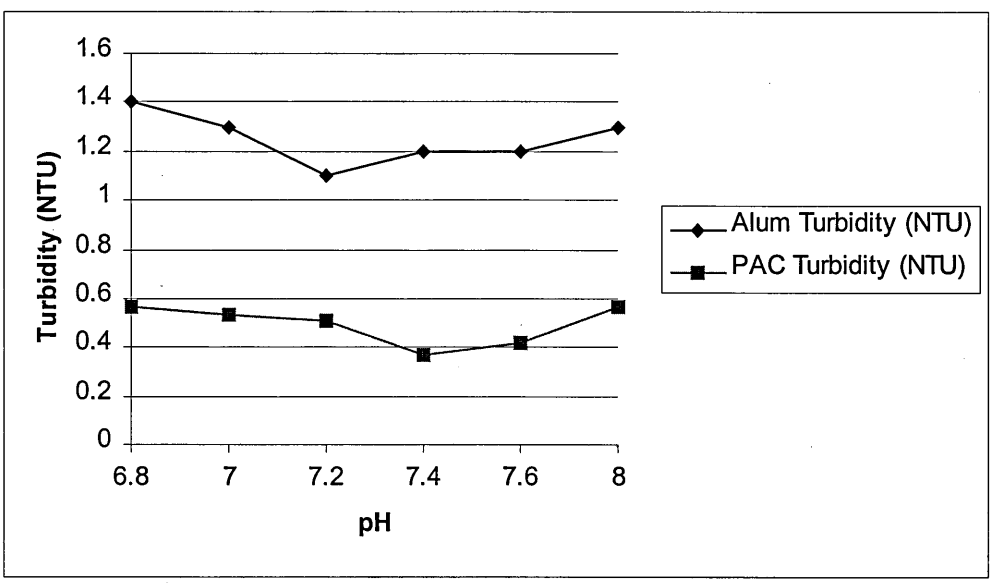


Figure 6.7 Al^{3+} and Al_{13} Performance as a function of pH

The results show PAC is more effective in removing turbidity than Alum in pre-ozonated water. The turbidity curve for Alum is shaped similarly to PAC, but Alum produced optimum turbidity removals at a lower pH than PAC. Furthermore, although the Al dose was identical the turbidity removals were greater with PAC than Alum as expected. These differences support the conclusion by Melia *et al.,* (1989) and Pouillot & Suty (1992), that different hydrolysed aluminium species exist between Alum and PAC.

The solubility plots in Appendix 4, show that PAC does not appear to precipitate until pH 7, indicating that at pH 7.4 Al_{13} becomes insoluble and precipitates giving optimum removals (Kaeding *et al.*, 1992; Edwards & Benjamin, 1992). App 4 also shows that Al^{3+} precipitates at a lower pH than that observed, although the pH of greatest insolubility is not as clearly defined for Al^{3+}. However the literature indicates that temperature greatly influences Al^{3+} solubility, and therefore may have influenced the results obtained (Van Benschoten & Edzwald, 1990).

6.5 Coagulant Control

The Aztec AC250 automatic coagulation dose prediction system had proved to be accurate in providing an measurement of the turbidity and pH of pre-ozonated water measurements which were used successfully by the AC250 coagulation control system for automatic coagulant dose prediction over most the trial period. Jar tests (Figure 5.18) showed conclusively that this system would not be capable of predicting the dose without the closed loop feedback system (Trim Factor) as shown in Figure 6.8.

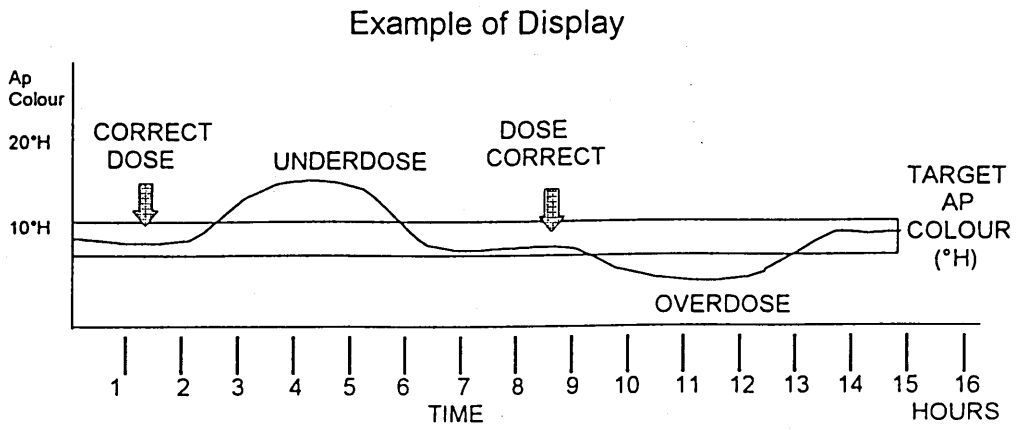


Figure 6.8 Example of Trim Factor Display (Everton, 1997)

The target value shown above is 8± 1^0H (apparent colour) which is an approximate value for Alum, PAC and Pass 100. Loss of dose is reflected by a rapid increase in apparent colour and then turbidity although pH monitoring at the flocculation stage will show this effect more rapidly.

Without the 'Trim factor', a situation could occur where the plant could be over-dosing or under-dosing for a considerable amount of time which would compromise the stability of the sludge blankets in the sedimentation tanks and hence the overall operation of the plant.

7.0 Commercial Implications

7.1 Coagulation Efficiency

The efficiency of the coagulation stage depends on different parameters including raw water quality, the chemistry of the coagulant, physical parameters of the process and the expected quality of the treated water. The most common forms of measuring this efficiency is by the optimisation of the following water quality parameters.

- Settled Turbidity
- Filtered Turbidity
- Residual Aluminium
- Dissolved Aluminium
- pH
- Removal of Algae, Chlorophyll and Phaeophytin
- Removal of Total Organic Carbon
- Removal of Metals, Mainly Manganese and Iron

The implications to which these contaminants are removed by coagulation are reflected upon the unit processes downstream from clarification.

Settled Turbidity

Settled turbidity gives a measure of the suspended particle matter passing onto the RGF's. Residual matter may lead to increased solid loads on the filters, which could reduce filtrate quality and increase backwash frequency. This would increase water losses, power and operating costs.

Filtered Turbidity

Filtered turbidity gives an indication of the solids remaining in the water after clarification and RGF processes. These solids will build up on the GAC filters, decreasing GAC effectiveness in pesticide and assimilable organic carbon removal, and increase the required backwash frequency.

Residual Aluminium

Residual aluminium is largely in the form of micro-flocs that will be removed by RGF's with the same implications as settled turbidity.

Dissolved Aluminium

Dissolved aluminium is not removed by any other unit process at the works. The dissolved aluminium concentration must be below the statutory concentration given in the Water Supply Regulations (1989), of 200µl.

Algal Removal

During warm sunny periods, algal counts in the raw water can be very high. Algae can build up on RGF's causing shorter run times, increasing water losses and backwash operating costs. The increased washing reduces the quality of the water passing onto the GAC filters which will compete with adsorption sites on the GAC, and decrease bed life of the GAC filters, increasing the regeneration frequency. Regeneration is a significant operating cost for GAC filters.

TOC Removal

The greater the TOC removal across the clarifier, the smaller the TOC load reaching the GAC filters. The TOC impairs the performance of the GAC in the same manner as described with filtered turbidity and algal removal.

Metals Removal

Manganese and iron present in the particulate form are removed by coagulation and sedimentation. Insoluble M^{3+} hydroxides are removed by adsorption onto coagulant flocs. Settled iron and manganese can cause pipe damage and water colourisation. For these reasons EEC directives concerning potable water fix guidelines levels of 50 and 20 μg/l for iron and manganese respectively and maximum permissible levels of 200 and 50 μg/l.

The following sections illustrate the cost implications of maintaining and operating present performance and the recommended alternatives of acid dosing and automatic coagulation control.

7.2 Coagulant Costs

Coagulant cost is a function of the product price, the aluminium concentration in the product, and the dose required. In the following calculations the costs are calculated relative to water treatment works grade aluminium sulphate, which contains 4.24% aluminium by weight, a specific gravity of 1.32 and costs £80 tonne. This corresponds to a cost per tonne of aluminium of £1886/tonne. PAC (5.3% Al^{3+}, by weight, s.g. 1.23)

costs 125/tonne. If PAC were to cost the same per tonne as aluminium the product would cost £100/tonne (£80/4.24% * 5.3%).

7.3 Coagulant Saving Using PAC

Alum is currently dosed at Burham during the months May to November. If PAC had been used instead of Alum during this period, the significant cost savings could have been made. For example: to achieve a settled turbidity of 1 NTU at ambient pH, an Alum dose of approximately 2.6 mg/l is required, compared to a PAC dose of 1.7 mg/l. This represents a saving of 0.9 mg/l on 2.6 mg/l, which is 34%. During the months of May to November 1998 the average plant dose of Alum was 4.5 mg/l. Using the above data, the potential cost savings of replacing Alum with PAC at 50 Ml/d is £14411.

7.4 Coagulant Saving Using PAC and Acid Dosing

Burham currently operates at ambient pH and at a higher coagulant dose than the predicted optimum dose, due to the absence of automatic coagulant control and acid dosing. The use of PAC during May to November however, is not a viable alternative unless the ambient pH is depressed and controlled at pH 7.5. To achieve a settled turbidity of 1 NTU at pH 7.5, a PAC dose of approximately 1.2 mg/l is required. The subsequent acid cost during this period is £1757. Using the above data, the potential cost savings of using PAC at pH 7.5 instead of Alum at ambient pH at 50 Ml/d would be £18373.

An additional benefit of reduced coagulant dose requirement is extended RGF run times. Currently Burham operates 8 RGF's that are washed every 30 hours, and require 1.6 Ml per day of treated water that must be treated and extracted. The addition of automatic coagulation control and PAC with acid dosing will approximately double the time period between washes for each filter and reduce the required water to 0.8 Ml per day. This will reduce the amount of water required. A further cost saving of £1000 can be made in the amount of coagulant required, exclusive of the power costs. The installation of an AC 1000 automatic coagulation control system will cost approximately £40000. The potential costs and savings associated with Burham are listed in Table 7.1, during a period of May to November 1998.

Table 7.1 Cost Implications of Automatic Coagulation Control at Burham

Variable	Installation and Purchase Cost £	Saving £
PAC Replacing Alum	27450	14411
Acid Dosing	0	5719
Sulphuric Acid	1757	0
Filter Backwash	0	1000
Ac 1000	40000	
Total	69207	21130

The capital cost associated with purchase and installation is greater than the potential cost savings for one year. However, with the clarification process being continuously controlled by the AC 1000, the optimum dose for the coagulant will be continually dosed, saving on coagulant whilst decreasing the RGF's backwash frequencies. In addition to this, the cost of INDA PAC is £100. The minimum predicted payback time period is less than 2 years.

7.5 Sludge Production and Handling Costs

An additional benefit of reduced coagulant dose requirement is reduced sludge production. Sludge dry solids are the sum of suspended solids removed from the raw water, and hydroxide floc formed by the coagulant. Clearly the solids contribution from the raw water remains constant if the dose is set to ensure the same clarifier performance, but the contribution by hydroxide floc can be reduced.

The reductions in sludge are given in Table 7.2. The percentage reductions represent sludge reductions for PAC at ambient pH and PAC at optimum pH 7.5 compared to Alum at ambient pH. PAC and Alum sludge volumes were calculated at a pre-ozone concentration of 1.5 mg/l and an optimum coagulant dose of 3.5 mg/l with 0.06 mg/l polymer.

Table 7.2 Sludge Volume Savings for PAC Compared to Alum at Optimum Coagulant Doses of 3.5 mg/l, Shown in Percentage Sludge Reductions at 2% Dry Solids at a Flow Rate of 50 Mld.

Coagulant	Sludge percentage (%) Reductions
Alum, ambient pH	100
PAC, ambient pH	33
PAC, pH 7.5	43

A further cost saving could be made with the reduction sludge volumes with use of PAC instead of Alum (33%) and PAC at an optimum pH of 7.5 (43%) during the months May to November.

8.0 CONCLUSIONS AND RECOMMENDATIONS

8.1 Conclusions

The conclusions drawn from the jar testing phase of this work are as follows:

1. Settlement rates and floc formation for Pass 100, Alum and PAC (WTS & INDA) from quickest and largest to slowest and smallest were: Pass 100 > PAC > Alum > Alba 18.
2. The addition of LT20 non-ionic polymer increased NOM removals, floc sizes and settlement rates for Alum and PAC. PAC > Alum > Pass 100 > Alba 18.
3. Non-ionic polymer coagulant and produced the highest NOM removals.
4. Alba 18 gave the poorest water quality in term of aluminium residual and turbidity.
5. Pass 100 gave the highest NOM removals at optimum coagulant dose, however under dosing and under dosing produced low turbidity removals and high aluminium residuals.
6. PAC was chosen as optimum coagulant as it produced the best removals when under or over dosed, and good NOM removals at optimum dose.
7. At optimum pH, settlement was quicker for Alum, Pass 100 and PAC. Settled turbidity removals were higher and can be put in descending order: PAC > Alum > Pass 100, Alba 18.
8. Optimum pre-ozone dose was 1.5 mg/l. Highest turbidity removals were achieved at a pre-ozone dose of 1.5 mg/l.

The conclusions from the pilot trials of Alum, PAC and Pass 100.

9. When operating with pre-ozonated water, Alum, PAC produced scum but Pass 100 did not.
10. With non-ozonised water, TOC and colour reduction was higher with PAC than Alum or Pass 100. The addition of pre-ozone to an optimum 1.5 mg/l increased turbidity removals for PAC and Alum by 19% and 15% respectively.
11. The addition of polymer enhanced turbidity, TOC, DOC and metal removals for PAC and Alum.
12. No significant difference between turbidity, TOC and metals removals occurred for INDA and WTS PAC.
13. Pre-ozonation increased algal and metal removals after clarification
14. Pesticide concentrations decreased in an almost linear fashion as pre-ozone concentrations increased. Above a pre-ozone concentration of 1.5 mg/l this increase was not great and so 1.5 mg/l was taken as optimum.
15. A direct increase in turbidity, TOC and colour removals resulted from a decrease in pH to optimum values for PAC, Alum and Pass 100.
16. Lower aluminium residuals were produced by PAC, than Pass 100 and alum.
17. With pre-ozone at 1.5 mg/l, PAC performs best at its optimum dose when taking into account turbidity, residual aluminium and removals of TOC, chlorophyll, phaeophytin, total iron and manganese, and colour.
18. The AC250 is unreliable in predicting the coagulant dose annually.
19. The potential cost savings in terms of aluminium dose for replacing Alum with PAC at 50 Ml/d is £14411.

20. The potential cost savings of using PAC at pH 7.5 instead of Alum at ambient pH at 50 Ml/d would be £18373.
21. A further cost saving could be made with the reduction sludge volumes with use of PAC instead of Alum (33%) and PAC at an optimum pH of 7.5 (43%) during the months May to November.
22. The minimum predicted payback time period is less than 2 years.

8.2 Recommendations

1. Install an AC 1000 to automatically control and dose acid and coagulant.
2. Carry out split full-scale trials with acid dosing with PAC to confirm reduced coagulant requirements.
3. Operate Burham WSW with PAC annually with acid dosing at pH 7.5 (if 3 is successful).

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Appendix 1: Burham Raw Water

	Pesticide	Total Iron	Total		Colour	Turbidity	TOC		Algal	
Date	(ng/l)	(mg/l)	Manganese (mg/l)	Date	(Hazen)	(NTU)	(mg/l)	Date	Count	pH
23-Mar	1307.5	0.339	0.076	23-Mar	16	12	4.3	23-Mar	4850	8
24-Mar	1258.5	0.345	0.081	24-Apr	17	8.2	4.7	24-Mar	4850	8
25-Mar	1170	0.349	0.099	25-Mar	17	8.5	4.8	25-Mar	2550	8
26-Mar	1107	0.637	0.107	26-Apr	14	8.1	4.5	26-May	5800	7.9
27-Mar	1009	0.356	0.084	27-Mar	14	6.7	4.4	27-Mar	1450	8
30-Mar	911	0.205	0.08	28-Mar	13	6	4.2	30-Mar	6800	8.2
01-Apr	822	0.246	0.085	29-Mar			3.9	01-Apr	8600	8.1
02-Apr	768.5	0.221	0.074	01-Apr	12	6	3.8	02-Mar	4500	7.9
03-Apr	878	0.165	0.072	02-Apr	12	4.5	4	03-Apr	5800	7.9
06-Apr	1058	0.162	0.054	03-Apr	12	4.2	4	06-Apr	1300	8
07-Apr	1294	0.243	0.065	06-Apr	11	7.6	4.6	07-Apr	5650	7.8
08-Apr	1509.5	0.288	0.073	07-Apr	14	12	4.9	08-Apr	2600	7.9
09-Apr	3579	0.37	0.07	08-Apr	17	15	5.3	09-Apr	1450	7.9
15-Apr	1806	0.43	0.06	09-Apr	22	19	5.9	14-Apr	2400	7.7
15-Apr	1741.5	0.31	0.06	14-Apr	22	20	6.6	15-Apr	1100	7.7
16-Apr	1611.5	0.453	0.08	15-Apr	23	18	6.2	16-Apr	2700	7.7
17-Apr	1416.5	0.467	0.064	16-Apr	28	17	6.4	17-Apr	2300	7.7
29-Apr	1108.5	0.66	0.064	17-Apr	20	16	6	29-Apr	1000	7.7
30-Apr	1127	0.764	0.091	29-Apr	21	17	6.2	30-Apr	2600	7.7
04-Apr	958.5	0.606	0.1	30-Apr	23	16	6.3	04-May	1700	7.8
05-May	964	0.49	0.11	04-May	24	16	5.9	05-May	1700	7.8
06-May	853	0.422	0.086	05-May	17	12.5	5.4	06-May	3800	7.9
07-May	787	0.465	0.144	06-May	16	8.2	5.2	07-May	5400	8
10-May	695	0.283	0.061	07-May	16	9.5	5.1	10-May	2300	7.8
11-May	671	0.17	0.044	10-May	14	5.9	5	11-May	3900	8.1
12-May	690.5	0.1425	0.04	11-May	12	3.6	4.7	12-May	4500	8.1
13-May	810	0.142	0.038	12-May	11	4.5	4.7	13-May	8100	8.4
14-May	785.5	0.127	0.038	13-May	14	5.2	4.7	14-May	3000	8.4

15-May	799	0.267	0.116	14-May	11	3.6	4.7	15-May	5400	8.5
18-May	735.5	0.25	0.091	15-May	11	6.4	4.6	18-May	19500	8.8
19-May	719	0.261	0.118	18-May	11	10	4.5	19-May	18500	8.7
21-May	751.5	0.244	0.092	19-May	8	6.5	4.5	21-May	15000	8.6
22-May	841.5	0.268	0.087	21-May	11	6.7	4.5	22-May	11300	9
26-Apr	914.5	0.202	0.074	22-May	10	9.5	4.6	26-May	9700	8.7
27-May	612.5	0.162	0.054	26-May	11	6.9	4.4	27-May	1500	8.2
29-May	763.5	0.219	0.091	28-May	9.3	7	4.3	29-May	7800	8.4
01-Jun	865	0.09	0.04	29-May	9	7	4.4	01-Jun	3000	8.2
02-Jun	831.5	0.114	0.05	01-Jun	9	2.9	4.6	02-Jun	5400	8.2
03-Jun	1029	0.246	0.105	02-Jun	9.6	5.9	4.2	03-Jun	7500	8.1
04-Jun	1184	0.188	0.076	03-Jun	8.7	6.4	4.3	04-Jun	7600	8.1
07-Jun	1271	0.197	0.084	04-Jun	9.9	8	4.5	07-Jun	4450	8.1
08-Jun	1165	0.158	0.14	06-Jun	8.6	8.5	4.5	08-Jun	4750	8
09-Jun	1203	0.221	0.12	08-Jun	8.7	10	4.3	09-Jun	5050	7.9
10-Jun	1212.5	0.288	0.131	09-Jun	8.7	11	4.6	10-Jun	4750	7.9
11-Jun	1184	0.348	0.168	10-Jun	8.8	11	4.5	11-Jun	6000	7.9
12-Jun	1118.5	0.169	0.082	11-Jun	9.1	12	4.4	12-Jun	6900	8
14-Jun	1078	0.267	0.118	12-Jun	8.3	10	4.2	15-Jun	6650	8
16-Jun	1067	0.191	0.075	14-Jun	10	7	4.6	16-Jun	7200	8.1
17-Jun		0.2	0.078	16-Jun	8.8	7	4.6	17-Jun	4800	8.1
18-Jun	1148.5	0.16	0.089	17-Jun	9.1	8.2	4.4	18-Jun	6300	8
23-Jun	1026	0.17	0.052	18-Jun	9.5	9.65	4.2	23-Jun	5100	8.1
24-Jun	1114	0.185	0.072	23-Jun	12.8	4.45	4.6	24-Jun	5100	7.7
25-Jun	1080	0.232	0.063	24-Jun	12.5	7.4	5.1	25-Jun	8500	7.8
26-Jun	1158	0.114	0.048	25-Jun	12	7.4	5.1	26-Jun	6350	7.7
29-Jun	1170	0.211	0.094	26-Jun	12	8	5	29-Jun	4500	7.8
30-Jun	1170	0.114	0.046	29-Jun	12	9	5.1	30-Jun	5600	7.9
01-Jul	1101	0.144	0.049	30-Jun	11	4.6	4.6	01-Jul	4800	7.7
02-Jul	920	0.123	0.042	01-Jul	11	7.25	5.7	02-Jul	6000	7.7
03-Jul	863	0.12	0.039	02-Jul	13	4.4	5.1	03-Jul	3000	7.7
06-Jul	970	0.105	0.038	03-Jul	11	3.7	5.4	03-Jul		

Pass 100, PAC (WTS & INDA), Alba 18 and Alum Jar Tests without polymer.
See Chart 6.1 for Floc Size Formation. Key: 1 = fastest 6 = slowest.

	Dose	Poly		Floc Size		Settlement			Settled Water Quality			Filtered Water Quality		
	(mg/l	Dose	Start	After	End of	After			Turb.	Al		Turb.	Al	
Coagulant	Al)	(mg/l)	pH	Mix	Mix	2 mins	5 mins	30 mins	(NTU)	(mg/l)	pH	(NTU)	(mg/l)	pH
Pass 100	2	0	8	A	A	6	6	5	4.8	0.21	7.8	1.4	0.07	7.8
Pass 100	2.5	0	8	A	B	4	4	3	2.9	0.2	7.8	0.72	0.04	7.8
Pass 100	3	0	8	A	B	3	3	2	1.2	0.06	7.8	0.58	0	7.8
Pass 100	3.5	0	8	A	D	1	1	1	0.6	0.02	7.8	0.42	0	7.8
Pass 100	4	0	8	A	D	2	2	4	1.2	0.09	7.8	0.52	0	7.8
Pass 100	4.5	0	8	A	B	5	5	6	1.8	0.14	7.8	0.59	0.02	7.8
Raw			8						5.9	0	8	1.6	0	7.8
	Dose	Poly		Floc Size		Settlement			Settled Water Quality			Filtered Water Quality		
	(mg/l	Dose	Start	After	End of	After			Turb.	Al		Turb.	Al	
Coagulant	Al)	(mg/l)	pH	Mix	Mix	2 mins	5 mins	30 mins	(NTU)	(mg/l)	pH	(NTU)	(mg/l)	pH
WTS PAC	1.5	0	7.9	A	D	6	5	5	1	0.1	7.6	0.92	0	7.4
WTS PAC	2	0	7.9	A	D	5	6	6	1	0.12	7.6	0.9	0	7.6
WTS PAC	2.5	0	7.9	A	D	4	4	4	0.8	0.07	7.6	0.65	0	7.6
WTS PAC	3	0	7.9	A	D	2	3	3	0.81	0.07	7.6	0.6	0	7.7
WTS PAC	3.5	0	7.9	A	D/E	1	1	1	0.84	0.06	7.6	0.57	0	7.7
WTS PAC	4	0	7.9	A	D/E	3	2	2	1	0.06	7.6	0.87	0	7.7
Raw									14	0	7.3	1.2	0	7.3
	Dose	Poly		Floc Size		Settlement			Settled Water Quality			Filtered Water Quality		
	(mg/l	Dose	Start	After	End of	After			Turb.	Al		Turb.	Al	
Coagulant	Al)	(mg/l)	pH	Mix	Mix	2 mins	5 mins	30 mins	(NTU)	(mg/l)	pH	(NTU)	(mg/l)	pH
Alum	2	0	8.3	A	B/A	5	5	5	1	0.16	6.8	0.93	0	7.4
Alum	2.5	0	8.3	A	B/A	4	3	4	1	0.11	6.8	0.9	0	7.4
Alum	3	0	8.3	A	B	1	2	3	0.86	0.08	6.9	0.7	0	7.4
Alum	3.5	0	8.3	A	B	2	1	1	0.85	0.07	6.9	0.72	0	7.3
Alum	4	0	8.3	A	B	3	4	2	0.88	0.12	7	0.62	0	7.3
Alum	4.5	0	8.3	A	B	6	6	6	1	0.12	7	0.9	0	7.3
Raw									14	0	8.3	1.2	0	8.1

	Dose	Poly		Floc Size		Settlement			Settled Water Quality			Filtered Water Quality		
	(mg/l	Dose	Start	After	End of	After			Turb.	Al		Turb.	Al	
Coagulant	Al)	(mg/l)	pH	Mix	Mix	2 mins	5 mins	30 mins	(NTU)	(mg/l)	pH	(NTU)	(mg/l)	pH
INDA PAC	1.5	0	8	A	D	6	5	5	1	0.1	7.6	0.51	0.04	7.8
INDA PAC	2	0	8	A	D	5	6	6	1	0.1	7.5	0.5	0.03	7.8
INDA PAC	2.5	0	8	A	D	4	4	4	0.8	0.08	7.5	0.54	0.03	7.8
INDA PAC	3	0	8	A	D	2	3	3	0.84	0.08	7.5	0.46	0.05	7.8
INDA PAC	3.5	0	8	A	D/E	1	1	1	0.86	0.07	7.4	0.46	0.02	7.8
INDA PAC	4	0	8	A	D/E	3	2	2	1	0.07	7.4	0.46	0.02	7.8
Raw									4.9	0	8	0.84	0	7.9
	Dose	Poly		Floc Size		Settlement			Settled Water Quality			Filtered Water Quality		
	(mg/l	Dose	Start	After	End of	After			Turb.	Al		Turb.	Al	
Coagulant	Al)	(mg/l)	pH	Mix	Mix	2 mins	5 mins	30 mins	(NTU)	(mg/l)	pH	(NTU)	(mg/l)	pH
Alba 18	2	0	8	A	A	6	6	6	1.2	0.14	7.8	1	0.1	
Alba 18	2.5	0	8	A	A	5	5	5	1.2	0.1	7.8	1	0.08	
Alba 18	3	0	8	A	A	2	2	3	1.1	0.1	7.8	1	0.08	
Alba 18	3.5	0	8	A	A	1	1	1	0.92	0.1	7.8	0.9	0.08	
Alba 18	4	0	8	A	A	3	3	2	1	0.11	7.8	0.9	0.09	
Alba 18	4.5	0	8	A	A	4	4	4	1	0.12	7.8	0.9	0.1	
Raw									7.2	0	8	1.2	0	

Pass 100, PAC (WTS & INDA), Alba 18 and Alum Jar Tests with LT20 polymer.
See Chart 6.1 for Floc Size Formation. Key: 1 = fastest 6 = slowest.

	Dose	Poly		Floc Size		Settlement			Settled Water Quality			Filtered Water Quality		
	(mg/l	Dose	Start	After	End of	After			Turb.	Al		Turb.	Al	
Coagulant	Al)	(mg/l)	pH	Mix	Mix	2 mins	5 mins	30 mins	(NTU)	(mg/l)	pH	(NTU)	(mg/l)	pH
Pass 100	3.5	0	8	A	D	5	4	3	1.2	0.04	8	1	0.01	8.1
Pass 100	3.5	0.02	8	A	D	6	6	6	5.2	0.36	7.9	1	0.07	8.1
Pass 100	3.5	0.04	8	A	D	4	5	5	4.1	0.32	7.9	1	0.05	8.1
Pass 100	3.5	0.06	8	A	D	3	3	4	2.7	0.3	7.9	9	0.02	8.1
Pass 100	3.5	0.08	8	A	D	2	2	2	2.6	0.27	7.9	0.95	0.01	8.1
Pass 100	3.5	1	8	A	D	1	1	1	2.8	0.19	7.8	0.98	0	8.1
Raw									5.8	0	8	1.4	0	8.2
	Dose	Poly		Floc Size					Settled Water Quality			Filtered Water Quality		
	(mg/l	Dose	Start	After	End of				Turb.	Al		Turb.	Al	
Coagulant	Al)	(mg/l)	pH	Mix	Mix	2 mins	5 mins	30 mins	(NTU)	(mg/l)	pH	(NTU)	(mg/l)	pH
WTS PAC	3.5	0	8	A	D	3	4	4	0.84	0.07	7.8	0.47	0	7.8
WTS PAC	3.5	0.02	8	A	D	1	3	3	0.66	0.07	7.8	0.42	0	7.8
WTS PAC	3.5	0.04	8	A	D	2	2	2	0.68	0.07	7.8	0.37	0	7.8
WTS PAC	3.5	0.06	8	A	D	4	1	1	0.65	0.07	7.8	0.32	0	7.8
WTS PAC	3.5	0.08	8	A	D	5	5	5	0.69	0.09	7.8	0.35	0	7.8
WTS PAC	3.5	1	8	A	D	6	6	6	0.84	0.1	7.8	0.39	0	7.8
Raw									5.8	0	8	1.4	0	8.2
	Dose	Poly		Floc Size		Settlement			Settled Water Quality			Filtered Water Quality		
	(mg/l	Dose	Start	After	End of	After			Turb.	Al		Turb.	Al	
Coagulant	Al)	(mg/l)	pH	Mix	Mix	2 mins	5 mins	30 mins	(NTU)	(mg/l)	pH	(NTU)	(mg/l)	pH
Alum	3.5	0	8	A	C	4	4	4	0.98	0.05	7.4	0.61	0	7.7
Alum	3.5	0.02	8	A	C	3	3	3	0.97	0.11	7.3	0.45	0	7.7
Alum	3.5	0.04	8	A	C	1	1	2	0.74	0.1	7.3	0.42	0	7.7
Alum	3.5	0.06	8	A	C	2	2	1	0.7	0.06	7.3	0.4	0	7.7
Alum	3.5	0.08	8	A	C	5	5	5	0.74	0.1	7.3	0.44	0	7.7
Alum	3.5	1	8	A	C	6	6	6	0.82	0.11	7.3	0.57	0	7.7
Raw									5.8	0	8	1.4	0	8.2

	Dose	Poly		Floc Size		Settlement			Settled Water Quality			Filtered Water Quality		
	(mg/l	Dose	Start	After	End of	After			Turb.	Al		Turb.	Al	
Coagulant	Al)	(mg/l)	pH	Mix	Mix	2 mins	5 mins	30 mins	(NTU)	(mg/l)	pH	(NTU)	(mg/l)	pH
INDA PAC	3.5	0	8	A	C	4	4	6	0.87	0.06	7.8	0.49	0	7.8
INDA PAC	3.5	0.02	8	A	C	3	3	2	0.69	0.07	7.8	0.45	0	7.8
INDA PAC	3.5	0.04	8	A/B	C	2	2	1	0.66	0.07	7.8	0.36	0	7.8
INDA PAC	3.5	0.06	8	A/B	C	1	1	3	0.64	0.07	7.8	0.32	0	7.8
INDA PAC	3.5	0.08	8	A/B	C	5	5	4	0.67	0.08	7.8	0.34	0	7.8
INDA PAC		1	8	A/B	C	6	6	5	0.79	0.11	7.8	0.39	0	7.8
Raw									5.8	0	8	1.4	0	8.2
	Dose	Poly		Floc Size		Settlement			Settled Water Quality			Filtered Water Quality		
	(mg/l	Dose	Start	After	End of	After			Turb.	Al		Turb.	Al	
Coagulant	Al)	(mg/l)	pH	Mix	Mix	2 mins	5 mins	30 mins	(NTU)	(mg/l)	pH	(NTU)	(mg/l)	pH
Alba 18	3.5	0	8	A	A	6	2	2	0.88	0.07	7.7	0.8	0.06	7.8
Alba 18	3.5	0.02	8	A	A	1	1	1	1	0.07	7.7	0.9	0.04	7.8
Alba 18	3.5	0.04	8	A	A	2	3	3	1	0.09	7.7	0.9	0.06	7.8
Alba 18	3.5	0.06	8	A	A	3	4	4	1.1	0.09	7.7	0.92	0.05	7.8
Alba 18	3.5	0.08	8	A	A	4	5	5	1.1	0.11	7.7	0.84	0.05	7.8
Alba 18	3.5	1	8	A	A	5	6	6	1.1	0.12	7.7	0.9	0.06	7.8
Raw									5.8	0	8	1.4	0	8.2

PAC WTS AND ALUM with LT22S polymer.
See Chart 6.1 for Floc Size Formation. Key: 1 = fastest 6 = slowest.

	Dose	Poly		Floc Size		Settlement			Settled Water Quality			Filtered Water Quality		
	(mg/l	Dose	Start	After	End of	After			Turb.	Al		Turb.	Al	
Coagulant	Al)	(mg/l)	pH	Mix	Mix	2 mins	5 mins	30 mins	(NTU)	(mg/l)	pH	(NTU)	(mg/l)	pH
Alum	3.5	0	8	A/B	C	4	4	4	1	0.1	7.3	0.6	0	7.5
Alum	3.5	0.02	8	A/B	C	3	2	2	0.93	0.1	7.3	0.46	0	7.5
Alum	3.5	0.04	8	A/B	C	1	1	1	0.63	0.05	7.3	0.45	0	7.5
Alum	3.5	0.06	8	A/B	C	2	3	3	0.7	0.04	7.3	0.45	0	7.5
Alum	3.5	0.08	8	A/B	C	5	5	5	0.73	0.08	7.3	0.45	0	7.5
Alum	3.5	0.1	8	A/B	C	6	6	6	0.81	0.1	7.3	0.45	0	7.5
Raw									6.4	0	8	1.2	0	8
	Dose	Poly		Floc Size		Settlement			Settled Water Quality			Filtered Water Quality		
	(mg/l	Dose	Start	After	End of	After			Turb.	Al		Turb.	Al	
Coagulant	Al)	(mg/l)	pH	Mix	Mix	2 mins	5 mins	30 mins	(NTU)	(mg/l)	pH	(NTU)	(mg/l)	pH
WTS PAC	3.5	0	8	A/B	C	4	3	3	0.68	0.06	7.6	0.37	0	7.7
WTS PAC	3.5	0.02	8	A/B	C	2	2	2	0.67	0.07	7.6	0.38	0	7.7
WTS PAC	3.5	0.04	8	A/B	C	1	1	1	0.64	0.07	7.6	0.38	0	7.7
WTS PAC	3.5	0.06	8	A/B	C	3	4	4	0.65	0.04	7.6	0.39	0	7.7
WTS PAC	3.5	0.08	8	A/B	C	5	5	5	0.67	0.07	7.6	0.4	0	7.7
WTS PAC	3.5	0.1	8	A/B	C	6	6	6	0.68	0.07	7.6	0.4	0	7.7
	Dose	Poly		Floc Size		Settlement			Settled Water Quality			Filtered Water Quality		
	(mg/l	Dose	Start	After	End of	After			Turb.	Al		Turb.	Al	
Coagulant	Al)	(mg/l)	pH	Mix	Mix	2 mins	5 mins	30 mins	(NTU)	(mg/l)	pH	(NTU)	(mg/l)	pH
Alum	2.5	0.04	8	A	C	3	2	2	0.91	0.1	7.5	0.5	0	7.7
Alum	3	0.04	8	A/B	C	2	1	1	0.81	0.04	7.5	0.44	0	7.7
Alum	3.5	0.04	8	A/B	C	1	3	3	0.72	0.01	7.5	0.4	0	7.7
Alum	4	0.04	8	A/B	C	4	4	4	0.76	0.06	7.4	0.42	0	7.7
Alum	4.5	0.04	8	A/B	C	5	5	5	0.78	0.06	7.4	0.47	0	7.6
Alum	5	0.04	8	A/B	C	6	6	6	0.79	0.06	7.4	0.51	0	7.6
Raw									6.4	0	8	1.2	0	8
	Dose	Poly		Floc Size					Settled Water Quality			Filtered Water Quality		

	(mg/l	Dose	Start	After	End of				Turb.	Al		Turb.	Al	
Coagulant	Al)	(mg/l)	pH	Mix	Mix	2 mins	5 mins	30 mins	(NTU)	(mg/l)	pH	(NTU)	(mg/l)	pH
WTS PAC	2.5	0.04	8	A/B	C	3	3	3	0.8	0.07	7.6	0.5	0	7.6
WTS PAC	3	0.04	8	A/B	C	1	2	2	0.67	0.07	7.6	0.43	0	7.7
WTS PAC	3.5	0.04	8	A/B	C	2	1	1	0.65	0.04	7.6	0.4	0	7.7
WTS PAC	4	0.04	8	A/B	C	4	4	4	0.68	0.04	7.5	0.41	0	7.7
WTS PAC	4.5	0.04	8	A/B	C	5	5	5	0.68	0.07	7.5	0.42	0	7.7
WTS PAC	5	0.04	8	A/B	C	6	6	6	0.61	0.09	7.5	0.42	0	7.7
Raw									6.4	0	8	1.2	0	8

PAC WTS AND ALUM with LT25 polymer.
See Chart 6.1 for Floc Size Formation. Key: 1 = fastest 6 = slowest.

	Dose	Poly		Floc Size		Settlement			Settled Water Quality			Filtered Water Quality		
	(mg/l	Dose	Start	After	End of	After			Turb.	Al		Turb.	Al	
Coagulant	Al)	(mg/l)	pH	Mix	Mix	2 mins	5 mins	30 mins	(NTU)	(mg/l)	pH	(NTU)	(mg/l)	pH
Alum	3.5	0	8	A/B	C	2	3	3	0.86	0.08	7.3	0.4	0	7.4
Alum	3.5	0.02	8	A/B	C	1	2	2	0.81	0.12	7.3	0.71	0.04	7.4
Alum	3.5	0.04	8	A/B	C	3	1	1	0.8	0.15	7.3	0.5	0.05	7.4
Alum	3.5	0.06	8	A/B	C	4	4	4	0.8	0.14	7.3	0.47	0.03	7.4
Alum	3.5	0.08	8	A/B	C	5	5	5	0.76	0.12	7.3	0.45	0.03	7.4
Alum	3.5	0.1	8	A/B	C	6	6	6	0.75	0.11	7.3	0.46	0.03	7.4
Raw									6.4	0	8	1.2	0	8
	Dose	Poly		Floc Size					Settled Water Quality			Filtered Water Quality		
	(mg/l	Dose	Start	After	End of				Turb.	Al		Turb.	Al	
Coagulant	Al)	(mg/l)	pH	Mix	Mix	2 mins	5 mins	30 mins	(NTU)	(mg/l)	pH	(NTU)	(mg/l)	pH
WTS PAC	3.5	0	8	A/B	C	3	3	3	0.56	0.05	7.7	0.44	0	7.8
WTS PAC	3.5	0.02	8	A/B	C	1	1	1	0.79	0.09	7.7	0.74	0.4	7.8
WTS PAC	3.5	0.04	8	A/B	C	2	2	2	0.76	0.1	7.7	0.69	0.02	7.8
WTS PAC	3.5	0.06	8	A/B	C	4	4	4	0.7	0.09	7.7	0.67	0.01	7.8
WTS PAC	3.5	0.08	8	A/B	C	5	5	5	0.78	0.08	7.7	0.62	0.02	7.8
WTS PAC	3.5	0.1	8	A/B	C	6	6	6	0.78	0.08	7.7	0.6	0.02	7.8
Raw									6.4	0	8	1.2	0	8
	Dose	Poly		Floc Size		Settlement			Settled Water Quality			Filtered Water Quality		
	(mg/l	Dose	Start	After	End of	After			Turb.	Al		Turb.	Al	
Coagulant	Al)	(mg/l)	pH	Mix	Mix	2 mins	5 mins	30 mins	(NTU)	(mg/l)	pH	(NTU)	(mg/l)	pH
Alum	2.5	0.04	8	A/B	C	2	3	3	0.94	0.19		0.69	0.04	7.5
Alum	3	0.04	8	A/B	C	1	2	2	0.9	0.17		0.6	0.04	7.5
Alum	3.5	0.04	8	A/B	C	3	1	1	0.8	0.15		0.54	0.05	7.5
Alum	4	0.04	8	A/B	C	4	4	4	0.9	0.16		0.54	0.06	7.5
Alum	4.5	0.04	8	A/B	C	5	5	5	0.94	0.15		0.56	0.09	7.5
Alum	5	0.04	8	A/B	C	6	6	6	1	0.15		0.57	0.09	7.5
Raw									6.4	0	8	1.2	0	8

	Dose	Poly		Floc Size		Settlement			Settled Water Quality			Filtered Water Quality		
	(mg/l	Dose	Start	After	End of	After			Turb.	Al		Turb.	Al	
Coagulant	Al)	(mg/l)	pH	Mix	Mix	2 mins	5 mins	30 mins	(NTU)	(mg/l)	pH	(NTU)	(mg/l)	pH
WTS PAC	2.5	0.04	8	A/B	C	6	6	6	0.78	0.1	7.4	0.69	0.03	7.7
WTS PAC	3	0.04	8	A/B	C	5	1	5	0.78	0.07	7.4	0.74	0.04	7.7
WTS PAC	3.5	0.04	8	A/B	C	1	2	1	0.75	0.1	7.3	0.69	0.02	7.6
WTS PAC	4	0.04	8	A/B	C	2	3	2	0.79	0.11	7.3	0.68	0.03	7.6
WTS PAC	4.5	0.04	8	A/B	C	3	4	4	0.79	0.14	7.3	0.71	0.03	7.6
WTS PAC	5	0.04	8	A/B	C	4	5	5	0.8	0.14	7.3	0.71	0.03	7.6
Raw									6.4	0	8	1.2	0	8

PAC WTS AND ALUM with LT20 polymer.
See Chart 6.1 for Floc Size Formation. Key: 1 = fastest 6 = slowest.

	Dose	Poly		Floc Size					Settled Water Quality			Filtered Water Quality		
	(mg/l	Dose	Start	After	End of				Turb.	Al		Turb.	Al	
Coagulant	Al)	(mg/l)	pH	Mix	Mix	2 mins	5 mins	30 mins	(NTU)	(mg/l)	pH	(NTU)	(mg/l)	pH
WTS PAC	3.5	0	8	A	D	3	4	4	0.84	0.07	7.8	0.47	0	7.8
WTS PAC	3.5	0.02	8	A	D	1	3	3	0.66	0.07	7.8	0.42	0	7.8
WTS PAC	3.5	0.04	8	A	D	2	2	2	0.68	0.07	7.8	0.37	0	7.8
WTS PAC	3.5	0.06	8	A	D	4	1	1	0.65	0.07	7.8	0.32	0	7.8
WTS PAC	3.5	0.08	8	A	D	5	5	5	0.69	0.09	7.8	0.35	0	7.8
WTS PAC	3.5	1	8	A	D	6	6	6	0.84	0.1	7.8	0.39	0	7.8
Raw									5.8	0	8	1.4	0	8.2
	Dose	Poly		Floc Size		Settlement			Settled Water Quality			Filtered Water Quality		
	(mg/l	Dose	Start	After	End of	After			Turb.	Al		Turb.	Al	
Coagulant	Al)	(mg/l)	pH	Mix	Mix	2 mins	5 mins	30 mins	(NTU)	(mg/l)	pH	(NTU)	(mg/l)	pH
Alum	3.5	0	8	A	C	4	4	4	0.98	0.05	7.4	0.61	0	7.7
Alum	3.5	0.02	8	A	C	3	3	3	0.97	0.11	7.3	0.45	0	7.7
Alum	3.5	0.04	8	A	C	1	1	2	0.74	0.1	7.3	0.42	0	7.7
Alum	3.5	0.06	8	A	C	2	2	1	0.7	0.06	7.3	0.4	0	7.7
Alum	3.5	0.08	8	A	C	5	5	5	0.74	0.1	7.3	0.44	0	7.7
Alum	3.5	1	8	A	C	6	6	6	0.82	0.11	7.3	0.57	0	7.7
Raw									5.8	0	8	1.4	0	8.2
	Dose	Poly		Floc Size		Settlement			Settled Water Quality			Filtered Water Quality		
	(mg/l	Dose	Start	After	End of	After			Turb.	Al		Turb.	Al	
Coagulant	Al)	(mg/l)	pH	Mix	Mix	2 mins	5 mins	30 mins	(NTU)	(mg/l)	pH	(NTU)	(mg/l)	pH
Alum	3.5	0	8	A/B	C	5	5	4	0.47	0.06	7.6	0.24	0	7.7
Alum	3.5	0.02	8	A/B	C	3	3	3	0.42	0.04	7.6	0.22	0	7.7
Alum	3.5	0.04	8	A/B	C	2	2	2	0.39	0.02	7.6	0.18	0	7.7
Alum	3.5	0.06	8	A/B	C	1	1	1	0.37	0.02	7.6	0.16	0	7.7
Alum	3.5	0.08	8	A/B	C	4	4	5	0.4	0.02	7.6	0.19	0	7.7
Alum	3.5	0.1	8	A/B	C	6	6	6	0.42	0.02	7.6	0.24	0	7.7
Raw									6.4	0	8	1.2	0	8

	Dose	Poly		Floc Size		Settlement			Settled Water Quality			Filtered Water Quality		
	(mg/l	Dose	Start	After	End of	After			Turb.	Al		Turb.	Al	
Coagulant	Al)	(mg/l)	pH	Mix	Mix	2 mins	5 mins	30 mins	(NTU)	(mg/l)	pH	(NTU)	(mg/l)	pH
WTS PAC	2.5	0.04	8	A/B	C	6	6	6	0.78	0.1	7.4	0.69	0.03	7.7
WTS PAC	3	0.04	8	A/B	C	5	1	5	0.78	0.07	7.4	0.74	0.04	7.7
WTS PAC	3.5	0.04	8	A/B	C	1	2	1	0.75	0.1	7.3	0.69	0.02	7.6
WTS PAC	4	0.04	8	A/B	C	2	3	2	0.79	0.11	7.3	0.68	0.03	7.6
WTS PAC	4.5	0.04	8	A/B	C	3	4	4	0.79	0.14	7.3	0.71	0.03	7.6
WTS PAC	5	0.04	8	A/B	C	4	5	5	0.8	0.14	7.3	0.71	0.03	7.6
Raw									6.4	0	8	1.2	0	8

PAC WTS AND ALUM with LT25 polymer.
See Chart 6.1 for Floc Size Formation. Key: 1 = fastest 6 = slowest.

	Dose	Poly		Floc Size		Settlement			Settled Water Quality			Filtered Water Quality		
	(mg/l	Dose	Start	After	End of	After			Turb.	Al		Turb.	Al	
Coagulant	Al)	(mg/l)	pH	Mix	Mix	2 mins	5 mins	30 mins	(NTU)	(mg/l)	pH	(NTU)	(mg/l)	pH
Alum	3.5	0	8	A/B	C	2	3	3	0.86	0.08	7.3	0.4	0	7.4
Alum	3.5	0.02	8	A/B	C	1	2	2	0.81	0.12	7.3	0.71	0.04	7.4
Alum	3.5	0.04	8	A/B	C	3	1	1	0.8	0.15	7.3	0.5	0.05	7.4
Alum	3.5	0.06	8	A/B	C	4	4	4	0.8	0.14	7.3	0.47	0.03	7.4
Alum	3.5	0.08	8	A/B	C	5	5	5	0.76	0.12	7.3	0.45	0.03	7.4
Alum	3.5	0.1	8	A/B	C	6	6	6	0.75	0.11	7.3	0.46	0.03	7.4
Raw									6.4	0	8	1.2	0	8
	Dose	Poly		Floc Size					Settled Water Quality			Filtered Water Quality		
	(mg/l	Dose	Start	After	End of				Turb.	Al		Turb.	Al	
Coagulant	Al)	(mg/l)	pH	Mix	Mix	2 mins	5 mins	30 mins	(NTU)	(mg/l)	pH	(NTU)	(mg/l)	pH
WTS PAC	3.5	0	8	A/B	C	3	3	3	0.56	0.05	7.7	0.44	0	7.8
WTS PAC	3.5	0.02	8	A/B	C	1	1	1	0.79	0.09	7.7	0.74	0.4	7.8
WTS PAC	3.5	0.04	8	A/B	C	2	2	2	0.76	0.1	7.7	0.69	0.02	7.8
WTS PAC	3.5	0.06	8	A/B	C	4	4	4	0.7	0.09	7.7	0.67	0.01	7.8
WTS PAC	3.5	0.08	8	A/B	C	5	5	5	0.78	0.08	7.7	0.62	0.02	7.8
WTS PAC	3.5	0.1	8	A/B	C	6	6	6	0.78	0.08	7.7	0.6	0.02	7.8
Raw									6.4	0	8	1.2	0	8
	Dose	Poly		Floc Size		Settlement			Settled Water Quality			Filtered Water Quality		
	(mg/l	Dose	Start	After	End of	After			Turb.	Al		Turb.	Al	
Coagulant	Al)	(mg/l)	pH	Mix	Mix	2 mins	5 mins	30 mins	(NTU)	(mg/l)	pH	(NTU)	(mg/l)	pH
Alum	2.5	0.04	8	A/B	C	2	3	3	0.94	0.19		0.69	0.04	7.5
Alum	3	0.04	8	A/B	C	1	2	2	0.9	0.17		0.6	0.04	7.5
Alum	3.5	0.04	8	A/B	C	3	1	1	0.8	0.15		0.54	0.05	7.5
Alum	4	0.04	8	A/B	C	4	4	4	0.9	0.16		0.54	0.06	7.5
Alum	4.5	0.04	8	A/B	C	5	5	5	0.94	0.15		0.56	0.09	7.5
Alum	5	0.04	8	A/B	C	6	6	6	1	0.15		0.57	0.09	7.5
Raw									6.4	0	8	1.2	0	8

	Dose	Poly		Floc Size					Settled Water Quality			Filtered Water Quality		
	(mg/l	Dose	Start	After	End of				Turb.	Al		Turb.	Al	
Coagulant	Al)	(mg/l)	pH	Mix	Mix	2 mins	5 mins	30 mins	(NTU)	(mg/l)	pH	(NTU)	(mg/l)	pH
WTS PAC	3.5	0	8	A/B	C	4	4	4	0.65	0.04	7.8	0.41	0	7.9
WTS PAC	3.5	0.02	8	A/B	C	3	3	3	0.62	0.02	7.8	0.37	0	7.9
WTS PAC	3.5	0.04	8	A/B	C	2	2	2	0.44	0	7.8	0.29	0	7.9
WTS PAC	3.5	0.06	8	A/B	C	1	1	1	0.4	0	7.8	0.24	0	7.9
WTS PAC	3.5	0.08	8	A/B	C	5	5	5	0.44	0	7.8	0.32	0	7.9
WTS PAC	3.5	0.1	8	A/B	C	6	6	6	0.49	0	7.8	0.34	0	7.9
Raw									6.4	0	8	1.2	0	8
	Dose	Poly		Floc Size		Settlement			Settled Water Quality			Filtered Water Quality		
	(mg/l	Dose	Start	After	End of	After			Turb.	Al		Turb.	Al	
Coagulant	Al)	(mg/l)	pH	Mix	Mix	2 mins	5 mins	30 mins	(NTU)	(mg/l)	pH	(NTU)	(mg/l)	pH
Alum	2.5	0.06	8	A/B	C	4	4	4	0.49	0.05	7.4	0.42	0	7.5
Alum	3	0.06	8	A/B	C	3	2	2	0.44	0.04	7.4	0.4	0	7.5
Alum	3.5	0.06	8	A/B	C	1	1	1	0.42	0.02	7.4	0.32	0	7.5
Alum	4	0.06	8	A/B	C	2	3	3	0.42	0.02	7.4	0.27	0	7.5
Alum	4.5	0.06	8	A/B	C	5	5	5	0.44	0.04	7.4	0.29	0	7.5
Alum	5	0.06	8	A/B	C	6	6	6	0.45	0.05	7.4	0.29	0	7.5
Raw									6.4	0	8	1.2	0	8
	Dose	Poly		Floc Size		Settlement			Settled Water Quality			Filtered Water Quality		
	(mg/l	Dose	Start	After	End of	After			Turb.	Al		Turb.	Al	
Coagulant	Al)	(mg/l)	pH	Mix	Mix	2 mins	5 mins	30 mins	(NTU)	(mg/l)	pH	(NTU)	(mg/l)	pH
WTS PAC	2.5	0.06	8	A/B	C	6	6	6	0.42	0.03	7.6	0.4	0	7.7
WTS PAC	3	0.06	8	A/B	D	1	2	2	0.39	0.01	7.6	0.37	0	7.7
WTS PAC	3.5	0.06	8	A/B	D	2	1	1	0.37	0.03	7.6	0.32	0	7.7
WTS PAC	4	0.06	8	A/B	D	3	3	3	0.39	0.03	7.6	0.337	0	7.7
WTS PAC	4.5	0.06	8	A/B	C	4	4	4	0.39	0.03	7.6	0.33	0	7.7
WTS PAC	5	0.06	8	A/B	C	5	5	5	0.44	0.03	7.6	0.34	0	7.7
Raw									6.4	0	8	1.2	0	8

APPENDIX 2

ALUM with LT20 polymer at a Pre-Ozone Concentration of 0.5 mg/l at pH 6.8, 7.0, 7.2, 7.4 and 6.8.
See Chart 6.1 for Floc Size Formation. Key: 1 = fastest 6 = slowest.

	Dose	Poly		Floc Size		Settlement			Settled Water Quality			Filtered Water Quality		
	(mg/l	Dose	Test	After	End of	After			Turb.	Al		Turb.	Al	
Coagulant	Al)	(mg/l)	pH	Mix	Mix	2 mins	5 mins	30 mins	0.6	(mg/l)	pH	(NTU)	(mg/l)	pH
Alum	2.5	0.06	6.8	A	C	4	3	4	0.54	0.15	7.4	0.47	0.04	6.9
Alum	3	0.06	6.8	A	C	1	1	2	0.46	0.09	7.4	0.32	0.04	6.9
Alum	3.5	0.06	6.8	A	C	2	2	1	0.49	0.04	7.4	0.38	0	6.9
Alum	4	0.06	6.8	A	C	3	4	3	0.6	0.04	7.3	0.41	0	6.9
Alum	4.5	0.06	6.8	A	C	5	5	5	0.62	0.06	7.2	0.62	0	6.9
Alum	5	0.06	6.8	A	C	6	6	6	0.84	0.06	7.1	0.74	0	6.9
Raw									4.5	0.04	7.8	0.67	0.04	8
	Dose	Poly		Floc Size					Settled Water Quality			Filtered Water Quality		
	(mg/l	Dose	Start	After	End of				Turb.	Al		Turb.	Al	
Coagulant	Al)	(mg/l)	pH	Mix	Mix	2 mins	5 mins	30 mins	(NTU)	(mg/l)	pH	(NTU)	(mg/l)	pH
Alum	2.5	0.06	7	A	D	4	4	4	0.66	0.12	6.9	0.49	0.04	7.6
Alum	3	0.06	7	A	D	1	1	1	0.56	0.05	6.9	0.36	0	7.5
Alum	3.5	0.06	7	A	D	2	2	2	0.46	0.06	6.9	0.38	0	7.4
Alum	4	0.06	7	A	D	3	3	3	0.5	0.07	6.9	0.4	0	7.3
Alum	4.5	0.06	7	A	C	5	5	5	0.69	0.09	6.9	0.61	0	7.3
Alum	5	0.06	7	A	C	6	6	6	0.89	0.1	6.9	0.79	0	7.3
Raw									4.5	0.04	7.8	0.67	0.04	8
	Dose	Poly		Floc Size		Settlement			Settled Water Quality			Filtered Water Quality		
	(mg/l	Dose	Start	After	End of	After			Turb.	Al		Turb.	Al	
Coagulant	Al)	(mg/l)	pH	Mix	Mix	2 mins	5 mins	30 mins	(NTU)	(mg/l)	pH	(NTU)	(mg/l)	pH
Alum	2.5	0.06	7.2	A	D	4	4	4	0.59	0.09	7.4	0.44	0	7.7
Alum	3	0.06	7.2	A	D	1	1	1	0.54	0.06	7.3	0.44	0	7.7
Alum	3.5	0.06	7.2	A	D	23	2	2	0.52	0.06	7.3	0.44	0	7.7
Alum	4	0.06	7.2	A	D	5	3	3	0.54	0.14	7.3	0.46	0	7.7
Alum	4.5	0.06	7.2	A	C	6	5	5	0.58	0.19	7.3	0.54	0	7.7
Alum	5	0.06	7.2	A	C	6	6	6	0.62	0.2	7.3	0.58	0	7.7

Raw									4.5	0.04	7.8	0.67	0.04	8
	Dose	Poly		Floc Size		Settlement			Settled Water Quality			Filtered Water Quality		
	(mg/l	Dose	Start	After	End of	After			Turb.	Al		Turb.	Al	
Coagulant	Al)	(mg/l)	pH	Mix	Mix	2 mins	5 mins	30 mins	(NTU)	(mg/l)	pH	(NTU)	(mg/l)	pH
Alum	2.5	0.06	7.4	A/B	D	4	4	4	0.51	0.21	7.3	0.41	0.02	7.4
Alum	3	0.06	7.4	A/B	D	1	1	1	0.49	0.19	7.3	0.29	0.02	7.4
Alum	3.5	0.06	7.4	A/B	D	2	2	2	0.58	0.19	7.3	0.34	0	7.4
Alum	4	0.06	7.4	A/B	D	3	3	3	0.57	0.19	7.3	0.29	0	7.4
Alum	4.5	0.06	7.4	A/B	D	5	5	5	0.64	0.19	7.3	0.32	0	7.4
Alum	5	0.06	7.4	A/B	D	6	6	6	0.71	0.18	7.3	0.44	0	7.4
Raw									4.5	0.04	7.8	0.67	0.04	8
	Dose	Poly		Floc Size		Settlement			Settled Water Quality			Filtered Water Quality		
	(mg/l	Dose	Start	After	End of	After			Turb.	Al		Turb.	Al	
Coagulant	Al)	(mg/l)	pH	Mix	Mix	2 mins	5 mins	30 mins	(NTU)	(mg/l)	pH	(NTU)	(mg/l)	pH
Alum	2.5	0.06	7.6	A/B	D	4	4	4	0.81	0.22	7.3	0.61	0.04	7.4
Alum	3	0.06	7.6	A/B	D	1	1	1	0.7	0.21	7.3	0.4	0.02	7.4
Alum	3.5	0.06	7.6	A/B	D	2	2	2	0.5	0.16	7.3	0.34	0	7.4
Alum	4	0.06	7.6	A/B	D	3	3	3	0.6	0.17	7.3	0.29	0	7.4
Alum	4.5	0.06	7.6	A/B	D	5	5	5	0.71	0.21	7.3	0.41	0	7.4
Alum	5	0.06	7.6	A/B	D	6	6	6	1	0.22	7.3	0.59	0	7.4
Raw									4.5	0.04	7.8	0.67	0.04	8

ALUM with LT20 polymer at a Pre-Ozone Concentration of 1.0 mg/l at pH 6.8, 7.0, 7.2, 7.4 and 6.8.
See Chart 6.1 for Floc Size Formation. Key: 1 = fastest 6 = slowest.

	Dose	Poly		Floc Size		Settlement			Settled Water Quality			Filtered Water Quality		
	(mg/l	Dose	Test	After	End of	After			Turb.	Al		Turb.	Al	
Coagulant	Al)	(mg/l)	pH	Mix	Mix	2 mins	5 mins	30 mins	0.6	(mg/l)	pH	(NTU)	(mg/l)	pH
Alum	2.5	0.06	6.8	A	C	4	4	4	0.69	0.01	6.8	0.64	0	6.8
Alum	3	0.06	6.8	A	C	1	1	1	0.61	0.01	6.8	0.58	0	6.8
Alum	3.5	0.06	6.8	A	C	2	2	2	0.59	0	6.8	0.56	0	6.8
Alum	4	0.06	6.8	A	C	3	3	3	0.64	0.04	6.8	0.58	0	6.8
Alum	4.5	0.06	6.8	A	C	5	5	5	0.69	0.04	6.8	0.66	0	6.8
Alum	5	0.06	6.8	A	C	6	6	6	0.74	0.04	6.8	0.68	0	6.8
Raw									4.5	0.04	7.8	0.67	0.04	8
	Dose	Poly		Floc Size					Settled Water Quality			Filtered Water Quality		
	(mg/l	Dose	Start	After	End of				Turb.	Al		Turb.	Al	
Coagulant	Al)	(mg/l)	pH	Mix	Mix	2 mins	5 mins	30 mins	(NTU)	(mg/l)	pH	(NTU)	(mg/l)	pH
Alum	2.5	0.06	7	A	C	4	4	4	0.7	0.05	7	0.64	0	7
Alum	3	0.06	7	A	C/D	1	1	1	0.63	0.05	7.1	0.59	0	7
Alum	3.5	0.06	7	A	C/D	2	2	2	0.61	0	7.1	0.55	0	7
Alum	4	0.06	7	A	C/D	3	3	3	0.62	0	7.2	0.58	0	7
Alum	4.5	0.06	7	A	C	5	5	5	0.68	0	7.2	0.64	0	7
Alum	5	0.06	7	A	C	6	6	6	0.73	0	7.2	0.64	0	7
Raw									4.5	0.04	7.8	0.67	0.04	8
	Dose	Poly		Floc Size		Settlement			Settled Water Quality			Filtered Water Quality		
	(mg/l	Dose	Start	After	End of	After			Turb.	Al		Turb.	Al	
Coagulant	Al)	(mg/l)	pH	Mix	Mix	2 mins	5 mins	30 mins	(NTU)	(mg/l)	pH	(NTU)	(mg/l)	pH
Alum	2.5	0.06	7.2	A/B	C	6	6	6	0.66	0.11	7.4	0.64	0	7.2
Alum	3	0.06	7.2	A/B	C/D	1	1	1	0.6	0.09	7.4	0.58	0	7.2
Alum	3.5	0.06	7.2	A/B	C/D	2	2	2	0.6	0.05	7.3	0.54	0	7.1
Alum	4	0.06	7.2	A/B	C/D	3	3	3	0.61	0	7.3	0.58	0	7.1
Alum	4.5	0.06	7.2	A/B	C/D	4	4	4	0.68	0	7.3	0.62	0	7.1
Alum	5	0.06	7.2	A/B	C	5	5	5	0.72	0	7.3	0.68	0	7.1
Raw									4.5	0.04	7.8	0.67	0.04	8

	Dose	Poly		Floc Size		Settlement			Settled Water Quality			Filtered Water Quality		
	(mg/l	Dose	Start	After	End of	After			Turb.	Al		Turb.	Al	
Coagulant	Al)	(mg/l)	pH	Mix	Mix	2 mins	5 mins	30 mins	(NTU)	(mg/l)	pH	(NTU)	(mg/l)	pH
Alum	2.5	0.06	7.4	A/B	C	4	4	4	1	0.11	7.6	0.54	0	7.7
Alum	3	0.06	7.4	A/B	C	1	1	1	1	0.1	7.5	0.44	0	7.7
Alum	3.5	0.06	7.4	A/B	C	2	2	2	0.84	0.05	7.5	0.43	0	7.7
Alum	4	0.06	7.4	A/B	C	3	3	3	1	0	7.5	0.44	0	7.7
Alum	4.5	0.06	7.4	A/B	C	5	5	5	1	0	7.5	0.48	0	7.7
Alum	5	0.06	7.4	A/B	C	6	6	6	1.1	0	7.4	0.55	0	7.7
Raw									4.5	0.04	7.8	0.67	0.04	8
	Dose	Poly		Floc Size		Settlement			Settled Water Quality			Filtered Water Quality		
	(mg/l	Dose	Start	After	End of	After			Turb.	Al		Turb.	Al	
Coagulant	Al)	(mg/l)	pH	Mix	Mix	2 mins	5 mins	30 mins	(NTU)	(mg/l)	pH	(NTU)	(mg/l)	pH
Alum	2.5	0.06	7.6	A/B	C	4	4	4	1	0.11	7.6	0.77	0.06	7.7
Alum	3	0.06	7.6	A/B	C	1	1	1	1	0.06	7.6	0.67	0.02	7.7
Alum	3.5	0.06	7.6	A/B	C	2	2	2	1	0.07	7.6	0.51	0.02	7.7
Alum	4	0.06	7.6	A/B	C	3	3	3	1	0.04	7.5	0.8	0	7.7
Alum	4.5	0.06	7.6	A/B	C	5	5	5	1	0.04	7.5	0.88	0	7.7
Alum	5	0.06	7.6	A/B	C	6	6	6	1.1	0.04	7.5	1	0	7.7
Raw									4.5	0.04	7.8	0.67	0.04	8

ALUM with LT20 polymer at a Pre-Ozone Concentration of 1.5 mg/l at pH 6.8, 7.0, 7.2, 7.4 and 6.8.
See Chart 6.1 for Floc Size Formation.
Key: 1 = fastest 6 = slowest.

	(mg/l	Dose	Test	After	End of	After			Turb.	Al		Turb.	Al	
Coagulant	Al)	(mg/l)	pH	Mix	Mix	2 mins	5 mins	30 mins	0.6	(mg/l)	pH	(NTU)	(mg/l)	pH
Alum	2.5	0.06	6.8	A	B/A	5	5	5	1.3	0.17	6.8	1	0.04	6.8
Alum	3	0.06	6.8	A	B/A	3	4	4	1.3	0.14	6.8	1	0.03	6.8
Alum	3.5	0.06	6.8	A	B	2	3	3	1.4	0.12	6.9	1	0.03	6.8
Alum	4	0.06	6.8	A	B	1	1	1	1.1	0.1	6.9	1	3	6.8
Alum	4.5	0.06	6.8	A	B	4	2	2	1.2	0.13	7	1.2	0.02	6.8
Alum	5	0.06	6.8	A	B	6	6	6	1.4	0.14	7	1.2	0.04	6.8
Raw									4.5	0.04	7.8	0.67	0.04	8
	Dose	Poly		Floc Size					Settled Water Quality			Filtered Water Quality		
	(mg/l	Dose	Start	After	End of				Turb.	Al		Turb.	Al	
Coagulant	Al)	(mg/l)	pH	Mix	Mix	2 mins	5 mins	30 mins	(NTU)	(mg/l)	pH	(NTU)	(mg/l)	pH
Alum	2.5	0.06	7	A	C/D	6	5	5	1.2	0.13	7.2	1	0.02	7.2
Alum	3	0.06	7	A	C/D	4	4	3	1.3	0.13	7.3	1	0.02	7.2
Alum	3.5	0.06	7	A	C	3	2	1	1.2	0.1	7.3	0.95	0.02	7.2
Alum	4	0.06	7	A	C	2	1	2	1	0.07	7.3	1	0.01	7.2
Alum	4.5	0.06	7	A	C	1	3	4	1	0.07	7.3	1	0.06	7.2
Alum	5	0.06	7	A	C	5	6	6	1.1	0.08	7.3	1.2	0.09	7.1
Raw									4.5	0.04	7.8	0.67	0.04	8
	Dose	Poly		Floc Size		Settlement			Settled Water Quality			Filtered Water Quality		
	(mg/l	Dose	Start	After	End of	After			Turb.	Al		Turb.	Al	
Coagulant	Al)	(mg/l)	pH	Mix	Mix	2 mins	5 mins	30 mins	(NTU)	(mg/l)	pH	(NTU)	(mg/l)	pH
Alum	2.5	0.06	7.2	A	D	3	3	3	1.7	0.08	7.1	1.1	0.02	7.2
Alum	3	0.06	7.2	A	D	2	2	2	1.2	0.06	7.1	1	0	7.2
Alum	3.5	0.06	7.2	A	D	1	1	1	1.1	0.02	7.1	0.97	0	7.2
Alum	4	0.06	7.2	A	D	4	4	4	1.1	0.07	7	0.98	0.02	7.3
Alum	4.5	0.06	7.2	A	D	5	5	5	1.2	0	6.9	0.95	0.06	7.2
Alum	5	0.06	7.2	A	D	6	6	6	1	0.08	6.9	0.98	0.06	7.2
Raw									14	0.01	8.3	1.2	0.01	8.5

	Dose	Poly		Floc Size		Settlement			Settled Water Quality			Filtered Water Quality		
	(mg/l	Dose	Start	After	End of	After			Turb.	Al		Turb.	Al	
Coagulant	Al)	(mg/l)	pH	Mix	Mix	2 mins	5 mins	30 mins	(NTU)	(mg/l)	pH	(NTU)	(mg/l)	pH
Alum	2.5	0.06	7.4	A/B	D	2	2	2	1.3	0.07	7.4	1	0	7.4
Alum	3	0.06	7.4	A/B	D	1	1	1	1.2	0.06	7.3	1	0	7.5
Alum	3.5	0.06	7.4	A/B	D	3	3	3	1.2	0.14	7.3	0.95	0.02	7.6
Alum	4	0.06	7.4	A/B	D	4	4	4	1.2	0.11	7.3	0.95	0.02	7.6
Alum	4.5	0.06	7.4	A/B	D	5	5	5	1.2	0.11	7.3	0.94	0.02	7.6
Alum	5	0.06	7.4	A/B	D	6	6	6	1.1	0.11	7.3	0.97	0.01	7.6
Raw									14	0.01	8.3	1.2	0.01	8.5
	Dose	Poly		Floc Size		Settlement			Settled Water Quality			Filtered Water Quality		
	(mg/l	Dose	Start	After	End of	After			Turb.	Al		Turb.	Al	
Coagulant	Al)	(mg/l)	pH	Mix	Mix	2 mins	5 mins	30 mins	(NTU)	(mg/l)	pH	(NTU)	(mg/l)	pH
Alum	2.5	0.06	7.6	A/B	C	6	6	6	0.42	0.03	7.6	0.4	0	7.7
Alum	3	0.06	7.6	A/B	D	1	2	2	0.39	0.01	7.6	0.37	0	7.7
Alum	3.5	0.06	7.6	A/B	D	2	1	1	0.37	0.03	7.6	0.32	0	7.7
Alum	4	0.06	7.6	A/B	D	3	3	3	0.39	0.03	7.6	0.32	0	7.7
Alum	4.5	0.06	7.6	A/B	C	4	4	4	0.39	0.03	7.6	0.33	0	7.7
Alum	5	0.06	7.6	A/B	C	5	5	5	0.44	0.03	7.6	0.34	0	7.7
Raw									14	0.01	8.3	1.2	0.01	8.5

ALUM with LT20 polymer at a Pre-Ozone Concentration of 2.0 mg/l at pH 6.8, 7.0, 7.2, 7.4 and 6.8.
See Chart 6.1 for Floc Size Formation. Key: 1 = fastest 6 = slowest.

	Dose	Poly		Floc Size		Settlement			Settled Water Quality			Filtered Water Quality		
	(mg/l	Dose	Test	After	End of	After			Turb.	Al		Turb.	Al	
Coagulant	Al)	(mg/l)	pH	Mix	Mix	2 mins	5 mins	30 mins	(NTU)	(mg/l)	pH	(NTU)	(mg/l)	pH
Alum	2.5	0.06	6.8	A	C	4	2	4	1	1	7.7	0.9	0	7.4
Alum	3	0.06	6.8	A	C	2	1	2	0.84	0.07	7.7	0.62	0	7.4
Alum	3.5	0.06	6.8	A	C	1	3	1	0.76	0.05	7.6	0.44	0	7.4
Alum	4	0.06	6.8	A	C	3	4	3	0.78	0.09	7.6	0.44	0	7.4
Alum	4.5	0.06	6.8	A	C	5	5	5	0.78	0.09	7.5	0.42	0	7.4
Alum	5	0.06	6.8	A	C	6	6	6	0.78	0.08	7.5	0.44	0	7.4
Raw									4	0	8	1.2	0.01	8.1
	Dose	Poly		Floc Size					Settled Water Quality			Filtered Water Quality		
	(mg/l	Dose	Start	After	End of				Turb.	Al		Turb.	Al	
Coagulant	Al)	(mg/l)	pH	Mix	Mix	2 mins	5 mins	30 mins	(NTU)	(mg/l)	pH	(NTU)	(mg/l)	pH
Alum	2.5	0.06	7	A	C	2	4	4	0.75	0.06	7.2	0.71	0.02	7.2
Alum	3	0.06	7	A	C	1	3	3	0.75	0.09	7.2	0.7	0	7.2
Alum	3.5	0.06	7	A	C	3	1	1	0.62	0.06	7.2	0.43	0	7.2
Alum	4	0.06	7	A	C	4	2	2	0.69	0.06	7.2	0.49	0	7.2
Alum	4.5	0.06	7	A	C	5	5	5	0.71	0.05	7.1	0.51	0	7.2
Alum	5	0.06	7	A	C	6	6	6	0.7	0.08	7.1	0.52	0	7.2
Raw									4	0	8	1.2	0.01	8.1
	Dose	Poly		Floc Size		Settlement			Settled Water Quality			Filtered Water Quality		
	(mg/l	Dose	Start	After	End of	After			Turb.	Al		Turb.	Al	
Coagulant	Al)	(mg/l)	pH	Mix	Mix	2 mins	5 mins	30 mins	(NTU)	(mg/l)	pH	(NTU)	(mg/l)	pH
Alum	2.5	0.06	7.2	A	D	2	3	4	0.89	0.09	7.6	0.54	0	7.4
Alum	3	0.06	7.2	A	D	1	2	2	0.82	0.08	7.5	0.5	0	7.4
Alum	3.5	0.06	7.2	A	D	3	1	1	0.77	0.09	7.4	0.4	0	7.4
Alum	4	0.06	7.2	A	D	4	4	3	0.8	0.08	7.3	0.44	0	7.4
Alum	4.5	0.06	7.2	A	D	5	5	5	0.82	0.07	7.3	0.42	0	7.4
Alum	5	0.06	7.2	A	D	6	6	6	0.84	0.02	7.3	0.43	0	7.4
Raw									4	0	8	1.2	0.01	8.1

	Dose	Poly		Floc Size		Settlement			Settled Water Quality			Filtered Water Quality		
	(mg/l	Dose	Start	After	End of	After			Turb.	Al		Turb.	Al	
Coagulant	Al)	(mg/l)	pH	Mix	Mix	2 mins	5 mins	30 mins	(NTU)	(mg/l)	pH	(NTU)	(mg/l)	pH
Alum	2.5	0.06	7.4	A/B	D	2	2	3	1	0.12	7.3	0.39	0	7.4
Alum	3	0.06	7.4	A/B	D	1	1	1	0.97	1	7.3	0.41	0	7.5
Alum	3.5	0.06	7.4	A/B	D	3	3	2	0.91	0.09	7.3	0.45	0	7.5
Alum	4	0.06	7.4	A/B	D	4	4	4	1	0.09	7.3	0.51	0	7.5
Alum	4.5	0.06	7.4	A/B	D	5	5	5	1	0.09	7.3	0.53	0	7.5
Alum	5	0.06	7.4	A/B	D	6	6	6	0.97	0.09	7.3	0.56	0	7.5
Raw									4	0	8	1.2	0.01	8.1
	Dose	Poly		Floc Size		Settlement			Settled Water Quality			Filtered Water Quality		
	(mg/l	Dose	Start	After	End of	After			Turb.	Al		Turb.	Al	
Coagulant	Al)	(mg/l)	pH	Mix	Mix	2 mins	5 mins	30 mins	(NTU)	(mg/l)	pH	(NTU)	(mg/l)	pH
Alum	2.5	0.06	7.6	A/B	D	2	2	2	0.64	0.14	7.8	0.25	0	7.7
Alum	3	0.06	7.6	A/B	D	1	1	1	0.52	0.11	7.8	0.2	0	7.7
Alum	3.5	0.06	7.6	A/B	D	3	3	3	0.54	0.08	7.7	0.46	0	7.7
Alum	4	0.06	7.6	A/B	D	4	4	4	0.64	0.06	7.7	0.61	0	7.7
Alum	4.5	0.06	7.6	A/B	D	5	5	5	0.68	0.06	7.7	0.66	0	7.7
Alum	5	0.06	7.6	A/B	D	6	6	6	0.71	0.04	7.7	0.67	0	7.7
Raw									4	0	8	1.2	0.01	8.1

Pass 100 with LT20 polymer at a Pre-Ozone Concentration of 2.0 mg/l at pH 6.8, 7.0, 7.2, 7.4 and 6.8.
See Chart 6.1 for Floc Size Formation. Key: 1 = fastest 6 = slowest.

	Dose	Poly		Floc Size		Settlement			Settled Water Quality			Filtered Water Quality		
	(mg/l	Dose	Test	After	End of	After			Turb.	Al		Turb.	Al	
Coagulant	Al)	(mg/l)	pH	Mix	Mix	2 mins	5 mins	30 mins	(NTU)	(mg/l)	pH	(NTU)	(mg/l)	pH
Pass 100	2.5	0.06	6.8	A	A	6	6	6	9	0.15	6.9	1.1	0.07	6.8
Pass 100	3	0.06	6.8	A	A	5	5	5	7.7	0.13	6.9	1.1	0.04	6.9
Pass 100	3.5	0.06	6.8	A	A	4	4	4	7.1	0.31	6.9	1.1	0.04	6.9
Pass 100	4	0.06	6.8	A	A/B	2	2	2	5	0.27	6.9	1	0.04	6.9
Pass 100	4.5	0.06	6.8	A	A/B	1	1	1	1	0.14	6.9	1	0.02	6.9
Pass 100	5	0.06	6.8	A	A/B	3	3	3	1	0.08	6.9	1	0.03	6.9
Raw									9	0	8	1.3	0	8.1
	Dose	Poly		Floc Size					Settled Water Quality			Filtered Water Quality		
	(mg/l	Dose	Start	After	End of				Turb.	Al		Turb.	Al	
Coagulant	Al)	(mg/l)	pH	Mix	Mix	2 mins	5 mins	30 mins	(NTU)	(mg/l)	pH	(NTU)	(mg/l)	pH
Pass 100	2.5	0.06	7	A	A	6	6	6	8.8	0.13	7.1	1.1	0.06	7
Pass 100	3	0.06	7	A	A	5	5	5	7.9	0.24	7	1.1	0.04	7.1
Pass 100	3.5	0.06	7	A	A	4	4	4	7.2	0.1	7	1.1	0.02	7.1
Pass 100	4	0.06	7	A	A/B	2	2	2	5	0.1	7	1	0	7.2
Pass 100	4.5	0.06	7	A	A/B	1	1	1	1	0.1	7	1	0	7.2
Pass 100	5	0.06	7	A	A/B	3	3	3	1	0.1	7	1	0	7.2
Raw									9	0	8	1.3	0	8.1
	Dose	Poly		Floc Size		Settlement			Settled Water Quality			Filtered Water Quality		
	(mg/l	Dose	Start	After	End of	After			Turb.	Al		Turb.	Al	
Coagulant	Al)	(mg/l)	pH	Mix	Mix	2 mins	5 mins	30 mins	(NTU)	(mg/l)	pH	(NTU)	(mg/l)	pH
Pass 100	2.5	0.06	7.2	A	A	6	6	6	9	0.12	7.3	1.1	0.04	7.2
Pass 100	3	0.06	7.2	A	A	5	5	5	8.1	0.14	7.4	1.1	0.056	7.3
Pass 100	3.5	0.06	7.2	A	A/B	4	4	4	7.2	0.1	7.4	1	0.05	7.3
Pass 100	4	0.06	7.2	A	A/B	2	2	3	5	0.14	7.4	1	0.04	7.4
Pass 100	4.5	0.06	7.2	A	A/B	1	1	1	1.2	0.16	7.4	1	0.01	7.4
Pass 100	5	0.06	7.2	A	A	3	3	2	1	0.18	7.4	1	0.01	7.4
Raw									9	0	8	1.3	0	8.1

	Dose	Poly		Floc Size		Settlement			Settled Water Quality			Filtered Water Quality		
	(mg/l	Dose	Start	After	End of	After			Turb.	Al		Turb.	Al	
Coagulant	Al)	(mg/l)	pH	Mix	Mix	2 mins	5 mins	30 mins	(NTU)	(mg/l)	pH	(NTU)	(mg/l)	pH
Pass 100	2.5	0.06	7.4	A/B	A	6	6	6	9	0.1	7.2	1.1	0.03	7.3
Pass 100	3	0.06	7.4	A/B	A	5	5	5	8	0.21	7.2	1	0.04	7.3
Pass 100	3.5	0.06	7.4	A/B	B	4	4	4	7	0.2	7.2	1	0.04	7.4
Pass 100	4	0.06	7.4	A/B	C	2	2	2	4.1	0.14	7.1	0.94	0.03	7.4
Pass 100	4.5	0.06	7.4	A/B	E/D	1	1	1	1	0.1	7.1	0.86	0	7.4
Pass 100	5	0.06	7.4	A/B	D	3	3	3	1.1	0.11	7.1	0.98	0	7.4
Raw									9	0	8	1.3	0	8.1
	Dose	Poly		Floc Size		Settlement			Settled Water Quality			Filtered Water Quality		
	(mg/l	Dose	Start	After	End of	After			Turb.	Al		Turb.	Al	
Coagulant	Al)	(mg/l)	pH	Mix	Mix	2 mins	5 mins	30 mins	(NTU)	(mg/l)	pH	(NTU)	(mg/l)	pH
Pass 100	2.5	0.06	7.6	A/B	A	6	6	6	9	0.1	7.7	1.1	0.01	7.8
Pass 100	3	0.06	7.6	A/B	A	5	5	5	8.1	0.18	7.8	1	0	7.8
Pass 100	3.5	0.06	7.6	A/B	C	4	4	4	7.1	0.2	7.9	1	0	7.8
Pass 100	4	0.06	7.6	A/B	D	2	3	2	4.2	0.15	7.9	0.9	0	7.8
Pass 100	4.5	0.06	7.6	A/B	E	1	1	1	1	0.09	8	0.82	0	7.8
Pass 100	5	0.06	7.6	A/B	E	3	2	3	1.1	0.1	8	0.94	0	7.8
Raw									9	0	8	1.3	0	8.1

Pass 100 with LT20 polymer at a Pre-Ozone Concentration of 1.5 mg/l at pH 6.8, 7.0, 7.2, 7.4 and 6.8.
See Chart 6.1 for Floc Size Formation. Key: 1 = fastest 6 = slowest.

	Dose	Poly		Floc Size		Settlement			Settled Water Quality			Filtered Water Quality		
	(mg/l	Dose	Test	After	End of	After			Turb.	Al		Turb.	Al	
Coagulant	Al)	(mg/l)	pH	Mix	Mix	2 mins	5 mins	6	(NTU)	(mg/l)	pH	(NTU)	(mg/l)	pH
Pass 100	2.5	0.06	6.8	A	C	6	6	5	3.8	0.25	7	1.5	0.1	7.2
Pass 100	3	0.06	6.8	A	C	5	5	3	3.8	0.24	7	1.4	0.12	7.3
Pass 100	3.5	0.06	6.8	A	C	3	3	2	3.8	0.2	7	1.2	0.14	7.3
Pass 100	4	0.06	6.8	A	C	2	2	1	2.7	0.12	7	1	0.1	7.3
Pass 100	4.5	0.06	6.8	A	C	1	1	4	1.1	0.11	7	1	0.07	7.3
Pass 100	5	0.06	6.8	A	C	4	4		1.2	0.14	7	1	0.07	7.3
Raw									9	0	8	1.3	0	8.1
	Dose	Poly		Floc Size					Settled Water Quality			Filtered Water Quality		
	(mg/l	Dose	Start	After	End of				Turb.	Al		Turb.	Al	
Coagulant	Al)	(mg/l)	pH	Mix	Mix	2 mins	5 mins	30 mins	(NTU)	(mg/l)	pH	(NTU)	(mg/l)	pH
Pass 100	2.5	0.06	7	A	C	6	6	6	3.8	0.19	7.1	1.3	0.09	7.4
Pass 100	3	0.06	7	A	C	5	5	5	3.7	0.2	7.1	1.2	0.09	7.4
Pass 100	3.5	0.06	7	A	C	3	3	3	3.6	0.18	7.1	1.1	0.11	7.4
Pass 100	4	0.06	7	A	C	2	2	2	2.8	0.11	7.1	1	0.1	7.4
Pass 100	4.5	0.06	7	A	C	1	1	1	0.85	0.08	7.1	0.55	0.02	7.4
Pass 100	5	0.06	7	A	C	4	4	4	1.1	0.15	7.1	0.94	0.06	7.4
Raw									9	0	8	1.3	0	8.1
	Dose	Poly		Floc Size		Settlement			Settled Water Quality			Filtered Water Quality		
	(mg/l	Dose	Start	After	End of	After			Turb.	Al		Turb.	Al	
Coagulant	Al)	(mg/l)	pH	Mix	Mix	2 mins	5 mins	30 mins	(NTU)	(mg/l)	pH	(NTU)	(mg/l)	pH
Pass 100	2.5	0.06	7.2	A	C	6	6	6	3	0.18	7.3	1.2	0.07	7.4
Pass 100	3	0.06	7.2	A	C	5	5	5	0.7	0.22	7.2	1	0	7.4
Pass 100	3.5	0.06	7.2	A	C/D	3	3	3	3.6	0.18	7.2	0.79	0.1	7.4
Pass 100	4	0.06	7.2	A	C/D	2	2	2	3.6	0.1	7.1	0.65	0.1	7.4
Pass 100	4.5	0.06	7.2	A	C	1	1	1	0.6	0.07	7.1	0.51	0	7.4
Pass 100	5	0.06	7.2	A	C	4	4	4	1.1	0.14	7.1	0.92	0.07	7.4
Raw									9	0	8	1.3	0	8.1

	Dose	Poly		Floc Size		Settlement			Settled Water Quality			Filtered Water Quality		
	(mg/l	Dose	Start	After	End of	After			Turb.	Al		Turb.	Al	
Coagulant	Al)	(mg/l)	pH	Mix	Mix	2 mins	5 mins	30 mins	(NTU)	(mg/l)	pH	(NTU)	(mg/l)	pH
Pass 100	2.5	0.06	7.4	A/B	D	6	6	6	3.6	0.18	7.5	1.4	0.07	8
Pass 100	3	0.06	7.4	A/B	D	5	5	5	3.6	0.2	7.5	0.87	0.07	7.9
Pass 100	3.5	0.06	7.4	A/B	D	3	3	3	322	0.1	7.5	0.48	0.06	7.9
Pass 100	4	0.06	7.4	A/B	D	2	1	1	2.6	0.06	7.5	0.44	0	7.9
Pass 100	4.5	0.06	7.4	A/B	D	1	2	2	0.52	0.08	7.5	0.36	0	7.9
Pass 100	5	0.06	7.4	A/B	D	4	4	4	0.56	0.09	7.5	0.52	0.02	7.9
Raw									9	0	8	1.3	0	8.1
	Dose	Poly		Floc Size		Settlement			Settled Water Quality			Filtered Water Quality		
	(mg/l	Dose	Start	After	End of	After			Turb.	Al		Turb.	Al	
Coagulant	Al)	(mg/l)	pH	Mix	Mix	2 mins	5 mins	30 mins	(NTU)	(mg/l)	pH	(NTU)	(mg/l)	pH
Pass 100	2.5	0.06	7.6	A/B	D	6	6	6	3.6	0.2	7.5	1.5	0.08	8
Pass 100	3	0.06	7.6	A/B	D	5	5	5	3.6	0.2	7.5	0.92	0.08	8
Pass 100	3.5	0.06	7.6	A/B	D	3	3	3	3.6	0.14	7.6	0.64	0.08	8
Pass 100	4	0.06	7.6	A/B	D	2	2	2	2.6	0.09	7.6	0.48	0.01	8
Pass 100	4.5	0.06	7.6	A/B	D	1	1	1	0.86	0.08	7.6	0.4	0	8
Pass 100	5	0.06	7.6	A/B	D	4	4	4	1	0.1	7.6	0.62	0	8
Raw									9	0	8	1.3	0	8.1

Pass 100 with LT20 polymer at a Pre-Ozone Concentration of 1.0 mg/l at pH 6.8, 7.0, 7.2, 7.4 and 6.8.
See Chart 6.1 for Floc Size Formation. Key: 1 = fastest 6 = slowest.

	Dose	Poly		Floc Size		Settlement			Settled Water Quality			Filtered Water Quality		
	(mg/l	Dose	Test	After	End of	After			Turb.	Al		Turb.	Al	
Coagulant	Al)	(mg/l)	pH	Mix	Mix	2 mins	5 mins	30 mins	(NTU)	(mg/l)	pH	(NTU)	(mg/l)	pH
Pass 100	2.5	0.06	6.8	A	A	5	5	5	3.4	0.21	7.1	1.4	0.09	7.3
Pass 100	3	0.06	6.8	A	A	4	4	4	3.3	0.24	7.1	1.2	0.09	7.3
Pass 100	3.5	0.06	6.8	A	A	2	2	2	3.3	0.19	7.1	0.97	0.12	7.3
Pass 100	4	0.06	6.8	A	A	1	1	1	1.5	0.12	7.1	0.79	0.02	7.3
Pass 100	4.5	0.06	6.8	A	A	3	3	3	0.71	0.14	7.1	0.6	0	7.3
Pass 100	5	0.06	6.8	A	A	6	6	6	1.1	0.21	7.1	1.1	0.07	7.3
Raw									9	0	8	1.3	0	8.1
	Dose	Poly		Floc Size					Settled Water Quality			Filtered Water Quality		
	(mg/l	Dose	Start	After	End of				Turb.	Al		Turb.	Al	
Coagulant	Al)	(mg/l)	pH	Mix	Mix	2 mins	5 mins	30 mins	(NTU)	(mg/l)	pH	(NTU)	(mg/l)	pH
Pass 100	2.5	0.06	7	A	A	5	5	5	3.2	0.18	7.3	1.2	0.07	7.6
Pass 100	3	0.06	7	A	A	4	4	4	3.2	0.22	7.3	1	0.09	7.6
Pass 100	3.5	0.06	7	A	C	2	2	2	3.2	0.17	7.3	0.77	0.1	7.5
Pass 100	4	0.06	7	A	D	1	1	1	1.4	0.09	7.3	0.74	0	7.5
Pass 100	4.5	0.06	7	A	C	3	3	3	0.52	0.09	7.1	0.4	0	7.5
Pass 100	5	0.06	7	A	B	6	6	6	1.1	0.21	7	1	0	7.5
Raw									9	0	8	1.3	0	8.1
	Dose	Poly		Floc Size		Settlement			Settled Water Quality			Filtered Water Quality		
	(mg/l	Dose	Start	After	End of	After			Turb.	Al		Turb.	Al	
Coagulant	Al)	(mg/l)	pH	Mix	Mix	2 mins	5 mins	30 mins	(NTU)	(mg/l)	pH	(NTU)	(mg/l)	pH
Pass 100	2.5	0.06	7.2	A	A	5	5	5	4.1	0.32	7.4	1.5	0.16	7.4
Pass 100	3	0.06	7.2	A	A	4	4	4	4	0.27	7.4	1	0.11	7.4
Pass 100	3.5	0.06	7.2	A	D	3	3	3	2.5	0.18	7.3	1.2	0.09	7.4
Pass 100	4	0.06	7.2	A	D	2	2	2	3	0.1	7.3	0.88	0.02	7.4
Pass 100	4.5	0.06	7.2	A	D	1	1	1	0.54	0.16	7.3	0.5	0	7.5
Pass 100	5	0.06	7.2	A	C	5	4	5	1.2	0.25	7.3	1	0	7.5
Raw									9	0	8	1.3	0	8.1

	Dose	Poly		Floc Size		Settlement			Settled Water Quality			Filtered Water Quality		
	(mg/l	Dose	Start	After	End of	After			Turb.	Al		Turb.	Al	
Coagulant	Al)	(mg/l)	pH	Mix	Mix	2 mins	5 mins	30 mins	(NTU)	(mg/l)	pH	(NTU)	(mg/l)	pH
Pass 100	2.5	0.06	7.4	A/B	D	6	6	6	3.3	0.19	7.6	1.2	0.17	7.8
Pass 100	3	0.06	7.4	A/B	D	5	5	5	3.4	0.22	7.6	0.89	0.1	7.7
Pass 100	3.5	0.06	7.4	A/B	D	3	3	3	3.6	0.31	7.6	0.69	0.06	7.7
Pass 100	4	0.06	7.4	A/B	D/E	2	2	2	3.4	0.14	7.6	0.54	0.06	7.7
Pass 100	4.5	0.06	7.4	A/B	D	1	1	1	0.51	0.1	7.6	0.35	0	7.7
Pass 100	5	0.06	7.4	A/B	D	4	4	4	1.2	0.19	7.6	0.72	0.14	7.7
Raw									9	0	8	1.3	0	8.1
	Dose	Poly		Floc Size		Settlement			Settled Water Quality			Filtered Water Quality		
	(mg/l	Dose	Start	After	End of	After			Turb.	Al		Turb.	Al	
Coagulant	Al)	(mg/l)	pH	Mix	Mix	2 mins	5 mins	30 mins	(NTU)	(mg/l)	pH	(NTU)	(mg/l)	pH
Pass 100	2.5	0.06	7.6	A/B	D	6	6	6	3.5	0.14	7.7	1.1	0.07	7.9
Pass 100	3	0.06	7.6	A/B	D	5	5	5	3.5	0.15	7.7	0.91	0.06	7.9
Pass 100	3.5	0.06	7.6	A/B	D	3	3	3	3.4	0.12	7.7	0.64	0.04	7.8
Pass 100	4	0.06	7.6	A/B	D	2	2	2	3.4	0.1	7.7	0.56	0	7.8
Pass 100	4.5	0.06	7.6	A/B	D	1	1	1	1.2	0.04	7.7	0.45	0	7.8
Pass 100	5	0.06	7.6	A/B	D	4	4	4	2.9	0.16	7.7	1	0.04	7.8
Raw									9	0	8	1.3	0	8.1

Pass 100 with LT20 polymer at a Pre-Ozone Concentration of 0.5 mg/l at pH 6.8, 7.0, 7.2, 7.4 and 6.8.
See Chart 6.1 for Floc Size Formation. Key: 1 = fastest 6 = slowest.

	Dose	Poly		Floc Size		Settlement			Settled Water Quality			Filtered Water Quality		
	(mg/l	Dose	Test	After	End of	After			Turb.	Al		Turb.	Al	
Coagulant	Al)	(mg/l)	pH	Mix	Mix	2 mins	5 mins	30 mins	(NTU)	(mg/l)	pH	(NTU)	(mg/l)	pH
Pass 100	2.5	0.06	6.8	A	A	6	6	6	9.4	0.19	7	1.4	0.09	7.1
Pass 100	3	0.06	6.8	A	A	5	5	5	9	0.32	7.1	1.5	0.14	7.1
Pass 100	3.5	0.06	6.8	A	A/B	4	4	4	7.8	0.3	7.1	1.2	0.16	7.1
Pass 100	4	0.06	6.8	A	A/B	2	2	2	5.4	0.17	7.1	1.2	0.1	7.1
Pass 100	4.5	0.06	6.8	A	A/B	1	1	1	1.1	0.12	7.1	1	0.1	7.1
Pass 100	5	0.06	6.8	A	A	3	3	3	2.7	0.1	7.1	1.4	0.17	7.1
Raw									12	0	8	1.6	0	8.1
	Dose	Poly		Floc Size					Settled Water Quality			Filtered Water Quality		
	(mg/l	Dose	Start	After	End of				Turb.	Al		Turb.	Al	
Coagulant	Al)	(mg/l)	pH	Mix	Mix	2 mins	5 mins	30 mins	(NTU)	(mg/l)	pH	(NTU)	(mg/l)	pH
Pass 100	2.5	0.06	7	A	A	6	6	6	9.4	0.2	7.2	1.3	0.1	7.3
Pass 100	3	0.06	7	A	A	5	5	5	9	0.3	7.1	1.3	0.12	7.2
Pass 100	3.5	0.06	7	A	A/B	4	4	4	7.8	0.26	7.1	1.2	0.14	7.2
Pass 100	4	0.06	7	A	A/B	3	3	3	5.5	0.15	7.1	1.1	0.1	7.2
Pass 100	4.5	0.06	7	A	A/B	1	1	1	1	0.1	7.1	1	0.07	7.2
Pass 100	5	0.06	7	A	A	2	2	2	2	0.1	7.1	1.3	0.07	7.2
Raw									12	0	8	1.6	0	8.1
	Dose	Poly		Floc Size		Settlement			Settled Water Quality			Filtered Water Quality		
	(mg/l	Dose	Start	After	End of	After			Turb.	Al		Turb.	Al	
Coagulant	Al)	(mg/l)	pH	Mix	Mix	2 mins	5 mins	30 mins	(NTU)	(mg/l)	pH	(NTU)	(mg/l)	pH
Pass 100	2.5	0.06	7.2	A	A	6	6	6	9.2	0.14	7.3	1.2	0.04	7.1
Pass 100	3	0.06	7.2	A	B	5	5	5	8.7	0.29	7.3	1.3	0.06	7.2
Pass 100	3.5	0.06	7.2	A	C	4	4	4	8.1	0.32	7.3	1	0.06	7.3
Pass 100	4	0.06	7.2	A	C	3	3	3	5.3	0.14	7.2	1.1	0.05	7.3
Pass 100	4.5	0.06	7.2	A	C	1	1	1	1.4	0.1	7.2	1	0.03	7.3
Pass 100	5	0.06	7.2	A	B/C	2	2	2	1	0.12	7.2	0.85	0.05	7.3
Raw									12	0	8	1.6	0	8.1

	Dose	Poly		Floc Size		Settlement			Settled Water Quality			Filtered Water Quality		
	(mg/l	Dose	Start	After	End of	After			Turb.	Al		Turb.	Al	
Coagulant	Al)	(mg/l)	pH	Mix	Mix	2 mins	5 mins	30 mins	(NTU)	(mg/l)	pH	(NTU)	(mg/l)	pH
Pass 100	2.5	0.06	7.4	A/B	C	6	6	6	8.4	0.14	7.2	1.2	0.04	7.2
Pass 100	3	0.06	7.4	A/B	D	5	5	5	8.2	0.26	7.3	1.3	0.06	7.2
Pass 100	3.5	0.06	7.4	A/B	D	4	4	4	7.4	0.23	7.3	1	0.05	7.2
Pass 100	4	0.06	7.4	A/B	D	3	3	3	4.2	0.1	7.2	1.1	0.05	7.2
Pass 100	4.5	0.06	7.4	A/B	D	1	1	1	1	0.09	7.3	0.4	0.03	7.2
Pass 100	5	0.06	7.4	A/B	D	2	2	2	0.85	0.12	7.3	0.87	0.05	7.2
Raw									12	0	8	1.6	0	8.1
	Dose	Poly		Floc Size		Settlement			Settled Water Quality			Filtered Water Quality		
	(mg/l	Dose	Start	After	End of	After			Turb.	Al		Turb.	Al	
Coagulant	Al)	(mg/l)	pH	Mix	Mix	2 mins	5 mins	30 mins	(NTU)	(mg/l)	pH	(NTU)	(mg/l)	pH
Pass 100	2.5	0.06	7.6	A/B	D	6	6	6	9.4	0.16	7.5	1.3	0.03	7.4
Pass 100	3	0.06	7.6	A/B	D	5	5	5	8.8	0.2	7.5	1.2	0.05	7.5
Pass 100	3.5	0.06	7.6	A/B	D	4	4	4	8	0.24	7.5	1.1	0.07	7.5
Pass 100	4	0.06	7.6	A/B	D/E	1	1	1	5	0.17	7.5	1	0.06	7.5
Pass 100	4.5	0.06	7.6	A/B	D/E	3	3	3	1.6	0.07	7.5	1	0.02	7.5
Pass 100	5	0.06	7.6	A/B	D	2	2	2	1	0.08	7.5	0.9	0.02	7.5
Raw									12	0	8	1.6	0	8.1

PAC (INDA & WTS) with LT20 polymer at a Pre-Ozone Concentration of 0.5 mg/l at pH 6.8, 7.0, 7.2, 7.4 and 6.8. See Chart 6.1 for Floc Size Formation. Key: 1 = fastest 6 = slowest.

	Dose	Poly		Floc Size		Settlement			Settled Water Quality			Filtered Water Quality		
	(mg/l	Dose	Test	After	End of	After			Turb.	Al		Turb.	Al	
Coagulant	Al)	(mg/l)	pH	Mix	Mix	2 mins	5 mins	30 mins	(NTU)	(mg/l)	pH	(NTU)	(mg/l)	pH
INDA PAC	2.5	0.06	6.8	A	B	1	2	2	0.94	0	7.3	0.7	0	7.2
INDA PAC	3	0.06	6.8	A	B	3	3	4	0.67	0	7.2	0.64	0	7.2
INDA PAC	3.5	0.06	6.8	A	B	3	6	6	0.74	0	7.2	0.62	0	7.2
WTS PAC	2.5	0.06	6.8	A	B	6	1	1	0.76	0	7.2	0.65	0	7.3
WTS PAC	3	0.06	6.8	A	B	1	4	3	0.76	0	7.2	0.59	0	7.3
WTS PAC	3.5	0.06	6.8	A	B	4	5	5	0.79	0	7.2	0.52	0	7.3
Raw									6.7	0	7.7	0.8	0	7.9
	Dose	Poly		Floc Size					Settled Water Quality			Filtered Water Quality		
	(mg/l	Dose	Start	After	End of				Turb.	Al		Turb.	Al	
Coagulant	Al)	(mg/l)	pH	Mix	Mix	2 mins	5 mins	30 mins	(NTU)	(mg/l)	pH	(NTU)	(mg/l)	pH
INDA PAC	2.5	0.06	7	A	B/C	1	1	1	0.92	0	7.4	0.69	0	7.5
INDA PAC	3	0.06	7	A	B/C	4	3	2	0.65	0	7.4	0.61	0	7.5
INDA PAC	3.5	0.06	7	A	B/C	5	6	3	0.72	0	7.3	0.6	0	7.5
WTS PAC	4	0.06	7	A	B/C	2	2	4	0.74	0	7.2	0.65	0	7.5
WTS PAC	4.5	0.06	7	A	B/C	3	4	5	0.74	0	7.2	0.57	0	7.5
WTS PAC	5	0.06	7	A	B/C	6	5	6	0.74	0	7.2	0.54	0	7.5
Raw									6.7	0	7.7	0.8	0	7.9
	Dose	Poly		Floc Size		Settlement			Settled Water Quality			Filtered Water Quality		
	(mg/l	Dose	Start	After	End of	After			Turb.	Al		Turb.	Al	
Coagulant	Al)	(mg/l)	pH	Mix	Mix	2 mins	5 mins	30 mins	(NTU)	(mg/l)	pH	(NTU)	(mg/l)	pH
INDA PAC	2.5	0.06	7.2	A	C	2	1	1	0.86	0.06	7.4	0.42	0.02	7.3
INDA PAC	3	0.06	7.2	A	C	4	4	4	0.76	0.08	7.4	0.46	0	7.3
INDA PAC	3.5	0.06	7.2	A	C	5	5	5	0.86	0.09	7.4	0.47	0	7.3
WTS PAC	4	0.06	7.2	A	C	1	2	2	0.78	0.05	7.4	0.4	0	7.4
WTS PAC	4.5	0.06	7.2	A	C	3	3	3	0.8	0.05	7.4	0.46	0	7.4
WTS PAC	5	0.06	7.2	A	C	6	6	6	0.67	0.05	7.4	0.48	0	7.4
Raw									6.7	0	7.7	0.8	0	7.9

	Dose	Poly		Floc Size		Settlement			Settled Water Quality			Filtered Water Quality		
	(mg/l	Dose	Start	After	End of	After			Turb.	Al		Turb.	Al	
Coagulant	Al)	(mg/l)	pH	Mix	Mix	2 mins	5 mins	30 mins	(NTU)	(mg/l)	pH	(NTU)	(mg/l)	pH
INDA PAC	2.5	0.06	7.4	A/B	C/D	1	1	1	0.65	0.05	7.7	0.42	0.02	7.8
INDA PAC	3	0.06	7.4	A/B	C/D	4	4	4	0.56	0.06	7.7	0.44	0	7.8
INDA PAC	3.5	0.06	7.4	A/B	D	3	3	3	0.62	0.07	7.7	0.5	0	7.8
WTS PAC	4	0.06	7.4	A/B	D	2	2	2	0.59	0.05	7.6	0.36	0	7.8
WTS PAC	4.5	0.06	7.4	A/B	D	5	5	5	0.51	0.04	7.6	0.44	0	7.7
WTS PAC	5	0.06	7.4	A/B	D	6	6	6	0.64	0.02	7.6	0.56	0	7.7
Raw									6.7	0	7.7	0.8	0	7.9
	Dose	Poly		Floc Size		Settlement			Settled Water Quality			Filtered Water Quality		
	(mg/l	Dose	Start	After	End of	After			Turb.	Al		Turb.	Al	
Coagulant	Al)	(mg/l)	pH	Mix	Mix	2 mins	5 mins	30 mins	(NTU)	(mg/l)	pH	(NTU)	(mg/l)	pH
INDA PAC	2.5	0.06	7.6	A/B	D/E	1	1	1	0.64	0.1	7.7	0.55	0.02	7.8
INDA PAC	3	0.06	7.6	A/B	D/E	3	3	3	0.48	0.07	7.7	0.46	0.02	7.8
INDA PAC	3.5	0.06	7.6	A/B	D/E	4	4	4	0.5	0.08	7.7	0.44	0.02	7.8
WTS PAC	4	0.06	7.6	A/B	D/E	2	2	2	0.56	0.09	7.6	0.5	0.03	7.8
WTS PAC	4.5	0.06	7.6	A/B	D/E	5	5	5	0.52	0.09	7.6	0.48	0.03	7.7
WTS PAC	5	0.06	7.6	A/B	D/E	6	6	6	0.54	0.09	7.6	0.47	0.03	7.6
Raw									6.7	0	7.7	0.8	0	7.9

PAC (INDA & WTS) with LT20 polymer at a Pre-Ozone Concentration of 1.0 mg/l at pH 6.8, 7.0, 7.2, 7.4 and 6.8. See Chart 6.1 for Floc Size Formation. Key: 1 = fastest 6 = slowest.

	Dose	Poly		Floc Size		Settlement			Settled Water Quality			Filtered Water Quality		
	(mg/l	Dose	Test	After	End of	After			Turb.	Al		Turb.	Al	
Coagulant	Al)	(mg/l)	pH	Mix	Mix	2 mins	5 mins	30 mins	(NTU)	(mg/l)	pH	(NTU)	(mg/l)	pH
INDA PAC	2.5	0.06	6.8	A	B	1	1	1	0.87	0.1	7.1	0.88	0.01	7.1
INDA PAC	3	0.06	6.8	A	B	3	3	3	0.65	0.11	7.1	0.57	0.03	7.1
INDA PAC	3.5	0.06	6.8	A	B	5	5	5	0.7	0.09	7	0.59	0.02	7.1
WTS PAC	2.5	0.06	6.8	A	B	2	2	2	0.72	0.1	7	0.8	0.02	7.1
WTS PAC	3	0.06	6.8	A	B	4	4	4	0.68	0.1	6.9	0.6	0.02	7.1
WTS PAC	3.5	0.06	6.8	A	B	6	6	6	0.68	0.1	6.8	0.57	0.02	7.1
Raw									12	0	8.4	1.1	0	8.2
	Dose	Poly		Floc Size					Settled Water Quality			Filtered Water Quality		
	(mg/l	Dose	Start	After	End of				Turb.	Al		Turb.	Al	
Coagulant	Al)	(mg/l)	pH	Mix	Mix	2 mins	5 mins	30 mins	(NTU)	(mg/l)	pH	(NTU)	(mg/l)	pH
INDA PAC	2.5	0.06	7	A	C	1	1	1	0.7	0.09	7.3	0.7	0	7.3
INDA PAC	3	0.06	7	A	C	4	4	4	0.64	0.09	7.3	0.55	0	7.3
INDA PAC	3.5	0.06	7	A	C	6	6	6	0.67	0.1	7.3	0.52	0	7.3
WTS PAC	4	0.06	7	A	C	2	2	2	0.69	0.07	7.3	0.61	0	7.3
WTS PAC	4.5	0.06	7	A	C	3	3	3	0.67	0.06	7.3	0.52	0	7.3
WTS PAC	5	0.06	7	A	C	5	5	5	..68	0.06	7.3	0.54	0	7.3
Raw									12	0	8.4	1.1	0	8.2
	Dose	Poly		Floc Size		Settlement			Settled Water Quality			Filtered Water Quality		
	(mg/l	Dose	Start	After	End of	After			Turb.	Al		Turb.	Al	
Coagulant	Al)	(mg/l)	pH	Mix	Mix	2 mins	5 mins	30 mins	(NTU)	(mg/l)	pH	(NTU)	(mg/l)	pH
INDA PAC	2.5	0.06	7.2	A	C/D	1	2	2	0.67	0.07	7.4	0.6	0	7.6
INDA PAC	3	0.06	7.2	A	C/D	4	4	4	0.62	0.07	7.4	0.52	0	7.6
INDA PAC	3.5	0.06	7.2	A	C/D	5	5	5	0.65	0.06	7.4	0.49	0	7.6
WTS PAC	4	0.06	7.2	A	C/D	2	1	1	0.64	0.06	7.4	0.55	0	7.6
WTS PAC	4.5	0.06	7.2	A	C/D	3	3	3	0.67	0.04	7.4	0.57	0	7.6
WTS PAC	5	0.06	7.2	A	C/D	6	6	6	0.67	0.04	7.4	0.52	0	7.6
Raw									12	0	8.4	1.1	0	8.2

	Dose	Poly		Floc Size		Settlement			Settled Water Quality			Filtered Water Quality		
	(mg/l	Dose	Start	After	End of	After			Turb.	Al		Turb.	Al	
Coagulant	Al)	(mg/l)	pH	Mix	Mix	2 mins	5 mins	30 mins	(NTU)	(mg/l)	pH	(NTU)	(mg/l)	pH
INDA PAC	2.5	0.06	7.4	A/B	D	1	1	1	0.65	0.07	7.5	0.54	0	7.7
INDA PAC	3	0.06	7.4	A/B	D	4	4	4	0.6	0.05	7.5	0.5	0	7.7
INDA PAC	3.5	0.06	7.4	A/B	D	5	5	5	0.6	0.07	7.5	0.47	0	7.6
WTS PAC	4	0.06	7.4	A/B	D	2	2	2	0.62	0.07	7.4	0.52	0	7.6
WTS PAC	4.5	0.06	7.4	A/B	D	3	3	3	0.62	0.04	7.4	0.53	0	7.6
WTS PAC	5	0.06	7.4	A/B	D	6	6	6	0.62	0.04	7.4	0.5	0	7.6
Raw									12	0	8.4	1.1	0	8.2
	Dose	Poly		Floc Size		Settlement			Settled Water Quality			Filtered Water Quality		
	(mg/l	Dose	Start	After	End of	After			Turb.	Al		Turb.	Al	
Coagulant	Al)	(mg/l)	pH	Mix	Mix	2 mins	5 mins	30 mins	(NTU)	(mg/l)	pH	(NTU)	(mg/l)	pH
INDA PAC	2.5	0.06	7.6	A/B	D/E	2	1	1	0.72	0	0.08	0.57	0	7.7
INDA PAC	3	0.06	7.6	A/B	D/E	4	3	3	0.7	0	0.06	0.55	0	7.7
INDA PAC	3.5	0.06	7.6	A/B	D/E	5	5	5	0.69	0	0.09	0.55	0	7.7
WTS PAC	4	0.06	7.6	A/B	D/E	1	2	2	0.69	0	0.09	0.55	0	7.7
WTS PAC	4.5	0.06	7.6	A/B	D/E	3	4	4	0.67	0	0.07	0.57	0	7.7
WTS PAC	5	0.06	7.6	A/B	D/E	6	6	6	0.67	0	0.07	0.54	0	7.7
Raw									12	0	8.4	1.1	0	8.2

PAC (INDA & WTS) with LT20 polymer at a Pre-Ozone Concentration of 1.5 mg/l at pH 6.8, 7.0, 7.2, 7.4 and 6.8. See Chart 6.1 for Floc Size Formation. Key: 1 = fastest 6 = slowest.

	Dose	Poly		Floc Size		Settlement			Settled Water Quality			Filtered Water Quality		
	(mg/l	Dose	Test	After	End of	After			Turb.	Al		Turb.	Al	
Coagulant	Al)	(mg/l)	pH	Mix	Mix	2 mins	5 mins	30 mins	(NTU)	(mg/l)	pH	(NTU)	(mg/l)	pH
INDA PAC	2.5	0.06	6.8	A	B	1	1	1	0.52	0.06	7.1	0.4	0	7.2
INDA PAC	3	0.06	6.8	A	B	3	3	3	0.51	0.03	7.1	0.36	0	7.2
INDA PAC	3.5	0.06	6.8	A	B	6	6	6	0.56	0.04	7.1	0.34	0	7.2
WTS PAC	2.5	0.06	6.8	A	B	2	2	2	0.55	0.07	7.1	0.34	0	7.2
WTS PAC	3	0.06	6.8	A	B	4	4	4	0.57	0.04	7.1	0.33	0	7.2
WTS PAC	3.5	0.06	6.8	A	B	5	5	5	0.55	0.04	7.1	0.37	0	7.2
Raw									4.9	0	8	0.84	0	7.9
	Dose	Poly		Floc Size					Settled Water Quality			Filtered Water Quality		
	(mg/l	Dose	Start	After	End of				Turb.	Al		Turb.	Al	
Coagulant	Al)	(mg/l)	pH	Mix	Mix	2 mins	5 mins	30 mins	(NTU)	(mg/l)	pH	(NTU)	(mg/l)	pH
INDA PAC	2.5	0.06	7	A	C	1	1	1	0.53	0.02	7.2	0.44	0	7.3
INDA PAC	3	0.06	7	A	C	3	3	3	0.53	0	7.2	0.4	0	7.3
INDA PAC	3.5	0.06	7	A	C	6	6	6	0.32	0.01	7.2	0.4	0	7.3
WTS PAC	4	0.06	7	A	C	2	2	2	0.49	0.02	7.2	0.45	0	7.3
WTS PAC	4.5	0.06	7	A	C	4	4	4	0.5	0	7.2	0.35	0	7.3
WTS PAC	5	0.06	7	A	C	5	5	5	0.5	0	7.2	0.37	0	7.3
Raw									4.9	0	8	0.84	0	7.9
	Dose	Poly		Floc Size		Settlement			Settled Water Quality			Filtered Water Quality		
	(mg/l	Dose	Start	After	End of	After			Turb.	Al		Turb.	Al	
Coagulant	Al)	(mg/l)	pH	Mix	Mix	2 mins	5 mins	30 mins	(NTU)	(mg/l)	pH	(NTU)	(mg/l)	pH
INDA PAC	2.5	0.06	7.2	A	C/D	1	1	1	0.52	0	7.2	0.49	0	7.4
INDA PAC	3	0.06	7.2	A	C/D	3	3	3	0.51	0	7.2	0.45	0	7.4
INDA PAC	3.5	0.06	7.2	A	C/D	6	6	6	0.49	0	7.2	0.47	0	7.4
WTS PAC	4	0.06	7.2	A	C/D	2	2	2	0.5	0	7.2	0.49	0	7.4
WTS PAC	4.5	0.06	7.2	A	C/D	4	4	4	0.5	0	7.2	0.44	0	7.4
WTS PAC	5	0.06	7.2	A	C/D	5	5	5	0.49	0	7.2	0.47	0	7.4
Raw									4.9	0	8	0.84	0	7.9

	Dose	Poly		Floc Size		Settlement			Settled Water Quality			Filtered Water Quality		
	(mg/l	Dose	Start	After	End of	After			Turb.	Al		Turb.	Al	
Coagulant	Al)	(mg/l)	pH	Mix	Mix	2 mins	5 mins	30 mins	(NTU)	(mg/l)	pH	(NTU)	(mg/l)	pH
INDA PAC	2.5	0.06	7.4	A/B	D	3	1	1	0.49	0	7.4	0.4	0	7.5
INDA PAC	3	0.06	7.4	A/B	D	2	4	4	0.37	0	7.4	0.31	0	7.5
INDA PAC	3.5	0.06	7.4	A/B	D	5	5	5	0.37	0	7.4	0.31	0	7.5
WTS PAC	4	0.06	7.4	A/B	D	4	2	2	0.44	0	7.3	0.4	0	7.5
WTS PAC	4.5	0.06	7.4	A/B	D	1	3	3	0.35	0	7.3	0.31	0	7.5
WTS PAC	5	0.06	7.4	A/B	D	6	6	6	0.39	0	7.3	0.34	0	7.5
Raw									4.9	0	8	0.84	0	7.9
	Dose	Poly		Floc Size		Settlement			Settled Water Quality			Filtered Water Quality		
	(mg/l	Dose	Start	After	End of	After			Turb.	Al		Turb.	Al	
Coagulant	Al)	(mg/l)	pH	Mix	Mix	2 mins	5 mins	30 mins	(NTU)	(mg/l)	pH	(NTU)	(mg/l)	pH
INDA PAC	2.5	0.06	7.6	A/B	D/E	2	2	2	0.52	0.06	7.4	0.48	0	7.5
INDA PAC	3	0.06	7.6	A/B	D/E	4	4	4	0.42	0.05	7.4	0.44	0	7.5
INDA PAC	3.5	0.06	7.6	A/B	D/E	5	5	5	0.42	0.02	7.4	0.4	0	7.5
WTS PAC	4	0.06	7.6	A/B	D/E	1	1	1	0.49	0.04	7.4	0.44	0	7.5
WTS PAC	4.5	0.06	7.6	A/B	D/E	3	3	3	0.44	0.04	7.4	0.41	0	7.5
WTS PAC	5	0.06	7.6	A/B	D/E	6	6	6	0.5	0.04	7.4	0.4	0	7.5
Raw									4.9	0	8	0.84	0	7.9

PAC (INDA & WTS) with LT20 polymer at a Pre-Ozone Concentration of 0.5 mg/l at pH 6.8, 7.0, 7.2, 7.4 and 6.8. See Chart 6.1 for Floc Size Formation. Key: 1 = fastest 6 = slowest.

	Dose	Poly		Floc Size		Settlement			Settled Water Quality			Filtered Water Quality		
	(mg/l	Dose	Test	After	End of	After			Turb.	Al		Turb.	Al	
Coagulant	Al)	(mg/l)	pH	Mix	Mix	2 mins	5 mins	30 mins	(NTU)	(mg/l)	pH	(NTU)	(mg/l)	pH
INDA PAC	2.5	0.06	6.8	A	B	1	1	1	0.87	0.1	7.1	0.88	0.01	7.1
INDA PAC	3	0.06	6.8	A	B	3	3	3	0.65	0.11	7.1	0.57	0.03	7.1
INDA PAC	3.5	0.06	6.8	A	B	5	5	5	0.7	0.09	7	0.59	0.02	7.1
WTS PAC	2.5	0.06	6.8	A	B	2	2	2	0.72	0.1	7	0.8	0.02	7.1
WTS PAC	3	0.06	6.8	A	B	4	4	4	0.68	0.1	6.9	0.6	0.02	7.1
WTS PAC	3.5	0.06	6.8	A	B	6	6	6	0.68	0.1	6.8	0.57	0.02	7.1
Raw									12	0	8.4	1.1	0	8.2
	Dose	Poly		Floc Size					Settled Water Quality			Filtered Water Quality		
	(mg/l	Dose	Start	After	End of				Turb.	Al		Turb.	Al	
Coagulant	Al)	(mg/l)	pH	Mix	Mix	2 mins	5 mins	30 mins	(NTU)	(mg/l)	pH	(NTU)	(mg/l)	pH
INDA PAC	2.5	0.06	7	A	C	1	1	1	0.7	0.09	7.3	0.7	0	7.3
INDA PAC	3	0.06	7	A	C	4	4	4	0.64	0.09	7.3	0.55	0	7.3
INDA PAC	3.5	0.06	7	A	C	6	6	6	0.67	0.1	7.3	0.52	0	7.3
WTS PAC	4	0.06	7	A	C	2	2	2	0.69	0.07	7.3	0.61	0	7.3
WTS PAC	4.5	0.06	7	A	C	3	3	3	0.67	0.06	7.3	0.52	0	7.3
WTS PAC	5	0.06	7	A	C	5	5	5	..68	0.06	7.3	0.54	0	7.3
Raw									12	0	8.4	1.1	0	8.2
	Dose	Poly		Floc Size		Settlement			Settled Water Quality			Filtered Water Quality		
	(mg/l	Dose	Start	After	End of	After			Turb.	Al		Turb.	Al	
Coagulant	Al)	(mg/l)	pH	Mix	Mix	2 mins	5 mins	30 mins	(NTU)	(mg/l)	pH	(NTU)	(mg/l)	pH
INDA PAC	2.5	0.06	7.2	A	C/D	1	2	2	0.67	0.07	7.4	0.6	0	7.6
INDA PAC	3	0.06	7.2	A	C/D	4	4	4	0.62	0.07	7.4	0.52	0	7.6
INDA PAC	3.5	0.06	7.2	A	C/D	5	5	5	0.65	0.06	7.4	0.49	0	7.6
WTS PAC	4	0.06	7.2	A	C/D	2	1	1	0.64	0.06	7.4	0.55	0	7.6
WTS PAC	4.5	0.06	7.2	A	C/D	3	3	3	0.67	0.04	7.4	0.57	0	7.6
WTS PAC	5	0.06	7.2	A	C/D	6	6	6	0.67	0.04	7.4	0.52	0	7.6
Raw									12	0	8.4	1.1	0	8.2

	Dose	Poly		Floc Size		Settlement			Settled Water Quality			Filtered Water Quality		
	(mg/l	Dose	Start	After	End of	After			Turb.	Al		Turb.	Al	
Coagulant	Al)	(mg/l)	pH	Mix	Mix	2 mins	5 mins	30 mins	(NTU)	(mg/l)	pH	(NTU)	(mg/l)	pH
INDA PAC	2.5	0.06	7.4	A/B	D	1	1	1	0.65	0.07	7.5	0.54	0	7.7
INDA PAC	3	0.06	7.4	A/B	D	4	4	4	0.6	0.05	7.5	0.5	0	7.7
INDA PAC	3.5	0.06	7.4	A/B	D	5	5	5	0.6	0.07	7.5	0.47	0	7.6
WTS PAC	4	0.06	7.4	A/B	D	2	2	2	0.62	0.07	7.4	0.52	0	7.6
WTS PAC	4.5	0.06	7.4	A/B	D	3	3	3	0.62	0.04	7.4	0.53	0	7.6
WTS PAC	5	0.06	7.4	A/B	D	6	6	6	0.62	0.04	7.4	0.5	0	7.6
Raw									12	0	8.4	1.1	0	8.2
	Dose	Poly		Floc Size		Settlement			Settled Water Quality			Filtered Water Quality		
	(mg/l	Dose	Start	After	End of	After			Turb.	Al		Turb.	Al	
Coagulant	Al)	(mg/l)	pH	Mix	Mix	2 mins	5 mins	30 mins	(NTU)	(mg/l)	pH	(NTU)	(mg/l)	pH
INDA PAC	2.5	0.06	7.6	A/B	D/E	2	1	1	0.72	0	0.08	0.57	0	7.7
INDA PAC	3	0.06	7.6	A/B	D/E	4	3	3	0.7	0	0.06	0.55	0	7.7
INDA PAC	3.5	0.06	7.6	A/B	D/E	5	5	5	0.69	0	0.09	0.55	0	7.7
WTS PAC	4	0.06	7.6	A/B	D/E	1	2	2	0.69	0	0.09	0.55	0	7.7
WTS PAC	4.5	0.06	7.6	A/B	D/E	3	4	4	0.67	0	0.07	0.57	0	7.7
WTS PAC	5	0.06	7.6	A/B	D/E	6	6	6	0.67	0	0.07	0.54	0	7.7
Raw									12	0	8.4	1.1	0	8.2

Pilot Plant Data: Raw Water Data

	Total	Dissolved	Dissolved	Dissolved				
	Aluminium	Iron	Manganese	Aluminium	DOC	TDS	Chlorophyll	Phaeophytin
Date	(mg/l)	(mg/l)	(mg/l)	(mg/l)	(mg/l)	(mg/l)	(ug/l)	1
20/03/98		0.084	0.038	0.034	5.4	285	6.5	1
23/03/98	0.202	0.064	0.048	0.049	4.9	320	5.5	3.6
23/03/98	0.182	0.059	0.052	0.024	4.3	310	7.4	3
24/03/98	0.21	0.08	0.052	0.028	4.8	320	7	1
24/03/98	0.177	0.099	0.055	0.06	4.7	325	8.6	1
25/03/98	0.308	0.077	0.051	0.051	4.7	315	5	2.8
25/03/98	0.197	0.066	0.052	0.03	4.5	310	8	2.7
26/03/98	0.218	0.047	0.053	0.019	4.6	310	8.2	4.5
26/03/98	0.149	0.044	0.054	0.007	4.6	320	3.9	1.5
27/03/98	0.304	0.035	0.049	0.007	4.4	320	5.9	2.6
27/03/98	0.205	0.039	0.051	0.016	4.3	320	8.6	1
30/03/98	0.323	0.053	0.046	0.017	4.1	325	2.8	2.1
30/03/98	0.279	0.05	0.044	0.016	4.2	315	6.2	4.9
31/03/98	0.111	0.06	0.044	0.032	3.7	305	5.8	1.3
31/03/98	0.191	0.05	0.043	0.025	3.8	320	6.2	9.5
01/04/98	0.203	0.05	0.039	0.019	4	320	6.5	3.4
01/04/98	0.15	0.045	0.039	0.014	3.9	330	4.6	8.6
02/04/98	0.158	0.05	0.037	0.018	4	325	5.2	4.9
02/04/98	0.07	0.032	0.036	0.007	3.9	315	6.4	
03/04/98	0.051	0.027	0.033	0.04	4	315		
06/04/98	0.053	0.04	0.023	0.195	4.3	310		
07/04/98	0.026	0.05	0.019	0.009	4.8	305		
07/04/98	0.061	0.137	0.018	0.13	4.6	300		
08/04/98	0.066	0.057	0.015	0.012	6	305		
08/04/98	0.096	0.081	0.017	0.017	5.1	310		
09/04/98	0.276	0.1	0.013	0.024	5.3	310		
09/04/98	0.128	0.093	0.014	0.026	5.4	210	5.5	
14/04/98	0.174	0.196	0.011	0.126	6.1	285	6	6.3

15/04/98	0.163				6.3	275	5.4	6
15/04/98	0.11				6.2	275	5.6	6
16/04/98	0.11	0.128	0.025	0.034	6.1	275	4.9	5.7
16/04/98	0.104	0.124	0.024	0.037	6.5	280	7.1	5.1
17/04/98	0.555	0.138	0.026	0.05	6.2	280	4.4	1
17/04/98	0.44	0.73	0.132	0.05	6.3	285	5.7	2.5
29/04/98	0.33	0.025	0.027	0.024	6.2	295	7.3	9.1
29/04/98	0.71	0.469	0.03	0.556	6.4	295	8	6.2
30/04/98	0.715	0.014	0.103	0.096	6.1	280	6.2	6.5
30/04/98	0.846	0.191	0.046	0.173	5.9	280	8.2	6.7
01/05/98	1.02	0.329	0.056	0.374	5.8	280	4.6	5.2
01/05/98	0.526	0.43	0.058	0.185	5.4	275	7.9	3.8
05/05/98	0.246	0.009	0.054	0.024	5.2	295	7.5	3.1
05/05/98	0.437	0.188	0.034	0.165	5.4	300	7.1	3
06/05/98	0.331	0.143	0.023	0.156	5.3	310	6.4	2.6
07/05/98	0.318	0.192	0.034	0.167	4.9	300	8.5	2.6
07/05/98	0.229	0.118	0.02	0.082	5.1	310	7.8	5.1
08/05/98	0.203	0.393	0.023	0.163	5	315	3.5	5.6
11/05/98	0.137	0.095	0.027	0.109	4.7	310	6.5	1.3
11/05/98	0.004	0.062	0.007	0.027	4.6	290	7.5	2.7
12/05/98	0.066	0.007	0.009	0.004	5	265	11	5.4
12/05/98	0.084	0.017	0.006	0.815	4.7	271	8.6	7.3
13/05/98	0.091	0.049	0.005	0.072	4.7	365	15	7.5
13/05/98	0.088	0.039	0.062	0.045	4.5	315	14	9.9
14/05/98	0.09	0.032	0.005	0.032	4.7	300	12	11
15/05/98	0.194	0.15	0.012	0.191	4.7	295	12	11
15/05/98	0.069	0.038	0.003	0.147	4.6	260	17	10
18/05/98	0.078	0.024	0.007	0.042	4.4	270	23	15
18/05/98	0.146	0.022	0.005	0.034	4.4	295	47	15
19/05/98	0.194	0.021	0.004	0.019	4.3	295	38	11
19/05/98	0.229	0.029	0.004	0.02	4.5	295	41	20
20/05/98	0.208	0.017	0.002	0.084	4.4	305	33	14

20/05/98	0.234	0.016	0.006	0.074	4.4	290	42	38
22/05/98	0.196	0.026	0.006	0.038	4.4	300	41	14
22/05/98	0.283	0.016	0.004	0.023	4.8	305	34	24
26/05/98	0.243	0.018	0.004	0.056	4.2	305	24	1
26/05/98	0.218	0.019	0.002	0.064	4.3	310	36	22
27/05/98	0.193	0.022	0.007	0.025	4.1	320	19	22
00/01/00	0.232	0.012	0.007	0.03	4.2	330	9.3	15
28/05/98	0.074	0.021	0.006	0.016	4.1	315	18	5
28/05/98	0.188	0.039	0.006	0.02	4.1	335	11	12
29/05/98	0.237	0.021	0.006	0.013	4	320	11	4.4
29/05/98	0.187	0.014	0.006	0.023	4.4	290	11	8.1
01/06/98	0.118	0.014	0.002	0.049	4.4	275	13	6.2
01/06/98	0.08	0.014	0.004	0.02	4.7	285	9.9	1
02/06/98	0.077	0.017	0.007	0.01	4.6	300	9.2	7.1
02/06/98	0.081	0.036	0.008	0.006	4.2	270	10	7.3
03/06/98	0.122	0.044	0.005	0.01	4.3	275	15	6.6
03/06/98	0.214	0.04	0.003	0.018	4.3	320	17	7.9
04/06/98	0.23	0.055	0.004	0.064	4.3	315	19	12
04/06/98	0.153	0.013	0.003	0.031	4.3	310	22	13
05/06/98	0.18	0.018	0.004	0.041	4.1	320	18	14
05/06/98	0.142	0.013	0.005	0.02	4.4	300	13	15
08/06/98	0.106	0.012	0.014	0.023	4.5	305	6.6	9.2
08/06/98	0.064	0.012	0.007	0.011	4.3	320	15	6
09/06/98	0.183	0.016	0.005	0.013	4.3	345	5.8	9.8
09/06/98	0.179	0.038	0.006	0.016	4.6	325	13	5.4
10/06/98	0.139	0.025	0.005	0.012	4.6	305	15	1
10/06/98	0.182	0.055	0.005	0.014	4.5	305	18	1
11/06/98	0.154	0.034	0.004	0.019	4.4	305	14	16
11/06/98	0.095	0.023	0.004	0.004	3.4	310	22	14
12/06/98	0.054	0.012	0.003	0.016	4.3	305	15	19
12/06/98	0.052	0.014	0.004	0.004	4.4	295	12	6.8
15/06/98	0.089	0.051	0.004	0.02	4.2	300	14	4.9

15/06/98	0.03	0.102	0.004	0.027	4.2	305	18	8.5
16/06/98	0.151	0.026	0.008	0.185	4.5	305	14	36
16/06/98	0.157	0.027	0.005	0.074	4.7	305	15	19
17/06/98	0.14	0.019	0.009	0.037	4.5	3000	13	9.2
17/06/98	0.172	0.019	0.006	0.022	4.3	305	18	8.6
18/06/98	0.058	0.041	0.009	0.01	4.4	325	12	1
18/06/98	0.044	0.029	0.005	0.024	4.2	305	12	1
19/06/98	0.127	0.026	0.008	0.013	4	305	13	9.7
19/06/98	0.151	0.037	0.006	0.028	4.7	325	12	
24/06/98	0.147	0.026	0.006	0.016	4.7	305	8.7	3
24/06/98	0.116	0.026	0.005	0.021	4.8	315	17	3.8
25/06/98	0.079	0.026	0.004	0.016	4.9	295	10	12
25/06/98	0.064	0.032	0.005	0.004	4.9	305	19	10
26/06/98	0.088	0.014	0.005	0.012	4.9	295	9.1	19
26/06/98	0.075	0.014	0.004	0.011	5.1	285	17	12
29/06/98	0.163	0.015	0.004	0.01	5.1	295	17	13
29/06/98	0.103	0.029	0.004	0.007	5.1	300	19	12
30/06/98	0.088	0.017	0.004	0.006	5.1	315	12	17
30/06/98	0.131	0.021	0.003	0.005	4.3	310	10	9
01/07/98	0.156	0.041	0.003	0.023	4.5	315	7.3	10
01/07/98	0.125	0.018	0.005	0.076	5.7	305	8.7	8.2
02/07/98	0.135	0.019	0.007	0.01	5.3	290	9.4	8.8
02/07/98	0.1	0.018	0.005	0.018	5.4	295	11	8.7
03/07/98	0.115	0.019	0.008	0.011	5.4	395	9.3	9.1
03/07/98	0.139	0.017	0.008	0.016	5.2	300	7.4	15
06/07/98	0.114	0.017	0.005	0.009	5.2	300	9	1
06/07/98	0.097	0.017	0.006	0.005	5.3	295	10	1
07/07/98	0.104	0.019	0.007	0.01	5.3	310	6	12
07/07/98	0.201	0.021	0.007	0.016	5.3	310	6	8.5
08/07/98	0.118	0.021	0.009	0.004	5.5	325	3.4	2.1
08/07/98	0.118	0.021	0.01	0.008	5.4	305	4.6	5.8

	Chlortoluron	Isoproturon	Liuron	MCPA	MCPB	2,4-D	Mecoprop	Dichloroprop	Diuron	Flutriaol	Pirimicarb	Atrazine	Simazine
Date	(mg/l)	(ng/l)	(ng/l)	(ng/l)	(ng/l)	(ng/l)	(ng/l)	(ng/l)	(ng/l)	(ng/l)	(ng/l)	(ng/l)	(ng/l)
20/03/98	91	670	22	41	10	10	82	10	43	225	360	16	225
23/03/98	83	545	13	35	10	10	78	10	48	290	380	18	200
23/03/98	78	530	10	35	10	10	70	10	44	260	365	18	200
24/03/98	73	530	10	29	10	10	71	10	44	280	375	17	205
24/03/98	72	490	10	33	10	11	67	10	43	280	370	18	215
25/03/98	68	480	10	31	10	10	61	10	43	265	380	17	185
25/03/98	66	445	10	28	10	10	56	10	42	285	395	18	205
26/03/98	63	445	10	28	10	10	62	10	43	260	365	17	190
26/03/98	64	400	10	29	10	10	50	10	42	280	370	16	180
27/03/98	59	390	10	27	10	10	63	10	43	285	370	15	125
27/03/98	59	305	10	32	10	10	57	10	43	270	370	15	135
30/03/98	57	305	10	37	10	10	79	10	46	270	310	18	125
30/03/98	47	300	10	34	10	10	56	10	46	270	320	16	120
31/03/98	48	300	50	33	10	10	49	10	44	235	345	16	110
31/03/98	48	270	33	28	10	16	56	10	49	135	345	12	80
01/04/98	50	280	37	34	10	10	52	10	49	265	350	18	120
01/04/98	48	265	43	27	10	10	50	10	51	10	350	19	125
02/04/98	49	260	55	30	10	10	55	10	48	250	355	17	105
02/04/98	43	245	53	27	10	10	50	10	48	250	360	19	115
03/04/98	46	245	63	25	10	10	49	10	51	270	375	19	115
06/04/98	46	285	26	46	10	28	105	17	89	295	256	19	320
07/04/98	46	300	20	69	10	43	145	19	93	265	265	19	265
07/04/98	48	325	25	71	10	45	165	15	95	230	250	19	335
08/04/98	55	370	20	52	10	43	140	10	97	225	235	21	370
08/04/98	55	350	10	68	10	46	170	18	125	235	235	22	515
09/04/98	62	385	10	75	10	55	205	13	130	225	205	22	640
09/04/98	70	370	14	85	10	52	215	16	130	225	210	23	610
14/04/98	73	340	10	93	10	56	215	19	142	200	170	24	640
15/04/98	75	325	10	80	10	46	220	15	140	155	175	22	680
15/04/98	78	305	10	80	10	44	210	10	140	165	180	22	640

16/04/98	78	320	23	71	10	51	195	16	140	160	160	24	610
16/04/98	76	335	30	58	10	38	135	13	140	145	165	23	620
17/04/98	76	93	15	63	10	52	180	10	140	145	145	35	590
17/04/98	75	170	10	28	10	37	91	10	72	240	15	22	600
29/04/98	48	175	22	84	10	35	190	17	87	145	145	18	305
29/04/98	17	165	10	82	10	10	215	17	86	105	145	25	330
30/04/98	53	165	10	83	10	10	190	20	90	155	155	20	350
30/04/98	46	160	10	89	10	10	180	16	85	150	175	26	370
01/05/98	49	160	10	75	10	10	155	19	95	165	160	19	365
01/05/98	41	97	26	82	10	10	180	10	82	94	150	23	325
05/05/98	10	105	46	62	10	10	140	10	87	150	240	22	255
05/05/98	33	94	10	71	10	10	145	10	94	210	260	22	250
06/05/98	46	105	10	45	10	10	120	10	85	210	250	18	230
07/05/98	40	82	10	45	10	10	49	10	89	225	290	18	245
07/05/98	40	91	29	49	10	10	100	10	75	235	220	21	205
08/05/98	45	99	10	49	10	15	115	10	75	235	265	17	22
11/05/98	10	69	10	47	10	18	78	10	96	165	275	17	170
11/05/98	10	88	10	24	10	16	110	10	93	260	300	15	155
12/05/98	36	53	17	35	10	18	94	10	85	175	275	12	130
12/05/98	10	51	17	34	10	10	89	10	96	225	330	13	120
13/05/98	10	61	36	29	10	13	93	10	96	165	320	14	175
13/05/98	36	61	33	27	10	22	98	10	91	160	350	13	180
14/05/98	23	55	35	29	10	20	110	20	93	270	355	13	130
15/05/98	44	53	39	36	10	13	93	20	80	320	340	15	1150
15/05/98	33	48	35	35	10	23	89	10	76	195	340	15	160
18/05/98	38	49	37	20	10	16	72	10	87	260	305	15	165
18/05/98	34	50	61	34	10	13	100	10	85	305	320	13	165
19/05/98	23	51	43	31	10	11	59	10	90	300	255	16	110
19/05/98	19	10	33	16	10	35	76	10	100	295	345	16	145
20/05/98	24	10	10	27	10	49	46	10	105	235	275	18	135
20/05/98	24	31	36	10	10	43	73	10	91	325	380	16	135
22/05/98	10	44	10	18	10	69	55	10	115	335	295	17	120

22/05/98	10	37	66	10	10	63	91	10	115	355	325	16	115
26/05/98	10	54	38	27	10	84	64	10	110	325	325	18	105
26/05/98	18	41	47	11	10	63	88	10	125	300	360		110
27/05/98	25	51	42	20	10	64	67	10	115	280	370		115
27/05/98	39	51	57	16	10	57	65	10	115	335	400		110
28/05/98	38	41	42	15	10	61	61	10	120	390	395		
28/05/98	43	42	68	21	10	57	63	10	120	390	395		
29/05/98	37	46	46	21	10	73	42	10	120	125	365		
29/05/98	27	46	10	21	10	46	68	10	125	340	410	24	100
01/06/98	27	34	10	10	10	65	34	10	195	310	315	26	105
01/06/98	27	41	10	33	10	86	65	10	190	310	365	33	110
02/06/98	36	38	10	10	10	68	65	10	210	305	360	33	105
02/06/98	40	37	10	26	10	69	71	10	210	335	345	35	105
03/06/98	31	43	10	28	10	55	42	10	255	300	380	34	105
03/06/98	35	10	10	25	10	86	29	10	290	280	400	31	99
04/06/98	45	43	10	19	10	82	48	10	290	305	365	35	92
04/06/98	42	42	10	10	10	82	48	10	275	315	390	42	91
05/06/98	58	49	10	65	10	94	72	10	300	340	370	50	99
05/06/98	68	47	10	78	10	115	66	10	285	295	370	52	100
08/06/98	73	48	66	130	10	95	68	10	305	320	375	56	105
08/06/98	63	41	10	160	10	115	73	10	295	345	355	55	92
09/06/98	64	39	10	140	10	87	44	10	275	335	370	54	100
09/06/98	61	41	10	170	10	94	65	10	295	370	440	59	95
10/06/98	55	34	10	97	10	115	67	10	270	325	345	56	92
10/06/98	63	33	10	135	10	105	78	10	270	385	415	60	105
11/06/98	59	10	10	145	10	95	69	15	270	355	405	61	100
11/06/98	44	37	10	155	10	100	80	12	255	355	385	56	97
12/06/98	66	37	10	135	10	96	64	10	285	385	420	57	105
12/06/98	63	25	62	110	10	96	69	10	270	390	435	60	100
15/06/98	53	30	10	120	10	75	40	10	275	355	320	53	96
15/06/98	57	10	10	115	10	93	61	10	265	380	420	51	110
16/06/98	52	44	10	71	10	77	48	10	265	390	375	65	95

16/06/98	10	45	10	115	10	90	58	10	265	400	395	58	85
17/06/98	72	38	10	72	10	71	87	10	260	325	360	71	115
17/06/98	64	38	10	89	10	74	140	10	255	320	360	7	90
18/06/98	66	40	10	59	10	74	81	10	265	215	360	73	115
18/06/98	68	42	10	90	10	88	135	10	255	330	325	73	105
19/06/98	63	40	10	35	10	80	145	10	250	195	380	80	105
19/06/98	73	43	10	63	10	105	155	10	240	335	360	88	89
24/06/98	71	18	10	66	10	84	125	10	215	275	330	195	105
24/06/98	67	10	10	83	10	94	150	10	215	280	330	215	135
25/06/98	64	10	10	76	10	55	91	10	240	200	325	205	140
25/06/98	28	10	10	73	10	55	99	10	220	245	435	165	140
26/06/98	52	10	10	35	10	66	105	10	225	335	440	220	105
26/06/98	55	10	10	38	10	67	110	10	225	260	440	215	140
29/06/98	75	10	10	44	10	65	92	10	205	255	435	225	130
29/06/98	60	21	50	44	10	74	99	10	190	330	425	220	130
30/06/98	60	10	55	34	10	74	87	10	205	310	440	240	130
30/06/98	58	10	51	38	10	62	79	10	210	390	445	205	135
01/07/98	54	10	51	20	10	54	74	10	190	375	412	230	110
01/07/98	53	10	10	33	10	55	66	10	190	380	405	230	125
02/07/98	54	10	10	10	10	43	65	10	180	370	410	180	125
02/07/98	63	10	10	21	10	50	65	10	185	355	400	205	92
03/07/98	44	10	10	10	10	52	56	10	175	345	345	225	110
03/07/98	43	10	10	10	10	54	69	10	175	240	380	165	115
06/07/98	38	10	10	23	10	34	42	10	155	325	380	200	87
06/07/98	26	23	10	19	10	48	55	10	140	295	295	205	94
07/07/98	27	24	10	10	10	41	50	10	150	235	330	110	110
07/07/98	29	10	10	19	10	48	62	10	160	300	355	105	56
08/07/98	54	37	10	15	10	38	51	10	160	320	350	140	60
08/07/98	56	10	10	27	10	48	79	10	160	200	320	165	395

Appendix 3: Pilot Plant Water Quality Data.

		Total	Total						
	Colour	Iron	Managese	TOC	DOC	Chlorophyll	Phaeophytin	Algae	Turbidity
DATE	Hazen	(mg/l	(mg/l	(mg/l)	(mg/l)	(ug/l)	(ug/l)	No/ml	NTU
20/03/98	5.8	0.055	0.044	3.6	3.5	1.9	1	1000	5
23/03/98	6	0.061	0.05	3.5	3.5	1.8	1	1000	2.7
23/03/98	5.3	0.058	0.052	4.4	6.1	6.8	3.3	1900	4.2
24/03/98	7.1	0.103	0.058	3.6	3.7	2.8	1	1300	3
24/03/98	7.1	0.105	0.058	3.7	3.7	0.4	1	1000	3
25/03/98	3.5	0.075	0.057	4.1	4	0.4	1	1000	2.7
25/03/98	5.3	0.094	0.05	4	4	1	1	1300	2.9
26/03/98	2.5	0.151	0.054	3.8	3.8	1.5	1	3800	3.5
26/03/98	2.7	0.09	0.065	3.6	3.6	3.1	1	1000	3.4
27/03/98	0.2	0.32	0.061	3.3	3.3	0.4	1	1000	3.4
27/03/98	2.2	0.168	0.089	3.2	3.1	9.2	3	1000	1.5
30/03/98	5.8	0.044	0.064	3.4	3.2	3.2	1	1000	1.1
30/03/98	5.3	0.042	0.05	3.3	3.2	4			1.5
31/03/98	5	0.049	0.049	3	2.8	1.7	1		1.1
31/03/98	5.3	0.038	0.046	3	2.9	1.7	1	6500	1.1
01/04/98	5.8	0.044	0.045	2.9	3.1	1	1.1	1300	1.3
01/04/98	6.1	0.045	0.043	3.2	3.1	0.7	1	1000	1.1
02/04/98	4.8	0.039	0.042	3.2	3	0.5	1	1000	1.3
02/04/98	5	0.032	0.043	3.1	2.8	1.6	1	1000	1.2
03/04/98	4.3	0.033	0.04	2.9	2.9			1000	1
06/04/98	5.1	0.044	0.035	3.1	3.2			1000	1.6
07/04/98	4.1	0.06	0.023	3.2	3.3			1000	1.2
07/04/98	3.6	0.066	0.027	3.5	3.3			1000	1.4
08/04/98	1.8	0.085	0.027	3.4	3.5			1000	1
08/04/98	4.6	0.094	0.041	3.6	3.6			1000	1.2
09/04/98	6.9	0.186	0.029	3.7	5			1000	1.2
09/04/98	2.3	0.054	0.043	5.1	3.1			1000	1

14/04/98	5.6	0.272	0.03	3.1	4.9	2.3	4.3	1000	1.1
15/04/98	3.3	0.081	0.052	5.5	3.8	4	2	1000	0.89
15/04/98	3.6	0.116	0.033	3.9	3.7		1.2	1000	0.91
16/04/98	2	0.07	0.044	3.8	3.2	0.6	1	1000	2.7
16/04/98	1.8	0.078	0.032	3.1	3.2	0.4	1	1000	2
17/04/98	2	0.088	0.031	3.4	2.9	0.4	1	1000	2
17/04/98	2.5	0.055	0.034	3	3.2	0.8	3.3	1000	2.1
29/04/98	11	0.66	0.03	3	5.7	1.4	3.1	1000	2
29/04/98	11	0.528	0.057	5.7	5.7	4.3	5.7	1000	2
30/04/98	4.6	0.184	0.067	4.9	5.1	7.1	1.9	1000	2
30/04/98	4.3	0.21	0.043	5	5.1	1	2	1000	3.5
01/05/98	5.4	0.087	0.045	4.4	4.3	1	1	1000	3.4
01/05/98	5.1	0.157	0.046	4.3	4.3	0.9	1	1000	3
05/05/98	4.9	0.067	0.051	3.5	3.1	0.7	1	1000	3.1
05/05/98	2.8	0.115	0.045	3.4	3.3	0.8	1	1000	1
06/05/98	2	0.109	0.05	3.7	3.7	0.6	1	1000	2.2
07/05/98	4.3	0.097	0.047	3.7	3.7	1.1	1	1000	2
07/05/98	3	0.114	0.049	3.5	3.5	1.5	1	1000	1
08/05/98	2.5	0.28	0.056	3.6	4	1.5	1	1000	1
11/05/98	7.4	0.8	0.058	4.1	3.5	1.8	1	3000	2.5
11/05/98	4.9	0.35	0.033	3.6	3.5	2	1	1200	1.8
12/05/98	5.1	0.35	0.012	3.7	4	2	1.5	1200	1.3
12/05/98	5.1	0.34	0.012	3.9	3.9	2.8	1.5	3600	1.2
13/05/98	5.9	0.52	0.016	4.1	4	3.1	2.8	1800	1.9
13/05/98	8	0.048	0.014	4.1	3.8	6.1	3.2	3000	23
14/05/98	6.9	0.042	0.014	3.9	3.9	5.8	2.9	2400	1.6
15/05/98	5.6	0.029	0.015	3.9	3.7	4	3.1	1000	1.9
15/05/98	5.1	0.044	0.014	3.8	2.9	4.2	3.5	1000	2.4
18/05/98	1.2	0.066	0.05	3	2.9	3.1	1	2400	2.5
18/05/98	2.3	0.044	0.042	3	2.8	5.1	1	1000	1.1
19/05/98	0.73	0.014	0.016	2.9	2.8	1.2	1	1700	1.2
19/05/98	0.73	0.018	0.018	3	3.8	1	1	3600	2.8

20/05/98	3.1	0.051	0.019	3.9	3.5	6.2	4	7200	2.7
20/05/98	2.3	0.046	0.024	3.6	3.2	3.1	1.6	1000	1.8
22/05/98	1.5	0.033	0.02	3.3	3.4	2.1	1.1	1200	1.5
22/05/98	2.8	0.045	0.025	3.5	3.2	3.1	2.6	1000	1.6
26/05/98	1.5	0.062	0.024	3.1	3.2	1.9	2	1000	1.1
26/05/98	1.8	0.047	0.024	3.1	3.2	1.8	2.1	1000	1.5
27/05/98	2.3	0.028	0.022	3.3	3.2	3.4	1.1	1000	2
00/01/00	1.8	0.026	0.022	3.2	3.3	3.6	1	1000	1.2
28/05/98	0.98	0.027	0.021	3.4	3.5	3.8	1.3	1200	2
28/05/98	1.5	0.042	0.042	3.6	3	2.8	1	1000	1.2
29/05/98	1.8	0.018	0.017	3.3	3.1	0.9	1	1000	1
29/05/98	1.5	0.023	0.023	3.3	3.3	1	1.5	1200	1.1
01/06/98	2.3	0.016	0.02	3.3	2.8	0.8	1.1	1000	1.8
01/06/98	1.8	0.022	0.025	2.8	3.6	0.5	1	6600	1.6
02/06/98	4.6	0.024	0.012	3.7	3.6	2.3	1.4	1000	2.4
02/06/98	4.6	0.016	0.009	3.7	3.5	2.1	1.3	4800	3.8
03/06/98	5.6	0.011	0.007	3.6	3.3	3	1.1	5400	3.7
03/06/98	5.1	0.023	0.011	3.2	4.1	2.7	2.2	1000	4.2
04/06/98	3.1	0.114	0.055	4.1	4.2	9.6	5.7	1000	3
04/06/98	2.3	0.106	0.052	4.3	3.1	7.2	3.8	1000	2.7
05/06/98	2.5	0.017	0.023	3.1	3.2	1.7	2.2	1000	1
05/06/98	1.2	0.016	0.023	3.1	3.1	3.3	2.9	1000	1
08/06/98	0.73	0.012	0.021	3.2	3.1	1.1	1	1000	2.1
08/06/98	0.73	0.026	0.025	3.2	3.4	1.3	1	1000	1.4
09/06/98	0.98	0.038	0.027	3.7	3.5	0.44	1	1000	1.2
09/06/98	0.69	0.026	0.029	3.4	3.8	0.4	1	1000	0.91
10/06/98	0.69	0.016	0.026	3.8	3.7	0.5	1	1000	1.2
10/06/98	1.2	0.014	0.023	3.7	3.5	3.8	3.7	1000	0.84
11/06/98	1.5	0.022	0.019	3.5	3.6	1.4	1	1300	1.4
11/06/98	1.5	0.018	0.018	3.6	3.5	0.7	1	1000	1.1
12/06/98	2	0.041	0.024	3.4	3.2	1.4	1.4	1000	1
12/06/98	2.3	0.03	0.026	3.5	3.4	1.3	1	3000	0.95

15/06/98	2.5	0.025	0.041	3.4	3.5	1.5	2.1	1000	1.5
15/06/98	2.8	0.021	0.03	3.6	3.3	1.4	1.7	1000	1.1
16/06/98	0.69	0.026	0.025	3.3	3.4	0.6	1	1000	1.5
16/06/98	4.6	0.027	0.021	3.5	3.5	0.4	1	1000	1.1
17/06/98	4.6	0.025	0.026	3.7	3.6	1.2	1	1000	1.5
17/06/98	1.8	0.025	0.027	3.6	3.2	0.46	1	1000	1.1
18/06/98	1.2	0.045	0.025	3.2	3.4	1.1	1	1000	1.6
18/06/98	2.8	0.03	0.025	3.4	3.2	0.6	1	1000	1.9
19/06/98	1.2	0.045	0.045	3.4	3.3	1.1	1	1000	1.7
19/06/98	1	0.035	0.03	3.3	3.3	1.3	1	1000	0.08
24/06/98	0.69	0.04	0.045	3.7	3.8	3.1	1	1800	1.4
24/06/98	3.8	0.054	0.035	3.7	3.9	2.6	1	1000	0.76
25/06/98	1.8	0.027	0.04	4.3	4.1	1.7	1	3600	1
25/06/98	2.8	0.032	0.054	4.3	4.1	1.1	1	1000	1.2
26/06/98	3.6	0.019	0.027	4.1	3.9	3	2.4	1800	0.99
26/06/98	2.3	0.021	0.032	4.3	4.1	3.4	1.9	1000	1.4
29/06/98	2.8	0.017	0.019	4.1	4.3	1.9	1	1000	1.5
29/06/98	2.3	0.02	0.021	4.5	4.3	2.3	1	4200	1.3
30/06/98	2.3	0.017	0.017	4.3	4.5	2.2	1	1000	1
30/06/98	2.5	0.023	0.02	4.4	4.4	2	1	1000	1
01/07/98	3.3	0.02	0.017	3.7	3.7	0.9	1	2400	1
01/07/98	6.4	0.022	0.023	4	4.1	1	4.7	1000	1
02/07/98	4.9	0.018	0.02	4	4.6	0.6	1.1	1000	1.2
02/07/98	4.1	0.024	0.022	4.4	4.5	0.9	1.7	1000	0.84
03/07/98	8	0.028	0.018	4.2	3.9	1.6	1	3600	2.2
03/07/98	4.9	0.098	0.024	4.1	4.3	2.3	1	1000	3.5
06/07/98	6.9	0.017	0.028	4.1	4	1.4	1	1000	1.1
06/07/98	3.1	0.017	0.098	5.2	5.4	5.1	2.1	1000	0.96
07/07/98	3.3	0.021	0.017	4.3	4.2	0.6	2.9	1000	2.7
07/07/98	4.3	0.026	0.017	4.4	4.5	0.7	1	1000	1.2
08/07/98	2.8	0.024	0.021	4.5	4.6	1	1.4	1000	1.4
08/07/98	4.6	0.025	0.026	4.5	4	0.9	1	1000	1.1

Appendix 3: Pilot Plant Water Quality Data.

		Total	Total						
	Colour	Iron	Managese	TOC	DOC	Chlorophyll	Phaeophytin	Algae	Turbidity
DATE	Hazen	(mg/l	(mg/l	(mg/l)	(mg/l)	(ug/l)	(ug/l)	No/ml	NTU
20/03/98	5.8	0.055	0.044	3.6	3.5	1.9	1	1000	5
23/03/98	6	0.061	0.05	3.5	3.5	1.8	1	1000	2.7
23/03/98	5.3	0.058	0.052	4.4	6.1	6.8	3.3	1900	4.2
24/03/98	7.1	0.103	0.058	3.6	3.7	2.8	1	1300	3
24/03/98	7.1	0.105	0.058	3.7	3.7	0.4	1	1000	3
25/03/98	3.5	0.075	0.057	4.1	4	0.4	1	1000	2.7
25/03/98	5.3	0.094	0.05	4	4	1	1	1300	2.9
26/03/98	2.5	0.151	0.054	3.8	3.8	1.5	1	3800	3.5
26/03/98	2.7	0.09	0.065	3.6	3.6	3.1	1	1000	3.4
27/03/98	0.2	0.32	0.061	3.3	3.3	0.4	1	1000	3.4
27/03/98	2.2	0.168	0.089	3.2	3.1	9.2	3	1000	1.5
30/03/98	5.8	0.044	0.064	3.4	3.2	3.2	1	1000	1.1
30/03/98	5.3	0.042	0.05	3.3	3.2	4			1.5
31/03/98	5	0.049	0.049	3	2.8	1.7	1		1.1
31/03/98	5.3	0.038	0.046	3	2.9	1.7	1	6500	1.1
01/04/98	5.8	0.044	0.045	2.9	3.1	1	1.1	1300	1.3
01/04/98	6.1	0.045	0.043	3.2	3.1	0.7	1	1000	1.1
02/04/98	4.8	0.039	0.042	3.2	3	0.5	1	1000	1.3
02/04/98	5	0.032	0.043	3.1	2.8	1.6	1	1000	1.2
03/04/98	4.3	0.033	0.04	2.9	2.9			1000	1
06/04/98	5.1	0.044	0.035	3.1	3.2			1000	1.6
07/04/98	4.1	0.06	0.023	3.2	3.3			1000	1.2
07/04/98	3.6	0.066	0.027	3.5	3.3			1000	1.4
08/04/98	1.8	0.085	0.027	3.4	3.5			1000	1
08/04/98	4.6	0.094	0.041	3.6	3.6			1000	1.2
09/04/98	6.9	0.186	0.029	3.7	5			1000	1.2
09/04/98	2.3	0.054	0.043	5.1	3.1			1000	1

14/04/98	5.6	0.272	0.03	3.1	4.9	2.3	4.3	1000	1.1
15/04/98	3.3	0.081	0.052	5.5	3.8	4	2	1000	0.89
15/04/98	3.6	0.116	0.033	3.9	3.7		1.2	1000	0.91
16/04/98	2	0.07	0.044	3.8	3.2	0.6	1	1000	2.7
16/04/98	1.8	0.078	0.032	3.1	3.2	0.4	1	1000	2
17/04/98	2	0.088	0.031	3.4	2.9	0.4	1	1000	2
17/04/98	2.5	0.055	0.034	3	3.2	0.8	3.3	1000	2.1
29/04/98	11	0.66	0.03	3	5.7	1.4	3.1	1000	2
29/04/98	11	0.528	0.057	5.7	5.7	4.3	5.7	1000	2
30/04/98	4.6	0.184	0.067	4.9	5.1	7.1	1.9	1000	2
30/04/98	4.3	0.21	0.043	5	5.1	1	2	1000	3.5
01/05/98	5.4	0.087	0.045	4.4	4.3	1	1	1000	3.4
01/05/98	5.1	0.157	0.046	4.3	4.3	0.9	1	1000	3
05/05/98	4.9	0.067	0.051	3.5	3.1	0.7	1	1000	3.1
05/05/98	2.8	0.115	0.045	3.4	3.3	0.8	1	1000	1
06/05/98	2	0.109	0.05	3.7	3.7	0.6	1	1000	2.2
07/05/98	4.3	0.097	0.047	3.7	3.7	1.1	1	1000	2
07/05/98	3	0.114	0.049	3.5	3.5	1.5	1	1000	1
08/05/98	2.5	0.28	0.056	3.6	4	1.5	1	1000	1
11/05/98	7.4	0.8	0.058	4.1	3.5	1.8	1	3000	2.5
11/05/98	4.9	0.35	0.033	3.6	3.5	2	1	1200	1.8
12/05/98	5.1	0.35	0.012	3.7	4	2	1.5	1200	1.3
12/05/98	5.1	0.34	0.012	3.9	3.9	2.8	1.5	3600	1.2
13/05/98	5.9	0.52	0.016	4.1	4	3.1	2.8	1800	1.9
13/05/98	8	0.048	0.014	4.1	3.8	6.1	3.2	3000	23
14/05/98	6.9	0.042	0.014	3.9	3.9	5.8	2.9	2400	1.6
15/05/98	5.6	0.029	0.015	3.9	3.7	4	3.1	1000	1.9
15/05/98	5.1	0.044	0.014	3.8	2.9	4.2	3.5	1000	2.4
18/05/98	1.2	0.066	0.05	3	2.9	3.1	1	2400	2.5
18/05/98	2.3	0.044	0.042	3	2.8	5.1	1	1000	1.1
19/05/98	0.73	0.014	0.016	2.9	2.8	1.2	1	1700	1.2
19/05/98	0.73	0.018	0.018	3	3.8	1	1	3600	2.8

20/05/98	3.1	0.051	0.019	3.9	3.5	6.2	4	7200	2.7
20/05/98	2.3	0.046	0.024	3.6	3.2	3.1	1.6	1000	1.8
22/05/98	1.5	0.033	0.02	3.3	3.4	2.1	1.1	1200	1.5
22/05/98	2.8	0.045	0.025	3.5	3.2	3.1	2.6	1000	1.6
26/05/98	1.5	0.062	0.024	3.1	3.2	1.9	2	1000	1.1
26/05/98	1.8	0.047	0.024	3.1	3.2	1.8	2.1	1000	1.5
27/05/98	2.3	0.028	0.022	3.3	3.2	3.4	1.1	1000	2
00/01/00	1.8	0.026	0.022	3.2	3.3	3.6	1	1000	1.2
28/05/98	0.98	0.027	0.021	3.4	3.5	3.8	1.3	1200	2
28/05/98	1.5	0.042	0.042	3.6	3	2.8	1	1000	1.2
29/05/98	1.8	0.018	0.017	3.3	3.1	0.9	1	1000	1
29/05/98	1.5	0.023	0.023	3.3	3.3	1	1.5	1200	1.1
01/06/98	2.3	0.016	0.02	3.3	2.8	0.8	1.1	1000	1.8
01/06/98	1.8	0.022	0.025	2.8	3.6	0.5	1	6600	1.6
02/06/98	4.6	0.024	0.012	3.7	3.6	2.3	1.4	1000	2.4
02/06/98	4.6	0.016	0.009	3.7	3.5	2.1	1.3	4800	3.8
03/06/98	5.6	0.011	0.007	3.6	3.3	3	1.1	5400	3.7
03/06/98	5.1	0.023	0.011	3.2	4.1	2.7	2.2	1000	4.2
04/06/98	3.1	0.114	0.055	4.1	4.2	9.6	5.7	1000	3
04/06/98	2.3	0.106	0.052	4.3	3.1	7.2	3.8	1000	2.7
05/06/98	2.5	0.017	0.023	3.1	3.2	1.7	2.2	1000	1
05/06/98	1.2	0.016	0.023	3.1	3.1	3.3	2.9	1000	1
08/06/98	0.73	0.012	0.021	3.2	3.1	1.1	1	1000	2.1
08/06/98	0.73	0.026	0.025	3.2	3.4	1.3	1	1000	1.4
09/06/98	0.98	0.038	0.027	3.7	3.5	0.44	1	1000	1.2
09/06/98	0.69	0.026	0.029	3.4	3.8	0.4	1	1000	0.91
10/06/98	0.69	0.016	0.026	3.8	3.7	0.5	1	1000	1.2
10/06/98	1.2	0.014	0.023	3.7	3.5	3.8	3.7	1000	0.84
11/06/98	1.5	0.022	0.019	3.5	3.6	1.4	1	1300	1.4
11/06/98	1.5	0.018	0.018	3.6	3.5	0.7	1	1000	1.1
12/06/98	2	0.041	0.024	3.4	3.2	1.4	1.4	1000	1
12/06/98	2.3	0.03	0.026	3.5	3.4	1.3	1	3000	0.95

15/06/98	2.5	0.025	0.041	3.4	3.5	1.5	2.1	1000	1.5
15/06/98	2.8	0.021	0.03	3.6	3.3	1.4	1.7	1000	1.1
16/06/98	0.69	0.026	0.025	3.3	3.4	0.6	1	1000	1.5
16/06/98	4.6	0.027	0.021	3.5	3.5	0.4	1	1000	1.1
17/06/98	4.6	0.025	0.026	3.7	3.6	1.2	1	1000	1.5
17/06/98	1.8	0.025	0.027	3.6	3.2	0.46	1	1000	1.1
18/06/98	1.2	0.045	0.025	3.2	3.4	1.1	1	1000	1.6
18/06/98	2.8	0.03	0.025	3.4	3.2	0.6	1	1000	1.9
19/06/98	1.2	0.045	0.045	3.4	3.3	1.1	1	1000	1.7
19/06/98	1	0.035	0.03	3.3	3.3	1.3	1	1000	0.08
24/06/98	0.69	0.04	0.045	3.7	3.8	3.1	1	1800	1.4
24/06/98	3.8	0.054	0.035	3.7	3.9	2.6	1	1000	0.76
25/06/98	1.8	0.027	0.04	4.3	4.1	1.7	1	3600	1
25/06/98	2.8	0.032	0.054	4.3	4.1	1.1	1	1000	1.2
26/06/98	3.6	0.019	0.027	4.1	3.9	3	2.4	1800	0.99
26/06/98	2.3	0.021	0.032	4.3	4.1	3.4	1.9	1000	1.4
29/06/98	2.8	0.017	0.019	4.1	4.3	1.9	1	1000	1.5
29/06/98	2.3	0.02	0.021	4.5	4.3	2.3	1	4200	1.3
30/06/98	2.3	0.017	0.017	4.3	4.5	2.2	1	1000	1
30/06/98	2.5	0.023	0.02	4.4	4.4	2	1	1000	1
01/07/98	3.3	0.02	0.017	3.7	3.7	0.9	1	2400	1
01/07/98	6.4	0.022	0.023	4	4.1	1	4.7	1000	1
02/07/98	4.9	0.018	0.02	4	4.6	0.6	1.1	1000	1.2
02/07/98	4.1	0.024	0.022	4.4	4.5	0.9	1.7	1000	0.84
03/07/98	8	0.028	0.018	4.2	3.9	1.6	1	3600	2.2
03/07/98	4.9	0.098	0.024	4.1	4.3	2.3	1	1000	3.5
06/07/98	6.9	0.017	0.028	4.1	4	1.4	1	1000	1.1
06/07/98	3.1	0.017	0.098	5.2	5.4	5.1	2.1	1000	0.96
07/07/98	3.3	0.021	0.017	4.3	4.2	0.6	2.9	1000	2.7
07/07/98	4.3	0.026	0.017	4.4	4.5	0.7	1	1000	1.2
08/07/98	2.8	0.024	0.021	4.5	4.6	1	1.4	1000	1.4
08/07/98	4.6	0.025	0.026	4.5	4	0.9	1	1000	1.1

APPENDIX 4: AC250 Predicted Turbidity and Laboratory Turbidity and pH. AC250 and Jar Test Predicted Coagulant Dose.

	Ozonated	AC250 Ozonated	Ozonated Water	AC250 Ozonated Water		Jar Test	AC250
Date	Water pH	Water pH	Total Turbidity (NTU)	Total Turbidity (NTU)	Date	Dose (mg/l)	Dose (mg/l)
17/03/98	7.6	8.2	17.5	20	17/03/98	4	3.2
18/03/98	7.5	8.1	18	9.3	18/03/98	3.5	3
23/03/98	7.5	8	14	27	23/03/98	3.5	3
24/03/98	7.7	8	9.8	10	24/03/98	4	3
25/03/98	7.7	8.1	9.4	12	25/03/98	4	3
26/03/98	7.8	8	7.8	9	26/03/98	3.5	3
27/03/98	7.6	8.1	8.4	9	27/03/98	3.5	3
30/03/98	7.5	8.2	7	5	30/03/98	3.5	3
31/03/98	7.6	7.7	6.1	4	31/03/98	3.5	3
01/04/98	7.4	7.8	6.1	5	01/04/98	3	2.5
02/04/98	7.7	7.9	6	5	02/04/98	3	3
06/04/98	7.4	7.9	5.7	6.4	06/04/98	3	2.8
07/04/98	7.5	7.9	9.6	10	07/04/98	3.5	3.1
08/04/98	7.7	7.7	13	11	08/04/98	3.5	3.2
09/04/98	7.9	7.7	16	14	09/04/98	4	3.2
07/04/98	7.6	7.7	21	19	07/04/98	4	3.2
14/04/98	7.2	7.7	23	13	14/04/98	4	3.2
15/04/98	7.7	7.7	20	13	15/04/98	4	3.3
16/04/98	7.5	7.7	19	13	16/04/98	4	3.2
17/04/98	8	7.7	18.5	14	17/04/98	4	3.2
29/04/98	7.7	7.8	19	12	29/04/98	4.5	4
30/04/98	7.6	7.7	18	12	30/04/98	4	3.8
01/05/98	7.4	7.7	17	11	01/05/98	4.5	3.8
04/05/98	7.6	7.8	19	11	04/05/98	4	3.8
05/05/98	7.9	8	10	11	05/05/98	4	3.3
06/05/98	7.9	8	10	11	06/05/98	4	3.8
07/05/98	7.9	7.9	10	9.4	07/05/98	4	3.2

08/05/98	8	7.9	6	7.5	08/05/98	3	3.2
12/05/98	8	7.7	7	7	12/05/98	3	3
13/05/98	8.2	8.4	5	9.3	13/05/98	3	3
14/05/98	8	8.4	6	10	14/05/98	3.5	3
15/05/98	7.8	8.4	7	9	15/05/98	4.5	3.3
18/05/98	8.3	8.8	11	15	18/05/98	4.5	3.3
19/05/98	8	8.7	7	6	19/05/98	5	3
20/05/98	8.2	8.5	8	8.6	20/05/98	4.5	3
21/05/98	8.4	8.6	9	8.7	21/05/98	4	3
22/05/98	7.9	7.4	12	7	22/05/98	3.5	3
25/05/98	7.8	8.2	9	8.2	25/05/98	4	3
26/05/98	8.2	8.3	8	8	26/05/98	3.5	3.5
27/05/98	8.1	8.2	8	8	27/05/98	4	3.5
28/05/98	8.3	8.2	8	7.2	28/05/98	3.5	3.5
29/05/98	7.9	8.2	9	10	29/05/98	4	3.5
01/06/98	8.2	8	9	12	01/06/98	4	3.5
02/06/98	7.9	8.2	9	12	02/06/98	4	3.5
03/06/98	8	8.2	10	12	03/06/98	4	3.5
04/06/98	7.8	8.1	10	11	04/06/98	4.5	3.5
05/06/98	7.7	8	9	10	05/06/98	4	3.5
09/06/98	7.6	8	10	11	09/06/98	4.5	3.5