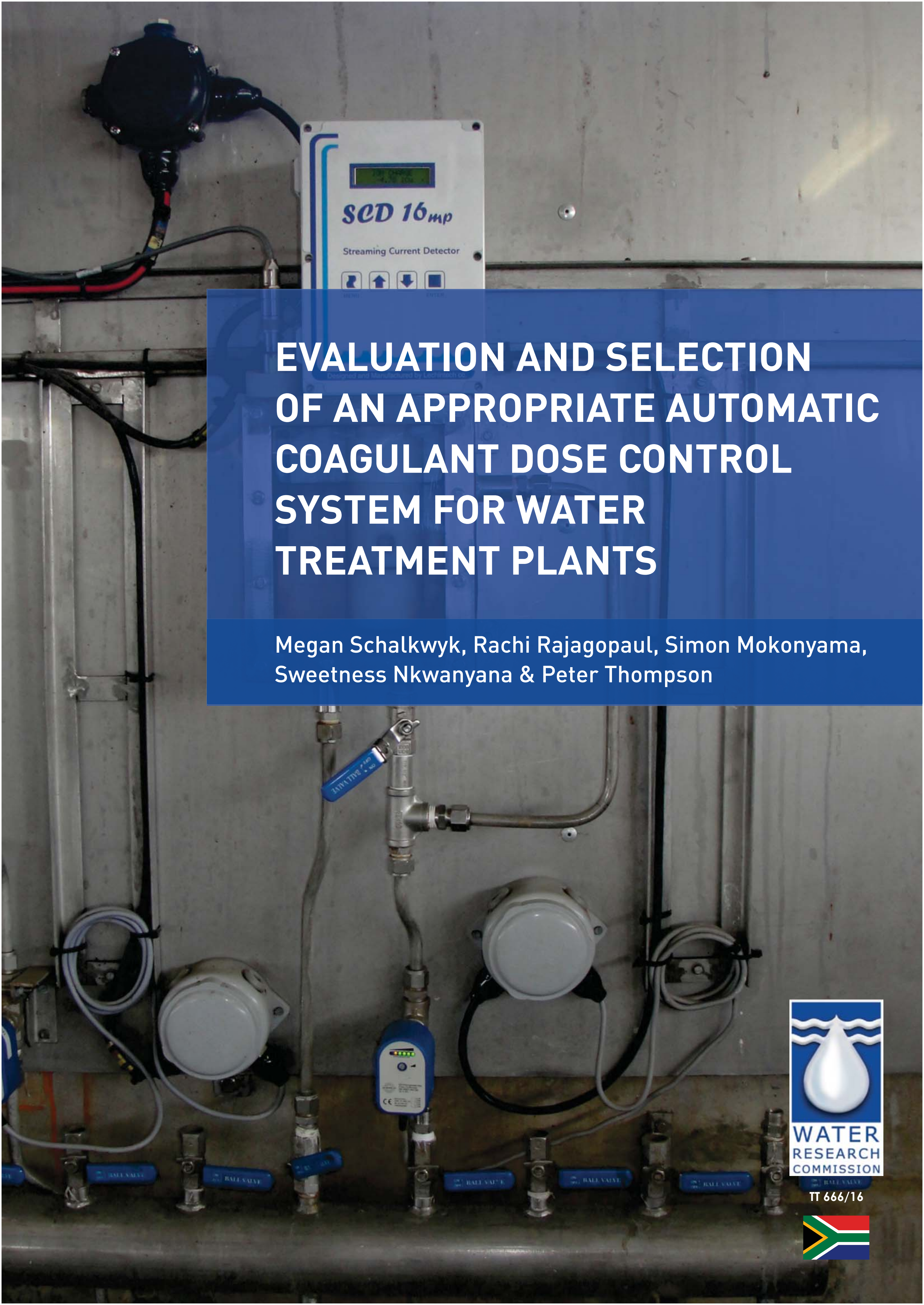

EVALUATION AND SELECTION OF AN APPROPRIATE AUTOMATIC COAGULANT DOSE CONTROL SYSTEM FOR WATER TREATMENT PLANTS

Megan Schalkwyk, Rachi Rajagopaul, Simon Mokonyama,
Sweetness Nkwanyana & Peter Thompson

WATER
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Water Research Commission

by

Umgeni Water

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EXECUTIVE SUMMARY

BACKGROUND

Due to the increased demand for safe drinking water, the impacts of climate change and the deterioration in the quality of raw water resources, drinking water service providers are under pressure to produce good quality potable water at an affordable price. Chemical dosing rates, especially coagulant dosing rates, affect both the quality of the final water and the cost of water treatment. Automatic coagulant dosing that is linked to the pertinent raw water parameters will optimise coagulant dosing, therefore decreasing costs and ensuring drinking water quality that complies with the South African National Standard for Drinking Water (SANS 241:2015).

AIMS

The aims of this report are to:

1. Determine proper and appropriate methods for automatic coagulant dose control on conventional water treatment systems.
2. Determine a mathematical model based on the raw water quality and coagulant (inorganic and organic) dosages.

METHODOLOGY

A comprehensive literature survey of peer-reviewed journals, equipment supplier input and relevant textbooks was undertaken in order to select the type of coagulant dosing equipment to be investigated. The literature survey indicated that where automatic coagulant dosing was implemented, the streaming current detector (SCD) was the more popular instrument for coagulation monitoring and control. Mathematical modelling based on historical process data and the neural networking modelling technique was used to a lesser extent where there were no large variations in raw water turbidity. There were also references to the possibility of using the particle counting technique for coagulant dose control. A national survey of water treatment plants that used SCD indicated that automatic coagulant dose control was very reliable.

Literature reviews also showed that mathematical models could only be used for a specific plant situation as each water treatment plant had its own unique system parameters. Data collected over a four-year period at a water treatment plant that uses river water abstraction were collected to create the neural network model and calibrate it.

The main thrust of the project was to investigate in more detail the streaming current measurement technique with the objective of gaining an understanding of the applicability and limitations of the SCD for coagulant dose control under different raw water conditions.

All experimental work involving the SCD and particle counting techniques was carried out at laboratory scale and pilot-plant scale, respectively. The mathematical model based on historical data was tested on raw water with a variable turbidity.

RESULTS AND DISCUSSION

Generally the SCD performed well for variable raw water turbidity. The SCD also produced acceptable results for raw water with organic colour. At a turbidity level of below 5 NTU, the SCD response was found to be slightly less sensitive; however, the addition of bentonite (a coagulant aid) increased the SCD sensitivity making it a suitable automatic coagulant dose control method.

Evaluation of the particle counting technique indicated that the method was unsatisfactory due to the following reasons:

- During this investigation the particle counter was placed downstream of the clarifier just before the water enters the sand filters; this location was later found to be operationally unsuitable. Clogging and fouling of the particle counter sensor also rendered this technique unsatisfactory; large colloidal particles caused sensor fouling and flow disruptions due to sensor clogging.
- The variability in the clarifier during steady state operation had a major influence on particle count and size, relative to coagulant dose.

Mathematical modelling

The mathematical model based on historical data failed to produce the desired results due to the following reasons:

- Process data were unreliable. Data were generated by operators who were untrained in analytical techniques. Analytical quality control was not robust resulting in errors in the data sets. The model was very sensitive to errors, resulting in unacceptable deviations from the true coagulant dose.
- The model responded poorly to datasets with high and variable raw water turbidity. The model appeared to produce better results in a small band of raw water turbidity of between 20-40 NTU.

CONCLUSIONS

- When used in the right environment, the SCD is the most appropriate automatic dose control system that is currently available in South Africa.
- The mathematical model based on historical water treatment plant data may be used to perform the automatic control of coagulant dosage, provided great care is taken in the quality control of analytical measurements that constitute the historical datasets. The mathematical model, once established, may be applicable to water treatment plant optimisation in addition to automatic coagulant dose control.
- Particle counting as a control technique was considered not to be an appropriate dose control system.

RECOMMENDATIONS

- A guideline for SCD operation and troubleshooting should be compiled.

- Further work to investigate the use of a mathematical model based on historical data for a specific case study is required.

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	City of Cape Town
	Sol Plaatje Municipality

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ACRONYMS & ABBREVIATIONS

ACH	Aluminium Chlorohydrate
AWWA	American Water Works Association
AWWARF	American Water Works Association Research Foundation
DACAR	Data Acquisition, Control and Reporting
DOC	Dissolved Organic Carbon
ICU	Ion Charge Unit
mg/L	Milligram per Litre
NOM	Natural Organic Matter
PDADMACs	Polydiallyl Dimethyl Ammonium Chloride
PLC	Programmable Logic Controller.
PV	Process Variable
SANS	South African National Standard
SC	Streaming Current
SCADA	Supervisory Control and Data Acquisition
SCD	Streaming Current Detector / Streaming Current Detection
SP	Set point
SUV	Specific Ultraviolet Absorption
TSS	Total Suspended Solids
UV	Ultraviolet
WTEU	Water Treatment Evaluation Unit
WRC	Water Research Commission
WTW	Water Treatment Works
WW	Water Works
ZP	Zeta Potential
[AL]	Aluminium content less than 2 mg/l
[PY]	Polyamines

CHAPTER 1: BACKGROUND

1.1 INTRODUCTION

The water industry is currently facing increased pressure to produce higher quality treated water at a lower cost. Conventional water treatment processes include chemical pre-treatment, coagulation, flocculation, settling, filtration and disinfection. Optimal chemical dosing is integral to the performance of each unit process in the treatment train.

The coagulation process is one of the major steps in the production of potable water. This process is used to remove colloidal particles from raw water. The main complexity in this process step is the timeous determination and automatic control of the optimum coagulant dose related to rapid changes in the quality of the incoming raw water. The current practice utilises the jar testing technique where an optimum coagulant dose is determined in the plant laboratory following the deterioration in treated water quality of one or more downstream processes.

The determined coagulant dose is then applied in the plant where further optimisation under full-scale plant conditions is conducted. The response time can be considerably reduced through automatic coagulant dose control. Coagulant overdosing leads to higher treatment costs and possible public health concerns, while under-dosing could lead to a failure to comply with the South African National Standard for Drinking Water (SANS 241:2015) and less efficient plant operation.

Climate change is projected to have a significant impact on raw water turbidity, particularly during the rainy seasons. The effect is more apparent at water treatment plants using river water abstraction than at plants using dam water abstraction, but it affects all plants. An effective automatic coagulant dose control system will benefit the entire water treatment industry.

1.2 PROJECT AIMS

The following were the aims of the project:

1. To determine proper and appropriate methods for automatic coagulant dose control on water treatment systems.
2. To develop a mathematical model that predicts optimum coagulant (inorganic and organic) responding to raw water quality changes.

1.3 SCOPE AND LIMITATIONS

The focus of this research project is on conventional water treatment plants. Figure 1.1 illustrates a conventional water treatment works; excluding treatment processes such as softening, activated carbon filters, biological treatment and ozone or ultraviolet treatment.

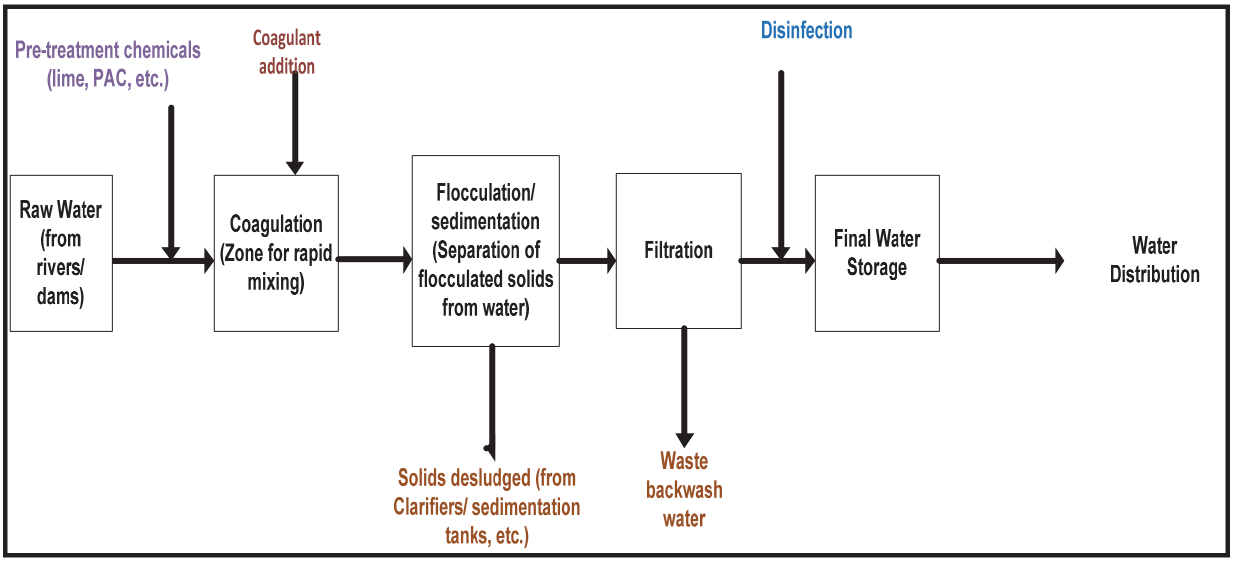


Figure 1.1: Conventional water treatment works

The scope of the project was to test automatic coagulant dose techniques selected during the literature review and to investigate the most feasible technique in more detail.

Tests were undertaken using samples from operating water treatment plants located in the Eastern Cape (Amatola Water), Western Cape (City of Cape Town), KwaZulu-Natal (Umgeni Water), North West Province (Magalies Water) and Northern Cape (Sol Plaatje Municipality).

CHAPTER 2: LITERATURE REVIEW

2.1 OBJECTIVES

The objective of the literature review was to:

- Explore coagulation mechanisms for inorganic and organic coagulants and their effects on the prediction of optimum coagulant dose.
- Review coagulant dose control systems currently used in conventional water treatment plants in South Africa and internationally.
- Review new developments in automatic coagulant dose control and assess their applicability to raw water and coagulant types.
- Determine which systems should be further investigated.

2.2 COAGULATION AND FLOCCULATION

The critical processes in water treatment are coagulation, sedimentation and filtration. These unit processes are used to remove particulate pollutants as well as dissolved solids which may affect human health. Particulate types and sizes (Figure 2.1) greatly affect the process efficiency of water treatment plants. The process of coagulation is defined by James Edzwald (2013) as "all the reactions and mechanisms that result in particle aggregation in the water being treated, including coagulant transformations (where applicable), particle destabilization, adsorbate uptake, and interparticle contacts. The physical process of producing interparticle contacts and particle aggregates (flocs) is termed flocculation."

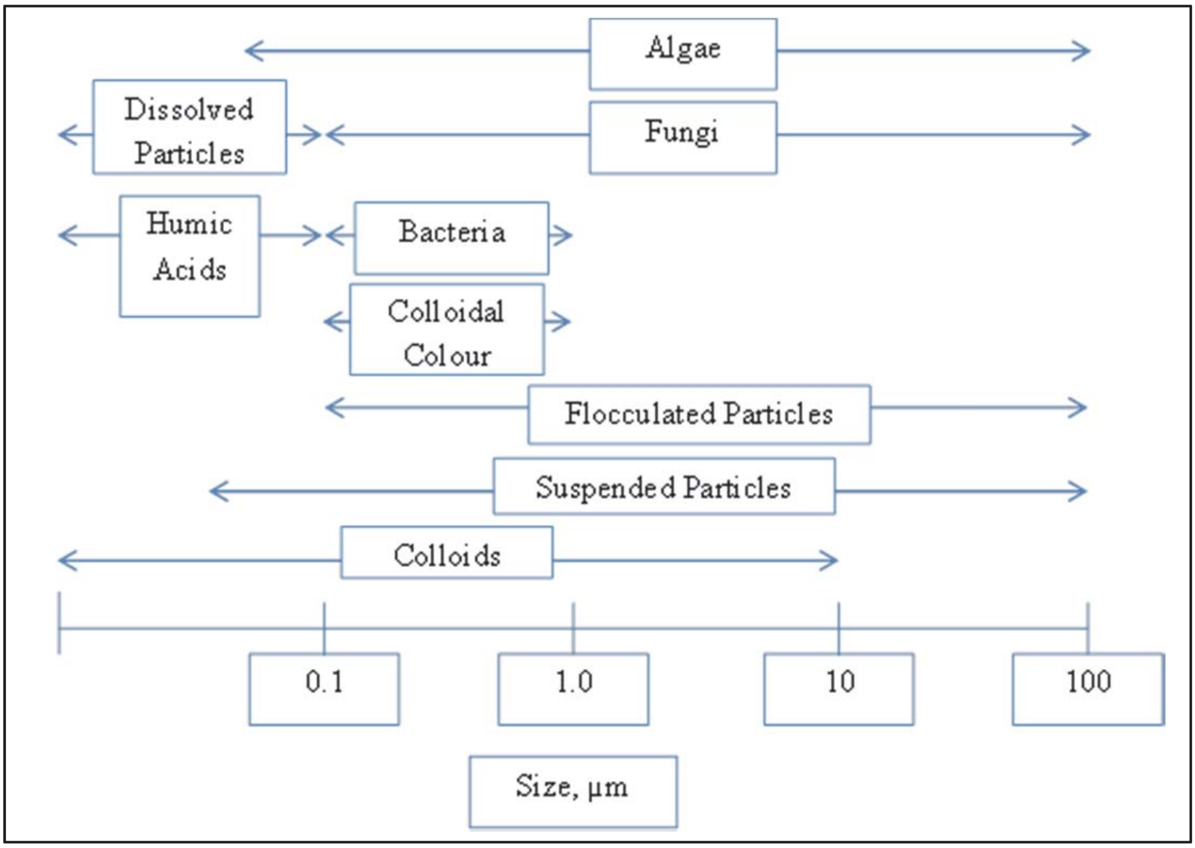


Figure 2.1: Some particulates present in water treatment (adapted from AWWA, 2011)

2.2.1 Contaminants

Coagulation facilitates the removal of both organic and inorganic contaminants in dissolved and suspended forms. These contaminants affect the water quality and the water treatment process. The contaminants may be characterised as follows:

2.2.1.1 Particles

Particles found in water vary widely in concentration, origin and size. Soil-weathering and biological processes are the principal sources of the majority of the particles found in water. Particles of clay, silt and terrestrial detritus are produced by soil weathering; other waterborne biological particles include algae, protozoa, bacteria and other higher microorganisms. Some suspended solids originate from chemical and biological processes within the water source while atmospheric deposition occurs when pollutants, such as dust, soot, ash, pollen spores, algal cells and other airborne particles, are transferred from air to water.

The presence of particles in water has a negative effect on water treatment processes, aesthetics and human health. Suspended particles can cause fouling within the water treatment process and have undesired impacts on removal process efficiencies, for example, colloids can shield microorganisms from disinfection (Edzwald, 2013).
Particles with light scattering properties can increase the water turbidity, giving the water an undesirable cloudy appearance. More importantly, particles such as pathogenic microorganisms affect human health.

2.2.1.2 Natural organic matter

Natural organic matter (NOM) originates both from outside the water body (transported into the water body) and within the water body as:

- Particulate organic matter e.g. algae,
- Dissolved organic carbon e.g. proteins,
- Organic matter produced by respiration and decay.

A large portion of the NOM found in unpolluted water consists of humic substances. Humic substances are derived from soil, chemical and biological processes such as decomposition of vegetation, etc. Humic substances are divided into the more soluble fulvic acid, which is predominant in most waters and the less soluble humic acid. These substances are anionic and of varying molecular weight.

The presence of NOM, above its threshold value has the following undesirable effects:

- Imparts an aesthetically unacceptable colour in water
- Affects particle stability
- Increases alkalinity
- Contributes to odour and taste problems
- Acts as precursors to disinfection by-products and other by-products
- Adversely effects water treatment processes such as chemical dosing
- Causes corrosion.

2.2.2 Theory of the electrical double layer

The most effective way to remove particulate contaminants through coagulation is by charge neutralisation. All coagulant types (under specific conditions) follow this mechanism of coagulation. The concept of charge neutralisation is closely related to the electrostatic nature of the colloid or particle. This electrostatic stability is explained by the theory of the electrical double layer. Figure 2.2 shows the various layers surrounding a single colloid or particle in solution.

The colloid is negatively charged and attracts positive ions from the solution to its surface to form a tight positive layer called the stern layer. Positive ions are still attracted to the negative colloid but are now repelled by the Stern layer creating a new layer around the Stern layer called the diffuse layer.

The diffuse layer has a higher concentration of positive ions closer to the colloid which gradually decreases further away from the colloid until an equilibrium concentration of positive and negative ions is reached.

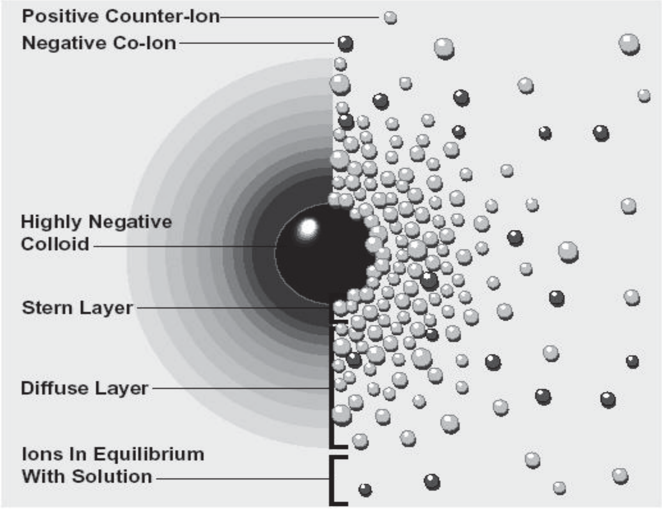


Figure 2.2: Illustrating theory of the electrical double layer (Source: Zeta-Meter Inc.)

Zeta potential, usually denoted using the Greek letter zeta (ζ), is explained using the theory of the electrical double layer as illustrated in Figure 2.2. The slip/shear plane is usually found where the Stern layer and the diffuse layer meet; zeta potential is the potential energy between the dispersion medium (bulk liquid) and the slip/shear plane. Zeta potential is an indicator of a particle's stability and net surface charge. The further away the zeta potential value is from zero (both positive and negative) the more resistant the particles are to aggregation. A negative zeta potential indicates a negative net surface charge.

2.2.3 Mechanisms of coagulation

Coagulation is affected by the following factors (Pontius, 1990):

- Total organic carbon and dissolved organic carbon (colour)
- Colloid concentration (turbidity)
- Temperature
- pH
- Anions and cations in solution
- Electrophoretic mobility or zeta potential
- Type of coagulant
- Coagulant dosage

However, the coagulation mechanisms are generally limited to surface charge neutralisation, sweep flocculation, adsorption and inter-particle bridging, as described below.

2.2.3.1 Surface charge neutralisation

Surface charge neutralisation is the easiest coagulation mechanism to monitor. It is also the controlling mechanism of most coagulant types. For automatic coagulant dosing this is the recommended coagulation mechanism. This method does however require precise control as it is very sensitive to the coagulant dose, as it operates over a limited band, and can be problematic for dilute suspensions.

This charge neutralisation mechanism occurs by direct reduction of the net surface charge which in turn reduces the thickness of the diffuse layer. This reduction in the thickness of the diffuse layer decreases the amount of energy required to bring the particles into contact.
Charge neutralisation occurs in two ways:

- The predominant mechanism of action is that the coagulant compound carrying an opposite charge to the net charge of the particle surface adsorbs onto the surface of the particle and neutralises the particle; this neutralisation then allows for aggregation.
- The second way to achieve charge neutralisation is by adjusting the chemistry of the solution; for example, if the stabilisation is caused by ionization then adjusting the pH of the solution will result in surface neutralisation which in turn leads to charge destabilisation.

Heterocoagulation is similar to charge neutralisation in that the coagulant adsorbs onto some particles changing the surface charge. This causes particles of different net surface charges to have an enhanced electrostatic attraction, increasing particle-particle interaction (Edzwald, 2013).

2.2.3.2 Adsorption and interparticle bridging

This coagulation mechanism takes place when a coagulant of high molecular weight and many reactive sites adsorbs onto more than one particle surface. The coagulant then acts as an interparticle bridge. Figure 2.3 illustrates this mechanism which is useful for dewatering and filtering processes.

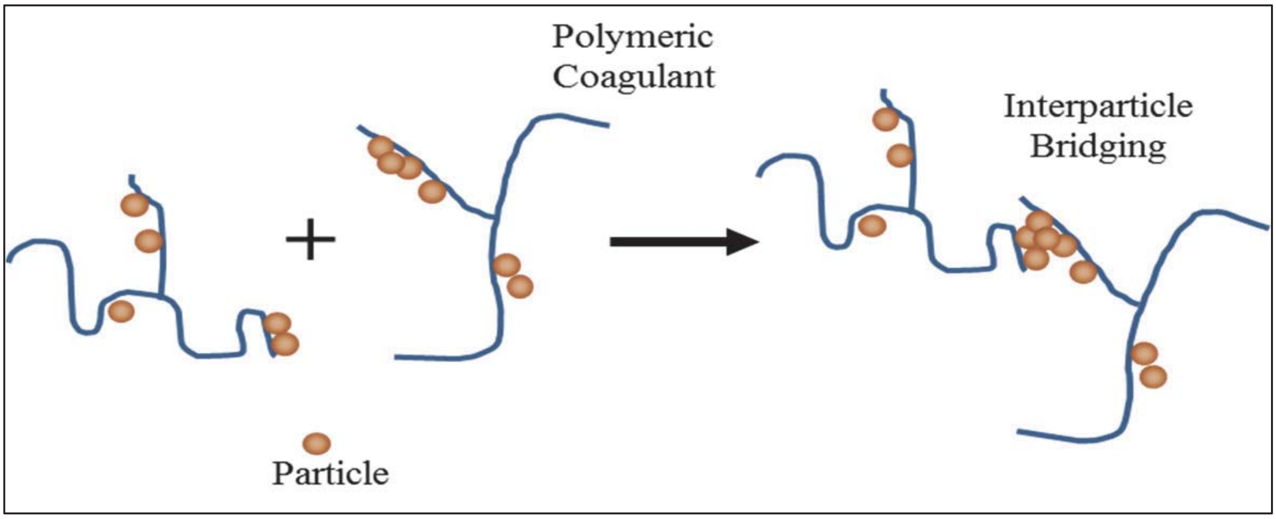


Figure 2.3: Coagulant acting as bridge between particles

2.2.3.3 Sweep flocculation

Sweep flocculation occurs when large doses of mineral salt coagulants are used and very large hydroxide precipitates are formed. The particles become enmeshed in the precipitate and can be “swept” out of the solution during sedimentation. This mechanism is illustrated in Figure 2.4 below. Sweep flocculation is not easy to monitor and requires high doses of coagulant.

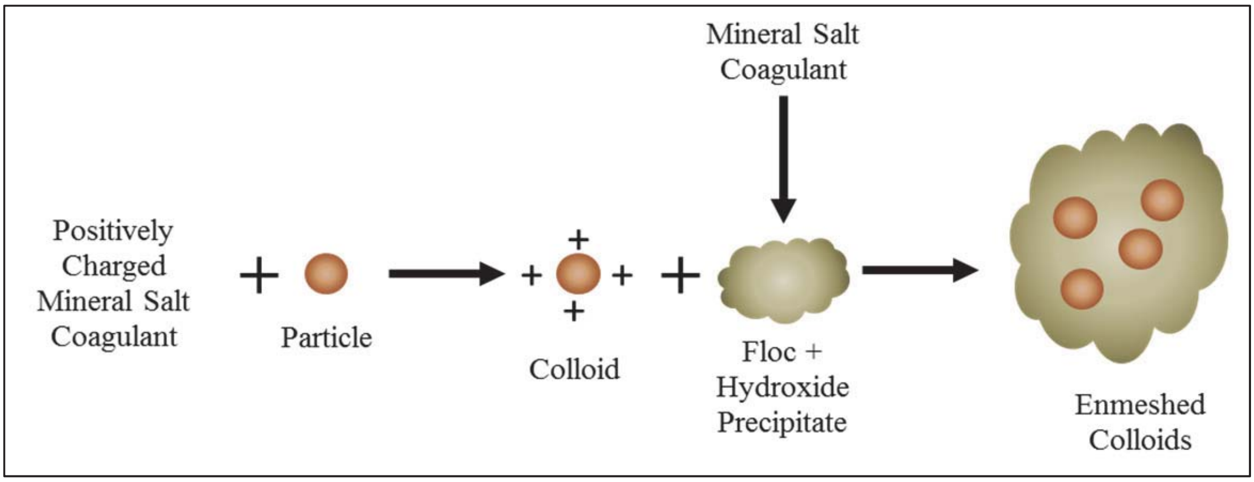


Figure 2.4: Sweep flocculation

These mechanisms can occur simultaneously as well as consecutively; however, which mechanism actually occurs is dependent on the factors affecting coagulation, mentioned previously in this section.

When overdosing mineral salt coagulants, particles can re-stabilise and the residual turbidity will increase. If more mineral salt coagulant is dosed, sweep flocculation will be the overriding mechanism and reduces the turbidity again. When overdosing organic/polyelectrolyte coagulants, particles can re-stabilise and increase turbidity. If even more organic/polyelectrolyte coagulant is dosed, the residual turbidity is not reduced. Figure 2.5 illustrates the relationship between turbidity and coagulant dose.

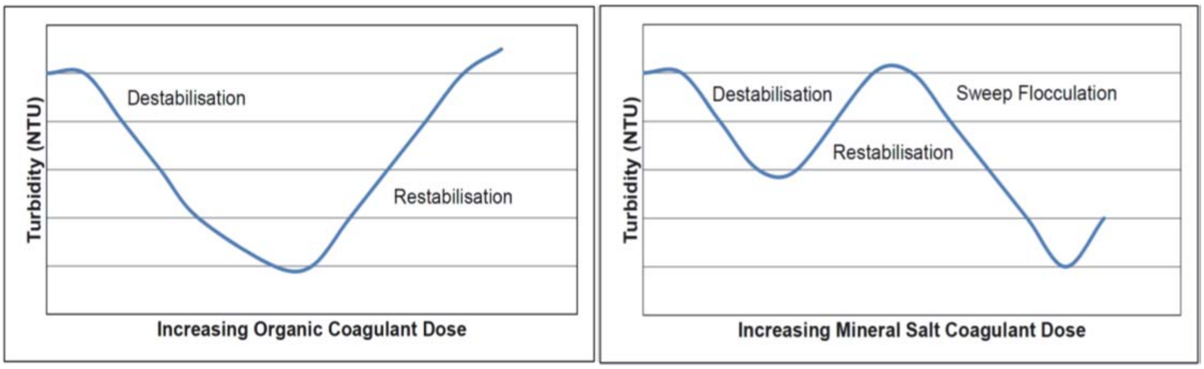


Figure 2.5: Showing the relationship between residual turbidity and increasing coagulation dose

2.3 COAGULANTS

There are two types of coagulants used in the water treatment industry; inorganic metal salt coagulants and polymeric/polyelectrolyte coagulants. Inorganic or mineral salt coagulants have been used for centuries while the polymeric (polyelectrolyte) coagulants are relatively new (Leopold and Freese, 2009). Polymeric coagulants may be used both as primary coagulants and for further addition as flocculants (sludge dewatering)/coagulant aids (filtration).

2.3.1 Mineral Salt Coagulants

The most common coagulants are mineral salts such as sulphate or chloride salts containing either iron or aluminium metal ions. Once dissolved in water these coagulants form hydrolysis products.

There are two possible mechanisms for the removal of particulate matter using this type of coagulant:

- Charge neutralisation: This occurs by the formation of multi-charge complexes with enhanced adsorption. These mechanisms require a specific pH range to work optimally.
- Sweep flocculation

Metal salt coagulants are also used for the removal of natural organic matter. The mechanisms for this are as follows:

- Charge neutralization caused by metal species binding to the anionic sites on the organic material
- Sweep flocculation.

To achieve optimal performance, the precipitate's solubility must be minimal; the point of minimum solubility (optimum pH for precipitation) occurs in a specific pH range for every metal. Coagulation diagrams are generalised diagrams showing the pH range and coagulant dosage required to create the correct environment for certain coagulation mechanisms to take place. Figure 2.6 below shows coagulation diagrams for both iron and aluminium salts. It can be seen on the alum coagulation diagram that a low coagulant dose (3-10 mg/L) and a pH of 5 allow charge neutralisation to be the dominating coagulation mechanism. The iron coagulation diagram shows that two mechanisms are involved when using ferric chloride and that the dominant mechanism is sweep flocculation.

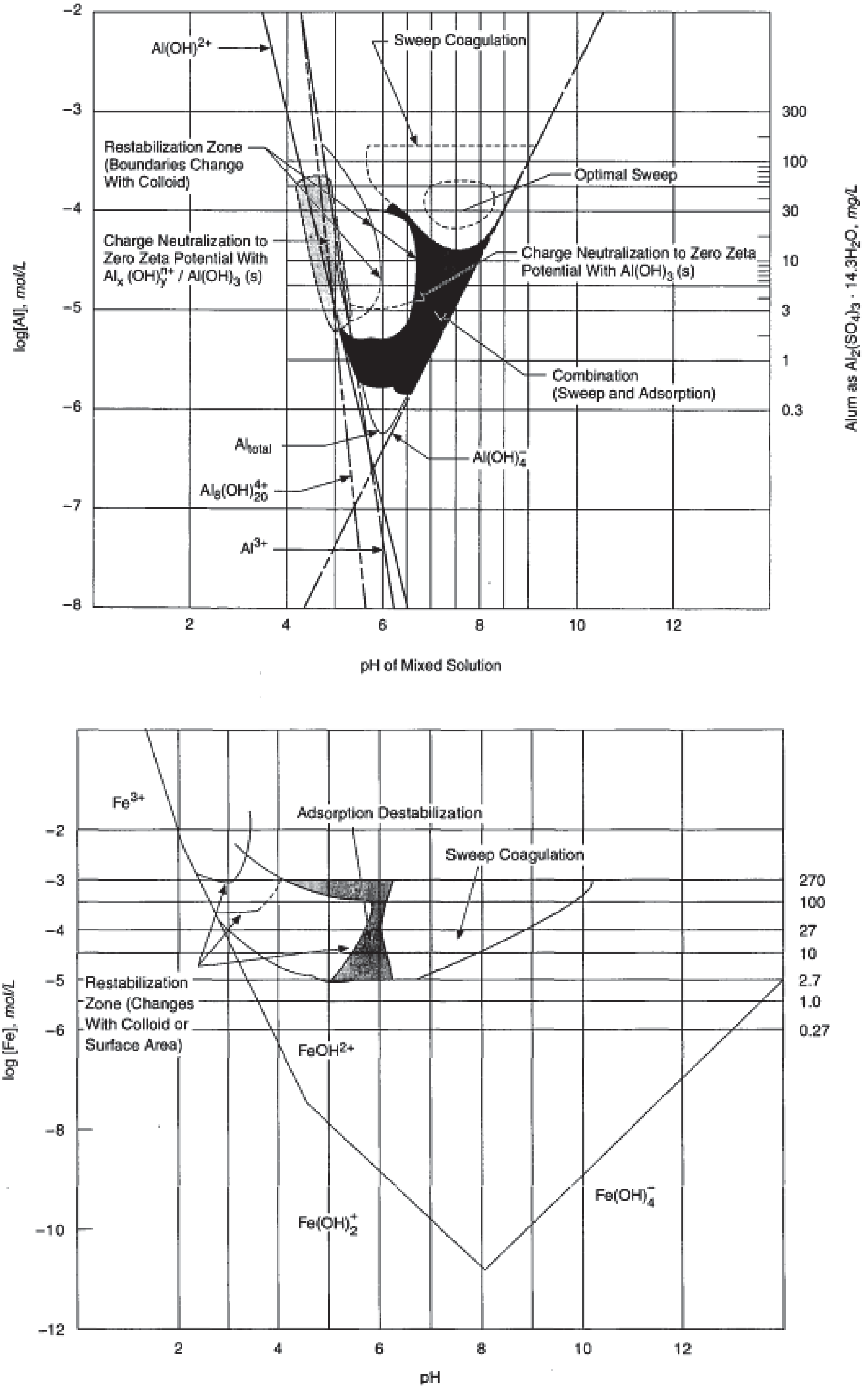


Figure 2.6: Coagulation diagrams for iron and aluminium (Source: Pontius, 1990)

The commonly used mineral salt coagulants are ferric chloride, aluminium sulphate (alum) and Polyaluminium chloride (PAC), with alum being the most widely used (Edzwald, 2008). Polyaluminium chloride is a pre-hydrolysed mineral salt coagulant which is said to have properties of polymeric/polyelectrolyte coagulants as well as mineral salt coagulants. These salts are less dependent on temperature, the mixing process and pH.

2.3.2 Polyelectrolyte/polymeric coagulants

2.3.2.1 Activated Silica

Activated silica was the first polyelectrolyte used. It was prepared on site by acidifying a sodium silicate solution. Negatively charged polysilicate compounds were formed during the acidification and were added to the raw water in conjunction with metal salt coagulants (Edzwald, 2013). Activated silica is used to treat low turbidity waters; although few modern plants use it.

2.3.2.2 Natural Coagulants

Natural organic coagulants are mostly used in developing countries as they are cheaper than their synthetic counterparts. They are made from natural organic compounds which include macerated *Moringa oleifera* seeds, chitosan from crustaceans and lignin such as modified Kraft lignin and lignosulphonates.

2.3.2.3 Polyelectrolyte coagulants

Polyelectrolyte coagulants are synthesised from subunits called monomers and will be the polymeric coagulants used during the research project. Polymeric coagulants are available in different forms, namely anionic, cationic and non-ionic (Leopold and Freese, 2009). Internationally, these coagulants are primarily used as flocculants or coagulant aids and would be used in conjunction with mineral salt coagulants for enhanced coagulation.

Cationic polyelectrolytes are used as primary coagulants or coagulant aids. They have relatively low molecular weights and use surface charge neutralisation as a coagulation mechanism. These polyelectrolytes are less effective on waters with high organic loads and dilute inorganic suspensions as they are not able to perform sweep flocculation.

Anionic and non-ionic polyelectrolytes are used as flocculent aids in sludge dewatering and as filter aids. They have high molecular weights and the coagulation mechanism they employ is interparticle bridging.

The coagulation mechanisms for organic coagulants are:

- Charge neutralisation caused by adsorption of ions onto the particle surface.
- Interparticle bridging: where a high molecular weight polymer molecule adsorbs simultaneously to more than one particle, physically pulling the particles together.

2.3.3 Coagulant Selection

The selection of an appropriate coagulant is dependent on the raw water quality, the chemical costs, the hazardous nature of the chemical and the water treatment process. Before a coagulant can be approved, physical tests have to be done to establish the correct coagulant and dosage. The jar test along with spectrophotometry can be used for coagulant selection, dosage selection and determination of optimum pH (Leopold and Freese, 2009). After selection of a suitable product and dose, the use of routine jar testing should be continually undertaken to optimise the plant performance.

Table 2-1 below gives a general summary of the types of coagulants and their advantages and disadvantages and Table 2-2 gives a general guideline for coagulant selection.

Table 2-1: Summary of Coagulants

Coagulant type	Inorganic coagulants	Polyelectrolyte coagulants
Commonly used in the water industry	Ferric chloride, ferric sulphate, aluminium sulphate, aluminium chloride, polyaluminium chloride, aluminium chlorohydrate (ACH)	Polyacrylamides, polyamines, poly (diallyldimethyl ammonium chloride) (PDADMAC)
Mechanism of coagulation	• Charge neutralisation • Sweep flocculation	• Charge neutralisation • Interparticle bridging
Uses in water treatment	• Particulate and NOM removal • Filtration aid	• Primarily coagulant aids internationally • Primary coagulant in South Africa • Used for sludge thickening and dewatering • Used to aid filtration
Advantages	• Good organic matter removal • Good turbidity reduction • Resultant sludge: good dewaterability	• Relatively low sludge volume due to mechanisms employed • Lower dosage required • Wide pH working range
Disadvantages	• Lowers alkalinity and pH • Narrows pH working range • Relatively high sludge volume	• Requires careful dose control • Some organic coagulants are susceptible to degradation if used in conjunction with pre-chlorination

Table 2-2: Coagulant Selection Guideline

Raw water characteristic	Recommended coagulant
Low alkalinity	Polyelectrolyte (Edzwald, 2013)
High alkalinity	Inorganic (Pontius, 1990)
Low turbidity	Inorganic coagulant or polyelectrolyte used in conjunction with a flocculant aid (e.g. bentonite) (Pontius, 1990)
High turbidity	Inorganic or polyelectrolyte (Edzwald, 2013)
High organics	Inorganic (Edzwald, 2013)

2.4 MANUAL COAGULANT DOSE CONTROL

The jar test simulates the coagulation/flocculation process of the water treatment plant to help optimise its performance. The required coagulant dose is determined by laboratory jar testing and is used as the initial set point for the coagulant dosing pump. Further adjustments can be made on the plant coagulant dose until the desired clarifier overflow and/or filtered water turbidity are achieved in the plant.

Manual coagulant dose control is adequate for situations where the raw water turbidity is constant over a long period of time. In reality, raw water turbidity can experience large variations depending on the raw water source, abstraction facility or seasonal raw water changes. This may require frequent operator intervention.

Proportional flow control is the simplest form of automated coagulant dose control as it responds to changing raw water inflow but not to fluctuations in the raw water quality. Proportional flow control is achieved by controlling the dosing pump rate as a ratio of the inlet flow rate. Raw water, clarifier effluent and filter effluent are manually monitored by the plant operators every two hours. When significant changes in raw water quality are observed, laboratory jar tests are carried out to determine the new coagulant dose in mg/L. The length of time between observing a change in the raw water quality and inputting the revised coagulant dose may be more than two hours, which may result in poor treated water quality.

2.4.1 Jar Tests

Jar tests are used to determine the optimum coagulant dose which is dependent on a number of factors, including raw water turbidity, pH, alkalinity, total organic carbon and ionic strength. A jar test mimics the water treatment process from raw water intake up to and including the clarification process.

Beakers containing raw water samples and magnetic stir bars are placed on a multi-position magnetic stirrer unit. Process chemicals are added in the same sequence as they would be added in the plant. One parameter, such as coagulant dose, is varied to achieve the optimum dosages.

Jar tests can be used to evaluate:

- Turbidity and/or colour removal
- Trihalomethane precursor removal
- Iron and manganese removal
- Taste and odour of treated water
- Process control such as coagulant and dosage selection, optimum pH, mixing energy, coagulant aid selection
- Sludge characteristics.

Jar testing can be done in conjunction with other tests such as spectrophotometry and streaming current detection to determine optimum coagulant dose.

2.4.2 Spectrophotometry

In some situations raw water colour is the main driver for the selection of coagulant type and dosage. Raw waters characterised by high levels of natural organic matter (NOM), are generally highly coloured. A good example of highly coloured water with low turbidity is the Western Cape raw water.

Spectrophotometry is based on the principle that light from a light source in a spectrophotometer, passing through a water sample in a cell, will be attenuated due to absorption of the incoming light of a specific wavelength by organic compounds in the sample.

Ultraviolet absorbance is easily determined using a spectrophotometer. The Beer-Lambert law relates the absorbance (at selected wavelengths) of specific groups of organics in solution to concentration. Specific ultraviolet absorbance (SUVA expressed as Abs/mg/L) is the absorbance of ultraviolet (UV) light in a water sample at a wavelength that is normalised for dissolved organic carbon (DOC); SUVA is determined by measuring the UV absorbance at 254 nm (expressed in units of per metre of absorbance) divided by the DOC concentration in mg/L. This method can be implemented on both laboratory batch scale or on a continuous system in a full-scale water treatment plant via online instrumentation.

To automatically control coagulant dosing in their water treatment plants, the City of Cape Town has been experimenting with spectrophotometry in the treatment of naturally coloured raw water due to organic compounds. They commissioned a pilot plant which used a system that combined SUVA, pH analysis and a mathematical modelling system named DACAR (Data Acquisition, Control and Reporting) to optimise the coagulant dosing. Using SUVA values and online readings of other parameters they decreased the use of coagulation chemicals by 5%. They have not implemented the system on the main plant, as control of pH adjusting chemicals and secondary coagulation had not been established (Flower, 2004).

2.4.3 Zeta Potential

Zeta potential (electrophoretic mobility) is measured using a zeta meter in a laboratory. A current is applied to the solution inside an electrophoresis cell and the speed and direction of the particles is measured using a stereoscopic microscope. This is known as the electrophoretic mobility. Zeta potential is sensitive to changes in ion concentration such as pH.

Zeta potential measurements are useful for:

- Coagulant determination
- Optimum pH determination
- Chemical dosage
- Evaluating dilution and mixing requirements.

2.5 AUTOMATIC COAGULANT DOSE CONTROL

Most South African water treatment plants (WTPs) still employ manual control methods for coagulant dosing. Automatic coagulant dosing does not require operator intervention as it is process controlled.

Process control is achieved by generating a reasonably accurate mathematical model representing the process and using this model to establish the typical control variables that can be manipulated to optimise the process operation (Altman, 2005).

There are two types of process control mechanisms: They are feed-forward control and feedback control.

- **Feedforward** – measures a raw water quality or parameter, to predict the required coagulant dose
- **Feedback** – measures the properties of the coagulated water after coagulant addition and rapid mixing.

Feedforward control is most useful on raw water sources that are subject to rapid variations in raw water quality. Raw water of a more consistent quality can best be manually controlled using flow proportional dosing pumps (EPA, 2014).

Figure 2.7 shows flow diagrams of each of these forms of process control starting with the disturbance.

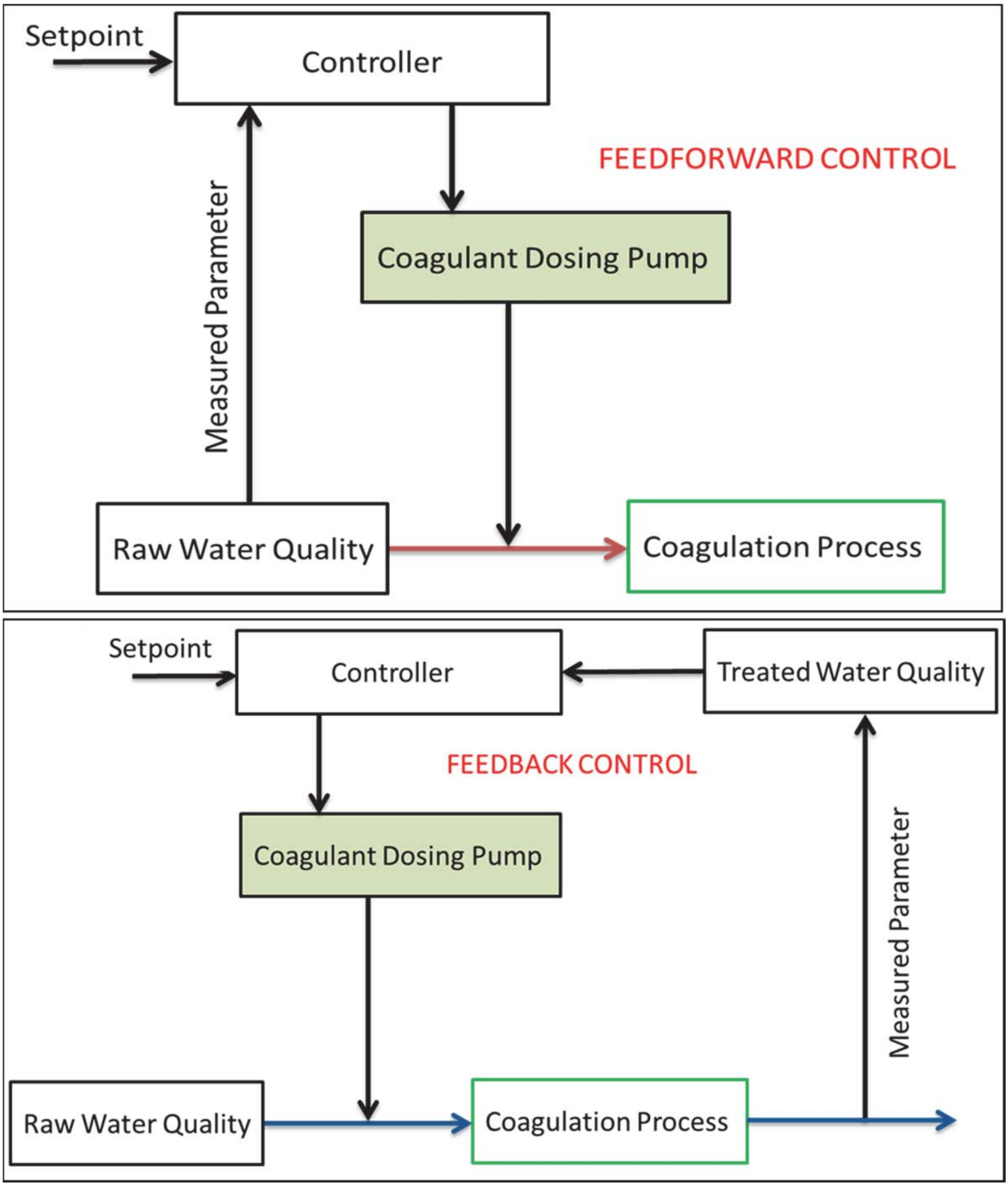


Figure 2.7: Illustration of feed forward and feedback control respectively

2.5.1 Control Loops

The loop is controlled by ensuring that the process variable (controlled parameter) does not deviate from the set point (required value to maintain). When the process variable (PV) is lower or higher than the set point (SP) the controller output (dosing pump) is adjusted accordingly.

Automatic control functions using proportional integral derivative (PID) control algorithms. The PID controller looks at the set point and compares it with the actual value of PV.

- **P** - The proportional term (P) in mV or mA or any other unit related to the controller output, adjusts the controller output in proportion to the difference between the set point and the value of the process variable. Increasing the proportional gain ensures a fast responding loop but too high a gain can result in an oscillating loop.
- **I** - The integral term (I) refers to the response time of the adjustment to the controller output as defined by the P, term. (I) sums the set point error over time and slowly adjusts the controller output until the error is zero. Controller error is defined as SP – PV (Smith, 2009). Integral action decreases set point error but too much integral action can cause the integral term to ramp up too quickly, causing set point overshoot.
- **D** - The derivative term (D) is the rate of change of 'I' with time. It further fine tunes the control loop and decreases the controller output when the rate of change in the process variable is increasing rapidly.

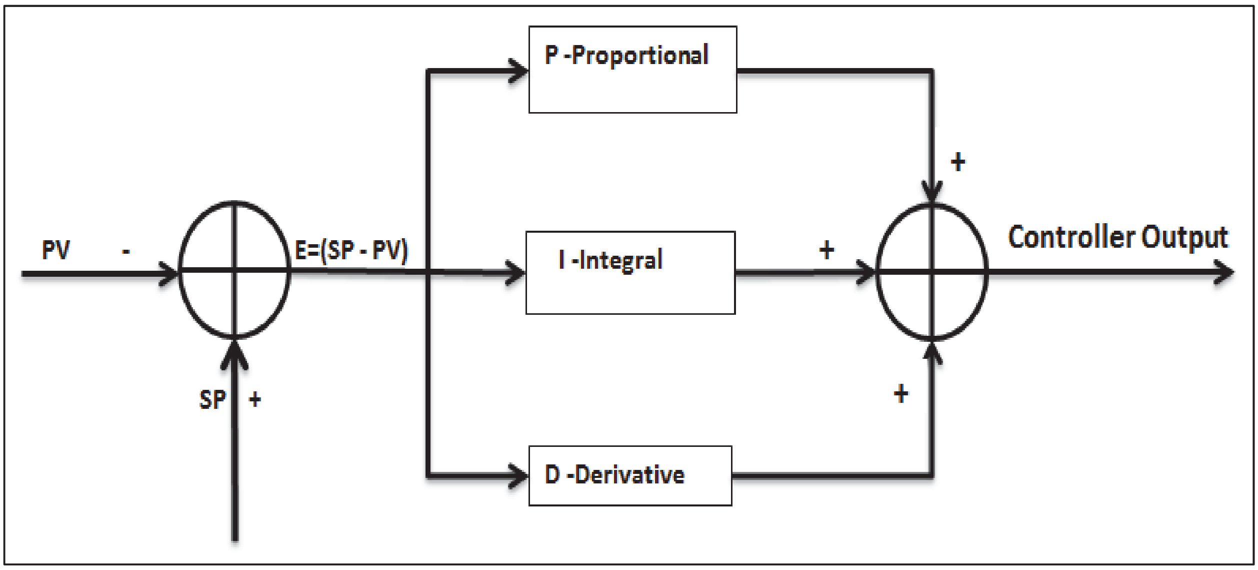


Figure 2.8: Block diagram of PID controller

The error is the value achieved when the process variable is subtracted from the set point indicated in Figure 2.8. The error is then multiplied by the P, I and D terms if they are activated for use. Then the resulting "error X control actions" are added together and sent to the controller output to control the required dosing rate. All three terms are used in PID control, only the P and I in the PI control and the P term in proportional control resulting in three modes of control:

- Proportional control (P-only)
- Proportional integral (PI)
- Proportional integral derivative (PID).

The control loop is calibrated by a process called tuning. This process calibrates all portions of the control loop for optimum control-loop response. This includes a suitable arrangement of variables such as (Smith, 2009):

- Chemical and electronic calibration of the control equipment (i.e. SCD)
- Correct tuning constants for the loop (PID terms)
- Correct stroke adjustment of the controller output (i.e. dosing pump).

Tuning of a PID requires the determination of the process gain, integral term and the derivative. The two most important dynamic characteristics of a process are the amount of dead time in the process and its time constant. Process dead time is referred to as transportation delay or reaction time for a change to register as a signal. The appropriate coagulant dose control system requires the selection of an appropriate form of analysis.

The options available for the analysis component used in a typical automatic coagulant dosing system are the following:

- Turbidity
- Streaming current detection
- Ultraviolet absorption
- Particle counting
- Settling monitoring
- Fluorometry
- Mathematical modelling.

The case studies revealed that generally more than one analysis method is used when optimising a coagulant dosing system.

2.5.2 Turbidity

Turbidity is defined by the American Public Health Association (APHA) as the “expression of the optical property that causes light to be scattered and absorbed rather than transmitted in straight lines through the sample”. It occurs due to the presence of suspended and colloidal particles in the water.

Turbidity is not affected by certain raw water constituents such as humic acids, which do affect coagulant dosage (Leopold and Freese, 2009). This limits the use of a turbidity meter to control primary coagulant dosage.

During their study of American water treatment plants, James Edzwald et al. (2008) found that where natural organic matter (NOM) was prevalent the amount of coagulant required was dependant on the NOM and not the turbidity. They developed a practical method for setting coagulant dosing based on two principles: the first is using optimum pH coagulation conditions with rapid mixing; and the second is dosing with sufficient coagulant to achieve optimum NOM removal (achieving the treated water UV_{254} goal). This study was completed at full-scale level using aluminium sulphate as the coagulant.

2.5.3 Fluorescence

Fluorescence is a process whereby light is absorbed by molecules. The absorbed light then excites the particles. The particles emit the absorbed energy when they return to an unexcited state. The wavelength of the realised energy is then measured.

There are fluorometers that can measure organics and turbidity. Two online or portable probes can then measure the parameters affecting coagulation dosage for dose control. No case studies have been done for the purpose of coagulant dosage optimisation or control (Peter Hiller, 2014).

2.5.4 Streaming Current Detection (SCD)

Currently the most commonly used automatic coagulation control system is streaming current detection/ion charge analysis. A streaming current detector (SCD) was first used for automatic coagulant dosing in water treatment internationally in the 1980s but was already being widely used in other industries such as pulp and paper and in water and wastewater treatment in the 1960s (Dentel, 1988). The SCD may be employed for online feedback control in applications where the charge density of the water may be altered, as with coagulant dosing, in water treatment plants. SCD monitoring is continuous and adjustment to coagulant dosage is relatively faster in comparison to the case when using jar tests.

A streaming current (SC) meter is an instrument for measuring the charge that exists on small suspended particles, and gives a reading of the streaming current in ICu (ion charge units). The ion charge measuring concept of streaming current detection is related to zeta potential by the equation

$$I = \zeta \omega f(G)$$

Where: I = ion charge, ζ = average zeta potential, ω = the motor speed and G = the cell/ chamber geometry (Dentel, 1988). Charged particles generate an electric current in the water. When the particles are moved up and down inside the chamber, the particles attach to the piston, and the electrodes can then measure the current giving an output known as streaming current (Edzwald, 2013).

The change in streaming current is related to change in the number of charged particles in water.
A simplified diagram of a streaming current detector (SCD) is given in Figure 2.9. The streaming current detector measures the net ionic and colloidal surface charge in the sample. The oscillating piston allows a continuous flow of sample into the sensor chamber. The piston and the chamber become coated with particles and the movement of the piston causes the separation of charged particles to occur. The migration of charge to the respective electrodes in the annulus produces a streaming current (SC). Following amplification and rectification, the SCD output is ready for coagulant dose control purposes.

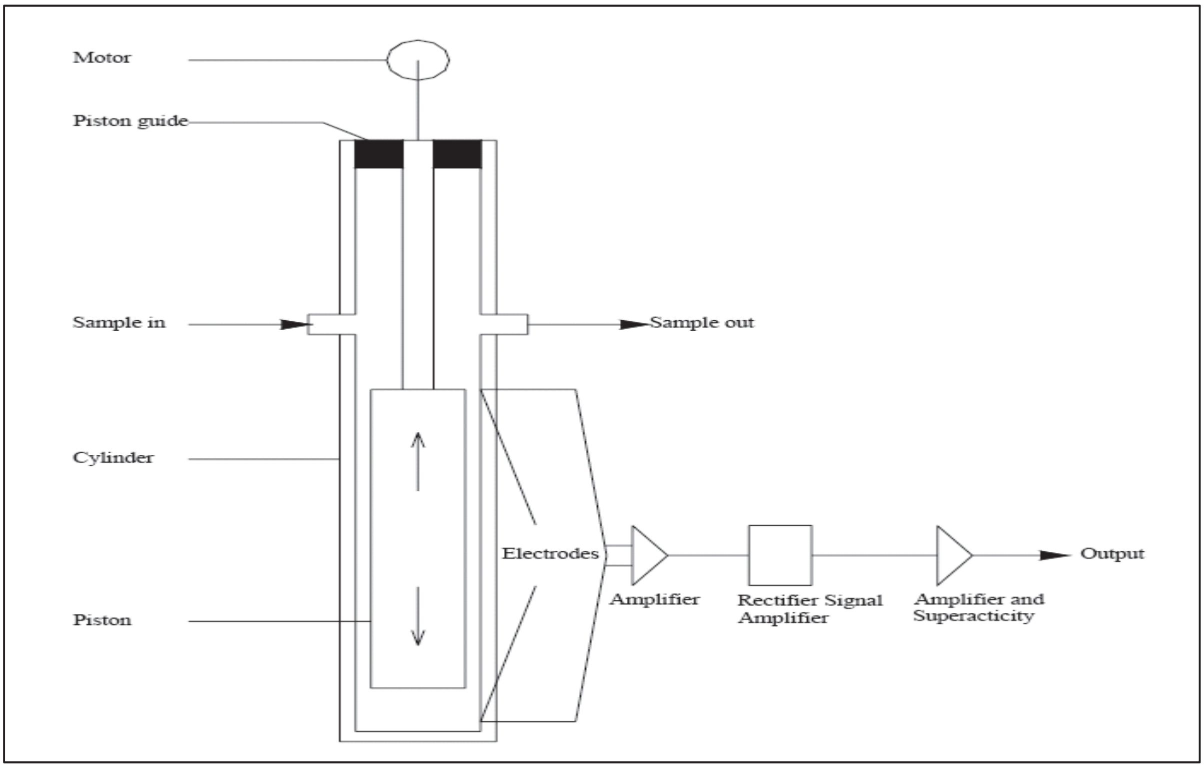


Figure 2.9: Illustration of streaming current detector (Source: Shengji Xia, March 2006)

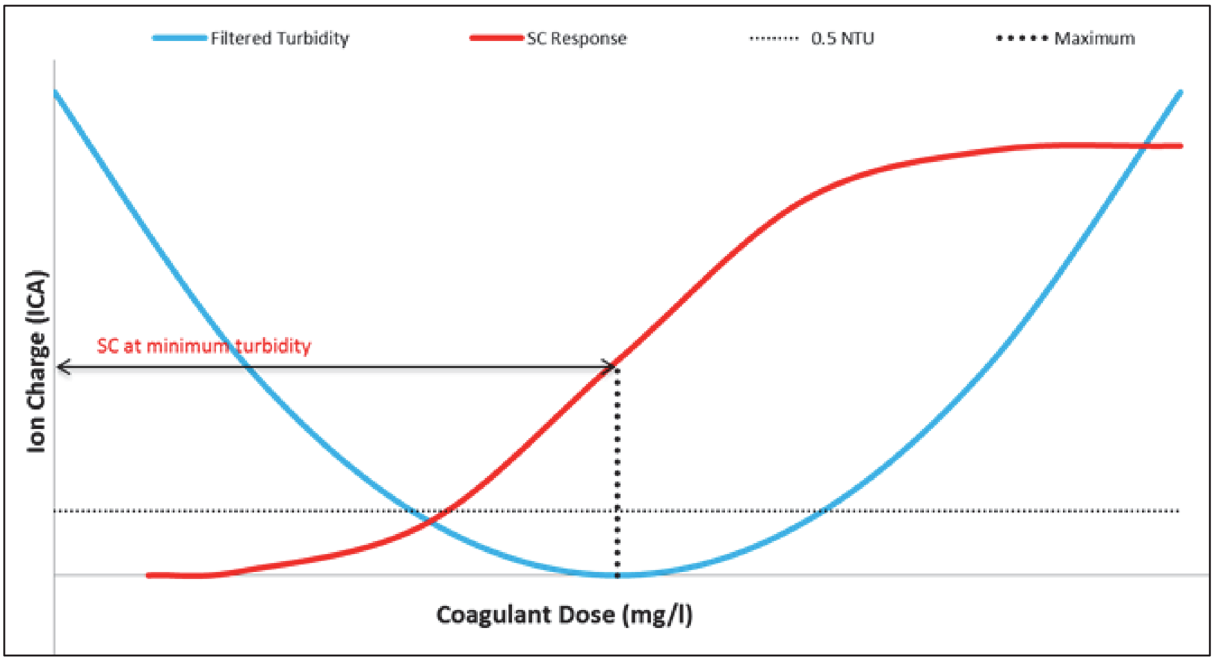


Figure 2.10: Diagram showing the theoretical relationship between SCD, turbidity and coagulant dose

Figure 2.10 above shows how the SCD responds to coagulant dosing. The SCD response is very sensitive during charge neutralisation; and during charge neutralisation at an SC set point there is only one corresponding coagulant dose (this is represented by the linear section of the SC Response curve).

Once out of the charge neutralisation dosage range the SC response is less sensitive to system changes leading to an SC set point which corresponds with more than one coagulant dose. This complicates control logic (AWWA Staff, 2002).

The SCD is claimed to provide a number of benefits in monitoring and controlling coagulant feed rates, including:

- Maintaining a consistently high quality of final water
- More consistent clarifier operation which allows for longer filter runs
- Automation and optimisation of coagulant usage
- Records changes in water chemistry
- Optimizes coagulation chemical usage.

Factors influencing SCD operation:

- Flow rate, as rapid flow decreases sample residence time.
- Particle size and type, grit should be removed and sample lines should be resistant to fouling and clogging.
- Mixing; sample should be completely mixed and SCD should be correctly positioned from the mixing unit.
- pH, as with zeta potential
- Soluble salts can impair reading though this varies with the type of salt

Numerous case studies have been done internationally using the SCD, both in the paper industry and in the water industry. A useful international case study was undertaken in the UK by the University of Sunderland and Northumbrian Water Limited. Two large-capacity pilot plants were run alongside Northumbrian Water's Broken Scar Water Treatment Plant, the main treatment plant, using the same raw water and aluminium sulphate as a coagulant.

It was found that pH had a large effect on the SCD reading and that when controlling the dosage system it was better to run one coupled control loop inclusive of both SC and pH instead of two separate control loops; one for each parameter. New Zealand has mandated the use of SCD for their top water grades, e.g. potable water.

Australia has also implemented SCD; in a case study of the Warragul Water Treatment Plant (Ablett, 2003), Gippsland Water upgraded Warragul WTP to use SCD by changing dosing points, etc. The water treatment plant treated raw water with a high turbidity and high colour. After running the plant using SCD, it was found that there was a significant reduction in chemical usage, operator input and dirty water events.

America has been using SCD for a long time and is now moving towards mathematical modelling. A study was completed in 2013 by Yavich and Van de Wege; they tested the use of SCD and a mathematical model on Holland water treatment plant where aluminium sulphate was used as a coagulant.

It was found that the SCD worked well but large changes in raw water turbidity required a change in set point (done manually using jar tests). The SCD was limited when sweep flocculation or high NOM was experienced. The model was more resilient but requires real-time, accurate process data and works on a feed-forward basis.

In South Africa very few water treatment plants use SCD. Umgeni Water is currently using streaming current detectors for coagulant control. Umgeni Water (Slatter, 1991) completed a theoretical and operational assessment on the implementation of the SCD on major WTPs within Umgeni Water. The report indicated that the SCD minimised under- and overdosing on the WTP. The chemical dosing was controlled such that the cost savings were noticeable. The units were accurate and achieved rapid measurement and parameter correction. The SCD worked well even during times of varying raw water parameters such as turbidity and flow.

The problems faced were mainly operational. The units required regular maintenance and cleaning. The use of lime elevated the SCD readings as they are sensitive to pH and ionic parameters such as calcium salts. The operators embraced the use of SCD and it was found to be “an invaluable tool to cost effective production of consistent quality water.”

At Rand Water a study was done by Sibiya (2013) to assess the feasibility of using the SCD for coagulation control using polymeric coagulants. The Vaal Dam was the source of the raw water used in the experiments. Jar tests were combined with SCD and readings were taken at 30-second intervals for the duration of 5 minutes and the average value was recorded. Polymeric coagulant (polymer blends) was dosed under rapid mixing. Sibiya (2013) concluded that the SCD shows potential for operational control optimisation.

2.5.5 Particle Counting and Sizing

There are many different types of particle counters using different operational methods to perform the main function of counting and sizing particles:

- Light blockage systems
- Monochromatic light-scattering systems
- Electrical resistance systems.

These analysers were created for use in the industrial sector. Particle counting in the water sector is mainly used outside South Africa and normally in conjunction with other control systems.

Particles are 3-dimensional but are normally characterised by their diameter and other parameters such as light blockage or scattering, electrical resistance or motion. Particle counting and sizing is easily accomplished on particles greater than 1 µm (Edzwald, 2013). In many of the articles that formed part of the literature review, particle counters were part of coagulant dosage system flow diagram but not mentioned in the text of the article. It will be interesting to investigate their value in water treatment.

2.5.6 Settling Monitoring

FlocDose is an analyser designed to determine the settling rate of particles in a sample of liquid. This product is used to control the dosage of the flocculent into the liquid where the sample was extracted (SRE Developments). The device consists of a chamber which is in direct contact with the turbid water. It uses a vacuum created inside the sampling chamber to draw in a sample of liquid. When the sampling chamber is full, the chamber is closed (by a pinch valve) and the settling rate inside the chamber is measured. An electrical signal (triggered by an algorithm) then manipulates the speed of the dosing pump. The user has to know the optimum settling time of the raw water to be able to input the set point.

2.5.7 Modelling Based on Historical Process Data

Research has been done recently on mathematical modelling using historical plant data to optimise coagulant dosing.

Charting data have been employed by operators for decades. Site-specific historical data are recorded over a number of years (for example turbidity versus optimal coagulant dose at a specific temperature and pH) and when conditions are similar to those recorded before, the operator manually changes the coagulant dose set point to suit the situation.

This idea has given rise to research focused on automating the charting system. The neural networks are known to successfully predict complex functions and have been used in modelling and control. They consist of many processing elements arranged in layers, each layer taking input from the weighted sum of the output of the previous elemental layer (Bernardete et al., 2005). The output of the layer is passed through a nonlinear function and becomes the input of the next layer. This system predicts the equation, which relates the inputs to the network outputs. For the network to function properly, training has to be completed to minimise the difference between real and neural outputs.

The inputs for the two-stage sensor developed by Bernardete et al. (2005) are raw water quality parameters, i.e. temperature, pH, turbidity, total carbonates, total suspended solids (TSS) and coagulant dose. After implementation and use, it was found that the neural model was able to align accurately to real data.

A different approach was investigated by Alaa Husaeen Wadie (2013). He developed online software to be used for the determination of an optimum coagulant dose. This approach uses stepwise regression techniques to develop predictive equations. The software is said to employ a feed-forward control approach, whereby the properties of the raw water are measured and used as information to determine and maintain the required coagulant conditions.

This method depends largely on the availability of detailed records of raw water quality and coagulation data; covering the full range of water quality likely to be encountered. It is recommended that data covering at least one annual cycle be used. Tests were done on this method on a small pilot plant with turbidity ranging from 0.1-40 NTU and historical data covering 18 months. This software program was found to support both inorganic coagulant and organic coagulant dosing. It is claimed to reduce the required operator intervention and improve the quality of the treated water. The program also allows users to customise and optimise the computer-generated design.

A mathematical model was implemented on a water treatment plant in western Michigan and a study of the operational effectiveness of the system was completed by John Wierenga and Alex Yavich (2005). The study showed that the implementation of a computer program for coagulant dose control greatly decreased the reaction time between an upset condition and the required change in coagulant dose. The water treatment plant could not use SCD as high doses of aluminium sulphate had to be used, causing sweep flocculation which interferes with the SCD function.

2.6 SUMMARY

This literature study has revealed that:

- The type of coagulant and the coagulation mechanism employed influences the selection of an automatic coagulant dose control system.
- The streaming current detector is currently the most popular system for automatic coagulant dose control. Historical modelling, although still somewhat of an enigma, is slowly being implemented in Europe and the United States.

Table 2-3 provides a summary of the coagulation control methods applicable to the project along with their advantages and disadvantages.

Table 2-3: Summary of Automatic Coagulation Control Methods

System	Principle of operation	Advantage	Disadvantage	Cost (2014)	Maintenance & operation
Streaming current detector	Ion charge analysis	• Principles relate to most parameters that affect coagulation • Easy operation and maintenance	Sensitive to pH, low raw water turbidity and sweep flocculation	R23 000	Monthly cleaning & calibration; requires basic operator training
Particle counting and sizing	• Light scattering • Light blockage • Electrical sensing	Helpful in filtration and when used in conjunction with other instruments	Difficult to operate on a full-scale plant	R65 000	Frequent cleaning; requires basic operator training
Spectrophotometry	Specific UV absorbance (SUVA)	Works well on waters containing high organics	Online unit available but not verified	R50 000	Monthly maintenance; requires basic operator training
Modelling based on historical process data	Mathematical processing of historical data	• Quick response time • Can be predictive • Ease of use	• Dependant on accuracy of historical data • Requires analyser inputs	R30 000	Monthly maintenance; requires basic operator training
Turbidity meter	Light scattering	Already online at WTPs for turbidity analysis	Does not detect organic loads or excess polymer	R40 000	Monthly cleaning & calibration

Water boards such as Magalies Water, Bloem Water and Rand Water are currently investigating implementing SCD. Umgeni Water has been utilising SCD for the past 17 years with good results.

CHAPTER 3: EXPERIMENTAL APPROACH

This chapter discusses the selection, experimental approach to the project and the methodology used to meet the project objectives.

3.1 SELECTION OF EQUIPMENT FOR TESTING

A typical automatic coagulant dosing system consists of the following components:

- Variable speed dosing pump that can respond to a feedback signal e.g. 4 to 20 mA
- A signal processor and controller, e.g. programmable logic controller (PLC)
- An appropriate on-line analyser, e.g. turbidimeter and streaming current detector (SCD) which will provide an output control parameter.

Automatic coagulant dosing systems generally differ from each other only in the selection of the control parameter that forms part of the loop, e.g. turbidity, iron charge or particle count. All the control equipment was standardised and the only variable was the controlled parameter.

The selection criteria for the automatic dose control system were as follows:

- Cost - capital, installation and operational costs
- Ease of installation – complexity of installation and how much space is required for installation.
- Maintenance costs – including the maintenance frequency and maintenance procedures
- Complexity of operation – level of operator training required or complexity of the control system and whether a PLC is required
- Limitations – the control parameter must be relevant to the specific treatment works coagulant dose drivers. The signals from on-line analytical instruments should be strong, stable and reproducible.

The SCD has been investigated internationally and has been successfully installed and operated on American and European water treatment plants. There have been articles in journals stating that it can be used for coagulant dose control for the removal of humic acids and low concentrations of NOM (Dental, 1988). With the technical evidence from the literature review and national interest in the implementation of the SCD, the SCD has become a key focus of this project.

The literature review indicated that the SCD does not function optimally at very low turbidity; therefore, since a few studies have shown the use of particle counters alongside other analysers on full-scale water treatment plants, the effectiveness of particle counters was also investigated in this project. Historical data indicated that the turbidity levels in two large dams in the KwaZulu-Natal region, Midmar Dam and Inanda Dam, have been dropping consistently over the years to their current turbidity values of less than 5 NTU. Therefore investigating the particle counter technique is relevant in the South African context. Lastly the use of a mathematical model for coagulant control was also investigated.

3.2 EXPERIMENTAL DESIGN AND METHODOLOGY

The equipment that was selected for investigation was first tested to determine its suitability for control. During this phase, the equipment was run manually and the response to changing parameters as well as operational challenges was noted. The equipment that performed well in these tests was then further tested to determine the quality of automatic coagulant dose control on a pilot scale. Investigations into equipment that did not perform well in the initial laboratory stage were discontinued.

For the mathematical model based on historical data, once the neural networking program was completed, the programme would be manually tested on plant data to determine how well the programme would work when in operation. The results of these “dry” tests would then determine whether or not the testing would move to the next phase.

CHAPTER 4: QUALITY CONTROL OF ANALYTICAL MEASUREMENTS

This chapter discusses the procedures used to ensure that the experimental results were accurate, repeatable and reliable. A summary of calibration and cleaning interventions for the analytical instruments used in this study is presented including a quality control procedure.

4.1 JAR TESTS

Variance tests were performed to ensure that the jar stirrer produced repeatable results, as a unit and across each stirrer.

Random variance testing on the jar stirrer was undertaken periodically. Variance testing was not done for each sample due to limited sample volume. The jar stirrer unit was not moved or tampered with throughout the experimental period, and the variances obtained from the unit were below 5%.

Three sets of jar tests were performed for the repeatability exercise. The variance was then determined using the formula below,

$$\text{Variance} = \Sigma \frac{(Xi - mean)^{\wedge}2}{N-1}$$

Where,
Xi is the output/ result
N is the sample number

Below is a sample calculation for the settled turbidity variance across each stirrer.

Table 4-1: Jar Test settled turbidity results

Sample number	Settled Turbidity (NTU) Output
1	0.596
2	0.597
3	0.639
4	0.641
5	0.613
Mean	0.617

$$\text{Variance} = \Sigma \frac{(Xi - mean)^{\wedge}2}{N-1}$$

$$= \frac{(0.596-0.617)^{\wedge}2}{5-1} + \frac{(0.597-0.617)^{\wedge}2}{5-1} + \frac{(0.639-0.617)^{\wedge}2}{5-1} + \frac{(0.641-0.617)^{\wedge}2}{5-1} + \frac{(0.613-0.617)^{\wedge}2}{5-1},$$

$= 0.000479,$ % Variance = 0.000479 *100 =0.05%

4.2 STREAMING CURRENT DETECTOR

To ensure that the SCD laboratory results were reproducible, the instrument stability was measured for each water sample. The procedure was as follows:

- 10 x 350 mL grab samples of a well-mixed raw water sample were measured on the SCD
- The SCD piston was immersed in the sample and a magnetic stirrer was used to continuously stir the sample
- The SCD was allowed to stabilise for 3 minutes and the reading recorded
- The variance was calculated.

The largest variance was found to be ±0.69%.

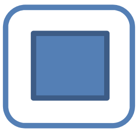
4.2.1 SCD Calibration Procedure

The SCD calibration for both laboratory and pilot plant was performed weekly and the procedure was as follows (extract of Lechintech SCD Operating and Instruction Manual):

- Add 1 mL of cationic standard to 1 L of distilled water and mix well for 2-3 minutes
- Now add 100 mL of the solution to 900 mL of distilled water and mix well
- Allow the solution to stand for one hour before calibrating the SCD
- Rinse the SCD in tap water before immersing it into the first beaker of calibration solution (500 mL)
- Allow the SCD reading to stabilise in the calibration solution
- Replace the 500 mL solution with a fresh 500 mL of the calibration solution
- Allow the SCD reading to stabilise, then use the menu prompts to calibrate the instrument

Press the MENU button

Press the UP ARROW button until the screen displays ‘**Calibrate SCD’**



Followed by pressing the ENTER button

- The SCD will automatically set the zero and gain values
- Calibration is complete when a value of 5.30 ICu is displayed on the screen.
- Rinse the SCD in fresh water once calibration has been completed.

4.2.2 SCD Maintenance

- The SCD was removed from the sample encasement.
- The encasement was then rinsed by opening the drain valve and scrubbing with a brush.
- The line to the sample encasement was flushed by allowing inflow into the encasement then opening the drain valve.
- The SCD was then returned into the sample encasement and normal operation resumed.

4.3 LABORATORY pH AND TURBIDITY METERS

Daily analytical quality control (AQC) tests were conducted to ensure that the experimental results were comparable, accurate and precise. The AQC procedure was conducted after every two tests on the turbidity meter and pH meter and can be seen in Figure 4.2.

4.4 PILOT PLANT TURBIDITY METER AND SCD

To ensure accuracy, corresponding readings from the pilot plant turbidity meter and SCD and the calibrated laboratory turbidity and SCD were taken and compared. If the variance was found to be above the 10% the online turbidity meter or SCD would be calibrated in accordance with the equipment operating manual. Figure 4.1 below is an example of the comparative testing. At the point where there was a consistent increase in the variance, in this case for a period of two days, the respective instrument was calibrated.

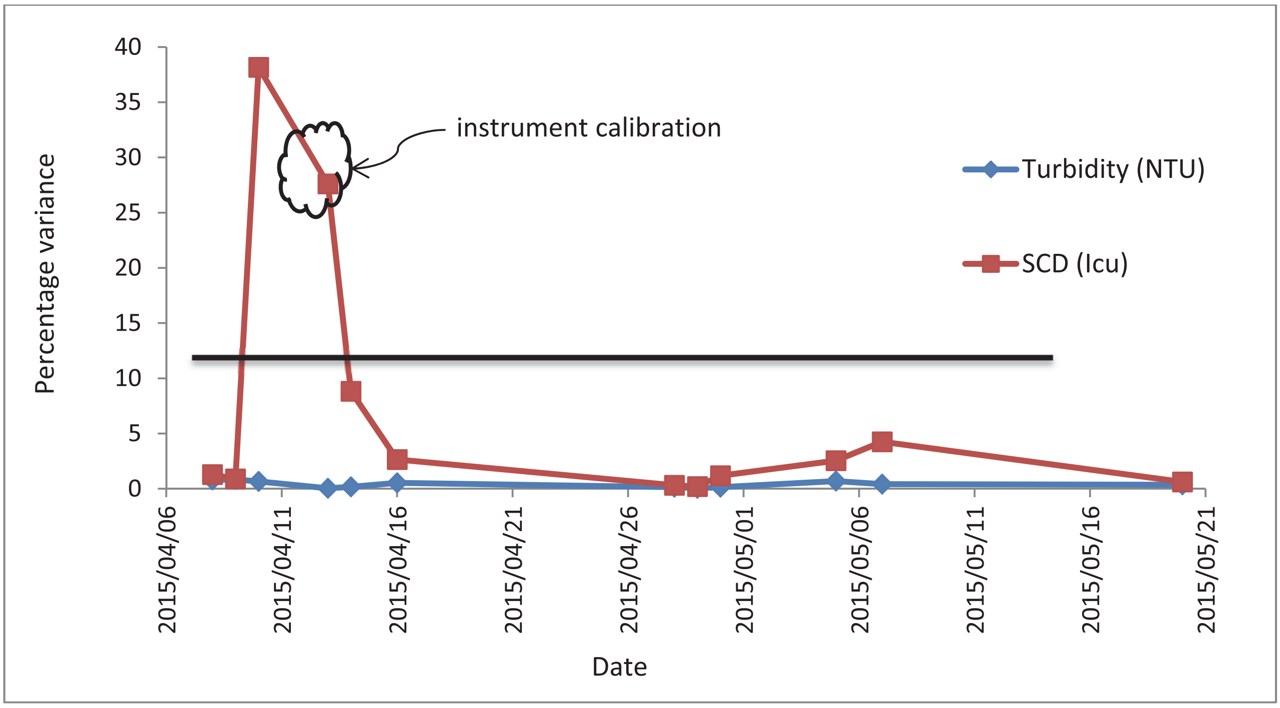


Figure 4.1: Percentage variance between manual and online readings for the turbidity and SCD

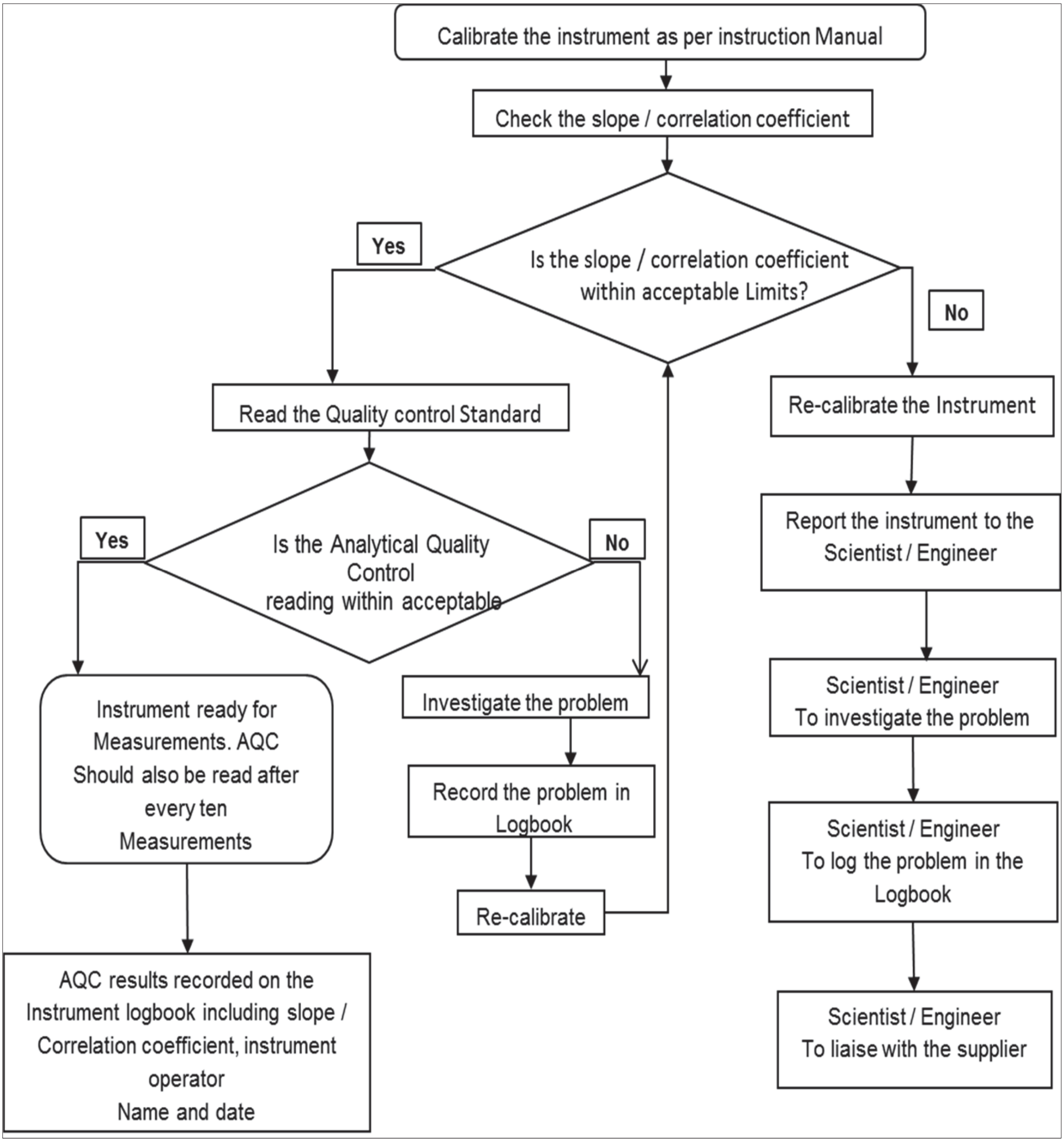


Figure 4.2: Analytical Quality Control Procedure

4.5 PARTICLE COUNTER

The particle counter was factory calibrated by the equipment supplier. The equipment does not lend itself to onsite calibration and calibration checks. The only intervention available was to flush the particle counter intermittently by passing ultrapure water through it and allowing the particle counts to stabilise at the lowest value. These values (particle size and counts) for the ultrapure water were recorded when the particle counter was cleaned and then compared in subsequent runs. If the values differed by more than 10%, then the particle counter was again cleaned and flushed using ultrapure water.

Reduction of the recommended flow rate (of 75 mL/min) through the sensor indicated potential sensor fouling. A drop in the cell condition to 85% indicated that cleaning ought to be performed. Constant maintenance was thus required to mitigate the effects of fouling.

A non-brush cleaning method was used which is outlined below:
- Standard laboratory cleaner or warm deionised water, i.e. less than 50 °C (depending on the availability) was prepared
- Using a syringe of a minimum size of 60 mL the cleaner or deionised water was injected through the sensor tubing
- The high pressure removes most of the fouling
- The flow rate was checked using a volumetric cylinder and stopwatch to ensure it had been restored to 75 mL/min.

If the a 10 to 15% drop in the cell percentage was observed from either the very first reading or the first reading after cleaning, a calibration in accordance with the operating manual was performed.

CHAPTER 5: PERFOMANCE EVALUATION OF PARTICLE COUNTER

This chapter describes the methods used to evaluate the performance of the particle counter, the results and the outcomes.

5.1 METHODOLOGY

An inline particle counter was installed on the water treatment evaluation unit (WTEU) pilot plant, which is located at Umgeni Water's Wiggins Water Treatment Plant. The pilot plant receives low turbidity water (usually less than 3 NTU) which is dosed with a coagulant and a coagulant aid. The water is then clarified and filtered. The pilot plant uses a sludge blanket clarifier for water treatment. Due to the low turbidity of the incoming raw water, bentonite is dosed as a coagulant aid to create and maintain the sludge blanket.

The particle counter was installed downstream of the clarifier to test whether or not it could be utilised as feedback control for the coagulant dose. The pilot plant process flow diagram is presented in Figure 5.1
The particle counter tallied and sized suspended particles into four size ranges (i.e. 1-5 µm, 5-10 µm, 10-15 µm and 15-25 µm). The purpose of this experiment was to determine how particle size and particle counts in the clarified water varied with incremental changes in coagulant dose. If there was a consistently reproducible relationship between particle counter output and coagulant dose, then the particle counting technique may be considered for use in an automatic coagulant dosing system.

- The particle counter sensor tubing was flushed with about 5 L of deionised water to obtain a baseline of clean water
- The optimum chemical dosages were determined from jar tests
- Laboratory measurements of clarified turbidity were recorded to confirm the accuracy and deviation of the online data being obtained.

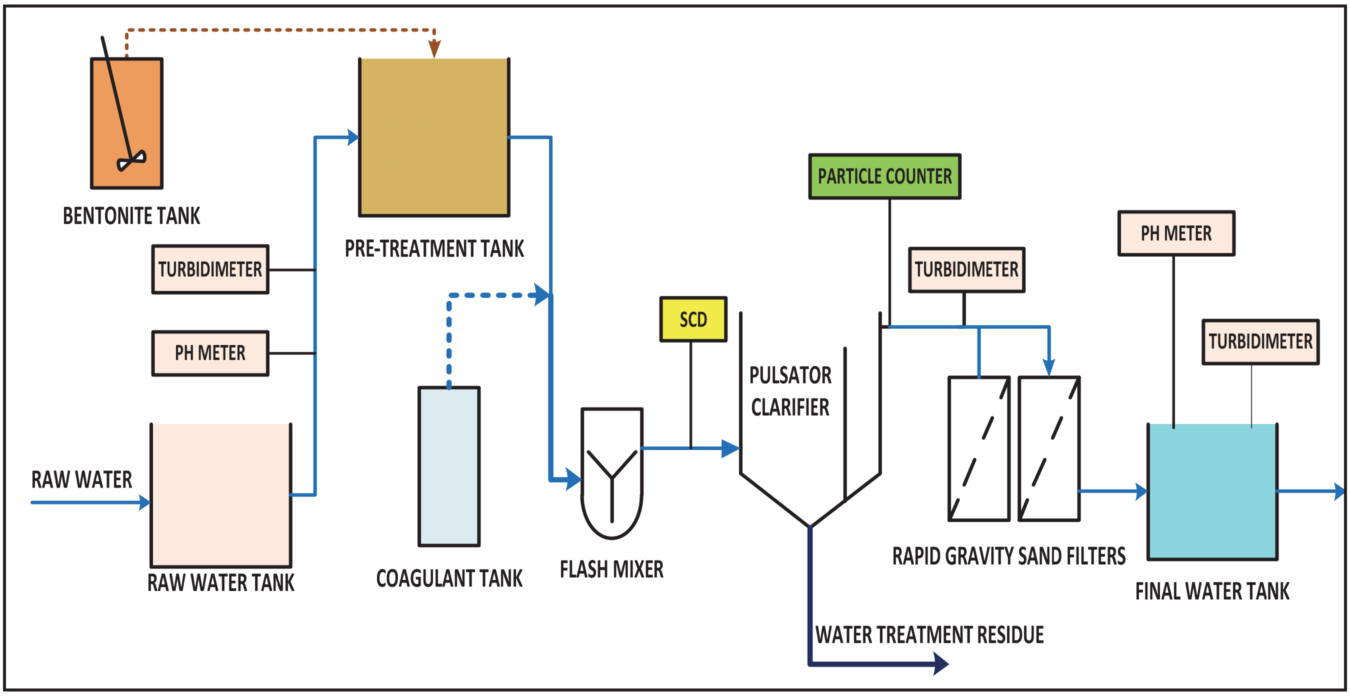


Figure 5.1: WTEU process flow diagram

5.2 RESULTS

The quality of the raw water quality entering the pilot plant during the trial is summarised in Table 5-1.

Table 5-1: The pilot plant raw water parameters

Determinant	Minimum	Maximum
pH	7.12	7.85
Turbidity (NTU)	0.34	0.79
Flow rate (L/h)	3750	3850

The polyelectrolyte coagulant dose was varied to determine the response of the particle counter and turbidity meter to coagulant dose.

- Optimum coagulant dose at 1.8 mg/L
- Optimum bentonite dose at 1 mg/L

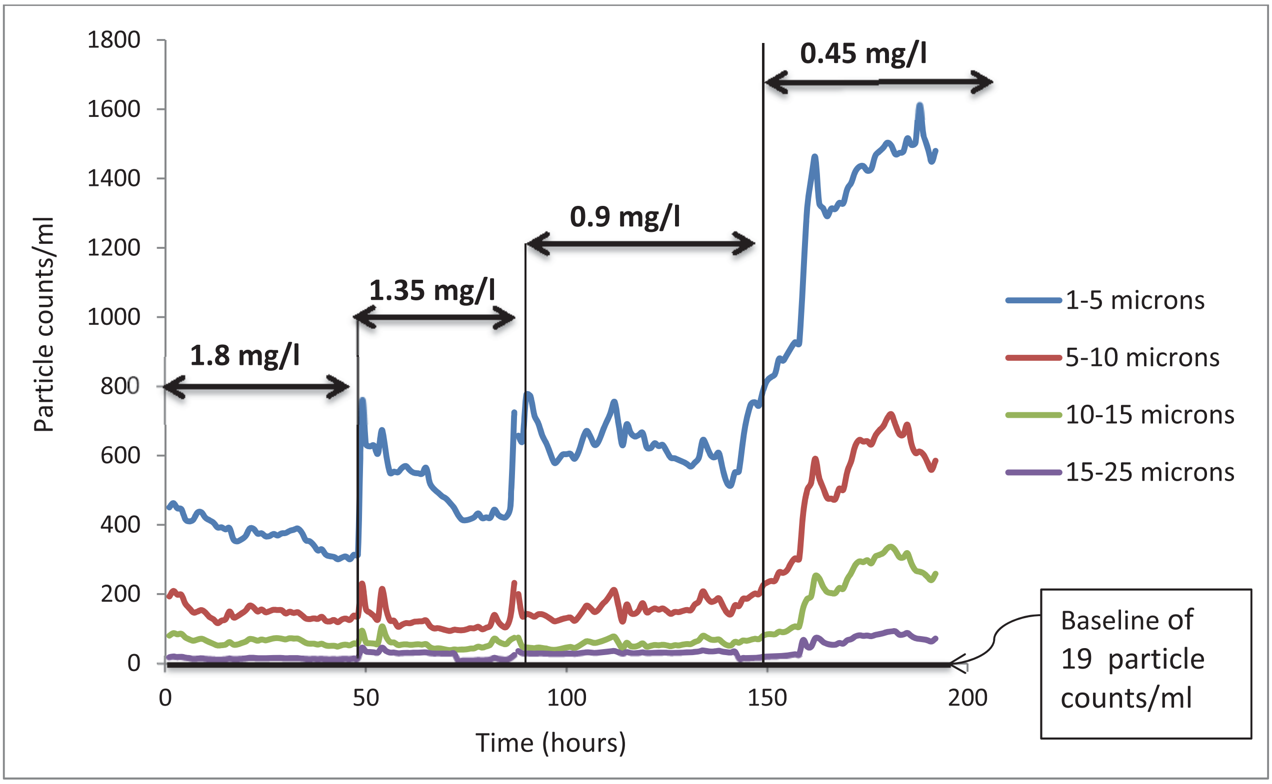


Figure 5.2: The effect on particle counts/mL with decreasing coagulant dosage over time

Figure 5.2 illustrates that there is an inverse relationship between particle counts/mL and polyelectrolyte dosage. As the polyelectrolyte dosage was decreased the number of particles in each size range increased. Most of the particles were found to be in the 1 to 5 µm size range. These are colloidal-size particles, while the larger particles (>10 µm) are suspended particles such as clays or detritus (Edzwald, 2013).

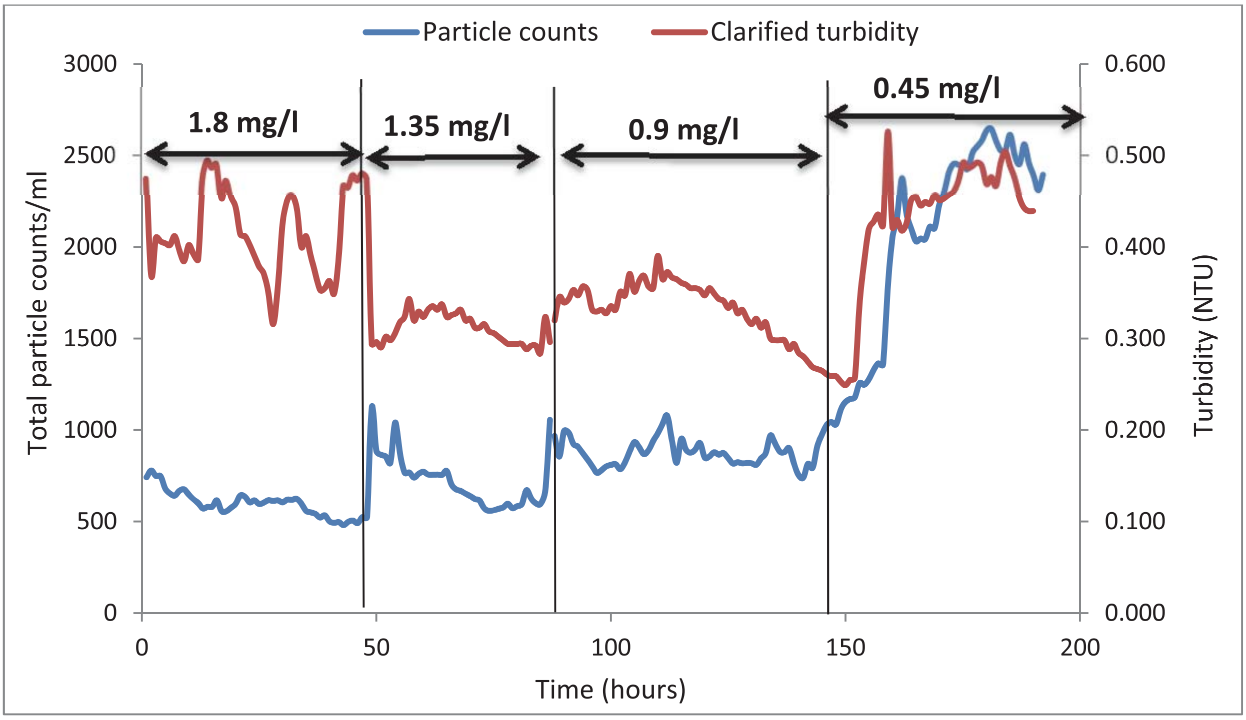


Figure 5.3: Effect of decreasing coagulant dosage on total particle counts and clarified water turbidity

Figure 5.3 shows the effect of decreasing the polyelectrolyte dosage (polymer blends) on the total particle counts/mL and clarified water turbidity. With decreasing polyelectrolyte dosage the clarified water turbidity decreases and plateaus, until it starts increasing. The total particle count (the sum of particles in all size ranges) tends to increase.

Because the clarifier requires a sludge blanket for operation its stability adds another variable to the system. As the coagulant dosage decreases, the particle settling within the clarifier decreases, which can disturb the sludge blanket causing solids carry-over.

Considering steady-state operation and to determine the trend, an average was calculated across each run as can be seen in Table 5-2.

Table 5-2: Average readings across each run for poly variations

	Polyelectrolyte coagulant Z553D dose			
	1.8 mg/L	**1.35 mg/l**	**0.9 mg/l**	**0.45 mg/l**
Clarified water turbidity (NTU)	0.42	0.31	0.34	0.41
Total particle count (counts/mL)	597	719	873	1963

5.3 DISCUSSION

The preliminary performance evaluation results showed that the particle counting and sizing technique is not satisfactory for coagulant dose control. It should be noted that in this study the particle counter was placed downstream of the clarifier in order to achieve coagulant dose control.
The tests were performed using a clarifier that required a sludge blanket to operate. The clarifier adds another dimension to the tests as coagulant dose is not the only variable affecting the particle counter readings. The instability of the sludge blanket due to other operational parameters apart from coagulant dose also affected particle counts and size. The particle counter readings were inconsistent and the instrument required cleaning twice a week.

The constant exposure to turbidity averaging 0.2 NTU caused a cell malfunction rendering the particle counter inoperable. It was decided that the particle counter would not be appropriate for full-scale use due to the frequent cleaning and sensitivity to even low turbidity levels (<5 NTU). Coagulation control tests were therefore not performed using the particle counter.

CHAPTER 6: MATHEMATICAL MODEL BASED ON HISTORICAL DATA

This chapter discusses the development of the neural network programme.

6.1 BACKGROUND

Artificial neural networks are classified as “black box” mathematical non-linear regression tools. They learn and identify correlative patterns between sets of input data and corresponding outputs. As in the human brain, learning starts with known data and eventually the brain is trained to adapt to changing environments but the basis is always what was learnt during the training period. As the saying goes “good judgment comes from experience, experience comes from bad judgment,” so the neural network needs “experience” to learn to make “good judgments”. This experience comes from training it with rich characteristic data of the system under consideration. The training of these neural networks is a form of non-linear regression and has developed into a tried and tested technique.

An artificial neural network is typically a massive parallel-interconnected network of processing elements (also called “artificial neurons”, nodes or units). The way in which these processing elements are mutually interconnected determines the network architecture. Over 50 different types of network architecture can be found in the literature (Morris et al., 1994; Bulsari, 1995). In this report the most common type of neural network architecture, called the feed-forward with back-propagation neural network, was used.

A feed-forward neural network is made up of layers of processing elements. An example of the structure of a feed-forward neural network with one input layer, one hidden and one output layer is illustrated in Figure 6.1. The data from the input layer are propagated through the network via the interconnections to processing elements in the first hidden layer where they are combined and modified by activation functions. The signals proceed in this way from layer to layer until they reach the output layer.

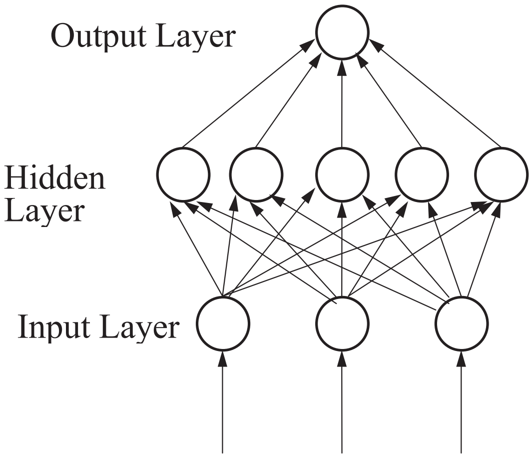


Figure 6.1: Example of a 3-5-1 Feed forward Network

The neural network package “Predict” was used for the simulation (NeuralWorks Predict, 1995). Predict uses one hidden layer only. Therefore, the network architecture is not fully determined in advance. The number of nodes in an output layer is given by a number of model output variables. For a hidden layer, Predict uses a method called “Cascade Learning” (Fahlmann and Lebiere, 1988) in order to determine a suitable number of hidden nodes.

The number of input nodes may correspond to the number of input variables chosen. Alternatively, Predict can employ its genetic algorithm to analyse input variables and to find the most advantageous set of them for neural network modelling. Every input variable may be used more times in different transformations. The genetic algorithm may identify principal process variables, which have the most significant effect on model outputs, and it may also disregard input variables that show small or negligible effect on the process under consideration.

6.2 PROCESS DATA

The information used for neural network prediction of the coagulant dosage was taken from historical data of one of Umgeni Water's potable water treatment plant. The 2 991 data points included the following input and output variables: pH, turbidity, conductivity, and temperature of raw water; water turbidity after clarification and after filtration (all input variables); and the optimum coagulant dosage in mg/L to reduce the water turbidity to below 5 NTU after clarification (output variable).

The neural network model with one input layer (all input variables and their transformations), one hidden and one output layer (output variable – coagulant dosage) has been developed based on these data. In the first step it was necessary to correct the format of data to exclude data points with some missing information and apparently wrong data, and data with variables outside the expected range, i.e. for temperature 9-36°C, for raw water turbidity 10-42 NTU.

All data used were for "successful" dosages of a coagulant (i.e. cases when the final turbidity meets the regulations (i.e. for clarifiers <5 NTU and after filtration <0.5 NTU). That means implicitly that the predicted dosage should be adequate to meet the regulatory limits for water turbidity.

6.3 RESULTS AND DISCUSSION

The processing elements in the input and hidden layer and between the hidden and output layer are weighted to minimise the differences between network outputs and the experimental values. This phase is called "neural network training". An objective function is specified which is a measure of how closely the outputs of the network match the target values from the training set of data. Experimental data stated above were used to find a relation between input variables and the final coagulant dose.

All experimental data collected in the process were used in developing (building and training) the neural network model. 80% of the data was used to develop the model and 20% of the data was used to test the model. Then the neural network was trained and the prediction accuracy of the model was evaluated using the root mean square error of prediction for the test set. The training was repeated several times for different data partitioning into the training and test sets and predictions for each test set were calculated.

Because the input-output relationship represented by a network did not depend on the way of splitting the experimental data into training and test sets, the training could be regarded as stable. Several neural network models were constructed using different combinations of input variables. The decision as to which model was the best one was made on the basis of a minimal value of a root mean square error chosen as an optimisation criterion

The predicted values of coagulant dose are plotted against the plant values in Figure 6.2.

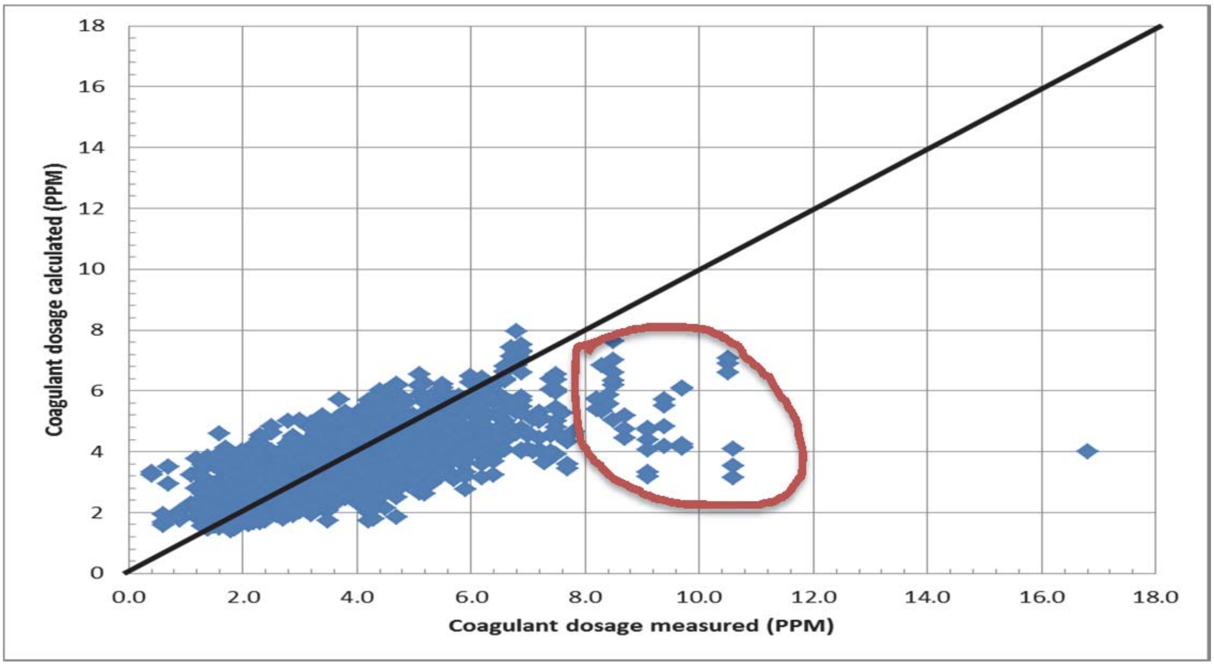


Figure 6.2: Calculated vs. Plant Coagulant Dose

Ideally, all the data points should lie on a diagonal. While there is a spread in the calculated values around the diagonal, the trend of prediction is promising. In about 1% of data the prediction was not successful at all (see the bottom right marked area in Figure 6.2). These data are excluded in Figure 6.3 which shows the measured and predicted values of a coagulant dose for the interval 0-8 mg/L.

Academically, it would appear that the neural network model gives the best prediction in this range. The reason for that is that most of the data used for neural net training were from this region. However, for the objectives of this investigation the variation between the predicted and calculated coagulant doses is too wide and economically unviable. For example, on Figure 6.3 for a measured coagulant dose of 3.5 mg/L the model could calculate a dose anywhere from 2-5 mg/L which is a variation of ±43%. Further full-scale testing of this model was discontinued.

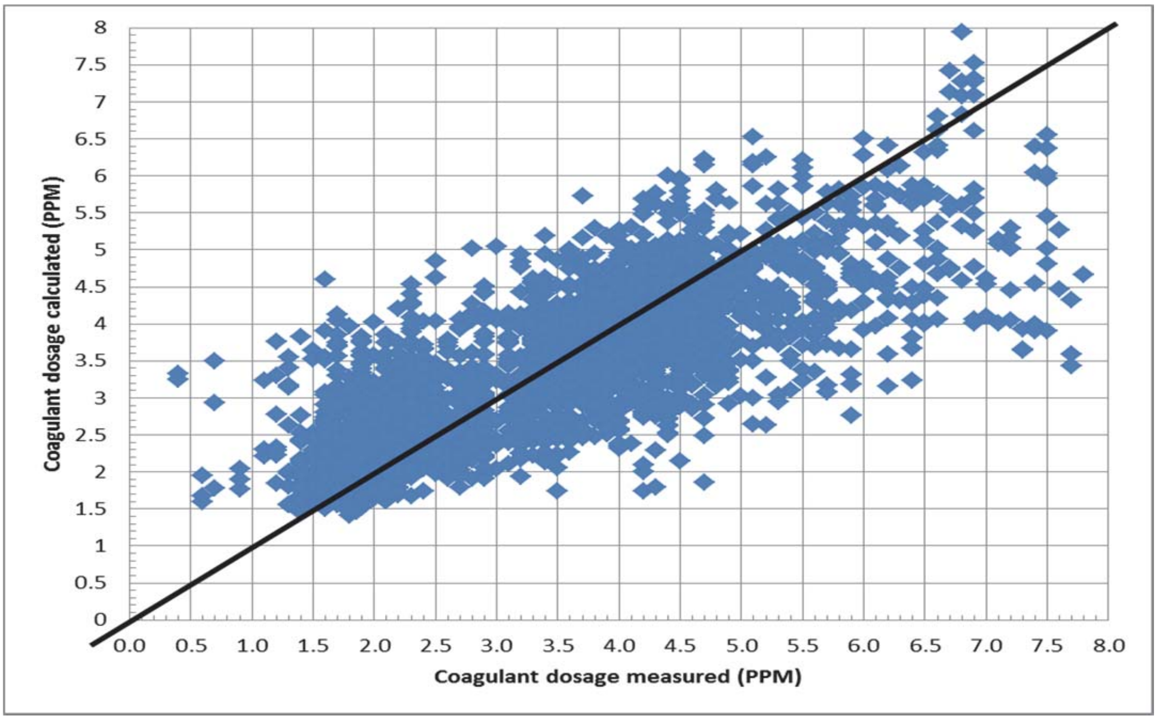


Figure 6.3: Calculated vs. Plant Coagulant Dose (0-8 mg/L)

CHAPTER 7: EVALUATION OF STREAMING CURRENT DETECTOR TECHNIQUE

This chapter discusses the evaluation of the SCD, the results and the outcomes.

7.1 LABORATORY METHODOLOGY

Raw water samples were collected from the Western Cape, Northern Cape, Eastern Cape, KwaZulu-Natal and the North West Province. No synthetic raw water samples were prepared. The primary raw water quality parameters used for comparison during this study were turbidity and colour.

The experiments were designed to provide information on the sensitivity and response of the streaming current detector (SCD) to different water types and common treatment chemicals used in conventional water treatment plants. The SCD sensitivity and response was measured by conducting SCD titrations. Jar tests were conducted concurrently with the SCD titrations to determine the relationship between the SCD response and the optimum coagulant dose. All of the water samples were tested with three coagulants, namely two mineral salt coagulants (ferric chloride and aluminium sulphate) and a polymeric coagulant.

7.1.1 SCD titrations

The SCD titrations were conducted on a bench-scale SCD using the following procedure:

- The Lechintech SCD 16mp piston was immersed in a 500 mL sample of raw water.
- A magnetic stirrer was used to continuously stir the sample and the SCD was allowed to stabilise for 3 minutes before the initial reading was recorded.
- To evaluate the effect of chemical addition on the SCD response, the chemical was dosed in predetermined increments. The SCD was allowed to stabilise for 3 minutes after each dose and the reading was recorded.
- The above steps were repeated until a full SCD response curve was obtained.

7.1.2 Jar test

The jar tests were conducted with the equipment depicted in Figure 7.1 using the following procedure:

Figure 7.1: Jar test equipment set-up

- 20 L of raw water was sampled from each site
- The initial ion charge unit (ICu), turbidity and pH of the raw water were determined and the results recorded
- 1000 mL aliquots of raw water were dispensed into each jar test beaker
- Chlorine, lime and coagulant were dosed in the same order as that used on the plant
- The velocity gradient for flash mixing the samples was 234.9 s^{-1} for 2 minutes
- The samples were then slow mixed at a velocity gradient of 59.4 s^{-1} for 15 minutes and floc sizes were recorded
- Samples were allowed to settle for 15 minutes and the settling rate was recorded, i.e. slow, moderate or fast
- Settled samples were analysed for turbidity; samples were then filtered and pH and turbidity were determined
- Colour was measured before and after the jar test on pre-determined samples.

7.2 LABORATORY RESULTS

This section is divided into 5 subsections. Each section evaluates the SCD response using both mineral salt and polymeric coagulants on the following raw water types:

- Turbidity below 10 NTU
- Turbidity above 10 NTU but below 100 NTU
- Turbidity above 100 NTU
- Coloured water
- Pretreatment chemicals

The figures below display the relationship between optimum coagulant dose and the ion charge unit. For the purpose of this study, the South African National Standard (SANS 241:2015) for a drinking water turbidity threshold of <1 NTU was set as a filtered water target. The Umgeni Water guideline of <5 NTU was used for settled water turbidity. The optimum dosage range is where the filtered turbidity curve is <1 NTU and the settled turbidity is <5 NTU. For highly coloured water the SANS 241:2015 requirement is that the colour of the final water be <15 mg Pt.–Co. For the purpose of this study an R^2 coefficient of determination of >0.90 shows strength of a linear relationship.

Due to the SCD principle of operation it is most sensitive and responsive to the charge neutralisation mechanism of coagulation. During charge neutralisation every ion charge set point corresponds to a single coagulant dose. The best example of this is a line with a gradient greater than zero. Outside of charge neutralisation the SCD response is less sensitive and one set point could correspond to multiple coagulant dosages making process control more complex (AWWARF, 2002).

The laboratory results will show whether or not the optimum coagulant dose for each system lies within the charge neutralisation or linear zone as this is the most effective range when using streaming current detection as an automatic coagulant dose system.

7.2.1 Raw water with turbidity below 10 NTU

To illustrate the behaviour of the streaming current detector (SCD) in raw water with a turbidity of below 10 NTU, raw water from Umgeni Water's Midmar Water Treatment Plant (WTP) in KwaZulu-Natal was used. The abstraction source for Midmar WTP is Midmar Dam. The plant uses conventional water treatment processes that include coagulation, clarification, filtration and disinfection.

Table 7-1: Midmar WTP raw water parameters

Parameter	Value
pH	6.94
Turbidity (NTU)	6.68
Plant optimum coagulant dose (mg/L)	2.1
Initial ion charge (raw water)	-2.94

7.2.1.1 Inorganic treatment of Midmar dam raw water

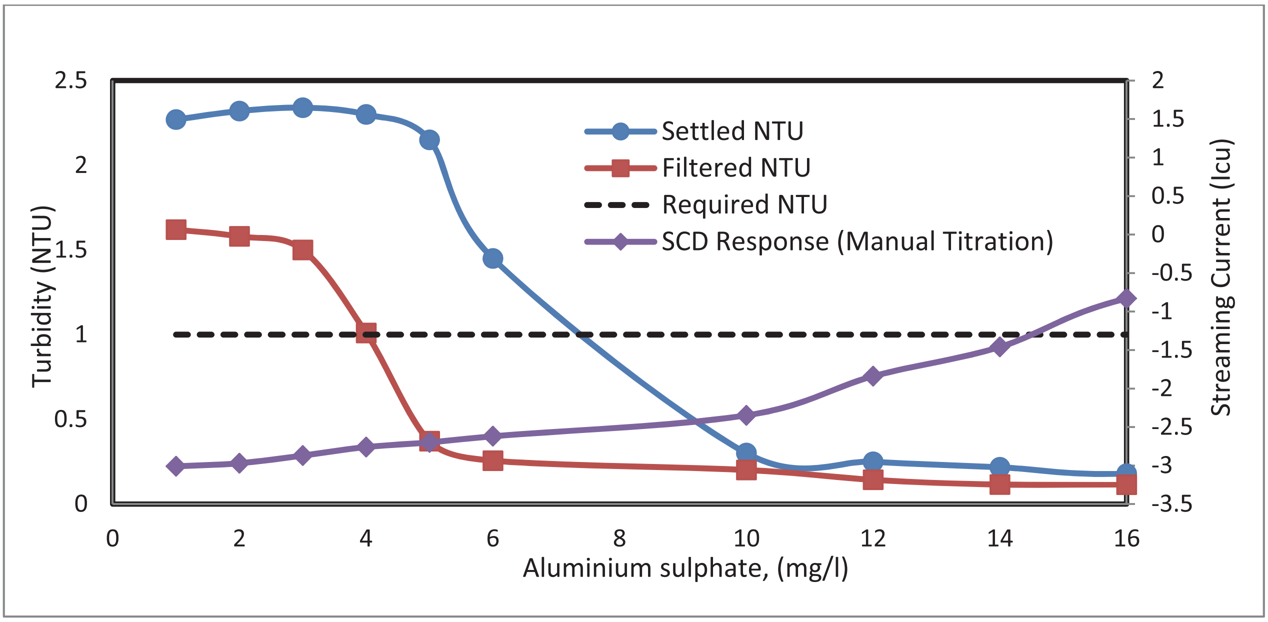


Figure 7.2: Relationship between aluminium sulphate dose and SCD response for Midmar raw water

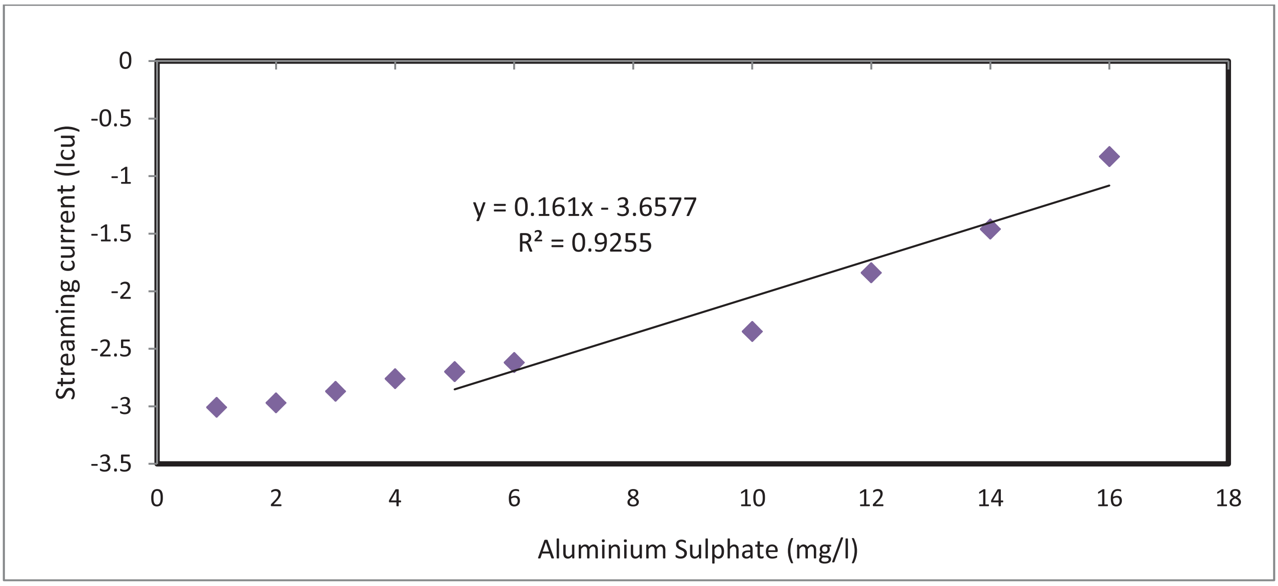


Figure 7.3: SCD response to increasing inorganic coagulant (alum) doses for Midmar raw water

Figure 7.2 illustrates the behaviour of the SCD as the dosage of the inorganic coagulant (alum) is increased from 0 to 16 mg/L. It can be seen that the optimum alum dose range was between 4 mg/L and 8 mg/L alum based on filtered turbidity and between 8 and 12 mg/L based on clarifier overflow turbidity. The SCD response over this optimum range had a coefficient of determination R^2 of 0.9255.

The pH of the solution during coagulation dropped from 6.8 to 6.5 which were within the optimal operating pH range for alum of 6–7.

7.2.1.2 Polyelectrolyte coagulant treatment of Midmar dam raw water

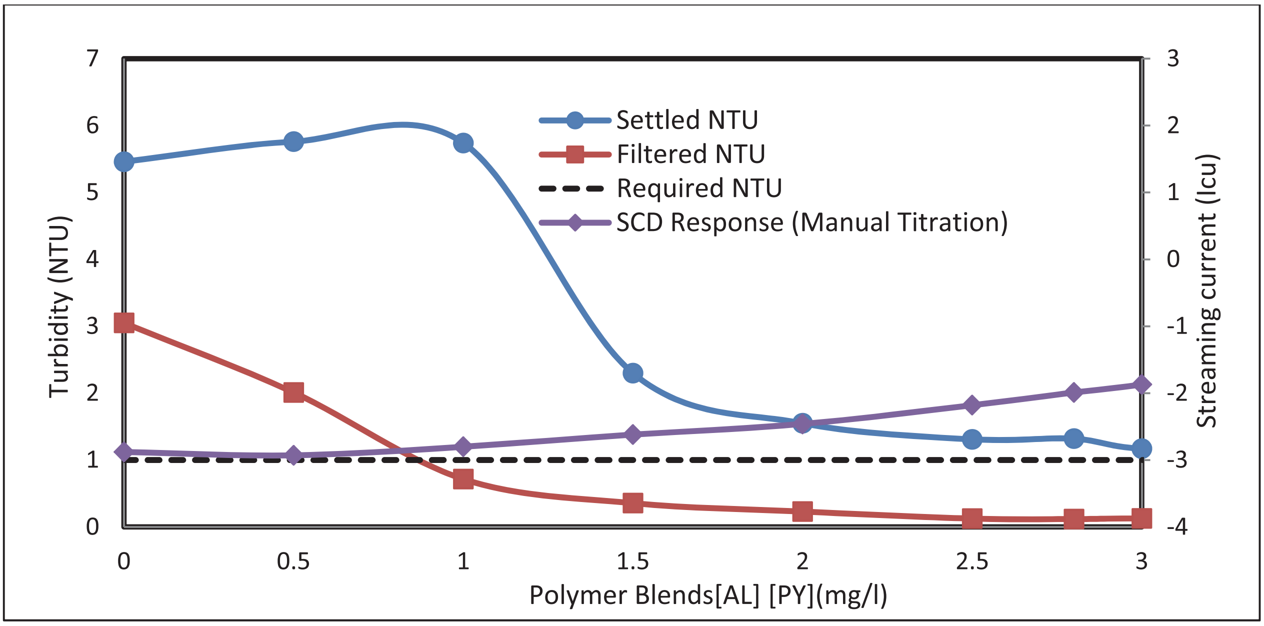


Figure 7.4: Relationship between coagulant dose and SCD response for Midmar raw water

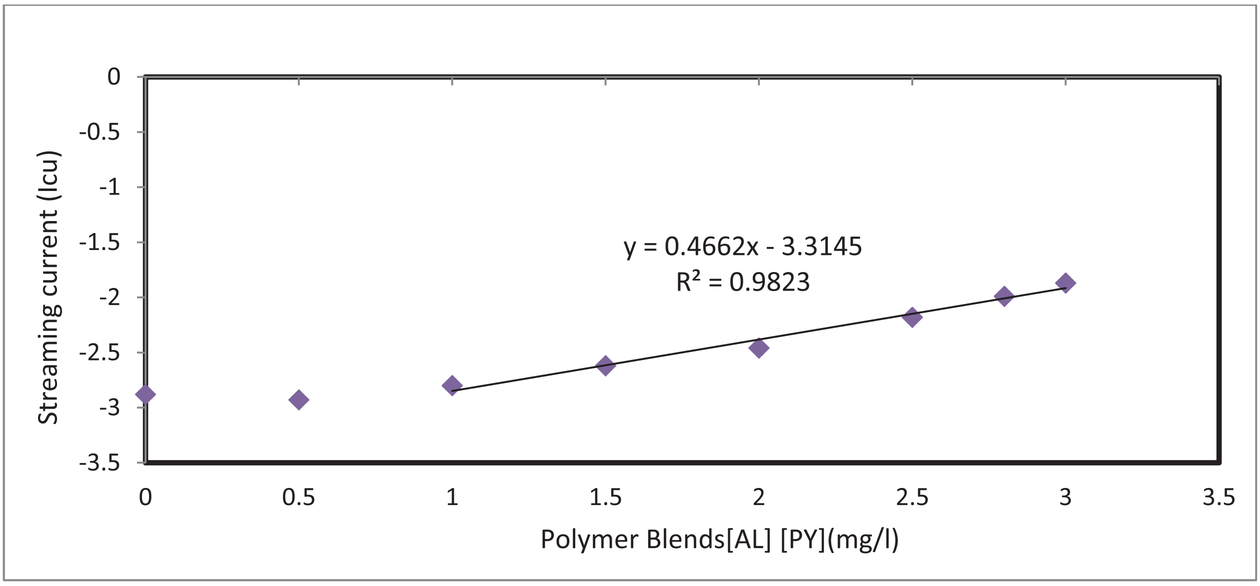


Figure 7.5: SCD response to increasing coagulant doses for Midmar raw water

Figure 7.4 illustrates the behaviour of the SCD as the concentration of polymeric coagulant is increased from 0 to 3 mg/L. It can be seen that the optimum range was 1.5 mg/L, where a settled turbidity of <5 NTU was reached. The SCD response over this coagulant dose range had a coefficient of determination R^2 = 0.9823. The plant optimum dose of 2.1 mg/L falls within the linear range, as seen in Figure 7.5.

7.2.2 Raw water with turbidity of between 10 and 100 NTU

To illustrate the behaviour of the streaming current detector in raw water with a turbidity of above 10 NTU but below 100 NTU, raw water from Amatola Water's Binfield Water Treatment Plant in the Eastern Cape was used. The abstraction source for Binfield WTP is the Binfield Dam. The raw water is treated using conventional water treatment processes that include coagulation, clarification, filtration and disinfection.

Table 7-2: Binfield WTP raw water parameters

Parameter	Value
pH	6.92
Turbidity (NTU)	21.35
Plant optimum coagulant dose (mg/L)	3
Initial ion charge (raw water)	-2.82

7.2.2.1 Inorganic coagulant treatment of Binfield WTP raw water

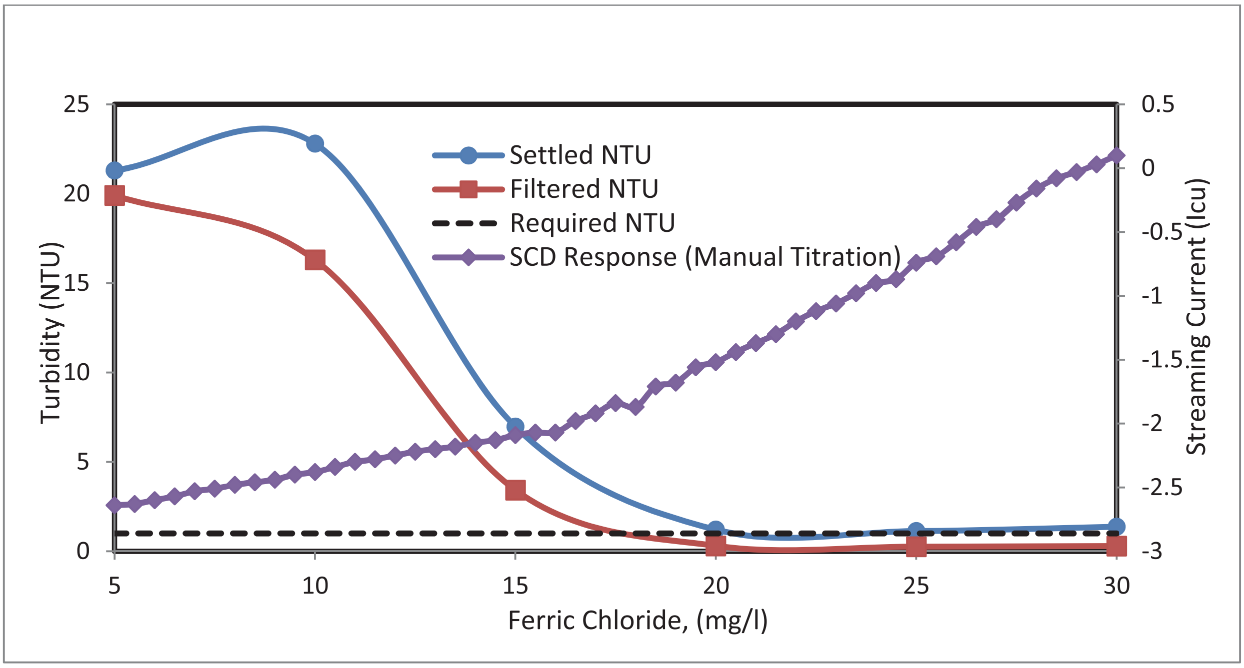


Figure 7.6: Relationship between ferric chloride dose and SCD response for Binfield raw water

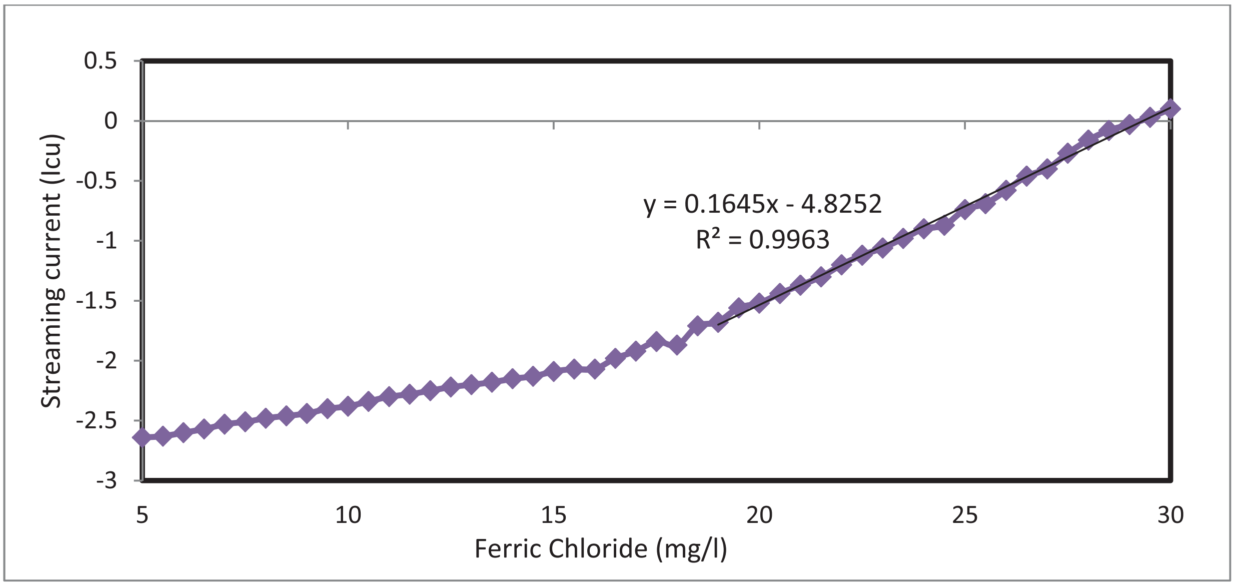


Figure 7.7: SCD Response to increasing coagulant doses for Binfield raw water

Figure 7.6 illustrates the behaviour of the SCD as the concentration of ferric chloride is increased from 5 to 30 mg/L. The optimum coagulant dose range for turbidity complying with the SANS 241:2015 limit was obtained between 20 and 30 mg/L. The pH during coagulation went from 6.21–5.70 which is within the optimal pH range of 5.5–6.5 for ferric chloride.

From Figure 7.7 it can be seen that the SCD response to dosage had a coefficient of determination R^2 of 0.9963 between 20 and 30 mg/L which overlaps with the optimum coagulant dosage.

7.2.2.2 Polymeric organic coagulant treatment of Binfield WTP raw water

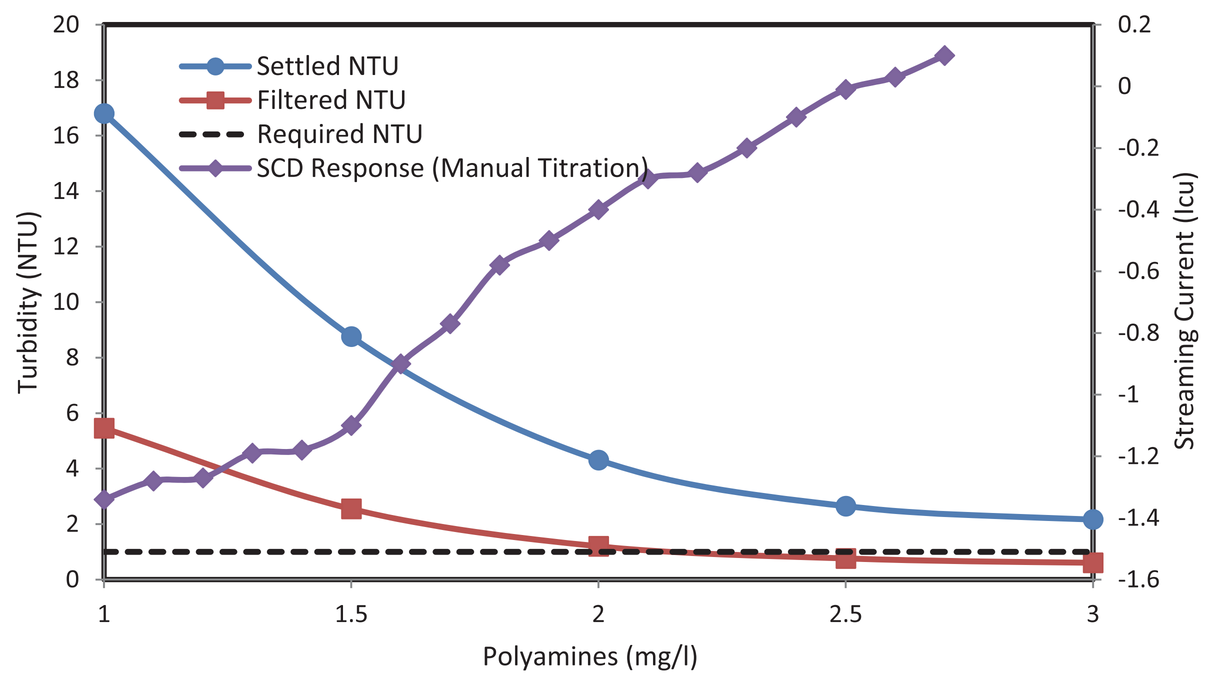


Figure 7.8: polymeric organic coagulant dose and SCD response for Binfield raw water

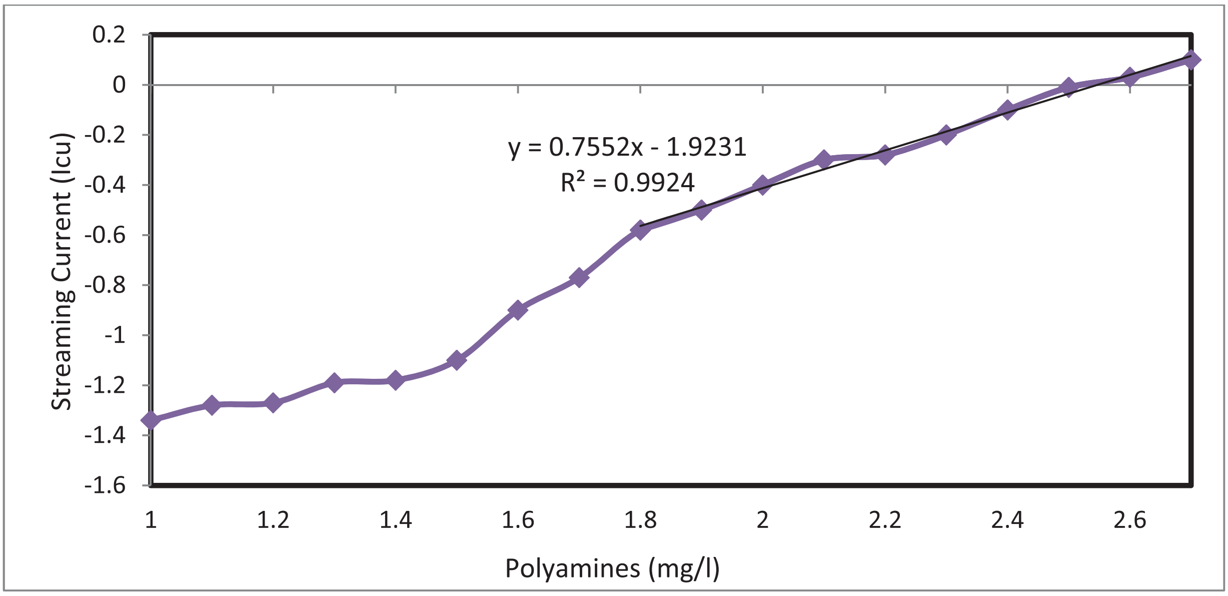


Figure 7.9: SCD Response to increasing polymeric organic coagulant doses for Binfield raw water

Figure 7.8 illustrates the behaviour of the SCD as the concentration of the polymeric coagulant dose is increased from 1 to 2.7 mg/L. It can be seen that the optimum range was found to be above 2.2 mg/L, where the SANS 241:2015 limit was reached. This is in line with the actual optimal coagulant dose for the plant. Figure 7.9 shows that the SCD/dosage relationship had a coefficient of determination R^2 of 0.9924 between 1.8 and 2.7 mg/L which overlaps with the optimum coagulant dosage.

7.2.3 Raw water with turbidity above 100 NTU

To illustrate the behaviour of the streaming current detector in raw water with a turbidity of above 100 NTU, raw water from Amatola Water's Nahoon Water Treatment Plant in the Eastern Cape was used. The abstraction source for Nahoon WTP is the Nahoon River. It uses dissolved air flotation for clarification.

Table 7-3: Nahoon WTP raw water parameters

Parameter	Value
pH	7.38
Turbidity (NTU)	135
Plant optimal coagulant dose (mg/L)	15
Initial ion charge (raw water)	-2.52

7.2.3.1 Inorganic coagulant treatment of Nahoon WTP raw water

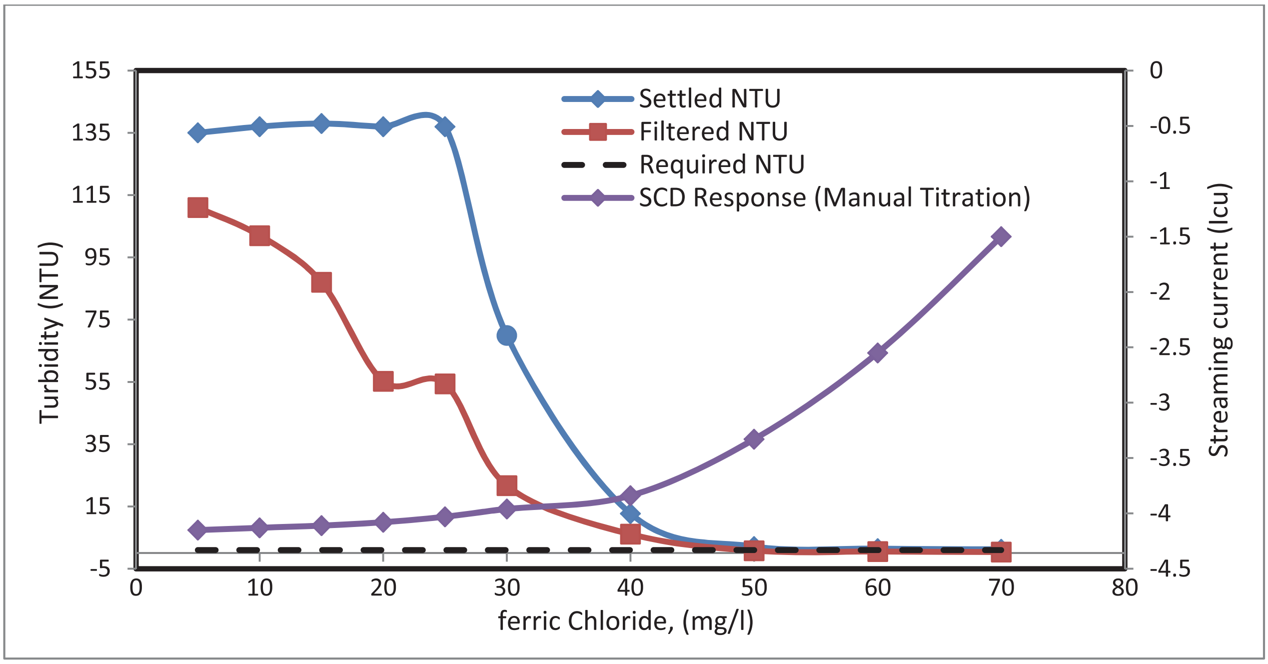


Figure 7.10: Relationship between inorganic coagulant dose and SCD response for Nahoon raw water

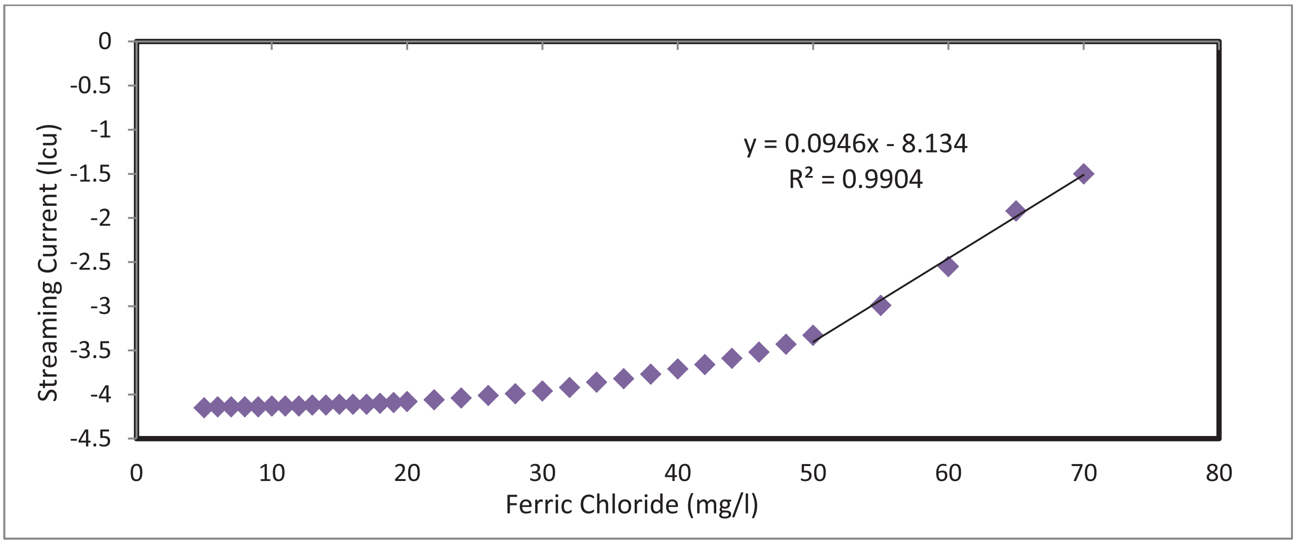


Figure 7.11: SCD Response to increasing coagulant (ferric chloride) doses for Nahoon raw water

Figure 7.10 illustrates the behaviour of the SCD as the concentration of the mineral salt coagulant is increased from 5 to 70 mg/L. It shows that the optimum coagulant dose range to achieve a turbidity of <1 NTU was obtained between 50 and 70 mg/L. From Figure 7.11 it can be seen that the SCD/dose curve had an R^2 coefficient of determination of 0.9904 between 50 and 70 mg/L which corresponds with the optimum coagulant dosage range. The pH during coagulation decreased from 6.98 to 6.51.

7.2.3.2 Polymeric organic coagulant treatment of Nahoon WTP raw water

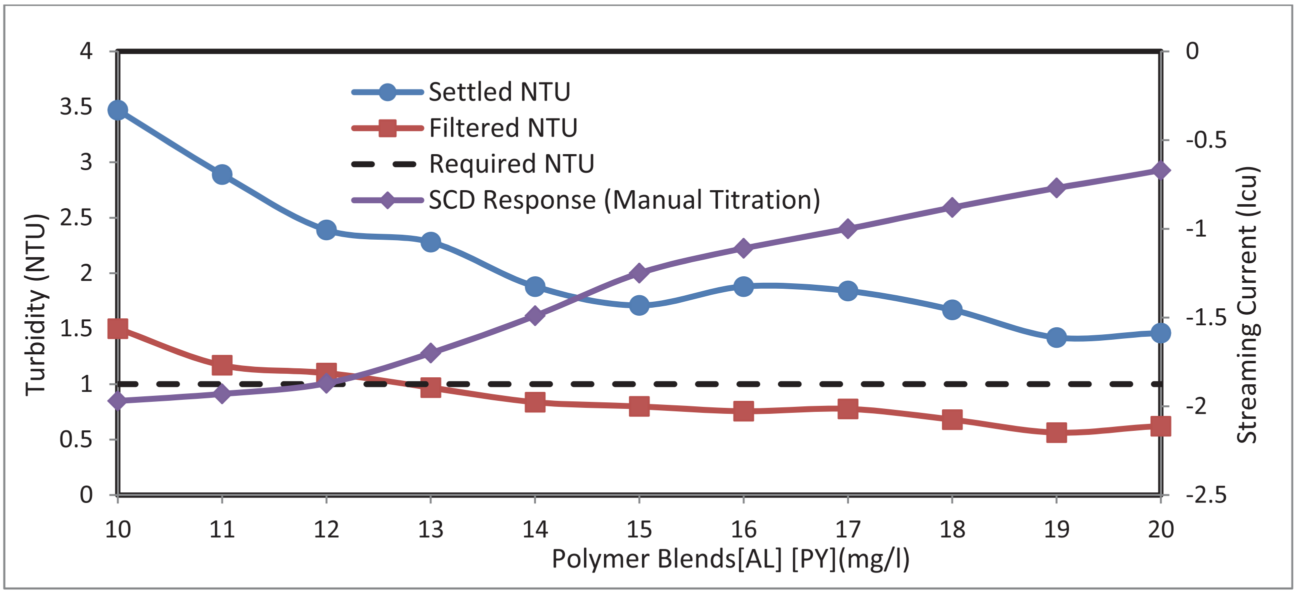


Figure 7.12: Relationship between coagulant dose and SCD response for Nahoon raw water

Figure 7.12 illustrates the behaviour of SCD as the concentration of polymeric organic coagulant dose is increased from 10 to 20 mg/L. The SCD response curve shows that the ion charge value increased with increased coagulant dosage. The SCD shows an insignificant response to coagulant additions at coagulant dosages below 12 mg/L. This was due to the high turbidity of the raw water.

Figure 7.12 illustrates that the optimum coagulant dose range complying with the SANS 241:2015 limit was obtained between 13 and 15 mg/L. The SCD response had an R^2 coefficient of determination of 0.9914 between 12 and 15 mg/L which overlaps with the optimum coagulant dosage. Automatic dose control is recommended as the continuously decreasing graphs indicate that overdosing could occur and go unnoticed.

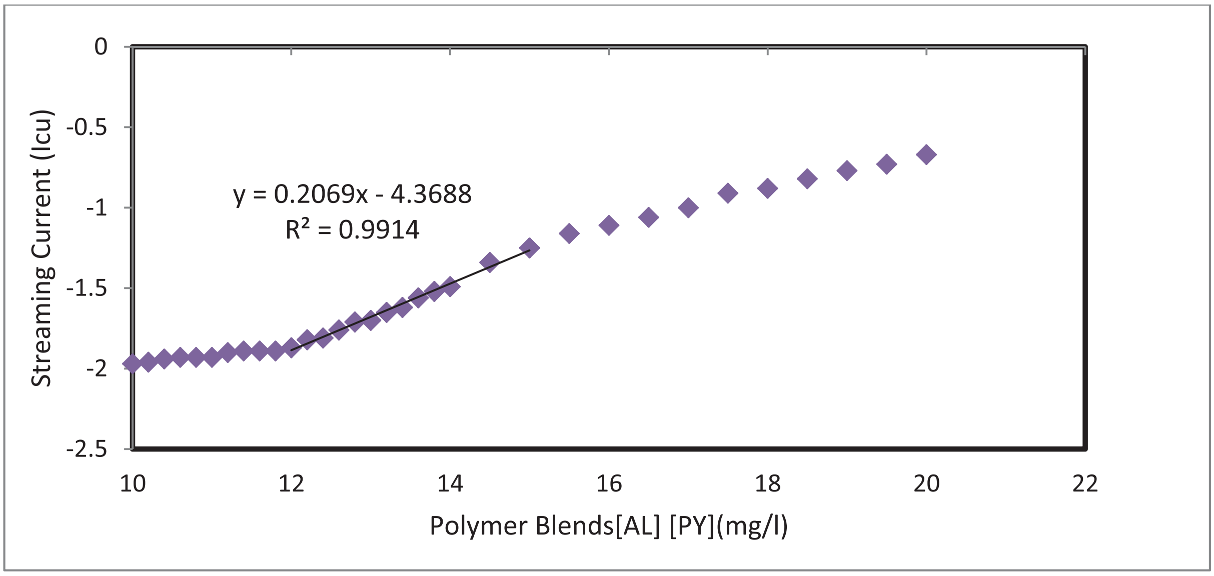


Figure 7.13: SCD Response to increasing coagulant doses for Nahoon raw water

7.2.4 Coloured water - water with colour values greater than 100 Pt-Co units

Raw water was obtained from Faure Water Treatment Plant in the Western Cape. Faure WTP has two raw water sources: Riversonderend (RSE) and Palmiet River. The Palmiet River water has high colour due to humic and fulvic acids, as compared to Riversonderend. This WTP uses conventional water treatment processes that include coagulation, flocculation, sedimentation, filtration and disinfection.

Table 5 presents the raw water sample parameters. The colour of the sample was not high since the SANS 241:2015 standard requires a potable water colour of ≤15 Pt-Co units and the raw water sample had a colour of 9.2 Pt-Co units. This is because the sample was taken when the Riversonderend abstraction point was being used as the raw water source.

Table 7-4: Faure WTP raw water parameters

Parameter	Value
pH	6.25
Turbidity (NTU)	17
Plant optimum coagulant dose (mg/L)	4.47
Initial ion charge (raw water)	-4.50
Colour (Pt-Co units)	9.20

7.2.4.1 Inorganic coagulant treatment of Faure WTP raw water

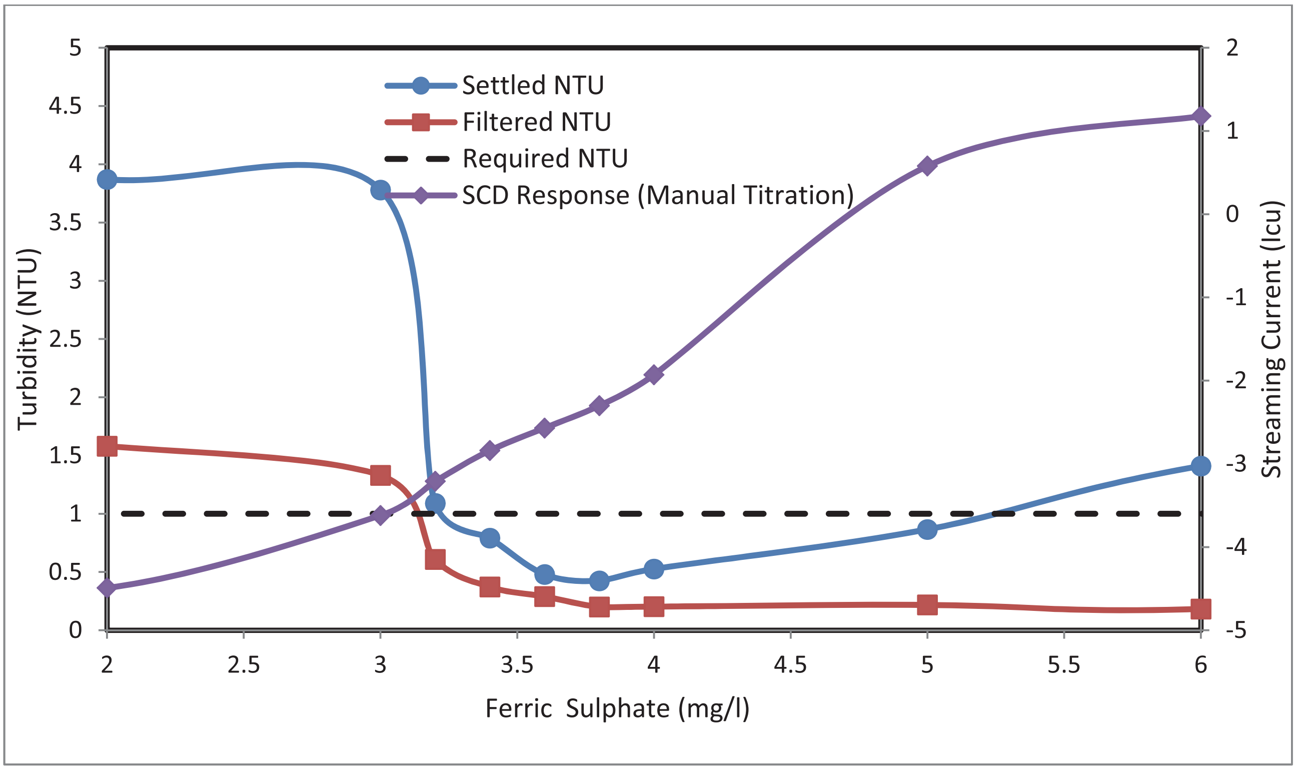


Figure 7.14: Relationship between coagulant dose and SCD response for Faure raw water

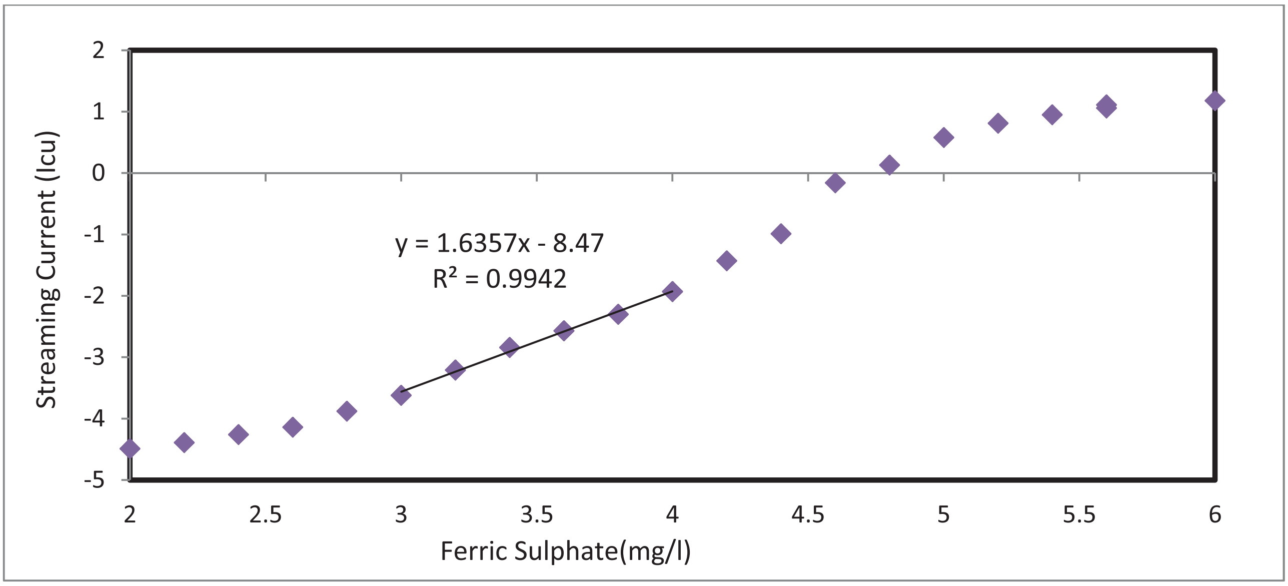


Figure 7.15: SCD response to increasing coagulant (ferric sulphate) doses for Faure raw water

Figure 7.14 it can be seen that the optimum range was found to be between 3.2 mg/L, where the SANS 241:2015 limit was reached, and 3.8 mg/L where the settled turbidity starts increasing again due to coagulant overdose. Figure 7.15 shows that the SCD response had an R^2 coefficient of determination of 0.9942 between 3 and 4 mg/L which overlaps with the optimum coagulant dosage.

7.2.4.2 Polymeric organic coagulant treatment of Faure WTP raw water

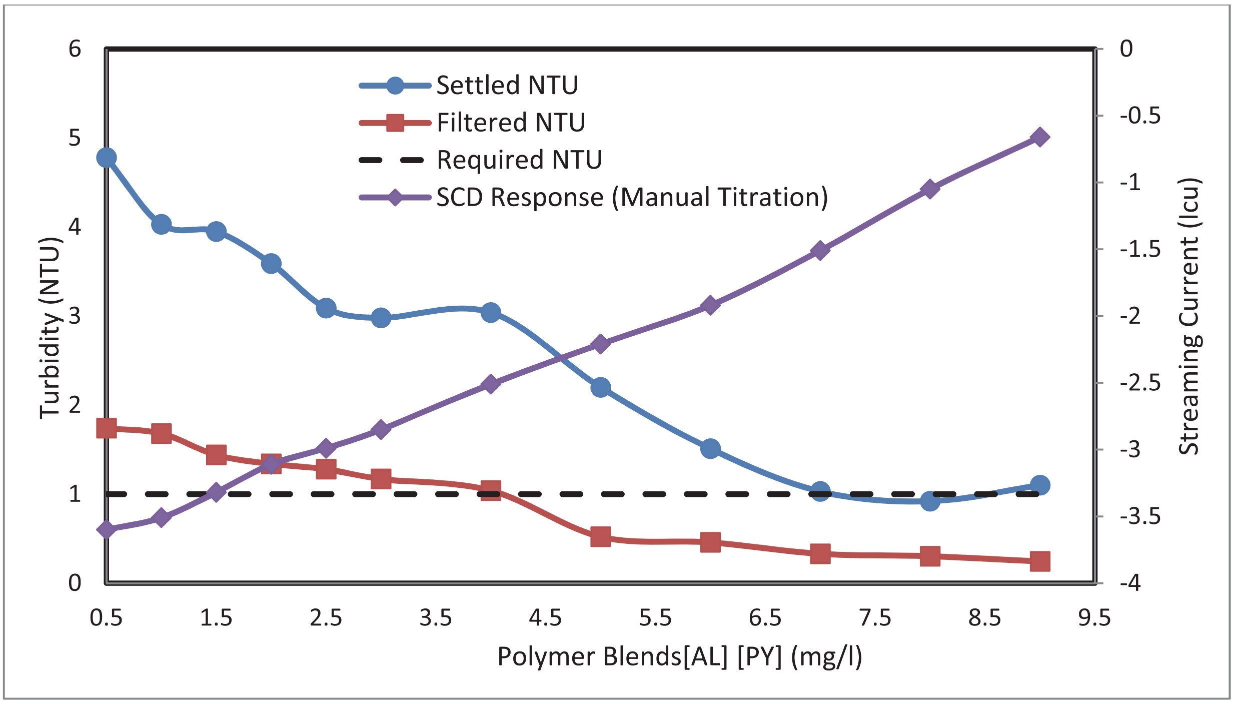


Figure 7.16: Relationship between coagulant dose and SCD response for Faure raw water

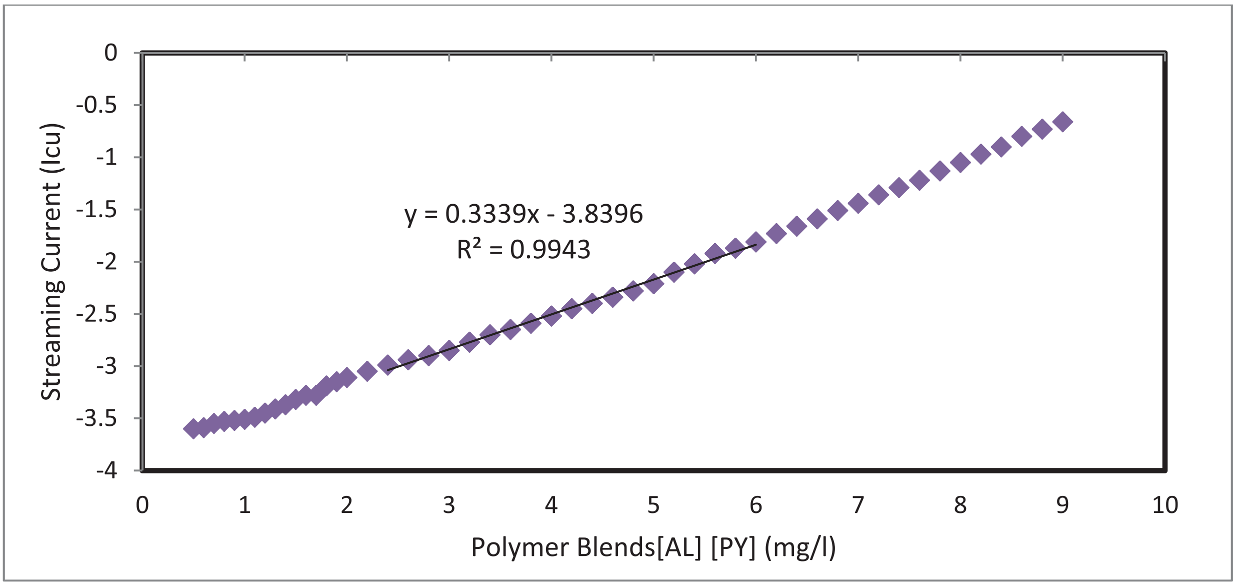


Figure 7.17: SCD response to increasing polymeric organic coagulant doses for Faure raw

Figure 7.16 illustrates the behaviour of SCD as the concentration of an organic coagulant is increased from 0.5 to 9 mg/L. The SCD response curve shows that the ion charge is positively correlated with coagulant dosage with an R^2 coefficient of determination of 0.9943. The optimum range was found to be between 5 mg/L, where SANS 241:2015 limit was reached and 8 mg/L where the settled turbidity starts increasing again due to coagulant overdose. The optimum coagulant dose was obtained within the linear region of the SCD response curve. During coagulation the pH decreased from 6.23– 5.89.

7.2.5 The effect of pretreatment on SCD response (turbidity below 10 NTU)

This set of tests was conducted to determine the effect of pretreatment chemicals on SCD stability. For the purpose of this study, low turbidity water from Umgeni Water's Midmar Water Treatment Plant was used; this plant has a capacity of 250 MLD. Raw water is abstracted from Midmar Dam and pre-treated with chlorine gas and bentonite. This WTP uses conventional water treatment processes that include pre-chlorination, coagulation, clarification, filtration and disinfection.

Coagulation is undertaken with a polymeric coagulant dosed before an in-line static mixer, after which lime is added prior to the coagulated water entering four Superpulsator® type clarifiers.

Table 7-5: Midmar WTP raw water parameters

Parameter	Value
pH	6.88
Turbidity (NTU)	2.5
Plant optimum coagulant dose (mg/L)	2
Initial ion charge (raw water)	-2.84

Figure 7.18 shows the relationship between optimum coagulant dose and SCD response without pretreatment chemical addition while Figure 7.19 shows the relationship with pretreatment chemical addition. Figure 7.20 compares the SCD response curves with and without pretreatment chemical addition.

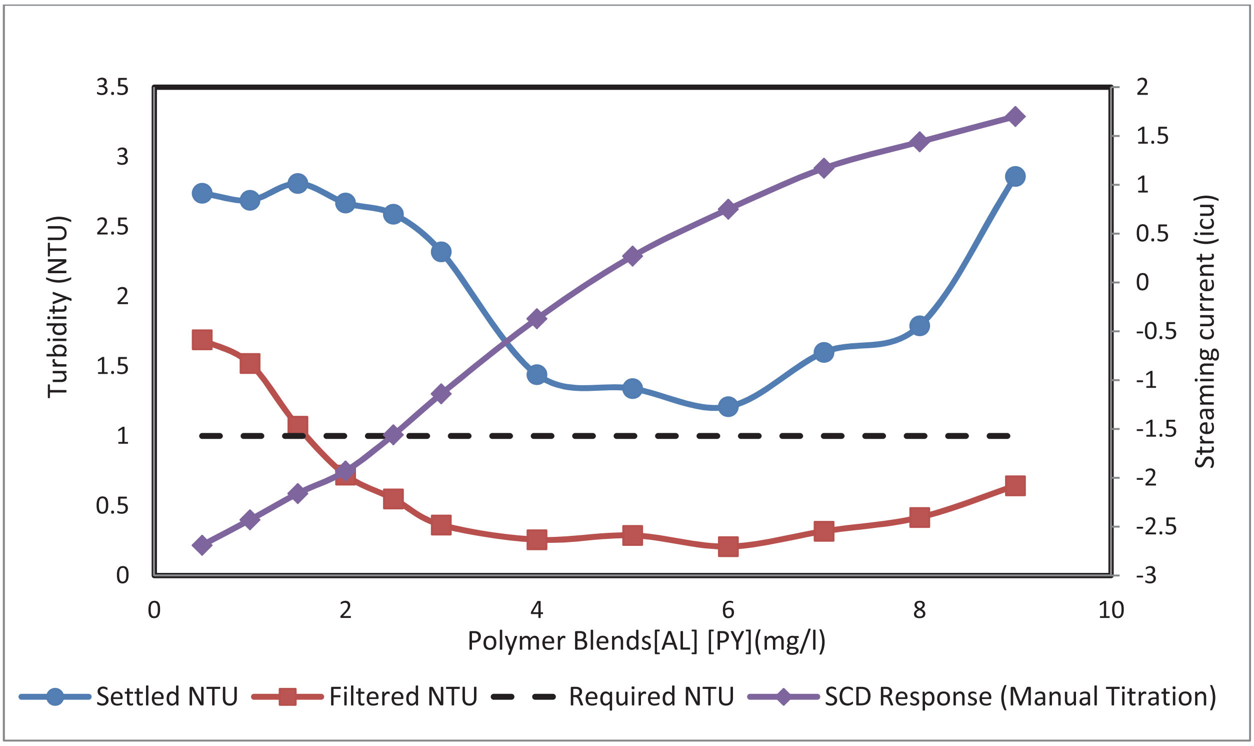


Figure 7.18: Relationship between coagulant dose and SCD response (without pretreatment)

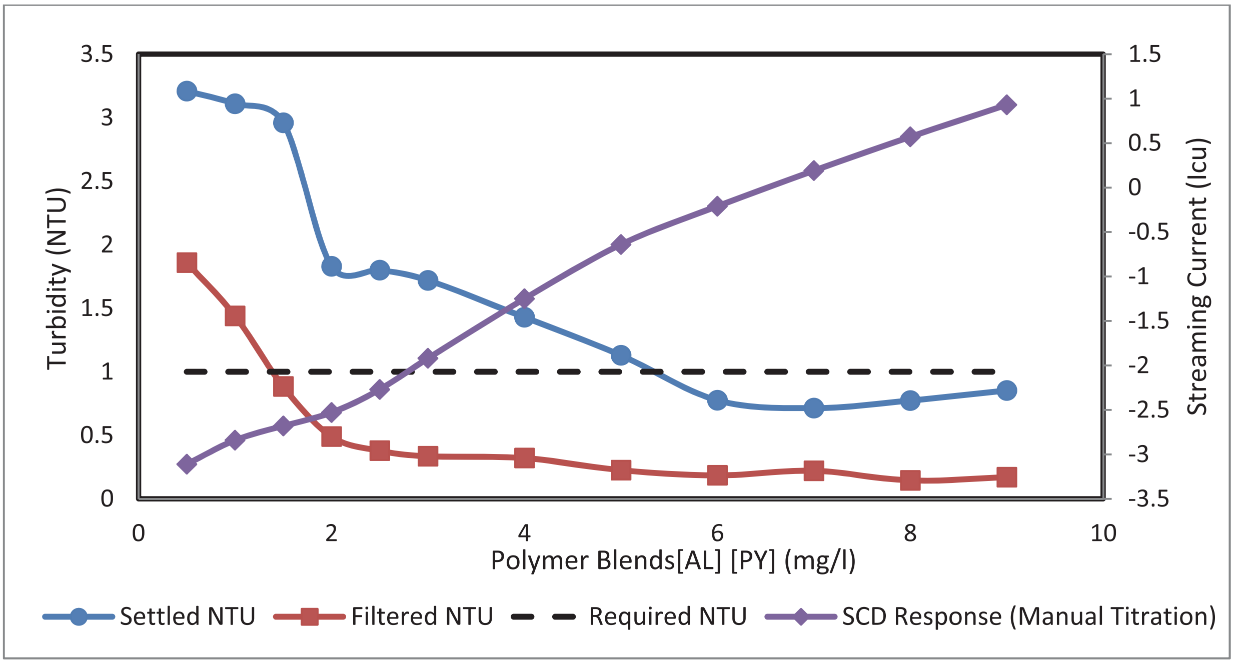


Figure 7.19: Relationship between polymeric organic coagulant dose and SCD (with pretreatment)

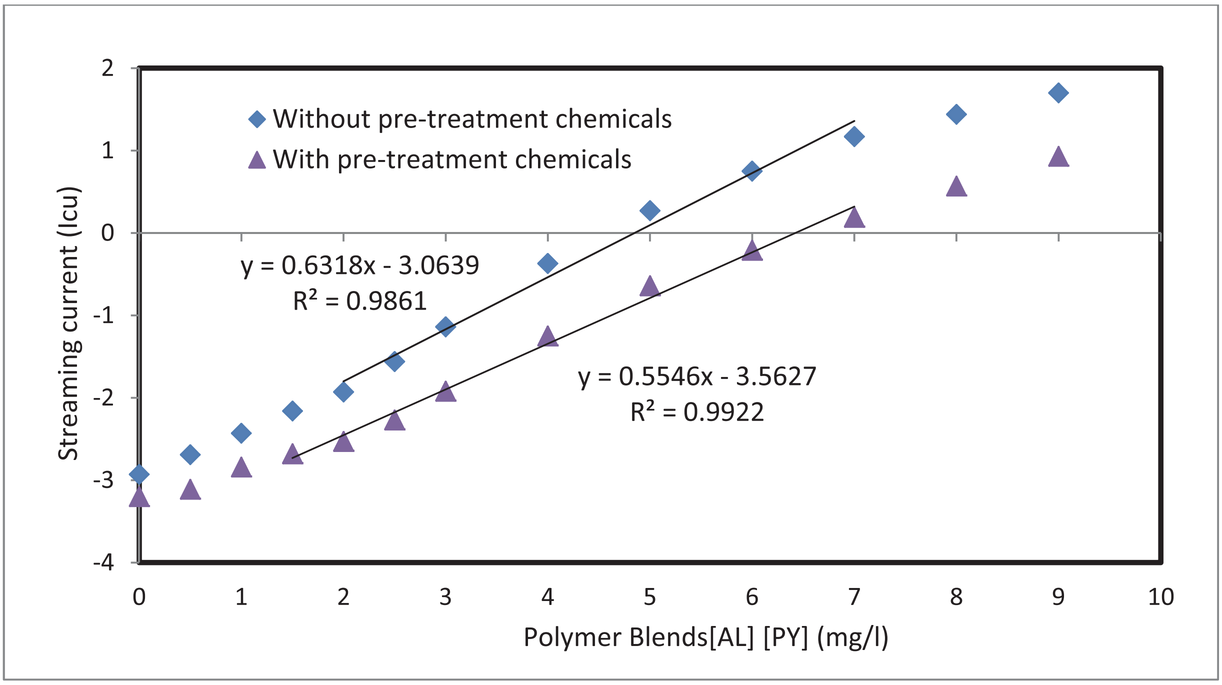


Figure 7.20: Graph comparing the linear section of the SCD responses

Comparing the two curves in Figure 7.20 it can be seen that the addition of the pretreatment chemicals improved the linearity of the SCD response curve from 0.9861 to 0.9922. This indicates the benefits of the pretreatment chemicals, especially bentonite for low turbidity applications.

7.3 LABORATORY FINDINGS

The SCD was found to be a suitable coagulant dose control system for all the raw water tested during the laboratory investigations. The titrations showed that SCD analyses was stable around the required chemical dosage and would be suitable for testing controllability on a large scale.

It was noted that as the turbidity of the raw water increased, the optimum coagulant dose was within the linear range of the SCD response to coagulant dose relationship (with R^2 >0.96). This indicates that the SCD would respond well to raw water quality changes and successfully control dosing.

For raw water with turbidity of less than 10 NTU, the optimum coagulant dose was still within the linear region of the SCD response to coagulant dose relationship; however the R^2 correlation was <0.95, This would imply that the SCD would not control raw water changes for low turbidity raw water as well as it would control dosing for higher turbidity raw water.

The SCD response to the inorganic coagulants was similar to that of the polymeric coagulants. The plant operations were mimicked; therefore the pH of the water being treated was not controlled. The SCD response was still stable within the optimum dose range.

7.4 PILOT TESTING METHODOLOGY

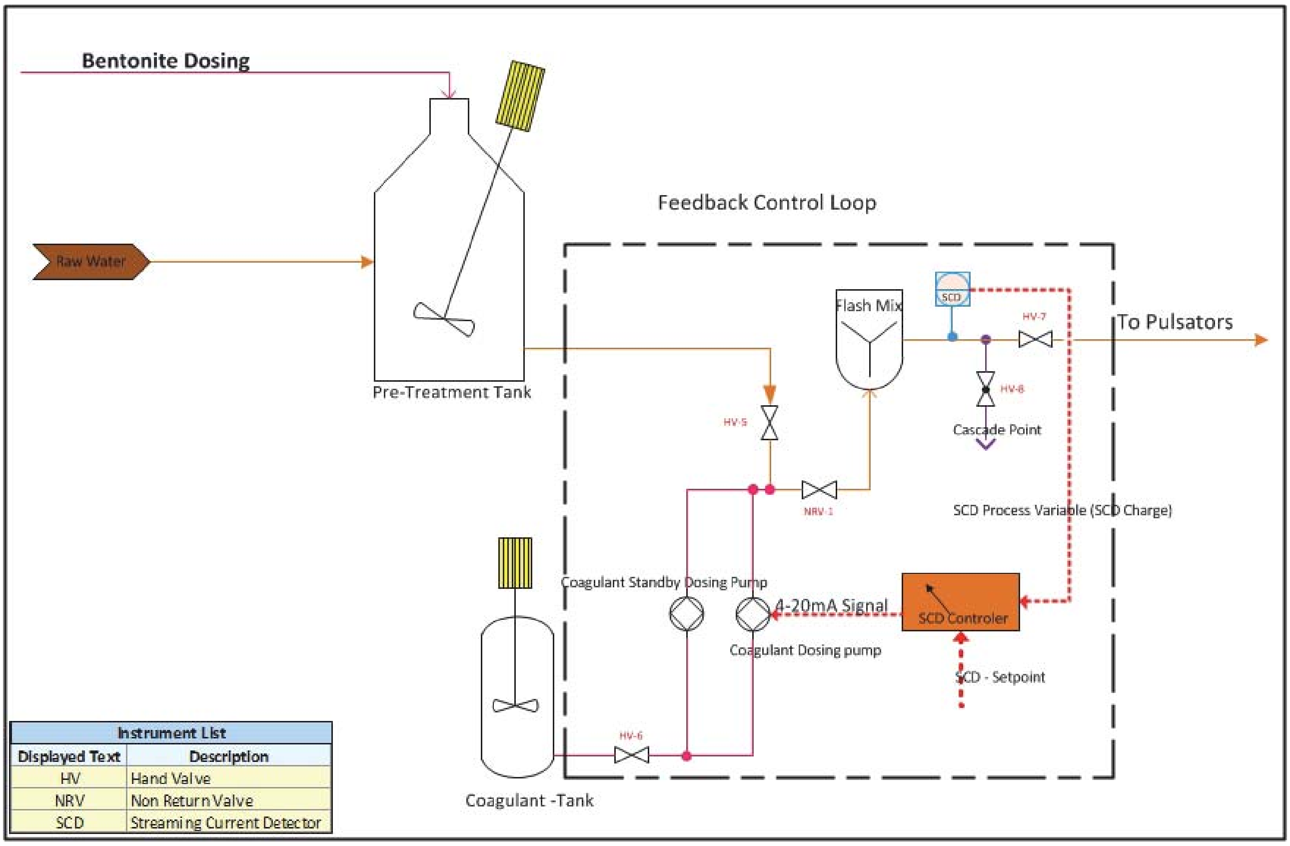
The main purpose for scaling up the evaluation from the laboratory scale to the pilot-plant stage was to understand the automatic control philosophy and to test the accuracy of the control loop in maintaining the correct coagulant dosage and final water quality. The SCD performed well in the laboratory tests proving that it could effectively monitor a wide range of raw waters with varying raw water characteristics. The water treatment evaluation unit (WTEU) pilot plant was again used for this part of the investigation. Due to its location at Umgeni Water's Wiggins Water Treatment Plant site, only low turbidity raw water was available for testing.

The WTEU is a semi-automatic PLC controlled conventional water treatment pilot plant with a 5 m^3/h capacity. A supervisory control and data acquisition (SCADA) system logged the raw water turbidity, the settled turbidity, the filtered water turbidity, the coagulant dose, and the SCD readings against time.

The pilot plant optimization was similar to that used in a full-scale water treatment plants. Optimum coagulant doses were determined from jar tests and applied to the pilot plant operated in manual mode. After making adjustments on the pilot plant to further optimise the coagulant dose, the plant was allowed to operate until it reached steady state. The SCD value at optimum process operating conditions for the desired filtered water/clarified water overflow turbidity was noted and used as the set point (SP) for the coagulant dosing control loop. The coagulant dosing system was then switched from manual mode to automatic dose control.

The total reaction time for a coagulant dose change to be effected was between 3 and 5 minutes. The residence time of the flash mixing tank was 2 minutes at the operating flow rate of 2.8 m^3/h. This implies that the SCD took 1 to 3 minutes to adjust the coagulant dose.

The diagram for the WTEU pilot plant, highlighting the automatic coagulant dosing system control loop, is presented in Figure 7.21. The SCD sampling port receives coagulated water and measures the SCD process variable (PV).



Instrument List

Displayed Text	Description
HV	Hand Valve
NRV	Non Return Valve
SCD	Streaming Current Detector

Figure 7.21: Feedback control loop based on properties of coagulated water

The SCD is continuously fed with a sample of the coagulated water shortly after rapid mixing whereby the charge on the sample is read by the SCD. This charge is the process variable which is sent to the controller and compared with the set point on the SCADA. An algorithm is used to calculate the resultant signal or output which is sent to the dosing pump.

7.5 PILOT TESTING RESULTS

From Figure 7.22 and 7.23, it can be deduced that for situations where the raw water turbidity is fairly constant, the SCD may not be required and the coagulant dosing system may be operated in manual mode with proportional control relative to the raw water flow rate. Figure 7.22 indicates that it is possible for coagulant to be under-dosed or overdosed, while the dosing pump flow rate changes, constantly responding to slight variations in the SCD process value relative to the set point.

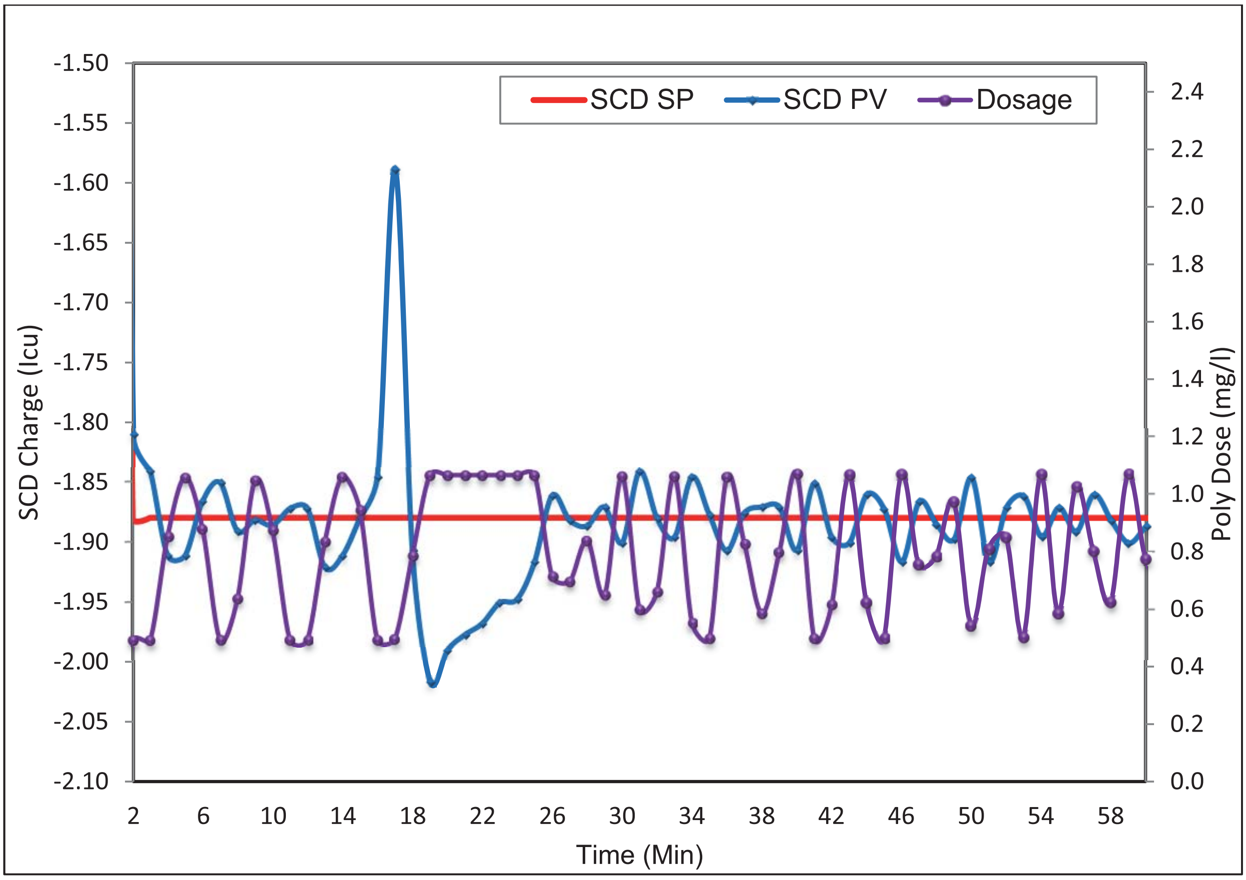


Figure 7.22: SCD and pump response relationship

From Figure 7.22 it can be seen that SCD control at low turbidity is energy intensive as the pump stroke frequency vary rapidly. The optimum coagulant dose was, however, maintained. Investigations into more efficient SCD control techniques were undertaken to reduce the large variation in pump stroke length.

The WTEU is modelled on the Wiggins Water Treatment Plant which is fine-tuned for the proportional integral derivative control. This fine-tuning is achieved by noting the plant’s steady state charge value and then increasing the pump output by 10%. Once this is done the time to reach a new stabilised charge is measured. These values are then used to calculate the proportional band and the integral time settings for the controller parameters. This control regime produces the results shown in Figure 7.23. The SCD PV is less variable and closely follows the set point; however, the pump dosing is variable.

At Wiggins Water Treatment Plant the quality of the final water and the cascade test results assist the plant personnel in deciding on when to change the calcium set point (ICa). When the final water turbidity gives an out-of-range value (NTU above 0.2 NTU), the jar test is performed to determine the new set point. However, because the jar test is performed once per 8-hour shift, results can only be observed at a later stage when the final water quality may have already been compromised.

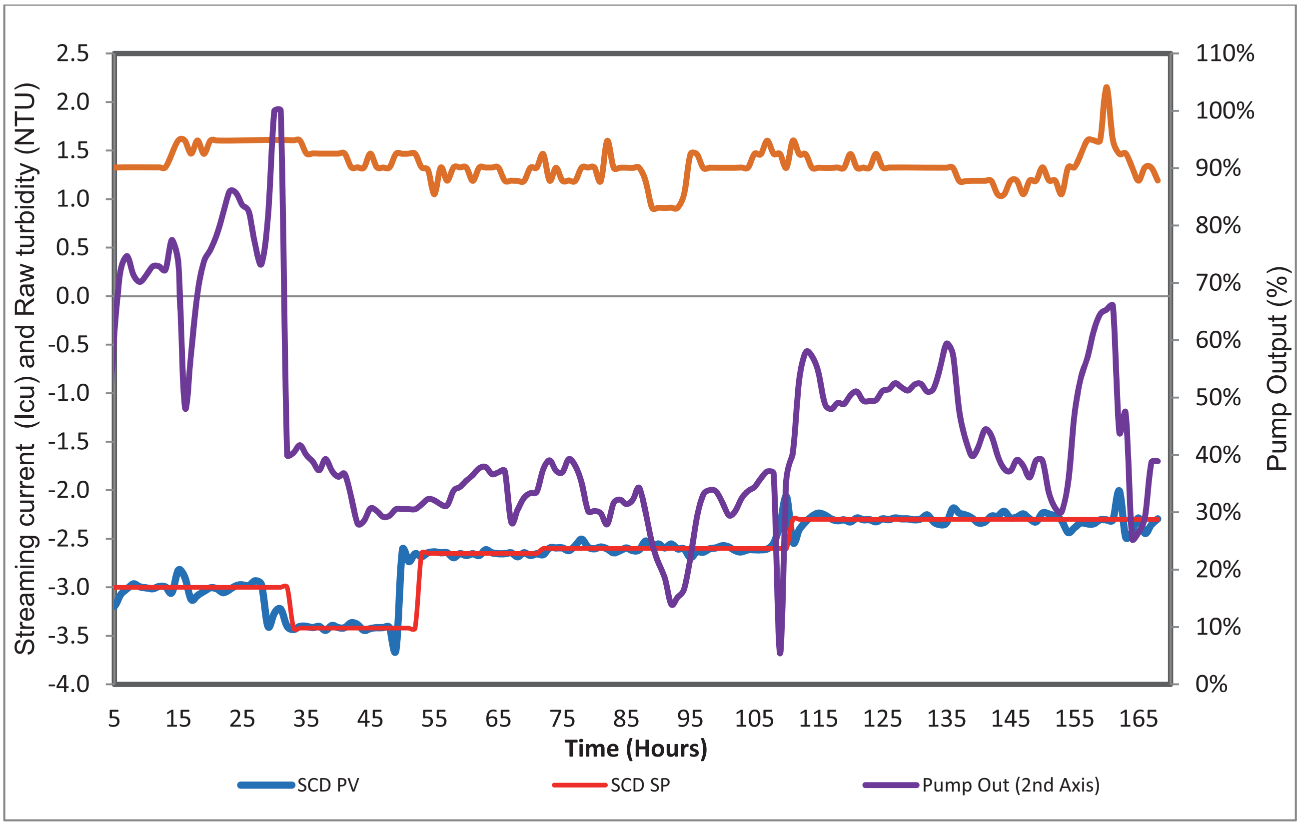


Figure 7.23: SCD response to Wiggins WTP raw water

The advantage of using the SCD is that a drift in the PV from the set point for a short period alarms the plant personnel to attend to the SCD to take corrective action timeously. This is observed in Figure 7.23 during the 29th and the 50th hours. An experienced process controller may change the SCD set point appropriately. This automatically alters the dosage.

Changing an SCD set point without following the normal jar test procedure for coagulant dose optimization is done if there is an eminent risk that the final water quality will deteriorate. Otherwise a jar test must be conducted to determine the appropriate dosage followed by the normal automatic dose optimization procedure.

Figure 7.23 shows the Wiggins Water treatment plant automatic SCD control trend that clearly demonstrates the need for a change in SCD set point for accurate SCD control. The raw water turbidity was fairly constant (ranging from 1.3 to 1.6 NTU). The dosing pump was operating at variable dosing rates for constant turbidity water. This can result from poor loop tuning practices such as a high gains that respond to small changes in coagulated water charge.

The plant was operated in manual mode for the first 4 hours and switched to auto control on the 5th hour and the SCD process variable was controlled towards the set point until the 29th hour. At hour 29 the PV was below set point and to ensure that PV≈SP, the coagulant dosing rate was increased. The dosing pump was then operated at maximum dosing capacity for 3 hours in order to increase the dosing rate; however, the PV could not reach the SP, signalling that the operator had to change the set point. Lowering the set point resulted in a more controllable loop where the coagulant dosing pump was operating at 25% capacity and the PV≈SP.

A quick verification of the laboratory tests was done at pilot scale to confirm SCD responses to incremental changes in coagulant dose (Figure 7.24).

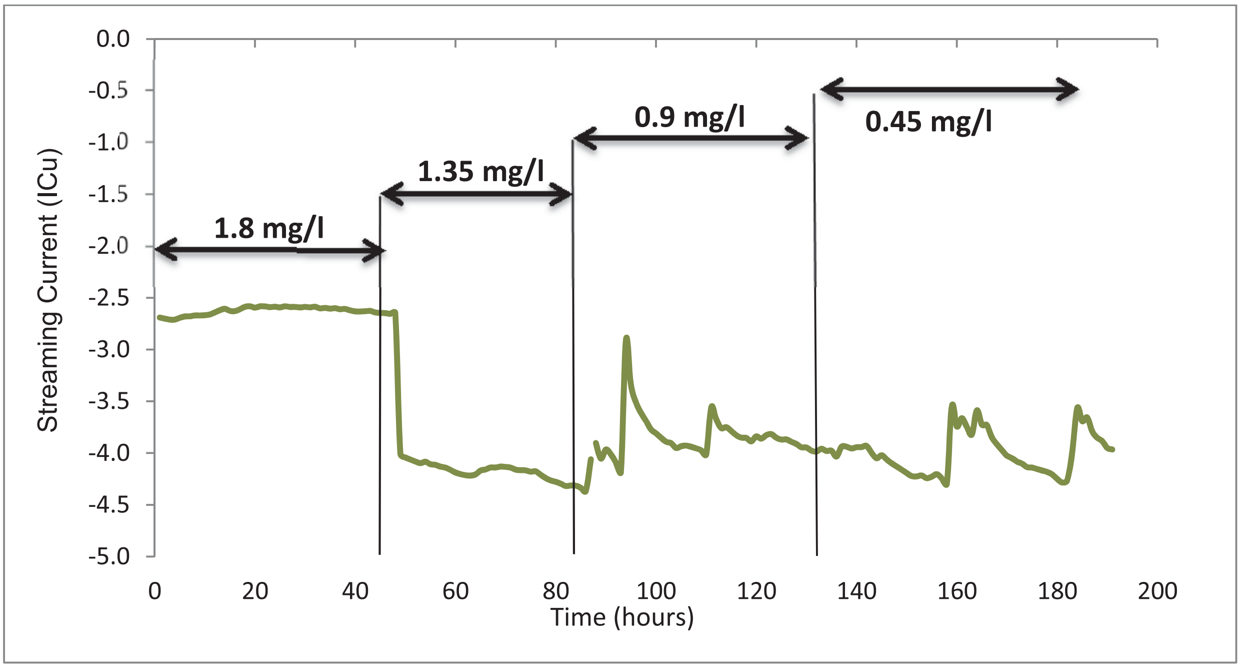


Figure 7.24: The effect of decreasing the coagulant dosage on SCD

Figure 7.24 illustrates a relatively steady reading of -2.63 at the optimum dose of 1.8 ppm. This is followed by a noticeable decrease as the polyelectrolyte dosage is reduced. This trend was expected as a decrease in the positively charged polymer dosage would result in a more negative SCD reading due to the lack of particle neutralisation. Further decreases in the dosage did not result in any further noticeable SCD variations as it stabilised at a charge of around -4 ICu. .

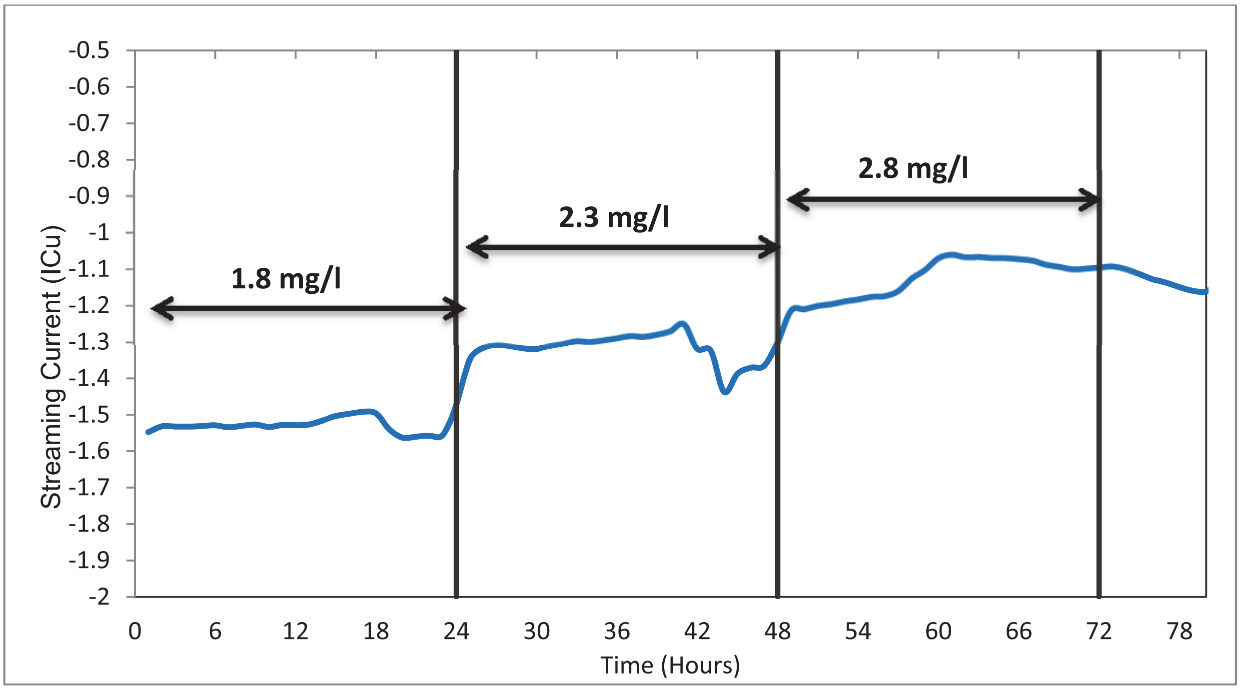


Figure 7.25: The effect of increasing the coagulant dosage on SCD

The effect of increasing the coagulant dose on the SCD follows a similar trend as decreasing the dosage, since the SCD responds until any further increase in the dosage does not cause any effect on the charge reaching saturation levels, as indicated in Figure 7.25.

7.6 FIELD RESULTS FROM HAZELMERE WATER TREATMENT PLANT

Umgeni Water’s Hazelmere Water Treatment Plant was originally built with a design capacity of 45 ML/d and abstracts water from the Hazelmere Dam, which is ±7 km away from the plant inlet. The plant was recently upgraded to increase the capacity to 75 ML/d in 2014. During the upgrade an automatic coagulant dosing control was installed using SCD as a control method. The treatment process consists of pre-chlorination, coagulation, flocculation, clarification, filtration and disinfection. The plant is equipped with bentonite dosing pumps; bentonite is used as a coagulant aid during periods of low water turbidity.

Hazelmere Water Treatment Plant is an example of using the SCD for automatic coagulant dose control in a relatively high raw water turbidity situation (30–40 NTU) compared to Wiggins Water Treatment Plant (<5 NTU). For manual coagulant dose control, the plant constantly optimises its polyelectrolyte (polymer blends) dosage based on the cascade test results, which is done once per shift. Jar tests are done once a week and whenever there is a sudden change in the raw water turbidity.

Automatic coagulant dose control by SCD is reverted to after the SCD set point is determined using the prescribed procedure.

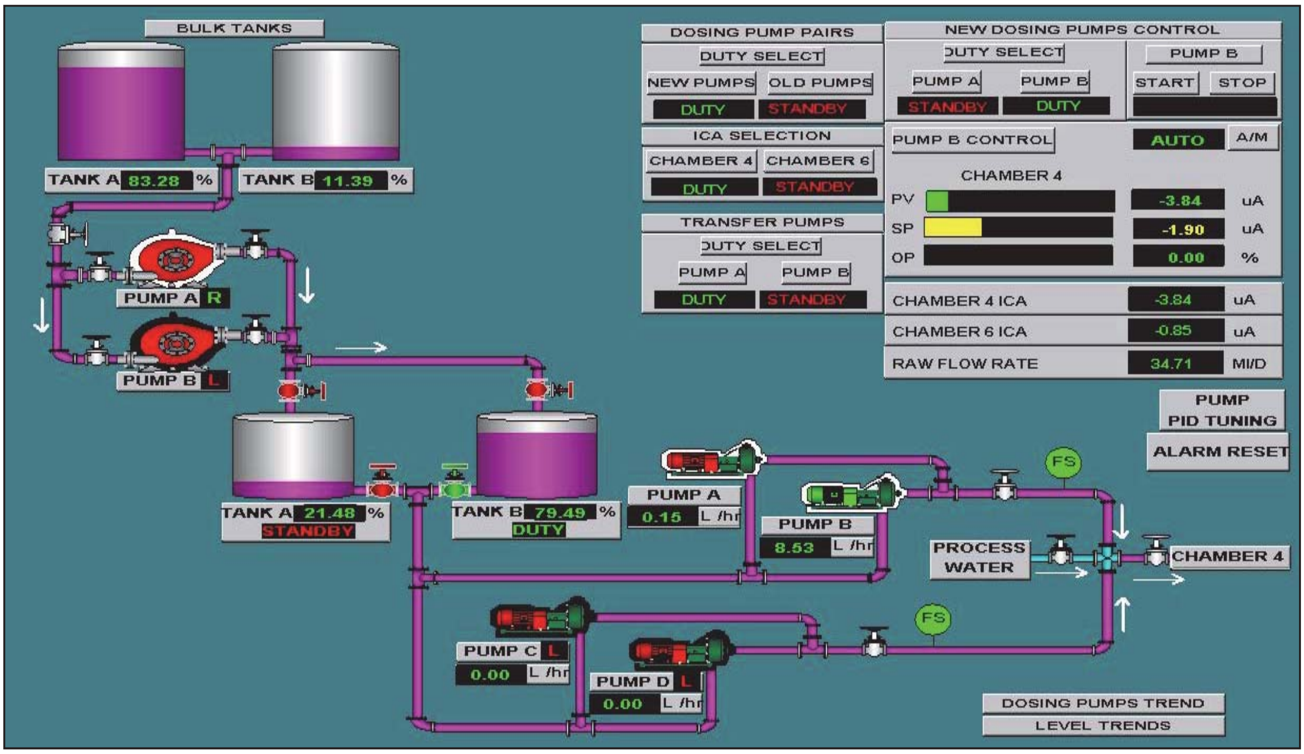


Figure 7.26: SCADA mimic of the Hazelmere WTP coagulant dosing

The plant was initially not operating in automatic mode, and the SCD was just used for monitoring. The reasoning from the plant operator was that the SCD had become fouled and needed cleaning. The fouling was caused because potassium permanganate was dosed as a pretreatment chemical and was affecting the operation of the SCD in automatic mode since it forms stains on the cell and the probe.

The SCD was then cleaned and the process was switched to automatic dosing. Figure 7.27 indicates that the control loop was poorly tuned as the process variable was not tracking the SCD set point, leading to coagulant overdosing.

A site drop test which was conducted by the process services (an independent department operating as process advisors) determined that the plant was dosing an average of 12 mg/L. The recommended dosage based on the jar tests was 8 mg/L.

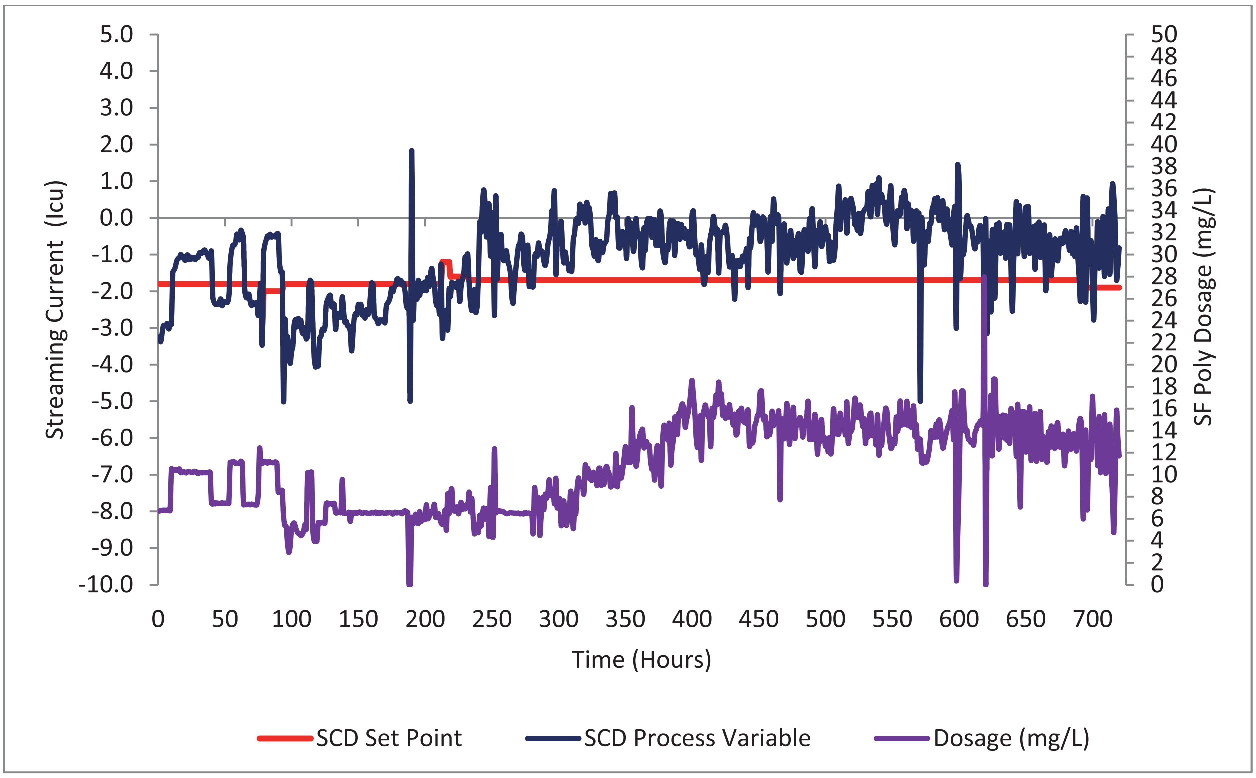


Figure 7.27: Poor SCD response at Hazelmere Water Treatment Plant due to poor tuning

Figure 7.28 indicates the trends observed when using the automatic coagulant dose control system with optimised control loop parameters. It can be seen that for a PV above the SCD set point (with SCD more positive) the pump responds appropriately by decreasing the dosage and when the PV is below the set point (at 30th, 65th and 90th hours) the pump output ramped up to increase the dosage slightly to (10.6, 10 and 7 mg/L) respectively. The graph shows minimal lag times between the pump response and the PV.
It was noted that the average dosage of 8.4 mg/L was maintained with the SCD auto control. This corresponded with the optimum dosage of 8 mg/L which was determined during jar tests.

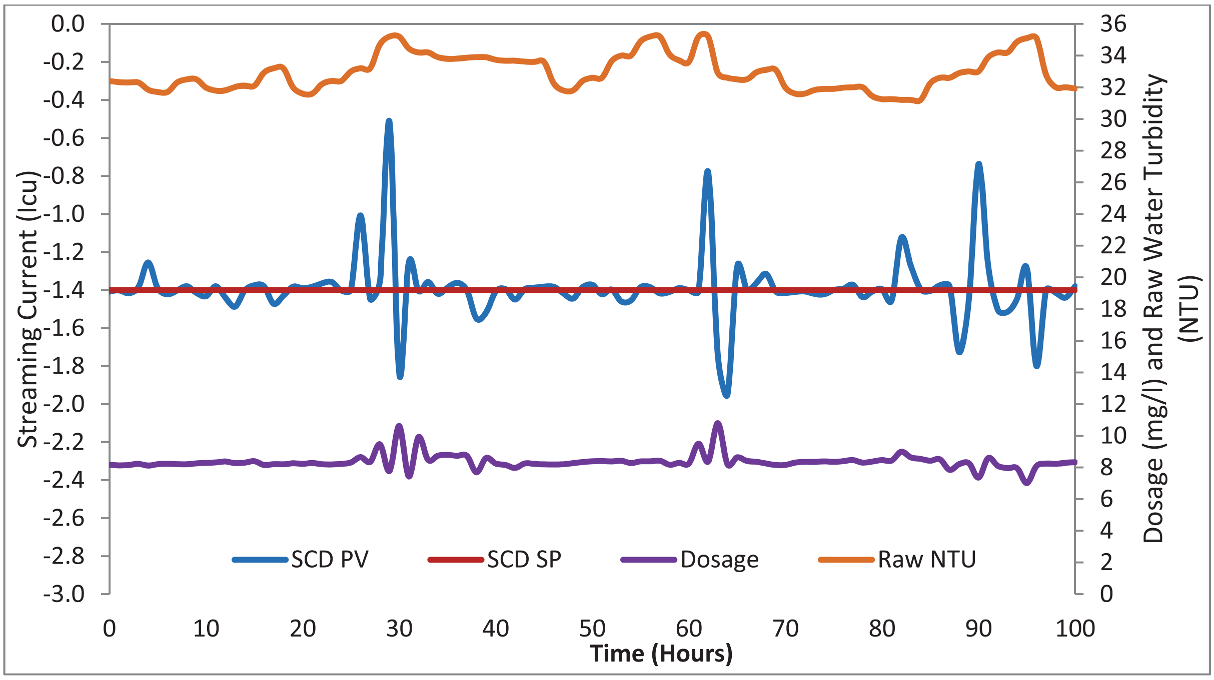


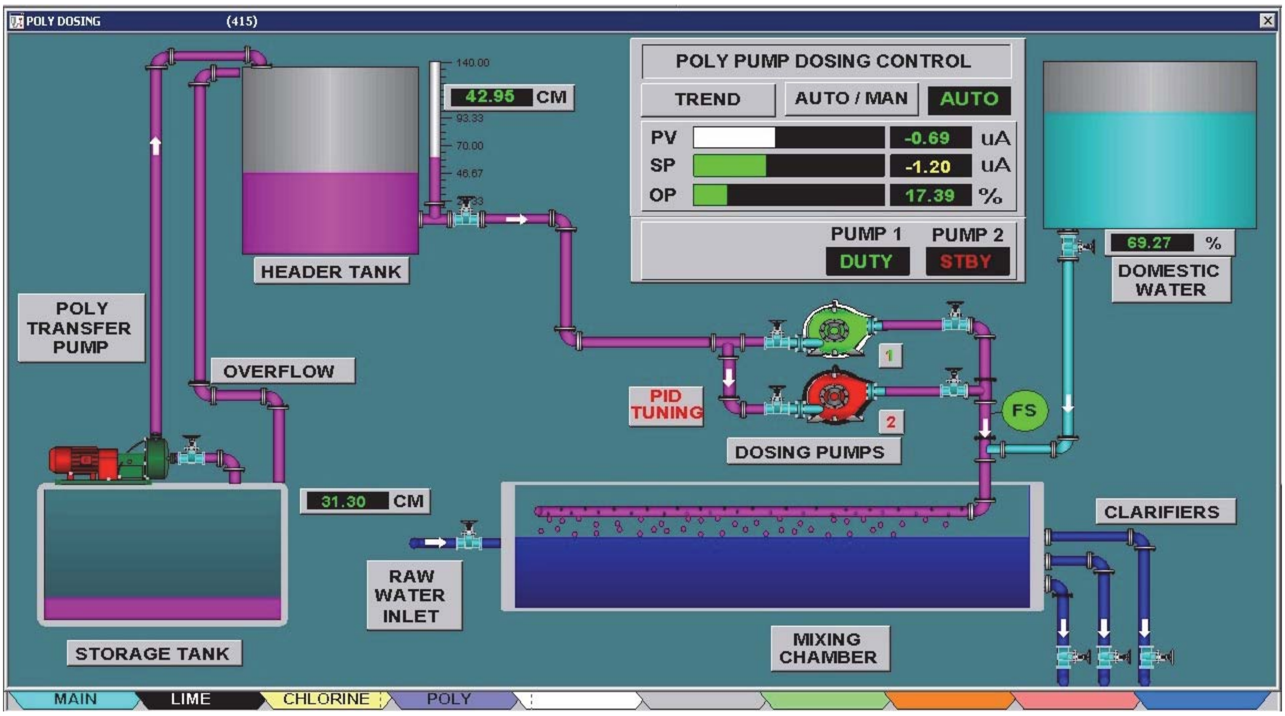
Figure 7.28: Hazelmere WTP optimised SCD response loop

Figure 7.28 shows that the SCD PV responded well to variations in the raw water turbidity for the Hazelmere Water Treatment Plant where the raw water turbidity was between 30 and 36 NTU, while for Wiggins Water Treatment Plant (1 - 2.5 NTU), the SCD PV was more erratic and required more operator intervention. This confirms the laboratory-scale findings that for low-turbidity raw water with minimal variations in turbidity, manual coagulant control may be more cost-effective than an SCD controlled automatic dosing system.

7.7 FIELD RESULTS FROM AMANZIMTOTI WATER TREATMENT PLANT

Umgeni Water's Amanzimtoti Water Treatment Plant is located in the Amanzimtoti area in Bhekulwandle. The plant receives raw water from the Nungwane Dam by gravity and has a design capacity of 24 ML/d. The water from the Nungwane Dam gravitates into the inlet chamber where coagulant (polymer blend) and hydrated lime are dosed. The inlet chamber is designed to achieve flash mixing through the turbulence created by the incoming raw water flow.

The coagulated water is then evenly distributed to feed three circular Bateman clarifloculator. Filtration is achieved by 13 Paterson Candy rapid gravity filters. Post-chlorination occurs on the filtrate lines that lead into the reservoirs where the potable water is stored before distribution.


POLY PUMP DOSING CONTROL

AUTO / MAN: AUTO

PV -0.69 uA

SP -1.20 uA

OP 17.39 %

PUMP 1 DUTY

PUMP 2 STBY

42.95 CM

31.30 CM

69.27 %

Figure 7.29: SCADA mimic of Amanzimtoti WTP coagulant dosing

The dosing system contains two dosing pumps which allow for remote operation and control via Supervisory Control and Data Acquisition (SCADA). The plant receives raw water with an average turbidity of 37 NTU.

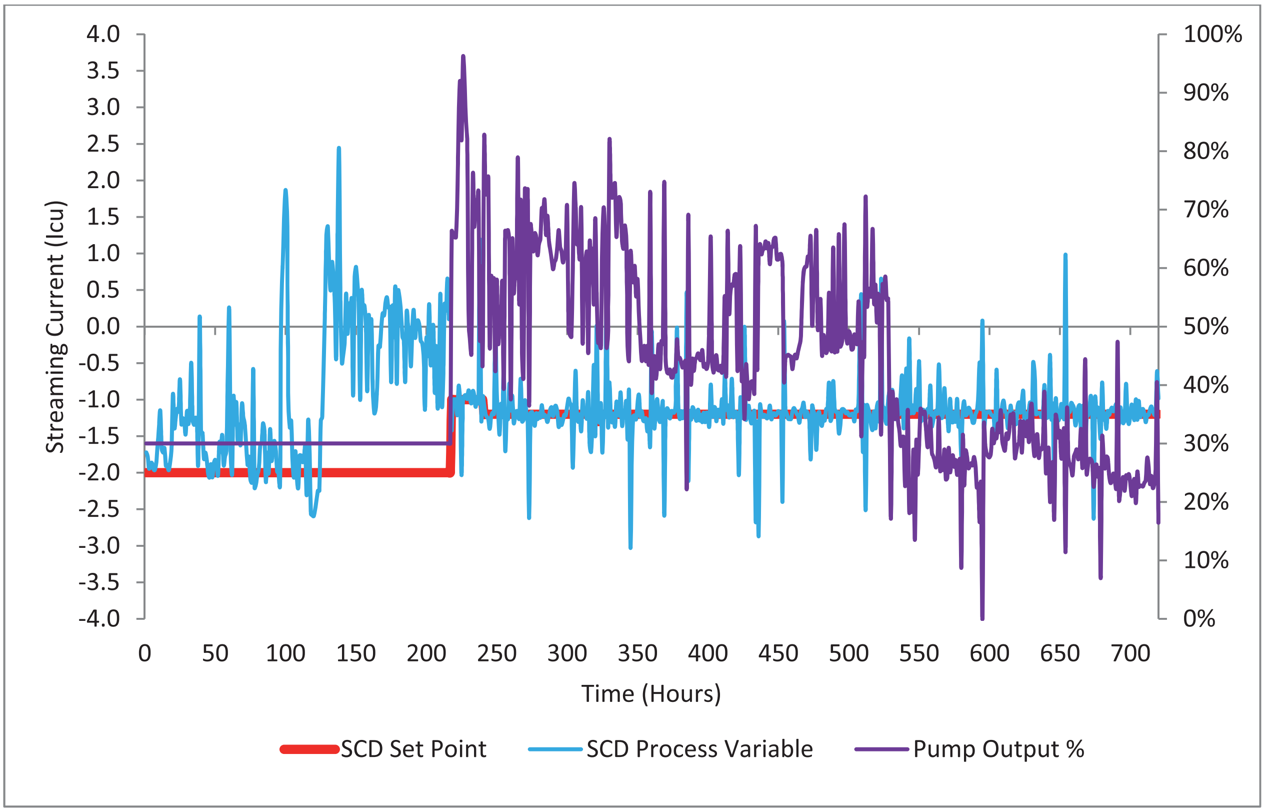


Figure 7.30: SCD response to Amanzimtoti WTP raw water

With the installation of the new SCD, the oscillator has a poor signal noise (S/N) ratio or high jitter level in the beginning and this requires a lower ration to prevent manifestations of random variation in phase (jitter and phase noise) in the pump operation.

The plant was operated in manual mode and switched to automatic mode during hour 218 as illustrated by Figure 7.30. This is an example of a well-tuned loop whereby the experience which was accumulated during the execution of this project was put into practice. The process variable was maintained on the process set point and the pump was dosing the appropriate amount of polymer (at around 50% pump opening). Comparison of the polymeric coagulant dosing conducted by the R&D division indicated that the plant was dosing 10.3 mg/L and the laboratory jar test dosage was 9.5 mg/L.

CHAPTER 8: CONCLUSIONS AND RECOMMENDATIONS

8.1 CONCLUSIONS

The following conclusions may be drawn from the laboratory- and pilot-scale studies conducted on the selected equipment for use in automatic coagulant dosing systems:

8.1.1 The particle counter technique is unsuitable for conventional water treatment processes. Particle counts including particle size variations were not directly attributable to coagulant dose alone as variations in the clarifier also affected particle counter outputs. Clogging and fouling of the particle counter sensor also rendered this technique unsatisfactory.

8.1.2 The mathematical model based on historical water treatment plant data was applicable in only a limited range of the data provided. The model produced erroneous outputs due to the large variations in raw water turbidity which commonly occur when extracting water from rivers,

The model was also very sensitive to the accuracy of the data. Considering the challenges faced by process controllers with respect to training, availability of functional, well maintained and calibrated laboratory or on-line analytical measuring equipment, the reliability of measurements under such circumstances may be negatively affected. The advantage of the model is its simplicity and it may be used in process optimization and trouble-shooting interventions provided the data used are accurate. A mathematical model could still be useful for coagulant dose control but more research is required.

8.1.3 The SCD was found to be the most robust automatic coagulant dose control system and produced favourable results. The detailed evaluation of SCD responses to different raw water turbidity indicated the following:

- Jar tests show a wide ‘optimum’ coagulant dosing range characterized by no change in turbidity as the coagulant dose is increased until re-stabilization of charge occurs. In practical terms, polymeric coagulants can be overdosed by between 4 and 8 mg/L without any noticeable deterioration in final water turbidity.
- The SCD operates most stable and sensitive to sample changes in the charge neutralisation zone where the SCD response has a unique dosage for given set point.
- For turbidity >10 NTU the SCD response was sensitive and stable.
- For turbidity <10 NTU the SCD response was still linear; however, it was less sensitive than at higher turbidity.
- Generally, bentonite did not affect SCD measurements but improved the SCD sensitivity. However, the effects of bentonite may vary depending on the type used, and the SCD response may thus be different.
- In the 6 to 9 pH range (typical raw water pH range) there was no significant effect of pH on SCD response.
- For consistently low raw water turbidities, below 10 NTU, an automatic coagulant dosing system is not necessary due to poor auto control. Manual control should be considered instead.
- Where organic coagulants are used with low and constant raw water turbidity, SCD based automatic coagulant dosing may result in under- or over-dosing.
- Weekly jar tests should be done to avoid coagulant overdosing or under-dosing.
- In-house engineers or control technicians need to be involved with the tuning of the loops (“tune by feel”) and should not rely on manufacturer’s settings only.

8.2 RECOMMENDATIONS

Based on the findings and conclusions of this study, the following recommendations can be made:

- A comprehensive SCD guideline document should be compiled, with details regarding areas of applicability, installation, operation, troubleshooting and maintenance. Further research is needed on the use of a mathematical model based on historical data for a specific case study. The research should include the following:
  - Data collection and verification
  - Development of a user-friendly model and software
- The effects of oxidants ($KMnO_4$ and chlorine) and PAC on the operation of the SCD should be determined when these pretreatment chemicals are used

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APPENDIX A: STREAMING CURRENT DETECTOR OPERATIONAL GUIDELINE

DOSING PUMPS

In order to successfully implement automatic dose control there may be a need to change the existing dosing equipment. Dosing pumps must easily be adapted to provide works flow pacing (e.g. by changing pump frequency on diaphragm pumps) and changes to dose (by changing stroke length). Pump replacement cost may be a significant element of implementing a fully automated system. But most plants have this types of pumps already installed.

1. The pump stroke length is adjusted to ensure an adequate delivery of coagulant at both the low and high flows into the plant, as well as daily average turbidity changes.
2. Ideally the pump should have speed control and also have electrically actuated stroke control based on a 4-20 mA signal from the SCD controller.
3. The pump capacity must be sized 4 times the normal requirement. This is on the basis that the plant flow meter is operating mid-range and the desired operating point for the pump stroke is 50% i.e. within the linear region.
4. To ensure process continuity, the SCD should be able to switch to a manual dosing control should problems with the sample flow to the SCD sample cell arise.

BASIC SET-UP AND OPERATION OF A STREAMING CURRENT DETECTOR (SCD) FEEDBACK CONTROL SYSTEM:

- The SCD sample point chosen must be close to the coagulant dosing point at a point where the coagulant and water are well mixed.
- Process lag time between sampling and delivery of the sample to the SC measurement cell should be as short (max 3 minutes) as possible.
- Before automatic dose control by SCD is implemented, jar tests should be conducted to determine the optimum coagulant dose is within the linear range of the SCD versus coagulant dose range.
- Variations in the raw water flow and quality, and coagulant dosage conditions should be minimised and be kept steady during initial setup of the SC controller.
- Once steady and satisfactory raw water and coagulation conditions are observed in the process then the streaming current charge is noted. The steady signal from the SCD that is observed, corresponding with the optimum coagulation dose at the plant is selected as the set-point setpoint.
- The SCD should be operated for a few days in manual control to observe how it operates under normal process operation.
- Frequent monitoring is necessary in the first few days of automatic dose control until confidence is gained in the chosen setpoint and the control of dosing. Re-adjustment of the setpoint may be required during this phase.
- Maintenance requirements are usually daily with turbidity above 100 or weekly manual cleaning (below 50 NTU) and annual service of instrument by equipment supplier.

OPERATION OF THE CONTROL LOOP (PARAMETER DETERMINATION)

The loop settings are P and I only, as the changes are quite slow on the plant, and there is no real need for a derivative action in the loop. Step changes in flow rate due to the raw water pumps being stopped and started can be accommodated with the loop parameters but there will be some oscillation in the control response if the changes are in the order of 25%.

The first thing to do before loop tuning is to ensure that the sample flow rate is stable and that the SCD has been calibrated. The manual describes a “bump test” which should be conducted to determine the initial loop parameters. One would then use these loop parameters and make some setpoint changes with the loop in auto and watch the loop response and make the necessary loop parameter changes to fine tune the loop. This is however the function of the technical staff and not the operators.

1. When the plant is operating at steady state with the controller in manual, the SCD charge is noted.
2. Make a 10% increase in the output value and start a stopwatch.
3. When the charge value stabilises, note the charge and the time lapsed. These values are used to calculate the proportional band and the integral time settings.

The cause of the change in charge was a 10% increase in pump output. Due to the delay time of flash mixing and carrying the sample to the sample pot, a lag time is observed between the output change and the beginning of the charge change.

The integral time is the time it takes for the charge to stabilise at the new charge value

$$Proportional\ band\ (PB)\ = \left(\frac{\%\,effect}{\%cause}\right) \times 100 = \left(\frac{Charge\ change}{Coagulant\ dose\ change}\right) \times 100$$

To slow the loop down the proportional band is multiplied by 1.5 to get actual PB

$$Gain = \frac{100}{PB}$$

There are no standard loop parameters, and the loop parameters are determined primarily by the raw water quality, the type of chemical being used, sample position and pipe length. They need to be determined for each application and treatment plant.

GOOD CONTROL PHILOSOPHY

The philosophy of operation is what the operator needs to know, and when they encounter a perceived problem, the technical staff should be in a position to make loop tuning adjustments.

The Setpoint is determined by a jar test which determines the optimum ppm dosage value. Using the raw water flow and required ppm dosage, one can determine the required ml/min dosage. With the controls in manual, set the dosage to the required level and allow the plant to settle – the stable SCD reading will now be your initial setpoint.

Summer to winter water quality changes will dictate the required setpoint for the optimum quality of water, so jar tests are essential to determining the required setpoint. If a setpoint is changed, make small changes and watch the results change over a period of hours (residence time of the clarifier) and don’t make any further changes until you see an effect of the change, be it positive or negative. Continue making small adjustment until the required water quality I achieved.

To ensure excellent coagulant control using the SCD the following are ideal conditions.

- During jar testing and coagulant dose increment titrations; the SCD response during manual titrations should have a slope greater than 0.2 to ensure effective coagulant dose control.

  $$(\Delta\ ICA)/(\Delta Dosage) \geq 0.2$$

- The ideal slope of the relationship between SCD charge and coagulant dose should be 1 but this is rarely found in practice due to raw water characteristics.
- A slope of zero is not recommended because this will result in an uncontrollable loop, in this case manual control is highly recommended. A flat or horizontal curve could result in the risk of overdosing of the coagulant. This is indicated in the figure below.

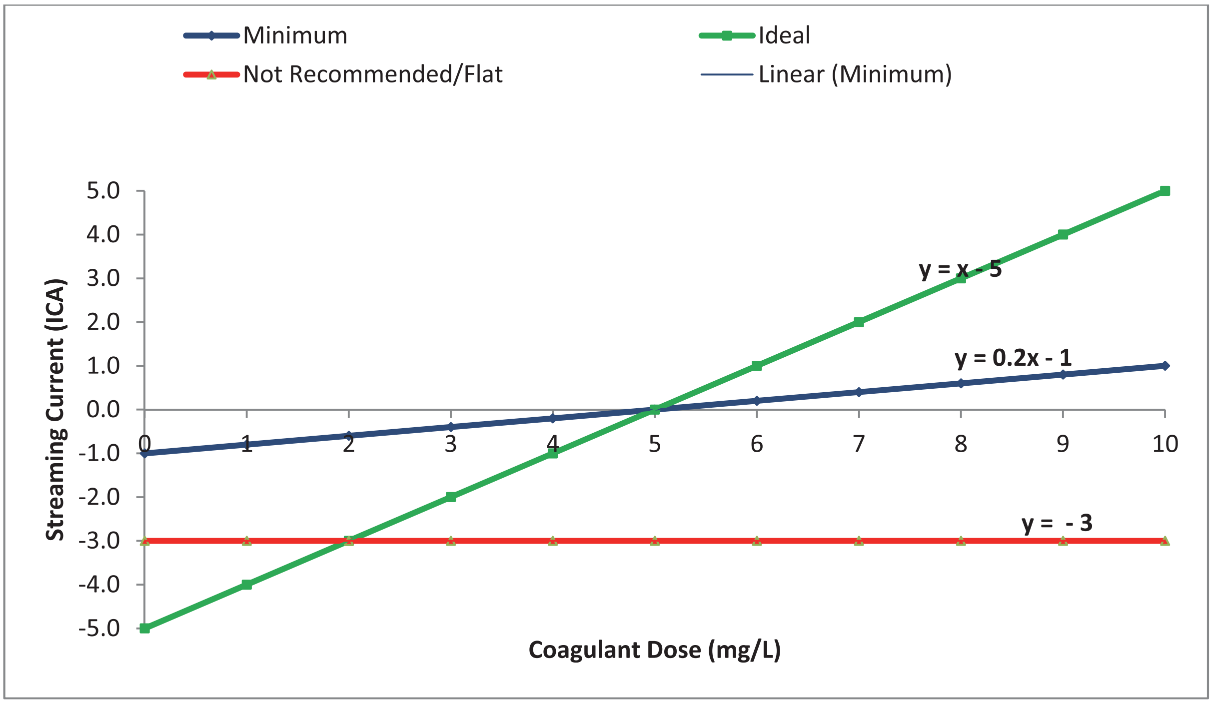


Figure 8.1: Optimal control conditions

Fine loop tuning is the responsibility of the technician that is doing the monthly cleaning and calibration of the unit. This is to avoid relying on operators to clean the instruments because experience has shown that one the SCD get dirty they switch to manual control instead of cleaning the SCD chamber. Any changes that are made should be guided by his findings during his maintenance or by the request of the operators based on measured variables like dosage rates, raw water flow, and final water quality.

The following conditions are the required parameters to monitor to ensure value for money of the automatic dose control. The advantage is that they are already being monitored at treatment plants as part of good plant operational practices and compliance to blue drop status requirements.

Instrumentation to monitor for efficient control

- Raw Water Flow rate
- Coagulant Dosing rate
- Streaming Current Set Point
- Streaming Current Process Variable
- Raw water Turbidity
- Settled Water Turbidity (Below 5 NTU)
- Filtered Water Turbidity (Below 1 NTU)

One of the most misunderstood phenomena was the SCD charge vs. NTU relationship and this should be communicated with users beforehand.
Research conducted by the equipment supplier and upon enquiry is that there is no direct relationship between turbidity and charge because of the organic nature of the colloidal suspension. There may be a lot of organic matter that does not necessary contribute to the turbidity, but will certainly contribute to the charge. The turbidity caused by silica loading may affect the turbidity and not necessarily the charge. This could lead to the perception that one is under dosing/overdosing to maintain a charge setpoint, but really serves to point to the fact that in those conditions, possibly a new setpoint should be selected.

APPENDIX B: BASE LINE OF PARTICLE COUNTER TESTING

Figure 8.2 and Table 8-1 indicate the results obtained during deionised flushing of the particle counter to obtain a baseline for particle counts. The baseline particle counts were then determined by averaging the counts obtained at relatively steady readings i.e. from 1 hour to 5 hours.

Table 8-1: Deionised Water Baseline Particle Counts

Time (hours)	1-5 microns	5-10 microns	10-15 microns	15-25 microns	Total
0.5	328	245	205	100	878
1	20	3	2	1	**26**
1.5	14	2	2	1	**20**
2	15	2	2	1	**20**
2.5	11	2	2	1	**16**
3	10	2	2	1	**15**
				AVERAGE	**19**

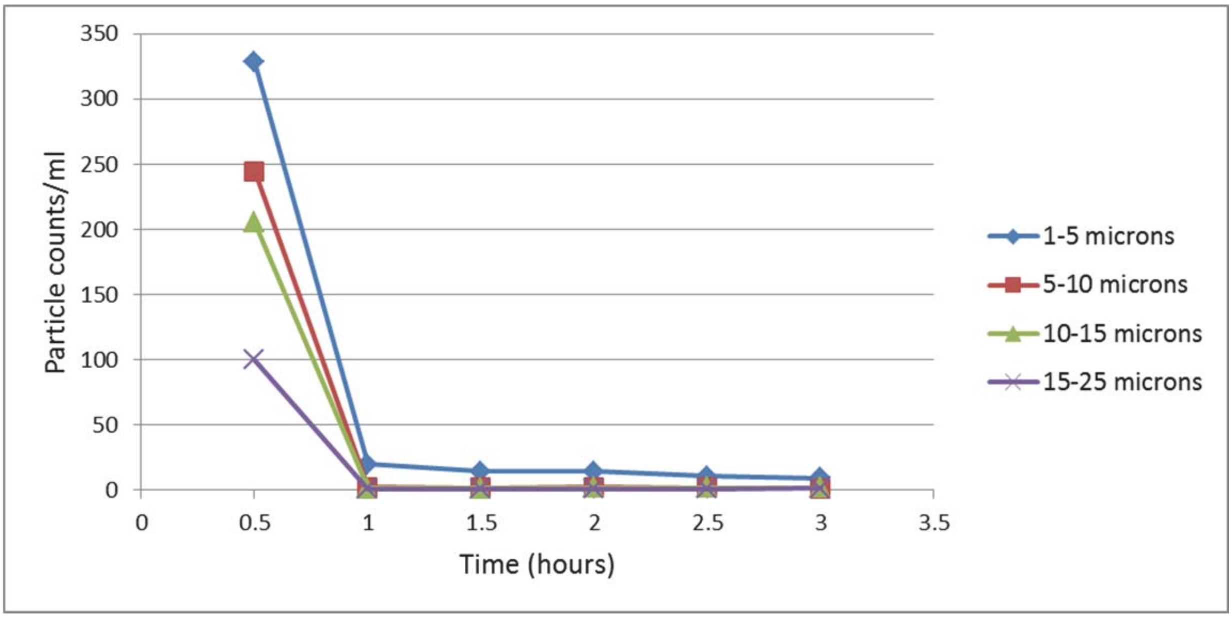


Figure 8.2: Deionised Flushing to Obtain a Baseline for Particle Count Reading

APPENDIX A: OPERATING MANUALS

LOW RANGE TURBIDIMETER CALIBRATION PROCEDURE

1. Prepare a 20.0 NTU standard by adding 5.0 mL of 4000 NTU formazin to a 1-L flask.
2. Dilute to the mark with deionized water and invert gently to mix.
3. Stop the sample flow, then drain and clean the body.
4. Drain the deionized water and pour the prepared 20.0 NTU standard into the turbidimeter body at step 12. Do not add additional 4000 NTU formazin.
5. From the Main Menu, select SENSOR SETUP and confirm.
6. Select the appropriate sensor if more than one is connected and confirm.
7. Select CALIBRATE and confirm.
8. Select USER PREPD CAL and confirm.
9. Select the available Output Mode (Active, Hold, or Transfer) from the list and confirm.
10. Stop the sample flow. Drain and clean the body and bubble trap. Fill the cylinder with1 L deionized water. Replace the head and confirm.

Important Note: *Carefully pour the DI water in such a way that minimizes any bubble formation that would result in a false, high reading.*

11. The measured reading (based on a gain of 1.0) is displayed. Confirm.
12. Enter the standard turbidity value of the user prepared standard and confirm.
13. Drain the cylinder. Pour the prepared standard into the cylinder and confirm.
14. The measured reading (based on a gain of 1.0) is displayed. Confirm.
15. The display will read GOOD CAL! GAIN: X.XX ENTER TO CONT. Confirm. (If the Calibration was unsuccessful. The display will read BAD CAL! Confirm to redo or exit.)
16. The display will read VERIFY CAL? Confirm to verify or exit without verification.
17. Select the verification type (i.e. wet or dry verification) or enter initials to complete calibration.
18. Return the sensor to measure mode and confirm.

ULTRATURB CALIBRATION PROCEDURE (WITH STANDARD SOLUTION)

1. Open the MAIN MENU.
2. Choose SENSOR SETUP and accept.
3. Choose the related sensor and accept.
4. Choose CALIBRATE and accept.
5. Choose STANDARD and accept.
6. Shut-off the feed and accept TURN OFF SAMPLE INLET.
7. Drain the measuring chamber using the lower feed union. Accept DRAIN MEAS. CHAMBER.
8. Connect the calibration syringe to the feed union (see Figure) and add the calibration standard. Accept POUR STD INTO MEAS. CHAMBER.

9. Accept PRESS ENTER WHEN STABLE x.xxx TRBFNU.
10. Enter the concentration of the standard solution. Accept CALIBRATE (x.xxx TRBFNU).
11. Remove the calibration syringe and accept REMOVE CALIBRATION SYRINGE.
12. Re-connect the feed and accept CONNECT SAMPLE INLET.
13. Open the feed and accept CAL READY OPEN INLET.
14. Accept OUTPUT ACTIVE.

PARTICLE COUNTER CALIBRATION PROCEDURE:

Calibration Requirements:

The following supplies will be needed to perform on-site calibration.

Qty	Description
4-5	1 Gallon Jugs Distilled Water*
20 ft	PC Sensor Tubing (1/4” OD x 1/8” ID)
5 ft	Semi-Rigid Tubing (5/32” OD x 3/32” ID)
1	MicroPipette (10 to 100) for accurate dosing of standard spheres
1	Rotameter (10 to 120 ml/min scale)
1	100 ml Graduated Cylinder
1	Particle Counter Cleaning Brush
1	Adjustable Tubing Clamp (Recommend ‘Keck Ramp Clamp’, Cole Parmer item)
1 pk	Barb Fittings (1/8” Barb x 1/8” NPT)
**	NIST Traceable PSL Spheres

****Note:** Typical sizes of PSL Spheres used for calibration are 2, 5, and 10 micron.

Procedure

Prior to calibration, ensure that Particle Counter is operating properly:

1. Thoroughly clean particle counter flow cell with sensor cleaning brush.
2. Place the 1 gallon jug of distilled water on top of the unit as shown in the picture below.

3. To hook up the tubing as shown in the picture, you will need one 3 foot piece of tubing going from inside the jug to the bottom of the sensor (Note: Rinse off tubing with clean water before inserting into the jug). Next is an 8 inch piece of tubing going from the top of the sensor to the bottom fitting of the rotameter. Finally, there is a 4 foot piece of tubing that is connected to the top fitting of the rotameter. Install the tubing clamp on the 4 foot piece of tubing.

4. Make sure the tubing clamp is open. Start flow through the tubing by applying suction to the end of the 4' piece of tubing coming off the top of the rotameter. Collect the water coming out of tubing into a beaker (this will be used to determine how much water was wasted out of the jug). Once flow has been started and the air bubbles removed from the tubing and sensor, close the tubing clamp to stop flow.

5. With water trapped in the sensor, verify sensor Laser % is between 90% and 110%. To view the Laser %, press the Down Arrow until the Status Page is displayed on the LCD. The Laser % and Cell % are indicated on the seventh row of characters on the LCD. If the Laser % is between 90 and 110%, proceed to step 6. If the Laser % is less than 90% or greater than 110%, proceed to Section 10.0 for instructions on adjusting the Laser Current. Upon completion of the adjustment procedure in Section 10.0, continue to step 6.

6. With water trapped in the sensor, verify sensor Cell % is between 95% and 105%. If the Cell % is between 95% and 105%, proceed to step 7. If the Cell % is less than 95% or greater than 105%, proceed to Section 11.0 for instructions on adjusting the Cell Voltage. Upon completion of the adjustment procedure in Section 11.0, continue to step 7.

7. Verify that the background counts are 0 for all bins. If the counts are greater than 0, Check the Flow Cell for debris and clean the flow cell. If the instrument continues to show counts greater than 0 then contact the factory for support.

8. Press **Menu** on the keypad. Using the Up and Down arrows scroll to SAMPLE SETUP and press enter. Then scroll to SAMPLE PERIOD and press enter. Using the Up, Down, Left and Right keys enter 10 and press enter. Scroll to SAMPLE FREQUENCY and press enter. Using the Up, Down, Left and Right keys enter 15 and press enter.

9. Press **Menu** two times or until the Chemtrac Logo is displayed on the LCD.

Blank Water Check:

1. Start flow through the sensor by opening the tubing clamp and use the adjustable clamp to get the flow near 75 ml/min (+/- 5 ml/min) as shown on the rotameter. Capture the water that is flowing out of the sensor and rotameter into a container as you will need to know how much sample was drained in step 3.

2. Allow the readings to stabilize and record the particle counts which appear on the LCD counts screen. Ideally, the blank counts should be less than 50 total counts 2 micron and above. If the counts are higher than 50 total counts, you will need to discard this volume of water and try another until one is found that gives under 50 total counts.

3. You will need to know the volume leftover in the jug before performing the below Pipette. Volume Calculations determines how much solution is to be extracted from the bottle of calibration spheres and injected into the jug. To do this, measure how much water was drained out of the gallon jug during the above testing. Typically, it should only require around 100 to 200 ml of water to perform the above blank water test.

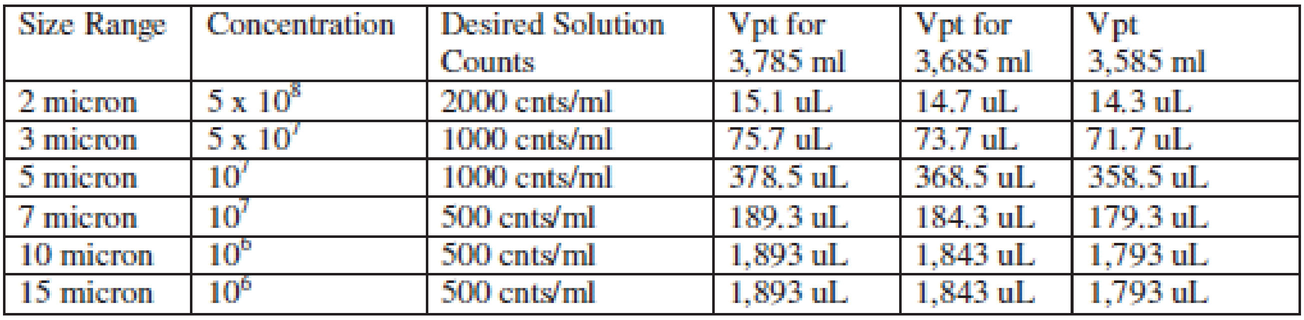
Subtract the amount used from 3,785 ml or whatever volume is shown on the jug (i.e. some jugs could be 4,000 ml versus 3,785 ml).

4. When selecting the spheres to start the calibration, it is recommended to start with the highest size range being calibrated and work down from there. For example, if calibrating the 2, 5, and 10 micron sizes; start with the 10 micron spheres first.

5. Once the size range to be calibrated is determined, perform the Pipette Volume Calculations.

Pipette Volume Calculation

If you drain out exactly 100 or 200 ml from the 1 gallon (US) jug during the blank water test, then the below chart can help you quickly determine the Pipette Volume (Vpt) you need to use for each size range you choose to calibrate. Otherwise, use the formula below this table to calculate the pipette volume needed to produce the Desired Solution Counts shown below.



Size Range	Concentration	Desired Solution Counts	Vpt for 3,785 ml	Vpt for 3,685 ml	Vpt 3,585 ml
2 micron	5×10^8	2000 cnts/ml	15.1 uL	14.7 uL	14.3 uL
3 micron	5×10^7	1000 cnts/ml	75.7 uL	73.7 uL	71.7 uL
5 micron	10^7	1000 cnts/ml	378.5 uL	368.5 uL	358.5 uL
7 micron	10^7	500 cnts/ml	189.3 uL	184.3 uL	179.3 uL
10 micron	10^6	500 cnts/ml	1,893 uL	1,843 uL	1,793 uL
15 micron	10^6	500 cnts/ml	1,893 uL	1,843 uL	1,793 uL

The following formula is used to calculate the proper amount of PSL spheres to inject into the blank water:

Pipette Volume = (S x Vml)/Con

S = Desired Solution Counts per ml (e.g. 1,000 cnts/ml)

Vml = Volume of Blank Water in ml (e.g. a gallon of water would be 3,785 ml)

Con = Concentration of Spheres (printed on the bottle)

Example: 5 micron example: Pipette Volume = (1,000 x 3,785)/(1 x 10^7)

Pipette Volume = .3785 ml (378.5 uL)

Adding Spheres to Blank Water

1. Ensure the PSL spheres are properly dispersed by placing them in an ultrasonic bath for 60 seconds or by the rotating bottle continuously for 1-2 minutes. **Do Not Shake The Bottle of Spheres.**

NOTE: If creating a solution for count accuracy, it is recommended to not use a container of microspheres that are more than ¾ depleted. As the container of spheres is depleted, the concentration accuracy of that container could be affected. It is important to thoroughly mix the container immediately prior to drawing off of it with a pipette, and it is important to not contaminate or cross contaminate by using dirty pipette tips.

2. Using the volume derived from the above **Pipette Volume Calculation** procedure, inject the calculated volume of PSL spheres solution into the container of Particle Free Water.

NOTE: Do not dip the pipette tip in the water. This is especially important with the 2 micron solution as the spheres are highly concentrated and the residual on the outside of the pipette tip can add considerable counts to the solution.

3. Once the spheres have been added, place the clean top back onto the jug and gently swirl the jug of water to disperse the spheres (Do not shake the bottle as this can introduce a lot of air bubbles).

Note: The spheres, especially those 10 micron and larger, will settle out over a period of time. To keep spheres in a suspension, it is important to gently swirl the bottle before each use and every 10 minutes while in use.

4. Place the jug back onto the top of the Particle Counter and re-insert the tubing.

Note: It is recommended to rinse off the tubing with clean water before re-inserting the tubing into the jug. Failing to do this can contaminate the jug and result in higher particle counts.

Calibration

1. Press **Menu** on the front panel. Using the Up and Down arrows scroll to SERVICE SETUP and press **Enter**. Then scroll to AUTO-CALIBRATION and press **Enter.** Finally, scroll to AUTO-ADJ THRESHOLD and press **Enter**.
2. Using the Up, Down, Left and Right keys enter the particle size to be calibrated then press enter. A message will appear instructing the user to start the flow of the solution through the sensor at 75 ml/min.
3. Start the flow of water through the tubing by opening the tubing clamp and adjust the clamp to set the flow for 75 ml/min (+/- 5ml/min). Allow any air bubbles that may be in the tubing or rotameter to pass through the sensor (wait approximately 15 to 30 seconds) before pressing **Enter**. If the particle concentration is insufficient the unit will time out and return to the CALIBRATION SETUP menu.

Note: It may be necessary to tap on the rotameter and tubing to dislodge bubbles.

4. When the calibration is finished the old and new values are displayed on the LCD. If the result is acceptable, then enter 1 and exit. The instrument will save the new threshold settings and restart.

Note: Be sure to record your initial and final settings. This will provide a written record in case you need to discuss what you are seeing with the factory and as a record of your actions.

5. Once the display returns to the size channel and counts screen, allow at least 2 sample cycles then verify a proper split is seen.
6. Record the data shown on the screen, and then stop the flow through the sensor by closing the tubing clamp.

Note: It is important to stop the flow through the sensor whenever you are not actually calibrating, otherwise you will waste valuable solution!

7. Verify the particles counts are evenly split (better than 60/40) across the edge bin. For example, if the test solution had 1000 5 micron particles, an ideal split in the 2-5 and 5-10 micron bins would be 500 counts in each bin. However, it is minimally acceptable to have 600 in one bin and 400 in the other. If the split appears to not be in tolerance, check your flow rate through the sensor. If necessary, perform the above calibration (steps 1 to 6) again.

Note: It is a good idea to compare the 'total count' for that solution to other units you calibrate using that solution. When calibrated with the same solution, the particle counters should agree (or match) to within 10%.

8. Once the sizing accuracy has been verified for the particle size under test, you are ready to move onto the next particle size.

Note: Use a new piece of tubing with each jug of calibration spheres – DO NOT move tubing between jugs as this can cross contaminate the solutions. Also, remember to gently swirl the jug before each use, and every 10 minutes while in use, to re-suspend particles that may have settled out.

9. When performing the 2 micron calibration, remember that the PC will only display around 50% (40 to 60%) of the particles. The other half of the concentration of particles falls under 2 micron and is not displayed on the instrument if you had a 2 micron solution of 2000 particles, you should have 800 to 1200 particles in the 2-5 micron bin after calibration.

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