OPTIMISATION OF CHEMICALS USED IN COAGULATION - FLOCCULATION PROCESS:

A CASE STUDY OF SABAKI WATER WORKS

BY

KINYA, M.K.

F56/7575/91

A THESIS SUBMITTED IN PART-FULFILMENT
FOR THE DEGREE OF MASTER OF SCIENCE
IN ENVIRONMENTAL HEALTH ENGINEERING,
UNIVERSITY OF NAIROBI

DECLARATION

THIS THESIS IS MY ORIGINAL WORK AND HAS NOT BEEN PRESENTED FOR A DEGREE IN ANY OTHER UNIVERSITY

9th August, 1994

M.K. KINYA
CANDIDATE

DATE:

THIS THESIS HAS BEEN SUBMITTED FOR EXAMINATION WITH MY APPROVAL AS A UNIVERSITY SUPERVISOR

AOtieno

10th August, 1994.

DR. F.A.O OTIENO
SUPERVISOR

DATE

ACKNOWLEDGEMENT

I wish to express my heartfelt thanks to my Supervisors, Dr. F.A.O. Otieno and Dr. P.M.A. Odira, both of the University of Nairobi. They made their own special insights available to me, and generously gave their time and interest and provided me with advice and suggestions during the preparation of this study.

I am also greatly indebted to H.P. Gauff K.G. Consulting Engineers for their financial support, as well as availing the necessary information to me. Special thanks are merited to Mr. David Baker, Head of the Water Section for his timely encouragement and unwavering assistance both which went a long way in helping me accomplish this study.

I would like to explicitly thank the following individuals for their contribution: Mr. Matheka, Mr. Abuya and Mr. Adwana all of National Water Conservation and Pipeline Corporation, not forgetting Mr. J.G. Thiongo, Mr. S.N. Nganga and Mrs. Muthoni Munene of the Public Health Engineering Laboratory, University of Nairobi. Not forgetting Mr. J. Gitau and Mr. K Musau of H.P. Gauff for their useful contribution during the field work.

To Mr. Ndiritu J.G. of the University of Nairobi, and Mr. K.B. Wangombe of H.P. Gauff, I offer my sincere appreciation. The computer knowledge they offered was exceptionally helpful.

And last but certainly not least, I wish to express my deep gratitude to Miss Hottensiah Chege, who did the bulk of typing.

To all, its a hearty thank you!

ABSTRACT

An investigation into the optimisation of chemicals used in coagulation-flocculation process in the Sabaki Water Works has been carried out. The theoretical part of the study was devoted to a survey of basic coagulation theory, flocculation Kinetics, pH and alkalinity as related to coagulant dosage. A brief review on polyelectrolytes; chemistry, mechanism of coagulation, health and environmental effects have also been tackled.

The experimental part of the research was carried out at the Sabaki Treatment Work's Laboratory during the period, November, 1992 to February, 1993. Investigations into the condition of natural alkalinity as related to alum and soda ash dosage were conducted. The possibility of using alternative/combined coagulants optimising on cost and treated water quality have also been considered. Coagulants tested for this purpose include: Alum, ferric chloride, catfloc-T and superfloc C573. Optimum coagulation pH of these coagulants for the Sabaki waters was determined.

The investigations carried out coupled with field observations suggest rather strongly that the Sabaki raw water contains enough natural alkalinity for purposes of coagulation with alum. For the experimental period the raw water alkalinity varied between 82 mg/l and 132 mg/l with a mean of 106 mg/l. Hence soda ash application should be discontinued and applied only for pH correction after filtration and chlorination when necessary.

Whilst on average polyelectrolytes cost about 15 times more than alum in Kenya, average emperical dosage ratio of 0.131 and 0.114 for catfloc:alum and superfloc:alum respectively was obtained. Thus no economically justified reasons were found to summarily reject alum as the primary coagulant in the Sabaki Water Works. However, a comparison of all relevant costs including subsequent sludge management was found necessary to provide a complete quantified comparison.

CONTENTS

CONTENTS (Cont'd)

CONTENTS (Cont'd)

LIST OF TABLES

LIST OF FIGURES

LIST OF FIGURES (Cont'd)

LIST OF PRINCIPAL SYMBOLS AND ABBREVIATIONS

(Other symbols and terms are defined where quoted).

AL = Aluminium.

ALK = Alkalinity in mg/l as calcium carbonate ($CaCO_3$).

APHA = American Public Health Association.

ASCE = American Society of Civil Engineers.

AWWA = American Water Works Association.

b = Particle collision frequency.

CLF = Clarified water.

DOSE = Chemical dose in mg/l.

F = Farady constant.

Fe = Iron.

FLOW = Inflow rate to Treatment Works in m^3/hr.

G = Free energy for chemical absorption.

hr = Hour.

IARC = International Agency for Research on Cancer.

J = Number of collisions.

K = Boltzmann constant.

kg = Kilogram.

KSh = Kenya Shilling.

l = Litre.

m = Metre.

mg = Milligram.

min = Minute.

N = Particles per unit volume.

NTU = Nephelometric turbidity units.

N/A = Not applicable.

LIST OF PRINCIPAL SYMBOLS AND ABBREVIATIONS (Cont'd)

P = Power.

PRE = Presettled.

R = Particle radius.

rpm = Revolutions per minute.

RWT = Raw water turbidity (NTU).

SD = Sampling date.

SODA = Soda ash.

T = Absolute temperature (K).

TUR = Turbidity in (NTU).

U.K. = United Kingdom.

USA = United States of America.

USEPA = United States Environmental Protection Agency.

μ = Dynamic viscosity.

ψ = Potential drop between solution and the absorption surface.

V = Volume.

Vol = Volume.

WHO = World Health Organisation.

WPCF = Water Pollution Control Federation.

Z = Charge on the ion being absorbed.

CHAPTER ONE

INTRODUCTION

1.1 Necessity

Safe and adequate water supply and environmental hygiene are essential for a healthy productive life. Normal surface water supplies are often polluted with materials arising from soil erosion, dissolution of minerals, decay of vegetation, micro-organisms, domestic wastes, animal wastes, industrial wastes etc. These materials may exist as suspended or finely divided particles which contribute the turbidity, colour and odour found in most natural surface waters.

For both, health and aesthetic points of view such waters are unacceptable for consumption. Treatment of such waters to remove these materials is accomplished conventionally by coagulation/flocculation, sedimentation, filtration and disinfection. The process of coagulation, which involves addition of metallic salts, polyelectrolytes and occasionally other chemicals for pH control or as coagulant aids, is usually the backborne for economical and efficient functioning of the other processes. For highly turbid waters, this process accounts for a large percentage of treatment works chemical cost.

Several studies have shown that, the process of coagulation is to a great extent influenced by the pH and alkalinity of the raw water (Dentel and Gossett (1988), Maudling and Harris (1968)). Additionally, for a particular water there exists an optimum pH and alkalinity for efficient operation. Consequently careful control of these parameters would result in minimal chemical dosage, hence great cost savings.

During the past decade, the Government of Kenya and external aid donors have invested a substantial amount of financial, technological and material resources in the

Mombasa and Coastal region water supply. Because resources are so limited, it is necessary to conserve whatever is available, and allocate it in the most rational manner. The stress being on appropriate health, environmental and social aspects. The primary goal being an economic one, to do with choosing techniques which make modest use of available capital resources, labour and local material optimally.

To meet the increasing water demand of Mombasa and Kenya's coastal region, a new piped water supply was established and put into operation in 1981. The raw water is diverted from the Sabaki river near Baricho about 40 km west of Malindi town. Conventional water treatment was adopted for the Sabaki Treatment Works. The flow in the Sabaki river and its tributaries having passed through valleys and hills experiences a major industrial and erosional pollution effects. Hence being the second largest Water Works in Kenya (second to Ngethu on Chania river), heavy operational losses are incurred towards meeting the Treatment Works chemical demand. Thus this study was geared towards the optimisation of chemicals used in the coagulation/flocculation process with Sabaki Water Works as a case study.

1.2 Study Objectives

Preliminary investigations were carried out from 25th August to 4th September 1992, which involved site visit and existing data perusal. From this it was envisaged that; the raw water in the Sabaki river contains enough natural alkalinity for complete and efficient coagulation process using alum as entailed in Section 2.5.2 of this report. As such there was no need of adding soda ash prior to clarification for purposes of increasing the natural alkalinity as was the case then. This being the case, then, huge amounts of money have been wasted in purchasing unnecessary commodity - soda ash. Thus it was necessary to investigate the condition of natural alkalinity throughout the Treatment Works.

The Sabaki Water Works was basically designed for initial removal of suspended solids in the presettlement tanks using a polyelectrolyte and then coagulation with alum at the clarifiers. From the time the Treatment Works started operating (1981), to the commencement of this study (1992), there has been a monopoly of using alum alone as a coagulant, both at the presettlement tanks and the clarifiers. Aluminium sulphate has a long, successful record as a coagulant in water treatment. In recent years, however, its continued use has been questioned for a number of reasons. This includes: health concerns about a possible but unconfirmed link between aluminium and alzheimer's diseases (Haarhoff and Cleasby (1988)), post precipitation of aluminium residuals in distribution systems (Costello (1984)), cost effectiveness compared with other coagulants (Qureshi and Malmberg (1985)), Voluminous alum sludge which complicates handling and disposal procedures (Kawamura (1976)), dosed in large amounts, thus, requiring alkali dosage for pH corrections. Attention world wide is therefore increasingly being focused on polyelectrolytes as alternative coagulants or coagulant aid. There is need in Kenya to keep abreast with modern technology.

Early investigators of the coagulation process in water treatment showed that pH was the single most important variable of the many that had to be considered (Dentel and Gossett (1988), Carnduff (1976), Jeffcoat and Singley (1975)). These investigators established that there exists at least one pH range for any given water within which good coagulation/flocculation occurs in the shortest time with a given coagulant dose. The extent of the pH range being affected by the type of coagulant used and by the chemical composition of the water as well as the concentration of the coagulant. Whenever possible, coagulation should be carried out within the optimum pH zone. Failure to operate within the optimum zone for a given water may result in waste of chemicals and may be reflected in lowered quality of the plant effluent. Coagulation with alum is usually optimal in pH ranges between 6.0 - 7.0 for most waters Davis and Cornwell (1991). Thus, with the Sabaki raw water averaging a pH of 8.3 coupled with soda ash addition, there was every possibility of inefficient use of alum in the coagulation process. This necessitated investigations into the effects of pH in the coagulation/flocculation process and to obtain optimal pH ranges for the Sabaki waters.

Taking into consideration these important overviews, the overall objectives of this study were to:-

(i) Evaluate the condition of natural alkalinity for optimum alum and soda ash dosage of the Sabaki Water Works. Hence establish whether the raw water contains enough natural alkalinity for complete and efficient coagulation using alum.

(ii) Investigate the possibility of using alternative metallic coagulants, polyelectrolytes and, a combination of alum and polyelectrolyte optimising on cost and treated water quality.

(iii) Evaluate the effects of pH correction prior to coagulant dosing, hence obtain optimum pH ranges for each coagulant tested in (ii).

(iv) Examine any other factors that may directly or indirectly affect the efficient operation of the coagulation - flocculation process of the Sabaki Water Works.

CHAPTER TWO

LITERATURE REVIEW

2.1 Impurities in Surface Waters

2.1.1 General

Pure water is defined as one consisting of an atom of oxygen combined with two hydrogen atoms. However, water which is absolutely pure is not available in nature; even water vapour condensing in the air contains solids, dissolved gasses and dissolved salts.

Impurities found in surface waters are introduced by dissolution and exchange reactions of the media that it comes into contact with in its course. These may comprise among others, soil erosion, dissolution of minerals, animal wastes, domestic wastes and micro-organisms. The impurities consist of a variety of turbidity producing suspended and dissolved solids ranging in size from course material which will not settle unless an external force or agent is applied.

2.1.2 Turbidity and Colour

Turbidity and colour are two measurements made to describe quantitavely the appearance of natural waters both in the raw water state and after treatment for public supply.

Although the substances causing turbidity and colour may not themselves be harmful to health, a very large part of water treatment is directed towards their removal to ensure an aesthetically attractive product which has been prepared for effective disinfection

(Yapijakis (1982)). The determination of turbidity and colour has therefore always been an important part of the examination of water for potable use.

The appearance of a water sample is the produce of the combined effects of scattering and absorption of light by dissolved and suspended material. Dissolved material absorbs light but particulate matter absorbs light and re-emits a proportion as scattered light.

Scattering of light is the cause of a hazy or milky appearance which is described by the turbidity, while colour is generally regarded as being imparted by dissolved material (Lamont (1981)). Lamont further argues that the separation of the two effects is not rigid because substances in solution do scatter light to some degree and particles in suspension may be coloured (e.g. iron compounds). Furthermore at high concentrations of suspended solids the appearance of a sample may be due as much to the attenuation of light by absorption as to the scattering of light. Treweek, (1979) indicated that neither scattering nor absorbance can be directly related to particle concentration as the optical properties involved in these measurements depend on the shape, size and refractive index of the suspended particles as well on their absorption spectra. Treweek further stated that as natural waters contain heterogeneous mixtures of suspended material of variable composition, it is impossible to establish any general relationship between turbidity and suspended solids concentration.

Lamont (1981) observed that in very special cases, where the suspended solids are of constant composition, it may be possible to develop an empirical correlation between turbidity and suspended solids concentration. However, such solutions may only be artificial ones and not natural surface waters.

2.1.3 Colloidal Dispersions

Cox (1969) termed as colloidal particles, those insoluble solids, such as clay, oxides of metals and micro-organisms, which are so finely subdivided that particle sizes are intermediate between the molecular dispersions of true solutions and sizes just about visible under a microscope.

An important property of the colloidal particles is that when in an aqueous solution individual particles develop electrical charges at the particle - water-interface (Committee Report (1971)). The origin of these charges may be due to the dissociation of the ionizable groups of the colloid itself, or, to the absorption of low-molecular-weight ions onto its surface. As a result of this charge development a charge balance must be established in the vicinity of the colloidal particle to fulfill the requirement of electroneutrality. Helmottz (as reported in the Committee Report (1971)) considered the picture of the charge balance as two surface charges separated by fixed constant distance. The particles on the particle surface formed either the positive or negative portion, whereas the opposite charges (counter ions) in solution comprises the other portion. This oversimplified model was later modified by Gouy (1910) (Committee Report (1971)) by introducing the concept of the diffuse double layer to which Chapman (1913) applied poissoin's equation to find the equilibrium distance of the ions in the double layer (Committee Report (1971)). Ultimately Stern suggested an electrical double layer that combined the helmoltz fixed layer.

In this Stern-Gouy diffuse double layer model (as illustrated in Figure 2.1) part of the counter ions remain in a compact, stern layer, on the charged colloid surface as a consequence of strong electrostatic forces as well as Van der Waals forces. The other part of the counter ion extends into the bulk of the solution and constitutes the so called Stern-Gouy diffuse layer.

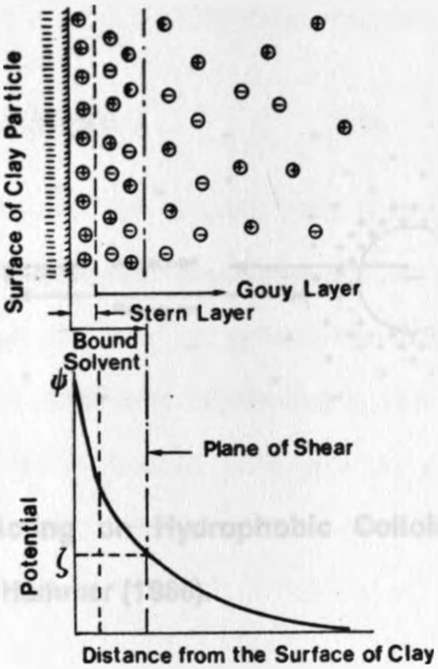


Fig. 2.1 **The Structure of the Stern-Gouy Double Layer and the Corresponding Potentials**
Source: Committee Report (1971)

2.1.4 Colloidal Stability

The term stability refers to the capacity of colloidal particles to remain dispersed as individual entities (Odira (1985)). According to Hammer (1986), hydrophilic colloids e.g. soap, soluble starch, synthetic detergents, and blood serum are stable because of their attraction to water molecules, and are therefore not easily coagulated. On the other hand, hydrophobic colloids, depend on electrical charge for their stability in suspension. The bulk of organic and inorganic matter in natural water is of this latter type. Forces acting on hydrophobic colloids are illustrated in Fig. 2.2.

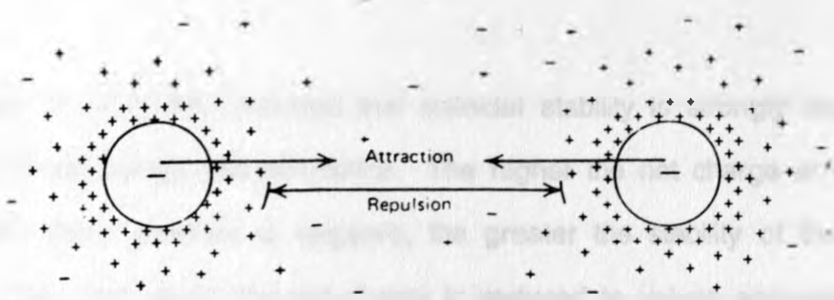


Fig. 2.2 **Forces Acting on Hydrophobic Colloids in Stable Suspension**
Source : Hammer (1986).

The individual hydrophobic particles are held apart by electrostatic repulsive force developed by adsorbed ions. The magnitude of the repulsive force developed by the charged double layer of ions attracted to a particle is referred to as zeta potential (Hammer (1986)). A natural force of attraction exists between any two masses (Van der Waals Forces). In quiescent conditions, Hammer (1986) suggested that colloidal suspensions remains dispersed indefinitely when the forces of repulsion exceed those of attraction and the particles are not allowed to contact.

The surface charge on colloidal particles is the major contributor to their long-term stability. Particles which might otherwise settle or coalesce are mutually repelled by their like charges. When two colloidal particles having the same sign of charge approach each other, the possibility of coalescence depends on the difference in their resultant Kinetic energy. The Kinetic energy can be supplied by either the Brownian movement or turbulent mixing, depending on the colloid size. In the Committee Report (1971) it is suggested that turbulent mixing provides driving force for destabilising colloidal systems of large size particles, whereas Brownian for small size particle.

Coalescence can thus be enhanced by reducing the resultant interaction energy, which is the net value of the coulombic electrostatic repulsive energy (Stumm and O'melia (1968)).

Posselt et al (1968) reported that colloidal stability is strongly dependent upon the colloids net-charge characteristics. The higher the net charge at the surface of the colloid, either positive or negative, the greater the stability of the colloid. Posselt concludes that when the net charge is reduced to values approaching zero, mutual repulsion of the particles is reduced sufficiently to permit interparticle collisions, agglomeration, and subsequent sedimentation. This phenomenon is illustrated in Fig. 2.3.

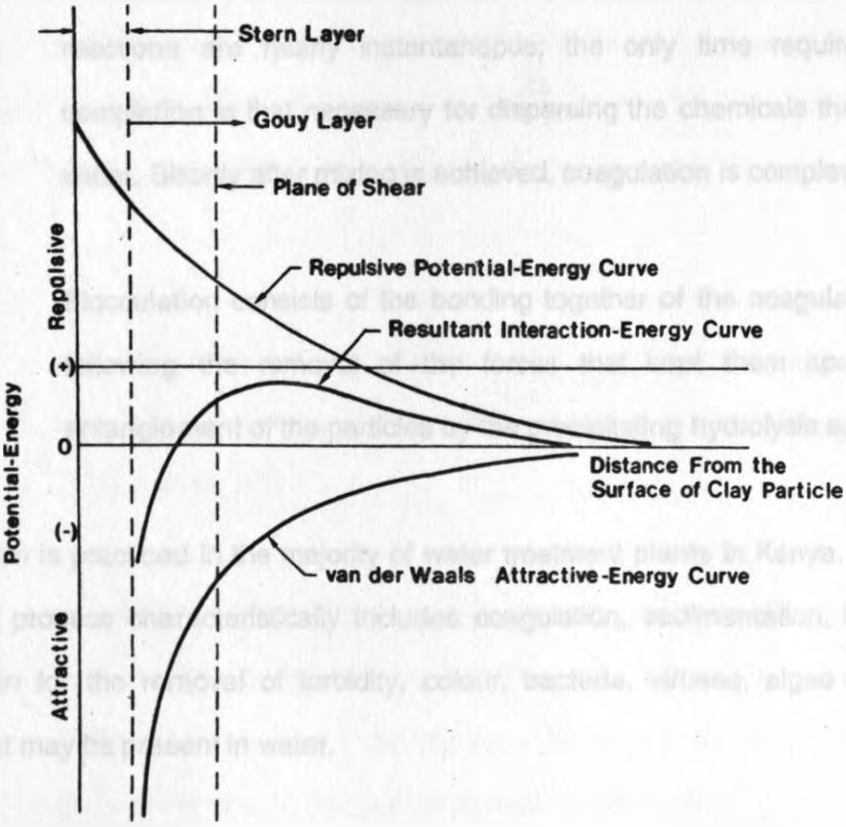


Fig. 2.3 Potential Energy of Interaction of Colloidal Particles

Source: Committee Report (1971)

2.2 Coagulation Theory

2.2.1 General

The terms coagulation and flocculation are often used interchangeably in many areas of chemical engineering practice. However, in the water treatment practice these terms are recognised to be separate and distinct although complementary, each describing a particular phase in the treatment of colloidal matter. Conley and Evers (1968) defined the process as follows:-

- Coagulation is the process of reducing the colloidal surface charge and the formation of complex hydrolysis and polymerisation species. These reactions are nearly instantaneous; the only time required for their completion is that necessary for dispersing the chemicals throughout the water. Shortly after mixing is achieved, coagulation is complete.
- Flocculation consists of the bonding together of the coagulated particles following the removal of the forces that kept them apart, and the entanglement of the particles by the precipitating hydrolysis species.

Coagulation is practiced in the majority of water treatment plants in Kenya. The overall treatment process characteristically includes coagulation, sedimentation, filtration and disinfection for the removal of turbidity, colour, bacteria, viruses, algae and organic debris that may be present in water.

2.2.2 History of Coagulation

The history of coagulation as given in the Committee Report (1971), dates from the early days of recorded history when various natural materials such as crushed almonds and beans in Egypt, nuts in India, and alum in China were used to clarify turbid waters. In these cases, the coagulation preceded sedimentation in a batch process - usually in jars or other earthen vessels for individual household consumption. In 1843 Simpson used alum experimentally in England prior to filtration, but this combination was not practiced municipally until after patent granted to Isaiah Hyatt in 1884 for the use of coagulant prior to rapid filtration. The Committee Report indicates that the first application was 1885 by the water companies of Somerville and Raritan in New Jersey. The report further records that the first scientifically performed study on coagulation was by Austern and Wilber in 1898 who suggested the use of alum prior to filtration.

2.2.3 Mechanisms and Stoichiometry of Coagulation

According to Posselt et. al,(1968) destabilisation of a colloid can be induced by one of the three primary physiochemical phenomena or (as is more often the case) by some combination thereof. Two of these are quite similar in mode of action and effect produced:

(i) reduction of surface potential by specific reaction of potential determining ions with the surface of the colloid, referred to as specific adsorption by Odira (1985), and

(ii) compression of the diffuse double layer and concomitant reduction of the zeta potential by inclusion of indifferent electrolytes. Posselt et. al,(1968) indicated that both of these reactions reduce the repulsive force between like - charged colloidal species to permit coalescence.

The third primary mechanism is the bridging of colloidal particles by either the attachment of polymeric species on two or more particles or by inclusion of particles in a floc mass. This latter mechanism is usually classified as flocculation.

The three mechanisms are now discussed in detail.

(a) Specific Ion Adsorption

According to the Committee Report (1971) specific ion adsorption occurs when the added coagulating agent is attracted to and adsorbed on the surface of the colloidal particles, thereby reducing the surface charge and the zeta potential. Particles may subsequently be joined by condensation - polymerization or normal aggregation.

Characteristics of this type of coagulation may be summarised as follows:-

(i) Partial, but not complete stoichiometry. Increased concentration of colloids, means increased surface area, requiring usually greater dosage of coagulant, but the relationship is not a direct proportionality (Posselt et. al,(1968).

(ii) Zeta potential is a controlling factor but dependent on adsorbality to reduce surface charge, rather than on general ionic strength (Committee Report (1971).

(iii) When excess ion adsorption takes place, the surface charge on the colloid will change sign. Eventually a colloidal restabilisation of particles with opposite sign of surface charge may occur (Barnes & Wilson (1983), Posselt et.al,(1968)).

(iv) The size and adsorbality of the coagulant ions is more important than the magnitude of their charge (Stumm and O'melia (1968)).

The mechanism, with small polymeric hydroxo aluminium and hydroxo-ferric ions acting as the specifically adsorbed species, is believed to be the principal mechanism operating to remove colour and turbidity in standard coagulation practice (Johnson and Amirtharajah (1983)).

Charge effects have some significance in connection with this type of coagulation. Stumm and O'melia (1968) have shown that the total adsorbability of an ion may be expressed as a molar free energy of adsorption, G, and may be represented by equation 2.1.

$$\Delta G^{\circ} = \Delta G^{\circ} + Z_{o}\, 2F\Delta\psi \; . \; . \; . \; . \; . \; . \; . \; . \quad (2.1)$$

where: ΔG° is the free energy for chemical adsorption

Z_{o} is the charge on the ion being adsorbed

F is Farady Constant of 96487 Coulombs MOL^{-1}, and

$\Delta\psi$ is the potential drop between the solution and the adsorption surface

Stumm and O'melia have shown that the overall term, ΔG°, must be negative for adsorption to occur. The more negative the value of ΔG°, the stronger the adsorption.

(b) Diffuse Double Layer Compression

This mechanism applies to the classical coagulation of colloids by simple ions. As stated in Section 2.1.3, classical colloidal particles are stabilised as a result of electrical charges at the surface of the particles which give rise to repulsive forces between them. As indicated in this section, repulsion is dependent on the zeta-potential, which is proportional to the product of the surface and the distance from the particle surface until surface charge has been neutralised in the bulk solution, the double layer thickness.

The effect of the added ions is primarily to reduce the double-layer thickness, the distance from the surface for charge neutralization. As this occurs, the zeta potentials of the particles are reduced correspondingly (Bames and Wilson (1983)). When a characteristic value for each type of colloid zeta potential is reduced, the repulsive forces are no longer great enough to keep the particles apart and coalescence occurs (Sawyer and McCarty (1967)).

Rubin and Blocksidge (1979) stated that the ability of simple counterions of the same charge to destabilize is directly related to their hydrated radius. However, They indicated that charge effects are more important, and ions of the same charge (i.e. co-ions) have very little effect.

(c) Molecular Bridging

Molecular bridging is a coagulation mechanism whereby the added chemicals, usually of large molecular size (e.g. polyelectrolytes), form bridges between the colloidal particles (Rubin and Blocksidge (1979)).

In its simplest form, according to Stumm and O'melia (1968), the chemical theory proposes that a polymer molecule can attach itself to the surface of a colloidal particle at one or more adsorption sites, with the remainder of the molecule extending into the solution. These extended segments may then interact with vacant sites on another colloid. Stumm and O'melia (1968) stated that each polymer molecule can have many functional groups that can potentially be adsorbed. They further stressed that increase in molecular weight usually leads to increase in the number and type of functional groups, hence, increase in the extent of adsorption.

In the bridging model, Stumm and O'melia (1968) indicated that:-

(i) Optimum destabilisation occurs when only a portion of the adsorption sites on the surface of the colloid are covered.

(ii) Polymer dosages that saturates the available surface of the dispersed phase produce restabilisation, because no sites are available for the formation of polymer bridges.

(iii) Under certain conditions, a destabilised suspension can be restabilised by extended agitation, due to the breaking of polymer surface bonds.

(iv) A direct relationship exists between the available surface area in the colloidal system and the amount of polymer required to produce optimum destabilisation.

Stumm and O'melia further indicated that molecular bridging between colloids is possible even if the polymer and the colloid are of opposite charge. Additionally, depending upon the forces responsible for polymer adsorption, the reduction in surface potential may either be the principal destabilisation mechanism or subsidiary to bridge formation.

2.3 Flocculation Kinetics

Destabilised primary colloidal particles can be induced to make contact with each other, thereby agglomerating into larger settleable particles. This inducement is the one referred to as the flocculation process.

According to Birkner and Morgan (1968), Smoluchowski (1917) published a mathematical theory for the coagulation Kinetics of colloidal suspensions. In this, Kinetic equations were presented to describe the rate of change in total particle concentration after the repulsive forces between similarly charged double layers surrounding the particles were reduced sufficiently to allow interparticle collisions. Smoluchowski developed two Kinetic equations. The first one described the Kinetic process when interparticle collisions occurred through Brownian diffusion of the individual colloidal particles. This is referred to as perikinetic flocculation. The second one, described the process when a laminar shear gradient cause particle transport at a point in a fluid. This is referred to as orthokinetic flocculation. Both these processes are described in the proceeding sections.

2.3.1 Perikinetic Flocculation

In this process, the joining together of the finely dispersed material after interparticle collisions have occurred owing to the random Brownian motion of the liquid molecules, implies that the colloidal particles have been destabilised and that the Van der Waals attractive forces predominate when the particles come close enough to interfere.

The rate of change in the number of particles due to Brownian motion were presented by Smoluchowski as shown in equation (2.2).

$$J_{ij} = \frac{2KT}{3\mu} (R_i + R_j) ({}^1/R_i + {}^1/R_j) N_i N_j \ . \ . \ . \ . \ (2.2)$$

where:	J	is the number of collisions
	R	is the particle radius
	N	is number of particles per unit volume
	K	is the Boltzmann constant
	T	is the absolute temperature
	μ	is the dynamic viscosity

the suffixes i and j indicate the number of primary particles comprising aggregates called i-fold and j-fold. For monosized spheres $(R_i + R_j)(^1/R_i + ^1/R_j) = 4$ (Swift and Freidlander (1964)). Hence, for total particle concentration N in time t:

$$\frac{dN}{dt} = J_{ij} = -\frac{4KT}{3\mu} N^2 \ldots\ldots\ldots\ldots (2.3)$$

which on integration gives:=

$$N_t = \frac{N_o}{1 + \frac{(4KTN_o)t}{3\mu}} \ldots\ldots\ldots\ldots\ldots (2.4)$$

where N_t and N_o are the number of particles present at time t = t and t = 0 respectively.

Odira (1985) records that equation (2.2) describes with sufficient accuracy the perikinetic flocculation even of heterogeneous suspensions.

2.3.2 Orthokinetic Flocculation

When the particles have aggregated to sizes larger than 1 µm, perikinetic flocculation ceases to be significant. Particle collision must then be induced by hydrodynamic movement, causing relative motion to the particles (Odira (1985)). This process is the one referred to as orthorkinetic flocculation.

The mathematical model developed by Smoluchowski (1917) in this case is described by equation 2.5.

$$b_{ij} = \frac{4\,(^{dv}/_{dz})}{3}\,(R_i + R_j)^3 N_i N_j \ldots\ldots\ldots (2.5)$$

in which b_{ij} is particle collision frequency, $^{dv}/_{dz}$ is laminar velocity gradient.

N, R and the suffixes $_i$ and $_j$ are as defined in Section 2.3.1.

Theories governing flocculation in conventional water treatment systems are fairly well known and the ranges of operating parameters like mean velocity gradient and residence time are easily obtainable by mathematical modelling and experimentation. For example, in practice the energy dissipated in shearing forces in the liquid is a controlling factor in the growth of flocs. The energy dissipated is usually related to the root mean shear rate G (S^{-}) (Barnes (1983)), given by equation 2.6.

$$G = \left(\frac{P}{\mu v}\right)^{1/2} \ldots\ldots\ldots\ldots\ldots\ldots\ldots (2.6)$$

where v is the tank volume, μ is dynamic viscosity and P is the power input.

2.4 Coagulants

2.4.1 Metallic Coagulants

According to Hammer (1986) the hydrolysing metal ions Fe (III) and Al (III) are the most common coagulants for water treatment. These includes:

(i) those based on aluminium, such as aluminium sulphate, sodium aluminate, potash alum, and ammonia alum, and

(ii) those based on iron, such as ferric sulphate, ferrous sulphate, chlorinated ferrous sulphate, and ferric chloride.

For the purpose of this study, details of aluminium sulphate and ferric chloride shall be of major interest. Both of these metal ions undergo relatively extensive hydrolysis and polymerisation in aqueous solution to yield a broad spectrum of charged species of different molecular size and charge density. Posselt (1968) stated that the nature of the predominant hydrolysis and polymerisation species formed is strongly dependent upon pH, other factors being constant. Posselt indicated that at low pH values positively charged species exist, whereas increase in pH leads eventually to the formation of negatively charged metal hydroxo polymeric form.

(a) Hydrolysis Equations

Hydrolysis of iron (III) and aluminium (III) to yield a variety of hydrolysis products has been studied by many investigators to explain solution properties (Licsko (1976), Oehler (1963), Yao (1967).

The reactions involved in chemical coagulation are essentially the same for both ferric and aluminium salts (Sawyer and McCarty (1967)). Aluminium sulphate usually called filter alum ($Al_2(SO_4)_3$ $14H_2O$), is the most commonly used (Cox (1969)). Additionally, since its reactions are almost similar to ferric salt reactions, its action will be discussed here.

The hydrolysis of aluminium ion in solution is complex and is not fully defined. In the hypothetical coagulation equations, aluminium floc is written as $Al(OH)_3$ Hammer (1986). This is the predominant form found in dilution solutions, near neutral pH in the absence of complexing anions other than hydroxide. McGhee (1991) and Committee Report (1971) have described the hydrolysis reactions as follows:-

Dissolution

$Al_2(SO_4)_3 \quad + \quad (H_20) \rightarrow 2AL^{3+} + 3SO_4^{2-}$ . . . (2.7)

Hydrolysis

$AL^{3+} + H_2O \rightleftharpoons ALOH^{2+} + H^+$ . . . . (2.8)

$ALOH^{2+} + H_2O \rightleftharpoons AL(OH)^+_2 + H^+$ . . . . (2.9)

$AL(OH)_2^{2+} + H_2O \rightleftharpoons AL(OH)_3 + H^+$ . . . . (2.10)

$AL(OH)_3 + H_2O \rightleftharpoons AL(OH)_4^- + H^+$ . . . .(2.11)

(b) Polymerisation

Polymerisation of the hydrolysis products in (a) to yield polynuclear species has been postulated by many investigators (Stumm and Morgan (1962), Matijevic et.al,(1961). Licsko (1976) reported that, Stumm and Morgan (1962); Hahn and Stumm (1967); Oehler (1963); Yao (1967), have studied the structure of the metal hydroxides formed in the course of clarification. In their opinion the metal hydroxides formed constitute a multi-nucleus complex in which the ratio of metals to hydroxides is slightly greater than 1:3. This is in agreement with the most widely accepted form of the complex ions suggested by Brosett et al (1954), the composition of which could be described by the formula $AL_x(OH)_{2.5.x}^{0.5x+}$

Matijevic et.al,(1961) have assumed the formation of $AL_8(OH)_{20}^{4+}$. According to Licsko (1976) the presence of complex $AL_{13}[O_4(OH)_{24}\ (H_2O)_{12}]^{7+}$ has been reported by Rausch and Bale (1964).

The net effect of metallic coagulant addition is seen to be the formation of large, insoluble, positively charged particles and production of free hydrogen ion from the water involved in the hydrolysis. This complex process is frequently represented by the simplified equation (2.12).

$$AL_2(SO_4)_3 + 6H_2O \rightarrow 2AL(OH)_3 + 3H_2SO_4 \ldots\ldots\ldots \quad (2.12)$$

The polymeric species formed and the effectiveness of coagulation depend on both the concentration of the coagulant and the properties of the solution to which it is applied.

Barnes & Wilson (1983) stated that coagulation with Fe (III) and Al (III) salts may be brought about by one, or a combination of the following mechanisms:-

(i) reduction of the zeta potential by adsorption of ions or complexes of opposite charge to the colloid;

(ii) compression of the double layer, thus enabling the coalescence energy barrier to be lowered;

(iii) Scavenging or enmeshment of colloids in a hydroxide floc, including the effect of increasing the floc volume fraction.

2.4.2 Polymers (Polyelectrolytes)

Synthetic polymers are long-chain high molecular - weight organic chemicals that have a strong tendency to adsorb on the surfaces of particles in an aqueous suspension. According to the Committee Report (1971), a polymer molecular is defined as a series of repeating chemical units (known as monomers) held together by covalent bonds.

Letterman and Pero (1990) described four major classes of polymers according to the type of charge on the polymer chain in aqueous solution:

(i) Cationic - those possessing a positive charge
(ii) Anionic - those possessing negative charges
(iii) Ampholytic - those that are both positively and negatively charged
(iv) Nonionic - Possess no ionizable functional groups.

The two researchers further indicated that the overall charge on the molecule is a function of the pH and ionic strength of the solution.

Polyelectrolytes have been used extensively in water and waste water treatment as primary coagulants, coagulant aids, filter aids and as sludge conditioners (Loganathan and Maier (1975). A list of some of the polyelectrolytes accepted for use in drinking water treatment by USEPA is given by Letterman and Pero (1990).

Laboratory studies by Beardsley (1973), that compare the effectiveness of cationic, anionic, and nonionic polymers indicate that of the three polymer group tested cationic polymers consistently achieve superior turbidity removal. Leu and Ghosh (1988) stated that when ionic or nonionic polymers are used as primary coagulants, a minimum molecular weight is necessary for the molecules to bridge the potential energy barrier between two negative colloids. The minimum size depends upon the number of charged groups and the degree of branching of the polymers, the charge on the colloidal particles and the ionic strength of the solution (Stumm and Morgan (1962)). Positively charged cationic polymers can function as destabilising agents by bridge formation, charge neutralisation, or both (Leu and Ghosh (1988).

2.4.3 Use of Polyelectrolytes In Water Treatment

(a) Coagulant Aids

Difficulties with coagulation often occur because of slow settling precipitates, or fragile flocs that are easily fragmented under hydraulic forces in basins and sand filters. Polyelectrolytes as coagulant aids benefits flocculation by improving settling (by acting as weighting agents) and toughness of flocs (Hammer (1986)). Additionally increased reaction rate, reduced coagulant dose, and extended optimum pH ranges of coagulation are obtained (McGhee (1991)). Thus, when used as coagulant aids polyelectrolytes do not aid coagulation, but rather in the subsequent flocculation of the destabilised particles. Bridging of primary flocs, is therefore, the most dominating mechanism when polyelectrolytes function as coagulant aids.

(b) Sludge Conditioner

In Kenya, waste generated in water treatment plants is usually disposed back to the rivers downstream of the intake. Sabaki Water Works is not an exception to this. Considering the growing global environmental conservation concern, treatment works will be forced to use alternative means of waste disposal. This will in effect force treatment works engineers to emphasise on volume and quality of sludge produced when choosing coagulants.

Alum, the coagulant in use in many treatment plants, produces a voluminous sludge that can be difficult to dewater (Carol and O'melia (1982)). Polymers may be used as either total or partial replacement for metal ion coagulants so as to reduce sludge volume. Carol and O'melia further reported that, for an alum to polymer ratio requirements of 50:1 for several waters , sludge production ratio was found to be 7:1. Barnes and Wilson (1983) indicated that use of polyelectrolytes produces sludge which is highly compressible. Hammer (1986) has also indicated that polyelectrolyte sludges are relatively dense and easier to dewater, unlike the gelatinous and voluminous aluminium hydroxide sludges. While stressing the need for focusing current research on polyelectrolytes Kawamura (1976) stated that, polyelectrolytes are advantageous in that:

(i) they reduce the sludge volume produced during treatment, and

(ii) improve the sludge dewatering process compared to alum or ferric salts.

(c) Filter Aid

Polymers are often applied just before granular bed filtration or added to backwash water to improve process performance. Letterman & Pero (1990) indicated that polymer aids are essential in high-rate filtration plants.

Loganathan and Maier (1975) emphasised that cationic polymers enhance turbidity removal when used to pretreat sand, diatomite, and glass bead filters. They further indicated that increased turbidity removal with cationic polymers could be attributed to electrostatic attraction and attachment of negatively charged turbidity particles to the positively charged (polymer treated) filter. Nonionic polymers have been shown to increase turbidity removal in filtration when dosed to the filter influent or when the filter media is pretreated by adding the polymer to the backwash water.

In their study, Loganathan and Maier (1975) reported that bridging mechanism, where suspended colloidal particles are captured by bridging to the polymer attached to the filter media extending its branch like structure into the water phase and traps particles, as the primary mechanism in polymer aided filters.

(d) Primary Coagulants

Many researchers have shown that polyelectrolytes can be used as full substitutes of metallic coagulants (Letterman and Pero (1990), Leu and Ghosh (1988)). Letterman and Pero (1990) stated that cationic polyelectrolytes are often referred to as primary coagulants, whereas nonionic and anionic polyelectrolytes are referred to either as coagulant aids or flocculants.

According to Barnes & Wilson (1983) the mode of action of the polymers is thought to be modelled accurately by an adsorption isotherm of the Langmuir type. For example,

$$\theta = \beta P_1 (1 - \beta P_1) \ldots\ldots\ldots\ldots\ldots (2.13)$$

where θ is the fraction of particle surface covered by polymer, β is a constant and P_1 is the equilibrium polymer concentration.

Leu and Ghosh (1988) stated that four principal mechanisms for adsorption exists. These are:

(i) electrostatic interactions between the ionised polymer and the charged particle surface;

(ii) hydrogen bonding;

(iii) hydrophobic bonding; and

(iv) specific adsorption.

Leu and Ghosh further stressed that the principal mechanisms appear to be bridging and charge neutralisation.

For a polymer to be useful as a destabilizing agent, it must adsorb on the suspended particles to be removed. When the polymer and the particles are opposite in charge, e.g. negatively charged suspended particles in the surface water and a cationic polymer, adsorption of the polymer can neutralise the charge on the particles (Sandell and Luner (1974)). In such situations, molecular weight may not be an important factor and polymers with lower molecular weights can be used. Letterman and Pero (1990) stressed that if too much polymer is added to a suspension, the overall surface charge may become positive. This occurrence known as restabilisation may adversely affect coagulation.

When simple charge effects are not significant, polymers must then bridge the small region between the particles, within which these particles repel each other. In this instance, polymers must be large enough to form the bridge. Therefore, in such instances, the high - molecular - weight polymers are preferable. The theory behind molecular bridging has been covered in Section 2.2.3 and is applicable to polyelectrolytes.

Studies conducted by Moffet (1968) have shown that polyelectrolytes may assume a flat configuration on the particle surface on account of the strong electrostatic repulsion between charged segments. This implies that, long loops extending into the solution are absent and bridging may not occur. Leu and Ghosh (1988), La Mer and Healey (1953) reported that the concentration of polymer needed for optimum flocculation is inversely proportional to its molecular weight.

2.4.4 Advantages of Polyelectrolytes over Metallic Coagulants

Correl and Robinson (1974), Kawamura (1967), Kavanaugh (1978), McGhee (1990), Hammer (1986), established that:-

(i) Large quantities of alum are required to treat highly turbid waters. Additionally, alum is acidic in nature, hence, soda ash or lime feed must be increased with alum dose increase to maintain desired pH. Polyelectrolytes do not alter the solution pH, hence, no correction is needed.

(ii) Polyelectrolytes improve sludge dewatering process compared to alum or ferric salts.

(iii) Polyelectrolytes reduce sludge volume produced during treatment, unlike the voluminous alum hydroxide sludge.

(iv) Polyelectrolytes prove effective in very small amounts, thus reduced costs in transport, storage, and dosing.

(v) Polyelectrolytes are effective over a wide pH range.

(vi) Polymer treatment in addition to removing organic substances from raw water, reduces the breakpoint chlorination process by more than half of that used during alum treatment.

2.4.5 Disadvantages of Polyelectrolytes

Kawamura (1991) & Leslie et-al,(1982) recorded that:-

(i) Polyelectrolytes exhibit a significant degree of selectivity to certain types of colloids.

(ii) Though they form large and strong flocs, polyelectrolytes do not produce a clear supernatant, because they are generally incapable of enmeshing all of the colloidal particles in raw water.

(iii) Unit cost for polymer is usually much higher than for alum or ferric chloride.

(iv) Most polyelectrolytes are nonbiodegradable.

(v) There exists some uncertainty about their long range toxicity, carcinogenicity, and mutagenicity for humans.

2.5 Variable Parameters of Concern

It is reported that the coagulation/flocculation process is very sensitive to many variables, for instance; temperature, type and dosage of coagulant, the nature of the turbidity producing substances, pH and alkalinity of the water (Maudling and Harris (1968), Carnduff (1976), Amirhor and Engelbrecht (1975)). For the purpose of this study the significance of pH and alkalinity as related to water treatment will be discussed in the next two sections.

2.5.1 Significance of pH in Water Treatment

The intensity of acidity or alkalinity of a sample is measured on the pH scale which is a way of expressing the hydrogen ion concentration. In the field of water supply, it is a factor that must be considered in chemical coagulation, disinfection, water softening, and corrosion control among others.

The importance of pH in the overall water treatment process and especially in coagulation cannot be over emphasised, since together with other solution variables determine the chemical species of the coagulant being added to water (Dentel and Gossett (1988). Maudling and Harris (1968) stated that the efficiency of the coagulation and flocculation process is markedly dependent on pH, and it is standard practice in water treatment to adjust pH so that optimum floc formation is achieved.

Jeffcoat and Singley (1975) reported that when lime is added before alum, the pH is raised to such a point that when alum is added, the optimum coagulation pH results. These researchers further noted that the optimum pH for coagulation increased with alum dose increase.

Sawyer and McCarty (1967) indicated that pH of the water is important in determining which particular hydrolysis species is predominant, lower pH values favouring those with positive charge. The researchers further stated that complexes of highest positive charge are most effective in increasing both the extent and rate of coagulation. Amirtharajah and Mills (1982) observed that the concentration of the various AL(III) hydrolysis species can be controlled by the final concentration of H^+ ions, i.e. by the pH. Amirtharajah and Mills also noted that the mechanism of coagulation with alum is strongly governed by the pH of the solution.

While demonstrating the importance of pH in coagulation Kawamura (1976) has shown that alum and ferric salts precipitate and coagulate with minimal solubility at certain pH ranges. Solubility curves in certain pH ranges for both alum and ferric hydroxides have been shown by Sawyer and McCarty (1967) (See Fig. 2.4). From these curves it is observed that at pH below 4 for ferric and 5 for alum it is not possible to ensure complete precipitation of these coagulating ions.

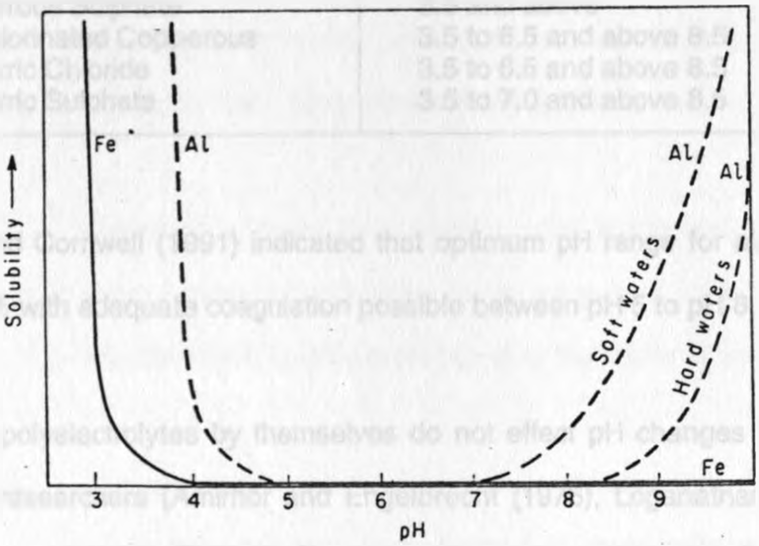


Fig. 2.4 **Solubility Curves for Ferric and Aluminium Hydroxides. Source: Sawyer and McCarty (1967)**

Optimum pH for coagulating with alum and ferric salts have been found to vary in different waters. This could be attributed to the difference in the colloidal properties of the particulate matter. This implies that it is necessary to obtain the optimum pH for the particular water being dealt with. Negatively charged colour colloids are coagulated most effectively at pH ranges 4.4 - 6.0 (Cox (1969)). Camduff (1976) noted that difficulties in coagulating with alum are particularly noticeable when the raw water pH exceeds 8.3

Typical optimum pH ranges for various metallic coagulants are outlined in Table 2.2.

Table 2.2 Typical Optimum pH Ranges for Various Metallic Coagulants Source: McGhee, (1991)

Coagulant	pH Ranges
Alum	4.0 to 7.0
Ferrous Sulphate	3.5 and above
Chlorinated Copperous	3.5 to 6.5 and above 8.5
Ferric Chloride	3.5 to 6.5 and above 8.5
Ferric Sulphate	3.5 to 7.0 and above 8.5

Davis and Cornwell (1991) indicated that optimum pH range for alum is approximately 5.5 to 6.5 with adequate coagulation possible between pH 5 to pH 8.

Though polyelectrolytes by themselves do not effect pH changes (Kawamura (1976)), several researchers (Amirhor and Engelbrecht (1975), Loganathan and Maier (1975)) have shown that the efficiency of polyelectrolyte in coagulation is a function of pH.

While studying the effects of pH on virus removal using a synthetic cationic polyelectrolyte, Amirhor and Engelbrecht (1975) observed that the extent of virus removal decreases as the pH of the suspending medium increases. They attributed this behaviour to a decrease in the positive charge density of the polyelectrolytes with an increase in the pH of the solution. Loganathan and Maier (1975) indicated that most commercially available polyelectrolytes used in water treatment have functional groups such as -COOH, -NH_2 and -OH. These groups are known to change their ionic character with pH. Hanson and Cleasby (1990) also emphasised that the monomer units in the polymer may have positively or negatively charged sites, and that, the overall charge, on the molecule is a function of pH and ionic strength of the solution. Therefore, pH is an important variable when considering the efficiency of polyelectrolytes in coagulation.

Carol and O'melia (1982) noted that when using a combination of alum and a polyelectrolyte, the order of chemical addition was important. Good results were obtained by adding alum first, followed by the polymer. This could be attributed to the effect of pH lowering to optimum pH range for the polyelectrolytes (since alum dosage lowers the pH).

Corrosion in water mains and water treatment plants can be a large economic burden. Kirmeyer and Logsdon (1983) listed the following problems caused by corrosion:

(i) Corrosion of materials in plumbing and distribution systems increases the concentration of hazardous material e.g. lead, cadmium, and other heavy metals, which could adversely affect the health of consumers.

(ii) Contaminants such as copper, iron, and zinc are also leached and may affect the aesthetics of the water (e.g. taste, colour or staining character) which is undesirable by consumers.

(iii) Deterioration of plumbing and distribution systems because of corrosion resulting in extensive and costly replacement.

pH is a major tool in corrosion control. Kirmeyer and Logsdon (1983) indicated that low pH favours corrosion. Langelier developed corrosion index determined from the pH value of the water from which the possibility of corrosion can be assessed (Barnes & Wilson 1983). If the index is negative calcium carbonate will dissolve, if positive calcium carbonate will deposit hence prevent corrosion. The role of pH in the corrosion of metals used in water distribution system has been summarised by Drane (WHO 1984, Vol 2).

pH is related in several different ways, to most water quality parameters as aqueous chemical equilibrium invariably involve hydrogen (and hydroxyl) ions.

A direct relationship between human health and the pH of drinking water is not easy to ascertain because pH is so closely associated with other aspects of water quality (WHO 1984, Vol 2). However, its importance could be appreciated on noting the effects of pH on disinfection efficiency. Additionally, while considering the optimisation of chemicals used in the coagulation/flocculation process it is also important to identify the implications on the subsequent treatment processes.

The germicidal efficiency of chlorine in water depends on the equilibrium of the hypochlorous acid and the hypochlorite ion. The efficiency is lower at high pH values, this being attributed to the reduction in hypochlorous acid concentration with increasing pH (Culp and Culp (1974)).

The reaction of chlorine when dissolved in water is as shown in equation 2.17.

$$Cl_2 + H_2O \rightarrow HOCl + HCl \,.\,.\,.\,.\,.\,.\,.\, (2.17)$$

the hypochlorous acid formed dissociates as shown in equation 2.18.

$$HOCl \rightleftharpoons H^+ + OCl^- \,.\,.\,.\,.\,.\,.\,.\,.\,.\,.\,. (2.18)$$

The hypochlorite ion and the hypochlorous acid are the actual disinfectant. From equation 2.18, it can be observed that increase in pH favours increases of OCl^- (Le Chartelier principle). The relative amounts of HOCl and OCl^- formed at various pH levels is given in Fig. 2.5.

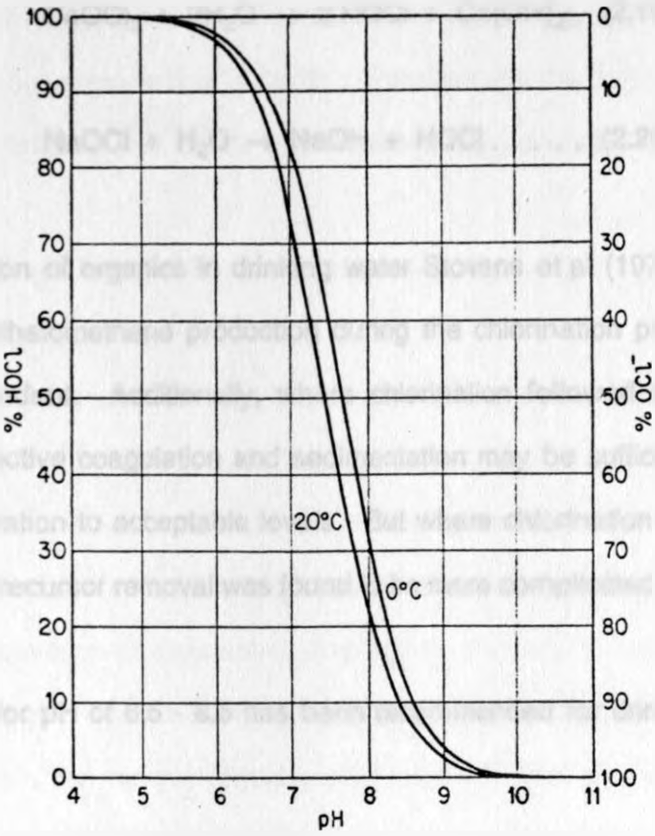


Fig. 2.5 **Relative Amounts of HOCl and OCl^- Formed at Various pH Levels**
Source: (Culp and Culp (1974))

From Figure 2.5 it can be observed that the relative amounts of HOCl and OCl^- existing at equilibrium is greatly influenced by the resultant pH. Culp and Culp (1974) reported that, the HOCl form is considered to be a far more effective disinfectant than OCl^-. They further indicated that HOCl had been found by several investigators to be 70 - 80 times bactericidal as OCl^-. Hence, increasing the pH reduces the germicidal efficiency, because most of the free chlorine exists as the less microbiocidal OCl^- at the higher pH levels. Similar observations can be made when using other disinfectant (e.g. tropical chloride of lime ($CaOCl_2$) and sodium hypochlorite (NaOCl). This is simply because the hypochlorous acid derived from their reaction with water behaves in a similar manner.

$$CaOCl_2 + 2H_2O \rightarrow 2\,HOCl + Ca(OH)_2 \quad . \; (2.19)$$

$$NaOCl + H_2O \rightarrow NaOH + HOCl \quad . \; . \; . \; . \; . \; (2.20)$$

Studying chlorination of organics in drinking water Stovens et al (1976), observed that the precursor to trihalomethane production during the chlorination process of drinking water is pH dependent. Additionally, where chlorination followed clarification at pH values near 7, effective coagulation and sedimentation may be sufficient to reduce the precursor concentration to acceptable levels. But where chlorination is carried at high pH, treatment for precursor removal was found to be more complicated.

A guideline value for pH of 6.5 - 8.5 has been recommended for drinking water (WHO (1984), Vol. 2).

2.5.2 Significant of Alkalinity in Water Treatment

Alkalinity of a water is a measure of its capacity to neutralise acids, or else to absorb hydrogen ions without significant pH change (Hammer 1986). Alkalinity in natural waters is usually attributed to hydroxide ions or carbonic species. The carbonic species will be present from the dissolution of carbonate minerals (e.g. limestone contains very high proportion of carbonate), while hydroxide ions are generated in some biological and chemical processes and are present in some industrial waste water (Barnes & Wilson (1983)). In coagulation, chemicals react with water to form insoluble hydroxide precipitates. For example aluminium sulphate added to water reacts in the manner shown in equation 2.23

$$Al_2(SO_4)_3 + 6H_2O \rightarrow 2Al(OH)_3 + 6H^+ + 3SO_4^{2-} \; . \; . \; . \; . \; (2.23)$$

The hydrogen ion released depresses the pH to the extent of preventing further $Al(OH)_3$ formation (Le Chatelier's principle). This renders the coagulation process inefficient, not unless, the H^+ ions are removed from solution. Bicarbonates present in the natural water acts as a buffer by reacting with H^+ ion in accordance to equation 2.24.

$$HCO_3^- + H^+ \rightarrow H_2CO_3 \rightarrow CO_2 + H_2O \ldots\ldots (2.24)$$

(The bicarbonate ion represent the alkalinity of water (Sawyer and McCarty (1967)).

Alkalinity must therefore be in excess of that destroyed by the acid released by the coagulant for effective and complete coagulation to occur. It may therefore be necessary to add alkalinity in the form of soda ash or limefeed to complete the coagulation process. To serve this purpose the alkalinity is added before alum dose, and is deemed necessary only when the natural alkalinity falls below 20 mg/l as $CaCO_3$ (Babbitt and Donald (1955)). Theoretically, about 1.0 mg/l of alum would require 0.5 mg/l of alkalinity (Hammer (1986).

Alkalinity is an important parameter in corrosion control. Calcium carbonate deposition may control corrosion. The rate of corrosion is inversely proportional to the alkalinity of the water (Cox 1969)). Hard water tends to precipitate Calcium Carbonate during distribution, as such, a film of Calcium Carbonate is formed on the metal surface preventing corrosion of the underlying metal (Barnes & Wilson (1983)). Excessive deposition of calcium carbonate is detrimental and may reduce the pipe carrying capacity. The Langelier index (Section 2.5.1) is used to predict the stability of water to deposit or dissolve calcium carbonate. This is applicable for pH ranges 6.5 to 9.5 (Hammer (1986)).

For corrosion control (by eliminating aggressive carbon dioxide) a minimum alkalinity value of 40 mg/l as $CaCO_3$ has been given by Hammer (1986). Hammer further mentions that this value will depend on the concentration of other ions present. Schock and Marvin (1983) found out that alkalinity as low as 30 mg/l as $CaCO_3$ was adequate for lead corrosion control. Cox (1969) recommends a minimum alkalinity value of 30 mg/l as $CaCO_3$ for corrosion control.

Alkalinity is also an important consideration in the lime/soda calculations for water softening. Lime reacts with bicarbonate alkalinity converting it to carbonate alkalinity. The carbonate ion combines with the calcium to form $CaCO_3$ (Sawyer and McCarty 1967).

Cox (1969) indicated that waters of low alkalinity are easily disinfected. The titration curve for a hydroxide-carbonate mixture is shown in Fig 2.6.

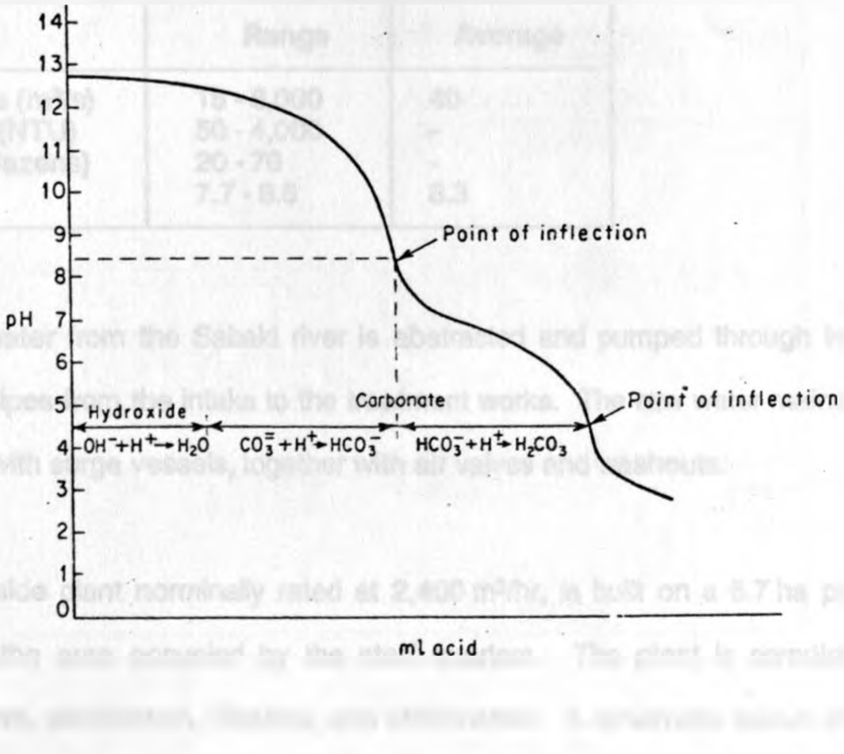


Fig. 2.6 **Titration curve for a hydroxide-carbonate mixture**
Source: Sawyer and Mc Carty (1967)

CHAPTER THREE

BACKGROUND TO THE TREATMENT PROCESS

3.1 General

The Sabaki Water Works is situated near Baricho 40 km west of Malindi town. The raw water is abstracted from Sabaki river. The flows in the Sabaki originate almost entirely from the Tsavo and Athi rivers upstream, whose runoff characteristics vary widely depending on the season. The river is very active regarding sediment transport and widely varying discharges. Some characteristics of the Sabaki river waters are shown in Table 3.1

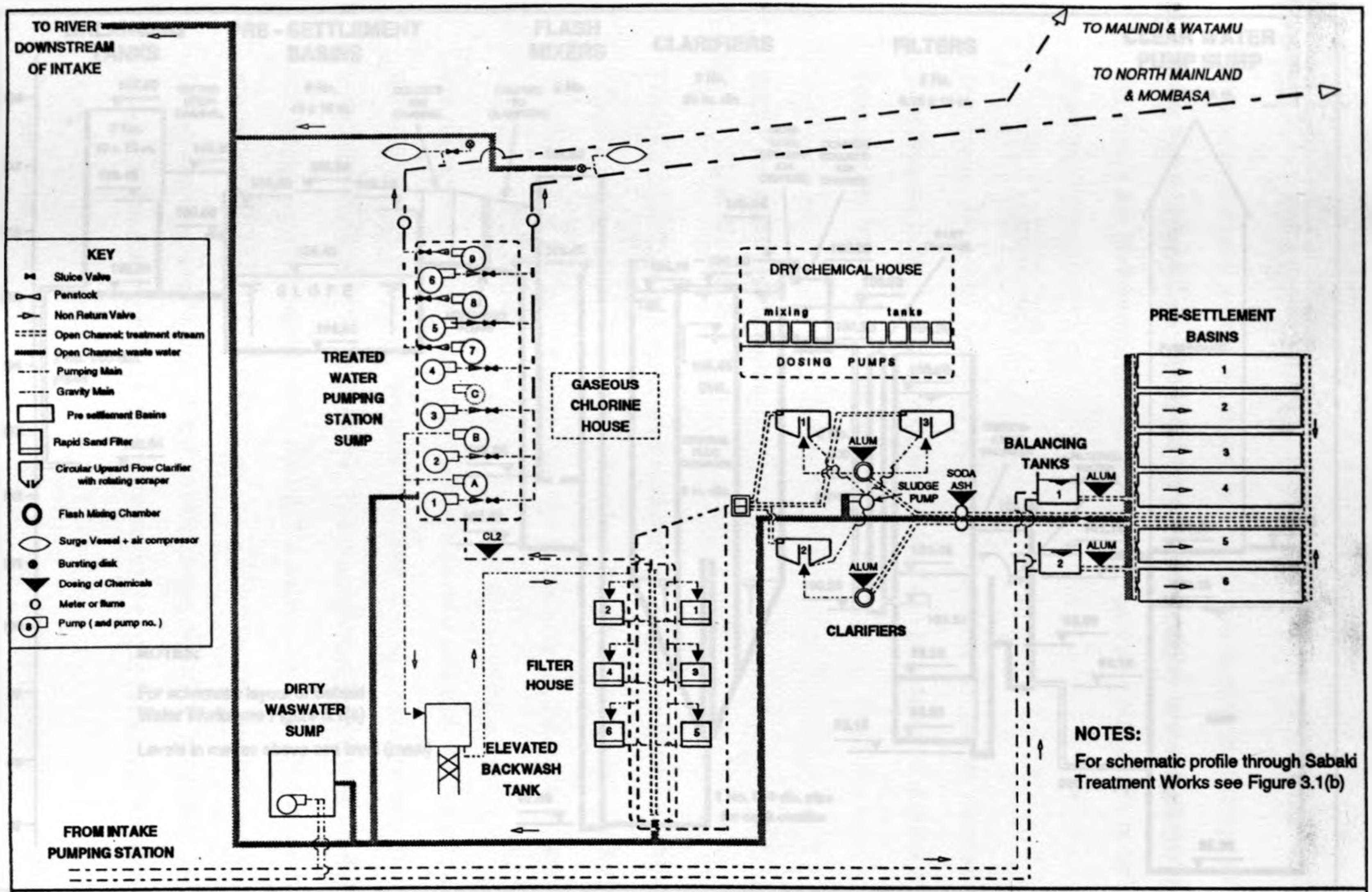
Table 3.1 **Characteristics of the Sabaki River Waters**
Source: Existing Data (1984 - 1992)

	Range	Average
Discharge (m^3/s)	15 - 8,000	40
Turbidity (NTU)	50 - 4,000	-
Colour (Hazens)	20 - 70	-
pH	7.7 - 8.6	8.3

The raw water from the Sabaki river is abstracted and pumped through twin 600 mm diameter pipes from the intake to the treatment works. The raw water mains have been equipped with surge vessels, together with air valves and washouts.

The river side plant norminally rated at 2,400 m^3/hr, is built on a 6.7 ha piece of land excluding the area occupied by the staff quarters. The plant is complete featuring pretreatment, clarification, filtration, and chlorination. A schematic layout and profile of Sabaki Water Works is as shown in Fig. 3.1 (a) and (b) respectively.

The general staff consists of 20 trained personnel and 43 untrained staff. The plant is operated 24 hrs/day. Operating staff works 8 hr rotating shifts.

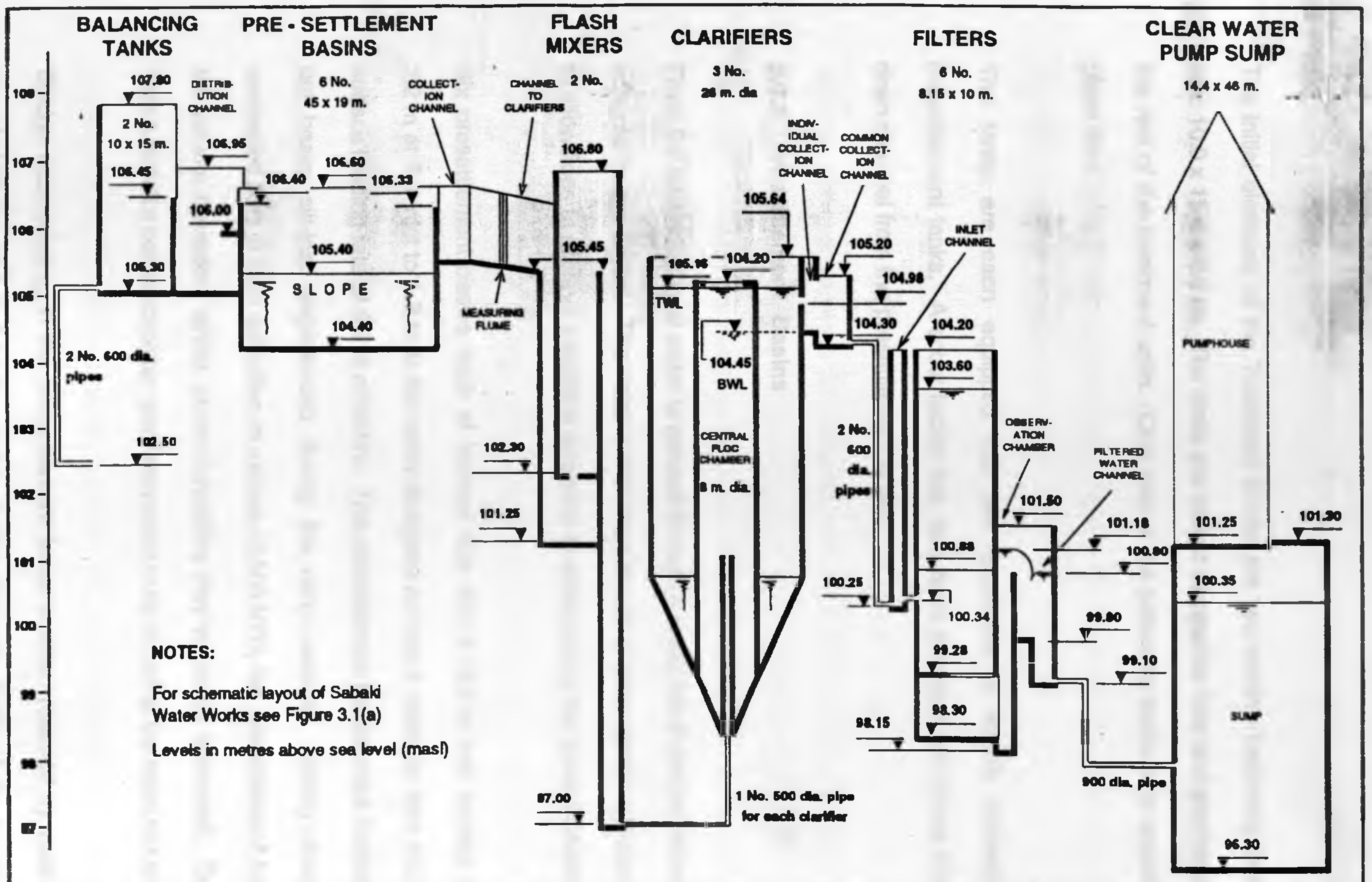


NOTES:

For schematic profile through Sabaki Treatment Works see Figure 3.1(b)

FIGURE 3.1(a) SCHEMATIC LAYOUT OF SABAKI WATER WORKS

NOT TO SCALE



NOTES:

For schematic layout of Sabaki Water Works see Figure 3.1(a)

Levels in metres above sea level (masl)

FIGURE 3.1(b) SCHEMATIC PROFILE THROUGH SABAKI TREATMENT WORKS NOT TO SCALE

3.2 Unit Operations and Processes

3.2.1 Balancing Tanks

The initial elements of the Treatment Works are two number balancing tanks each of size 10.0 x 15.0 x 2.5 m. The tanks are meant to equalise flow and provide a "head" to the rest of the treatment units. Only one of the balancing tanks is in operation at any given time.

The tanks are each equipped with two penstocks to enable bypassing of the presettlement tanks. A scour facility has also been provided and drains into the open drain channel from the presettlement tanks.

3.2.2 Presettlement Basins

From the balancing tank water is passed through a rapid mix chamber, where chemical coagulants are dosed. The water is then lead though a "slow speed agitation" channels to allow flocs to achieve a suitable size prior to settlement in the presettlement basins.

Six presettlement basins each of internal size 45.0 x 19.0 m and varying depth from 2.2 m at the inlet to 1.2 m at the outlet designed to have a retention time of 2 hours at a surface loading rate of 0.468 $m^3/m^2/hr$. The presettlement basins were intended to settle out heavy silt-load experienced during the rainy season. During design, it was envisaged that at high turbidities in excess of 500 NTU, the presettlement basins would be put into operation, whilst, at low turbidities they would be bypassed. During these high turbidities polyelectrolytes were supposed to be dosed at the rapid mix chamber.

Sludge accumulating in the presettlement tanks is often reduced by opening a gate provided at the inlet and joining to the sludge channel. Each of the six presettlement basins is equipped with a fire hydrant (F.H.). These are used for sludge removal and thorough cleaning of the basins. This is accomplished by opening the sludge gates at the inlet and directing jets of water to the sludge.

3.2.3 The Clarifiers

From the presettlement basins the water flows into the presettled water open channels, and each is lead into separate flash mixing compartment for secondary coagulation before flowing into the clarifiers.

The channels are 1.2 m wide and are provided with interconnecting penstocks for flow control to the flash mixers. Along the channels, two venturi flumes (non-operational) equipped with a kent meter flow integrator intended for flow measurements have been provided. Just after the venturi flumes, chemical feed lines from the chemical house for soda ash dosing in the event of low presettled water alkalinity are provided. Overflow facilities are also provided for each channel into the sludge drainage.

Two flash mixers equipped with an electrically driven stirrer to serve the three clarifiers are installed for alum mixing. Alum is fed from the chemical house as the water enters each flash mixer.

The clarifiers are of the upward flow type with an overall diameter of 26.0 m. The coagulated water from the flash mixer is fed via a 500 mm diameter pipe into the central compartment of the biflocculators (floc chamber) wherein two variable speed stirrers with a rotational speed of 4 rpm gently stir the coagulated water for bigger floc formation (flocculation). A motorised rotating bridge structure fitted with a plate walkway, handrailing, central bridge support column and scraper have been installed. The purpose of the rotating bridge structure is to continuously scrape the sludge produced and direct it to the centre of the clarifier, for continuous drain off, via a 200 mm diameter sludge drain to a collector sump fitted with a submersible pump. The submersible pump lifts the sludge to the sludge drain next to the chamber.

The clarified water is discharged from the biflocculators through a series of orifices set into the concrete wall, and enters a peripheral clarified water collector for onward transmission to the clarified water channels and ultimately to the filters.

3.2.4 The Filters

Six rapid flow sand filters of the declining rate type are provided for the works. Each of the filters was designed to handle 375 m^3/hr. The six filters are interconnected by a common influent header with individual inlets entering below the normal low operating water level of the filters and outlets discharging into the clear water channel provided with a weir to assure a minimum static water level in the filters above the surface media. The water level is the same in all operating filters, with the cleanest filter, filtering the highest flow and the dirtiest filter the lowest.

The original filter media gradation was as shown in Table 3.2. Each filter contains five different grades of media resting on a concrete floor. Lateral strainer pipes are provided and allow filtered water to pass into the common outlet during normal operations, and provide air for scouring during filter backwashing

Table 3.2 Original Filter media Gradation of the Sabaki Water Works
Source: Scott and Partners (1982)

Material	Size (mm)	Depth of Bed (m)	Total Quantity Tonnes
1. Anthracite	1 - 2	0.3	150
2. Fine sand	0.5 - 1.0	0.45	360
3. Course sand	1.0 - 2.0	0.15	120
4. Fine gravel	6.0 - 9.0	0.15	120
5. Shingle	13.0 - 19.0	0.10	120

The filtration process was meant to be automated. It is understood that the automated mode of the filter control centre failed almost immediately after being put into operation largely due to incompleteness of the automation and lack of appropriate trained personnel to man and deal with failures of the automation. At present filtration process is operated manually.

Headloss measurements of the filters are not carried out as this was supposed to be done using the automation control. As such backwashing of the filters is based on a routine basis. The filters were meant to be backwashed when the headloss on the filter was in excess of 1.9 m. A 400 m^3 capacity, elevated, reinforced concrete tank has been provided for the purpose of holding backwashing water. The tank is fed with treated water.

3.3 Chemical Dosing

3.3.1 Coagulant Dosing (Alum Dosing)

Four tanks each of capacity 46 m^3 are provided as alum solution tanks and are located in the chemical house. The tanks are made of Braithwaite (glass reinforced plastic) and are externally supported by I-beams. Each solution tank is equipped with centrally located motorised stirrer for dissolving the coagulant.

At any given time only one of the solution tanks is in use while the others are being used to dissolve the coagulant or are being cleaned. Alum, available in lump form is fed manually into the solution tanks for dissolving.

Four reciprocating metered pumps are also provided for purposes of dosing the coagulants. Two of the pumps are for dosing into the rapid mix chamber at the balancing tanks while the other two are for dosing at the flash mixer before the clarifiers. For each set of the dosing pumps, one is in operation while the other one is a standby. Pipework and valves from and to the chemical dosing pumps are connected in series such that a pump can draw coagulant from any solution tank. The pumps are metered for dosage control. Suction and delivery pipework of 50 mm diameter are installed with dosing points at each of the balancing tanks and the flash mixers.

The Sabaki Water Works was designed with the aim of dosing polyelectrolyte at the presettlement tanks. Aluminium sulphate was to be dosed at either or at both the balancing tanks rapid mix chambers and/or at the flash mixers depending on raw water turbidity. The design recommended the use of a polyelectrolyte at high turbidities greater than 500 NTU. Available records at the Water Works do not show the use of any polyelectrolyte. Therefore the works have never been subjected to polyelectrolyte except possibly during commissioning. Coagulation with aluminium sulphate is used throughout the year both at the presettlement basins and the clarifiers. The alum is supplied in lump form in 100 kg bags mostly from Kel Chemicals Ltd. Thika. Assaying for purity of alum is not carried out, as such the quality of the product may be poor.

The usual jar test is the main instrumental control for alum dosing. The test is carried out daily (usually in the morning) and the dosage level selected on the basis of residual turbidity. There exists no clearly defined residual turbidity criterion for choosing the right dosage. With the estimated raw water flow into the works and alum strength, the dosing pump settings for the selected level of dose is derived from the manufacturers calibration curves provided in the Laboratory.

The amount of coagulant dosage selected from the jar test is distributed according to the judgement of the Laboratory technician, some to the balancing tank and some to the clarifiers. No Jar test is conducted for the presettled water to determine the optimal dosage for the clarifiers. From available records there is a bias towards dosing more coagulants at the presettlement tank than at the clarifiers at any give time. The selection of higher dosage for the presettlement appears to have been largely influenced by the capacity of these basins.

3.3.2 Soda Ash Dosage

Two 64 m^3 capacity soda ash solution tanks of the same make as the alum solution tanks are installed in the chemical house. Each of these tanks is equipped with a pair of motorised stirrers and are connected to reciprocating metering pumps for dosing soda ash to the presettled water at the venturi flume, for alkalinity addition, and at the filtered water channel for pH correction. No pH adjustments are made after filtration as the line intended for pH correction is used for dosing Tropical Chloride of Lime (Calcium hypochlorite) as a disinfectant. This was a later modification after the chlorine gas system designed earlier failed.

Soda ash is supplied in 50 kg bags mostly from Magadi Soda and is stored in the chemical house. The chemical is dosed at the venturi flume, whenever the technicians feel the pH is low. No alkalinity test is conducted to justify its application at this point. The amount dosed is based on a rule of thumb, and alkalinity test is done once every week for the sake of recording. This is not appropriate.

3.3.3 Disinfectant Dosing

A gaseous chlorine system installed for disinfection is located in a single chlorine room, adjacent to the treated water pumps. The gaseous chlorine dosing system was put out of operation in 1984 largely due to progressive failure arising from lack of preventive maintenance and spare parts. The design anticipated the use only of chlorine gas supplied in drums and dosed into the filtered water outlet by means of a pump operated vacuum producing injector.

Despite the breakdown of the gaseous chlorine system, chlorine gas supply is currently very difficult to obtain. As such the Treatment Works have converted the dosing lines intended for pH correction, to a Tropical Chloride of Lime (TCL) dosing line to facilitate disinfection after filtration.

Two solution tanks each of capacity 46 m^3, connected to two reciprocating metered pumps are used for dissolving T.C.L. Originally these facilities were intended for dosing polyelectrolytes.

3.4 Organisational Structure

The Sabaki Water Works are run by the Engineer-in-Charge who reports to the Regional Manager in Mombasa. He is a Mechanical Engineer with experience mostly in the installation and maintenance of pumping plant, but limited previous work involving water treatment. The selection of such an Engineer to head operations appears to have been largely influenced by the overiding difficulty in keeping the mechanical plant operational. He is assisted by the Officer-in-Charge. The staff presently working under them are illustrated in Fig. 3.2.

Of the 63 working staff 68% of them are not trained, though they have gained invaluable specific experience on the job, such untrained staff may be limited in that, they are not in a position to deal with situations that they have not previously encountered.

The electrical and mechanical inspectors together with the team under them oversees the inspection and maintenance of the electrical and mechanical equipments respectively. These includes chemical feeders and pumps.

The water inspectors deal with the periodical inspection of the entire treatment plant. With the subordinate staff working under them to do the actual works, they ensure among other things that raw and treated water pumps are functioning, chemical dosing is being carried out, backwashing of the filters is appropriately done, desludging and cleaning of the various units is performed.

The two laboratory technicians handle all required water quality tests to ensure that the water being produced is potable at all times. General labour includes manual cleaning of the various treatment units and compound maintenance.

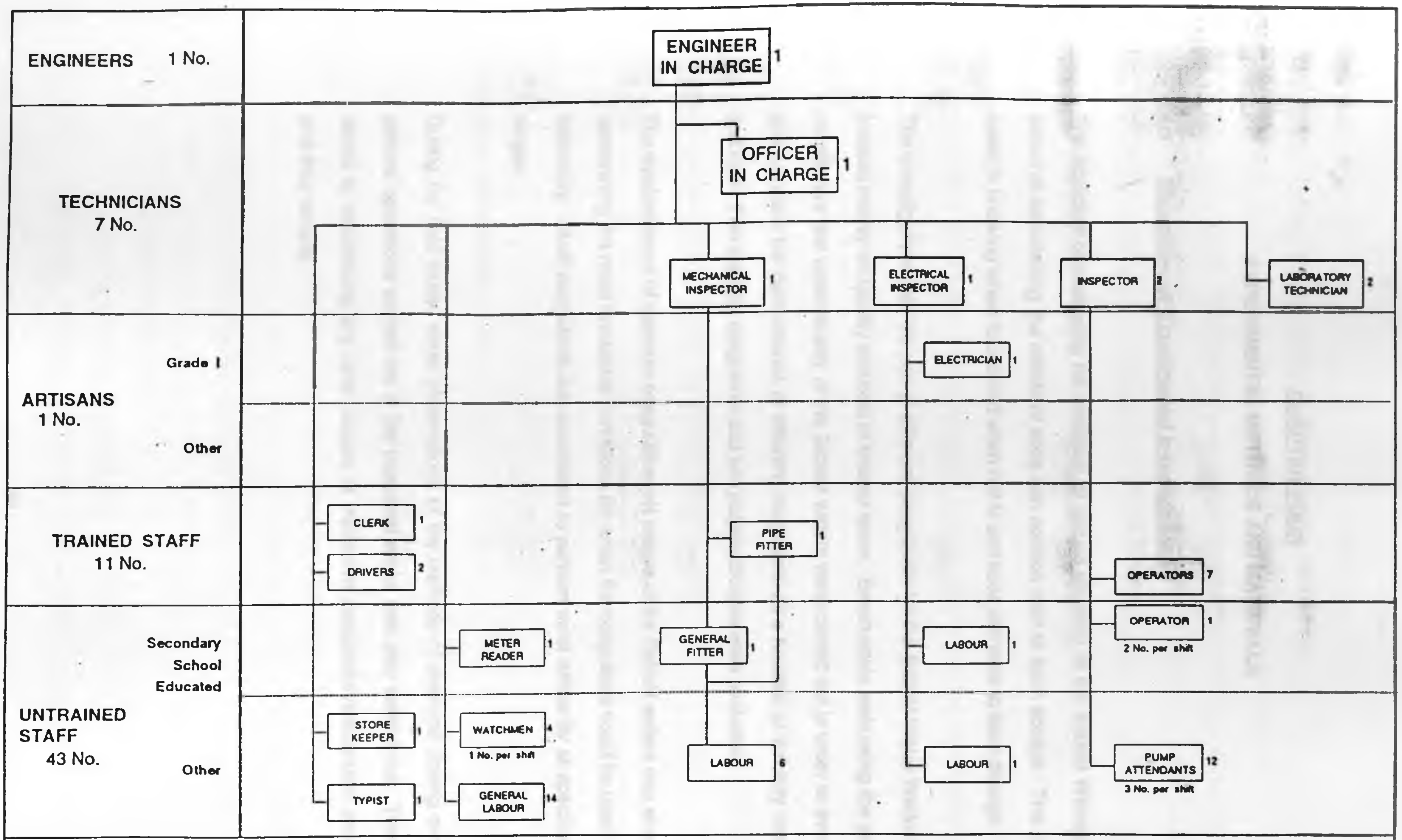


FIGURE 3.2 THE ORGANISATIONAL STRUCTURE OF THE SABAKI WATER WORKS

CHAPTER FOUR

EXPERIMENTAL METHODS AND MATERIALS

4.1 Objectives of Experimental Investigations

The objective of evaluating the condition of natural alkalinity of the Sabaki Waters was aimed at establishing the effects of soda ash addition prior to alum dosage. This would assist in knowing when to add and when not to add soda ash prior to alum dosage.

The investigations into the use of different coagulants for the Sabaki Water Works have focused mainly on quality and cost of treated water. Bench-scale tests using the jar test on different raw water quality of the Sabaki waters were carried out in order to evaluate and compare the performance of different coagulants as a function of turbidity removal and cost. Two metallic coagulants and two polyelectrolytes were evaluated.

The establishment of optimum coagulation pH ranges of the Sabaki waters was aimed at determining the most favourable conditions for which the coagulants could be used most effectively. Most coagulants are considered to perform most efficiently at specified pH ranges.

During the field study, visual observations of the methods of chemical dosing and the general operations carried out in the treatment works was also carried out. This was aimed at establishing any other causes of ineffective coagulation/flocculation process, and their remedy.

4.2 Scope of Investigations

The scope of the investigations was divided into two separate but related parts in accordance with the objectives outlined. In one part; daily monitoring of the treatment plant performance, including visual observations was carried out. In the second part; bench-scale tests using the jar tests was carried out daily on the raw water drawn from the balancing tank of the Treatment plant. This involved jar testing on different coagulants and combinations of coagulants with varied doses, as well as varying the pH in others. Parameters investigated both in plant monitoring and bench-scale tests include; alkalinity, pH and turbidity. Turbidity measurements were carried out as a measure of coagulation/flocculation performance.

The experimental studies were conducted at the Sabaki Treatment Works Laboratory owned by the National Water Conservation and Pipeline Corporation. This was carried out during the period November, 1992 to February, 1993.

4.3 Experimental Materials

4.3.1 Coagulants

Four commercially available coagulant chemicals were selected for the study: Aluminium sulphate (filter alum) -AL_2SO_4. $13H_20$*, Ferric chloride - $FeCl_3$. $6H_2O$; Two cationic polyelectrolyte namely superfloc C573+ and catfloc T^s.

The properties of the coagulants are summarised in Table 4.1

---

* *Kel Chemicals Ltd. Thika*

\+ *American Cynamid Co., polyacrylamide*

s *Calgon Corp, Pittsburgh, Pa, Dimethyl diallyl ammonium chloride*

Table 4.1 Properties of Coagulants Used

Chemical Name	Trade Name	Containers	Available Form	Solubility in Water
1. Aluminium sulphate	Filter alum	100 kg bags	Lump	Finite
2. Ferric chloride	Crystal ferric chloride	100 kg bags	Yellow-brown lump	Finite
3. Dimethyl diallyl ammonium chloride	Catfloc T	Drums (Fibre glass)	Clear to pale yellow liquid	Soluble in all proportions
4. Polyacrylamide	Superfloc C573	Drums (Fibre glass)	Amber liquid	Infinite

Aluminium sulphate was chosen because it has been used extensively at the Water Treatment plant and is an effective chemical for the removal of particles from high and low turbidity waters. Hence it has been used as the reference frame for comparing with the other coagulants. Ferric coagulants are considered to have a relative lower cost (Correl and Robinson (1974)), though corrosion problems are usually experienced both in handling and supplying especially in natural waters of high iron content.

Cationic polymers are able to destabilise the negative particles that occur in natural waters and can function as effective primary coagulants (Stump and Novak (1979)). Limitations of the polyelectrolytes exists due to the fact that certain doses must not be exceeded hence requiring highly skilled labour. For example; a maximum dose of 50 mg/l and 20 mg/l for both catfloc T and superfloc C573 respectively, have been accepted by USEPA. These limits have been put due to the fact that polyelectrolytes contain contaminants from the manufacturing process which are of significant health concern. The contaminants such as epichlorohydrin and acrylamide and their effects are given by Letterman and Pero (1990).

Nonionic and anionic polyelectrolytes were not studied, though it is plausible that some could function effectively. It was expected that since the Sabaki waters are highly turbid cationic polyelectrolyte would perform more effectively than others. This was because most turbidity causing particles are negatively charged (Cox 1969)).

4.3.2 Sample Collection and Reagent Preparation

20 litre clean plastic containers were used to draw raw water samples used in the jar tests, from the balancing tank of the Treatment plant (refer to Fig. 3.1). To ensure representative samples were examined, the containers were rinsed several times with the water to be sampled. Samples of pretreated, clarified and filtered effluents were drawn from the respective channels using clean 1 litre glass beakers rinsed both in distilled water and sample water. These were aimed at demonstrating the efficiency of the treatment process.

All dilutions and solutions were made using appropriate amounts of distilled water. Except for the coagulants which were of commercial grade, other chemicals used were the analytical reagent grade. 0.1% solutions of the polyelectrolytes and 10% solutions of both ferric chloride and aluminium sulphate were prepared on weekly basis for the jar tests. Stock sulphuric acid solution was prepared by dissolving analytical reagent grade in water to a concentration of 1N H_2SO_4. 0.02N H_2SO_4 solutions were prepared on weekly basis by diluting the stock solution. NaOH and HCl used for pH control were also prepared in a similar manner

4.4 Experimental Methods

4.4.1 Bench-Scale Study

Bench-scale tests were designed using several different Sabaki raw water to evaluate the effectiveness of the various test coagulants, and their performance as related to pH of the water.

Coagulation/flocculation tests were carried out using a six paddle stirrer* unit equipped with a floc illuminator. Water samples were placed in the beakers, and appropriate amounts of coagulant stock solutions added by pipette. Two minutes of rapid mixing at 100 rpm were allowed to ensure thorough mixing of the reagent. The stirring speed was then reduced to 30 rpm and continued for a period of 15 min. This was to provide a period of gentle agitation for flocculation of the coagulated particles. The mixing was followed by 20 min of settling after which the supernatant was decanted and measurements for turbidity, pH, and alkalinity carried out.

To evaluate the possibility of using alternative coagulants, each of the four coagulants was tested in turn for the same raw water quality. In this, varied doses of the coagulant being considered were pipetted into each of the six beakers and the procedure described here applied. When used in combination, alum and polyelectrolyte were normally added simultaneously to the rapid mix unit. On rare occasions they were added sequentially. This latter format was necessary to establish the best dosage locations for each coagulant. In most runs, varied polyelectrolyte dosage were used with fixed alum dosage.

For the experiment to be made at different pH values the desired pH was adjusted by adding 0.1N and 0.01 NaOH or 0.1N and 0.01N H_2SO_4 appropriately. The second

---

* *Phillips and Bird Inc. for Richmond, Va 23228*

minute in each case was used to make final small adjustments of the pH. The pH values recorded in the results section were measured after coagulant addition and settling was over. A pH meter which was standardized every morning using pH 4 and 7 buffer solutions was used for the pH measurements. During the flocculation and settling periods, the physical appearance and relative settling rate of the flocs was noted.

4.4.2 Plant Monitoring Tests

The purpose of these tests was to evaluate the effectiveness of the treatment process, together with evaluating the condition of natural alkalinity in the Sabaki waters. This was conducted by collecting representative samples from the presettlement, clarified, filtered and disinfected water which was analysed for alkalinity, pH, turbidity and colour. Standard methods of measurements of these parameters were used (APHA, 1975). The amounts of coagulant and soda ash dosage at various dosage locations were recorded. Along with this tests, visual observation of the treatment works unit operations and processes were also carried out during sampling. Notes on sludge accumulation, dosage methods, filter backwashing as well as their effects were recorded. The experimental results are presented in tabular form in Appendix A, while the general observations are included in Chapter 5.0.

CHAPTER FIVE

RESULTS, ANALYSIS AND DISCUSSION

5.1 General

Turbidity measurement is a variable index of removal of other materials in water. The degree of turbidity removal usually parallels the removal of micro-organisms, viruses and other substances (Yapijakis (1982)). As such residual turbidity measurements were adopted to indicate performance in this study.

A review of the plant monitoring data (Appendix A1 and A2) showed that under normal working conditions the filters could accommodate a load of upto 50 NTU and reduce the turbidity to values well under 5.0 NTU, which is within WHO standards (WHO (1984) - Vol 2). This value was found to allow the filtration stage to operate efficiently, and to avoid (in particular) any disruption caused by excessive turbidity. Thus in this study a residual turbidity (in the jar test) of 50 NTU was adopted to indicate the required performance of the settled water before filtration.

Typical examples of cases where the filters were able to accommodate turbidity ≥ 50 NTU is presented in Table 5.1. From this table, it can be observed that for clarified water above 50 NTU one cannot predict whether the filters will be able to reduce the turbidity to the required level or not, as evidenced by table 5.1.

Table 5.1 Typical Examples of Filter Turbidity Removal

Date	Source	Clarified Water Turbidity (NTU)	Final Water Turbidity (NTU)
17/12/1991	Appendix A2	70	14
24/12/1991	Appendix A2	55	4.5
26/12/1991	Appendix A2	50	4.0
19/11/1992	Appendix A1	65	2.2
16/12/1992	Appendix A1	90	5.8

In this study unless otherwise stated, optimum coagulant dosage are used to refer to the minimum value that gave the desired performance. Optimum pH referred to the pH that gave optimum dosage and lying within acceptable limits.

Due to the large amount of data collected, only selected examples of the data will be presented either in tabular or graphical form in the following sections. However, the complete data is presented in the Appendices of this report.

5.2 Conditions of Natural Alkalinity in the Sabaki

5.2.1 General

The conditions of natural alkalinity in the Sabaki waters and the effects of soda ash addition were investigated both in plant and the jar test. The results are presented in Appendices A1, A3, A4 and A5. A summary of the results are presented intermittently with the discussion in the ensuing sections for purposes of clarity.

5.2.2 Alkalinity Consumption

A summary of average alkalinity consumption per unit alum added in the jar tests for the Sabaki waters is presented in Table 5.2(a). These values were calculated as shown in Appendix B1 of this report. The alkalinity and alum values used here are presented in Appendix A4. For the experimental period an average alkalinity consumption value of 0.32 mg/l alkalinity per 1.0 mg/l alum was obtained. This value is less than the theoretical value of 0.5 mg/l as indicated in Section 2.5.2 of this report. The difference could possibly be attributed to the fact that surface waters contain other impurities which do not account for alkalinity, but whose alum demand must also be met.

This empirical value is important in estimating whether alkalinity addition is necessary in coagulation with alum. This is possible when given a targeted alkalinity in the treated water. For example; if the raw water alkalinity is 100 mg/l as $CaCO_3$ and a residual alkalinity of 20 mg/l is required then soda ash dose would be necessary when alum dose exceeds 250 mg/l. This is obtained using equation 5.2:

$$D_m = \frac{RA - TA}{AC} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (5.2)$$

where D_m is Alum dose above which alkalinity correction would deem necessary

RA is the Raw water alkalinity

TA is the Targeted alkalinity of treated water

AC is the Alkalinity consumption value

However, for accuracy purposes alkalinity measurement of the selected dose in the jar test should be conducted.

Table 5.2(a) Average Alkalinity Consumption Values in the Jar Test.

Sampling Date	Average Alkalinity Consumption (mg/l as $CaCO_3$ per mg/l alum)
18/11/92	0.42
19/11/92	0.31
21/11/92	0.29
23/11/92	0.29
24/11/92	0.32
26/11/92	0.33
27/11/92	0.34
28/11/92	0.43
30/11/92	0.26
01/12/92	0.26
02/12/92	0.29
03/12/92	0.19
14/12/92	0.38
15/12/92	0.26
21/01/93	0.47
26/01/93	0.26
27/01/93	0.27
28/01/93	0.28
29/01/93	0.27

5.2.3 Effects of Soda Ash Addition

Results of residual turbidity versus alum dose with and without soda ash addition for 30/11/1992 and 03/12/1992 are presented in Fig. 5.1 (a) and Fig. 5.1 (b) respectively. These results are aimed at illustrating the negative effects that excessive alkalinity could have on the efficiency of alum as a coagulant.

Whilst boosting the natural alkalinity by adding soda ash, is aimed at effective and complete coagulation to occur (Section 2.5.4), it is apparent from Fig. 5.1(a) and 5.1(b) that its excessive addition can be counter productive (i.e. renders alum less effective), especially for highly alkaline waters like those of the Sabaki river.

From the graphs in Fig. 5.1 it is apparent that the effect of soda ash addition on flocculation efficiency is significant. From Fig. 5.1(a) it can be observed that for the raw water turbidity of 1800 NTU and alum dose of 120 mg/l, a residual turbidity of 420 NTU is obtained without soda ash addition, while addition of 50 mg/l of the same reduces the turbidity to 600 NTU. A similar observation is made in Fig. 5.1(b) where for the raw water turbidity of 3,600 NTU and alum dose of 180 mg/l, a residual turbidity of 200 NTU and 1,000 NTU is obtained without and with 50 mg/l soda ash addition respectively. This indicates that soda ash addition is not only profitable but can be counterproductive when the raw water contains enough natural alkalinity.

In these figures the significance of the intercepts of the lines has not been established but appears to be related to the critical point where extra addition of alum dosage requires soda ash correction.

To further illustrate the effect of soda ash application on the efficiency of alum, soda ash dosage in the plant was stopped on request on several occasions. The results are presented in Appendix A1, while a summary is given in Table 5.2(b).

Table 5.2(b) Plant Turbidity Removals with and without Soda Ash Addition

Date	RWT (NTU)	Pre-set Alum Dose	Pre-set Tur.	Soda Dose	CLF Dose	CLF Tur.	Filter Tur.	Final Tur.
17/11/1992	650	100	55	50	30	14	0.7	1.8
17/11/1992	600	100	55	N/A	30	28	0.8	2.4
30/11/1992	1,800	120	650	50	60	55	6.1	6.0
30/11/1992	1,800	120	650	N/A	60	40	4.0	5.0

On the two days recorded in Table 5.2(b) turbidity measurements of the raw water, presettled, clarified, filtered and final water were taken during soda ash dosage. A similar procedure was conducted 8 hrs after soda ash application was stopped, but with similar alum dosage. The turbidity of the raw water did not change during this time. From these results it can be observed that on 17/11/1992 soda ash addition was of no relevant use since in both cases (with and without soda ash addition) the final water was within acceptable WHO standards of < 5 NTU. On 30/11/1992 a better clarified effluent was obtained without soda ash application than with.

The negative effects of alkalinity addition observed in the above results could be attributed to the cross-linking suggested by Letterman et-al, (1979). These researchers observed that increase in anions such as bicarbonate increases the cross-linking between stable positive aluminium hydroxide. This proposed cross-linking causes an increase in the mean particle size in the suspension leading to increased turbidity. Soda ash addition causes an increase in the anions which may then have resulted in the increased turbidity.

The above discussion does not preclude the addition of soda ash when using alum as a coagulant. It only illustrates the negative effect that excessive alkalinity would have on alum coagulation. Additionally, as Fig. 5.1 (a) and (b) illustrate higher alum dosages will ultimately require alkalinity correction.

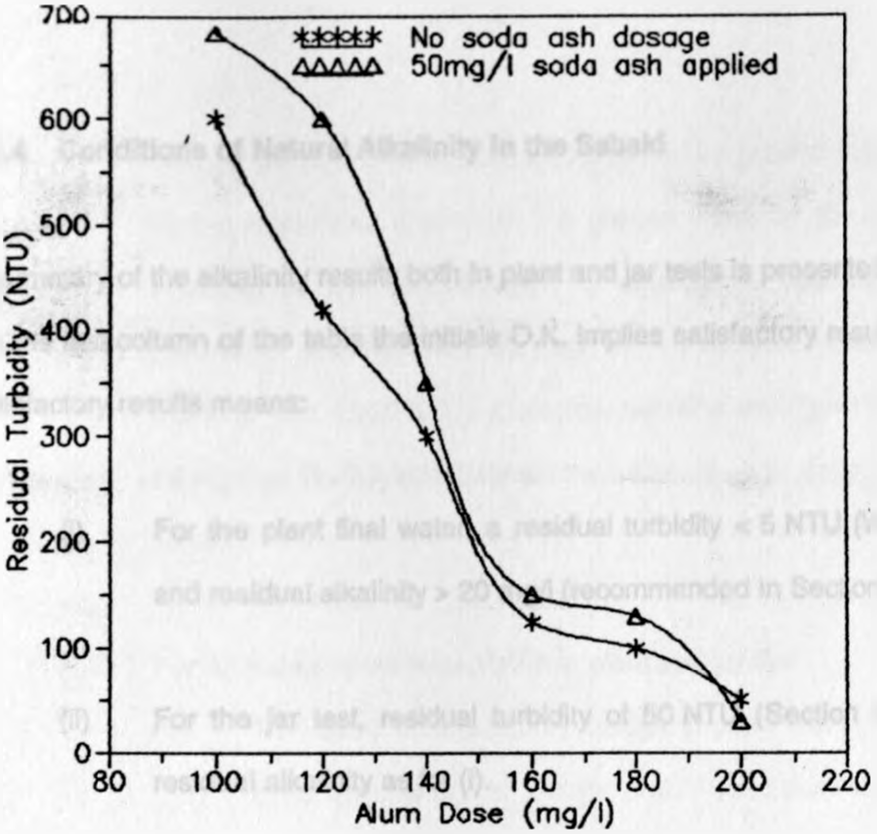


Fig. 5.1 (a) Variation of residual turbidity versus alum dosage with and without soda ash addition. (SD 30/11/1992)

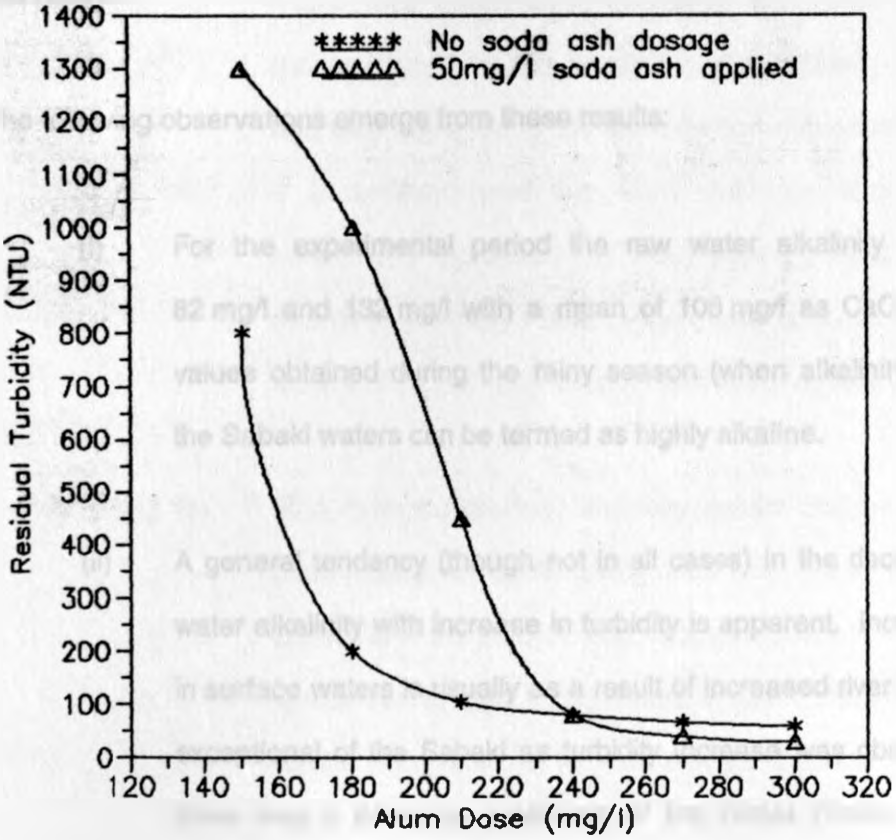


Fig. 5.1 (b) Variation of residual turbidity versus alum dosage with and without soda ash addition. (RWT = 3600 , SD 03/12/1992)

5.2.4 Conditions of Natural Alkalinity in the Sabaki

A summary of the alkalinity results both in plant and jar tests is presented in Table 5.2(c). On the last column of the table the initials O.K. implies satisfactory results. In this table satisfactory results means:

(i) For the plant final water, a residual turbidity < 5 NTU (WHO standards), and residual alkalinity > 20 mg/l (recommended in Section 2.5.4),

(ii) For the jar test, residual turbidity of 50 NTU (Section 5.1), and similar residual alkalinity as for (i).

When one or more of these conditions are not satisfied the initial N.O.K. appears in the last column.

The following observations emerge from these results:

(i) For the experimental period the raw water alkalinity varied between 82 mg/l and 132 mg/l with a mean of 106 mg/l as $CaCO_3$. With these values obtained during the rainy season (when alkalinity is usually low) the Sabaki waters can be termed as highly alkaline.

(ii) A general tendency (though not in all cases) in the decrease of the raw water alkalinity with increase in turbidity is apparent. Increase in turbidity in surface waters is usually as a result of increased river flow. This is not exceptional of the Sabaki as turbidity increase was observed whenever there was a downpour upstream of the Water Works. The observed tendency can be attributed to the fact that alkalinity in surface water is as a result of dissolution of minerals through which it flows. In low flows, the bulk of the flow is likely to be contributed by ground water. Additionally, during high flows dilution of the ground water by the rainwater occurs, resulting in low concentration of alkalinity. The minimum recorded raw water alkalinity was 82 mg/l on 15/12/1992 when the raw water turbidity was 4,000 NTU. Coincidentally this also gave the least value of 26 mg/l as $CaCO_3$ alkalinity for the selected alum dose of 200 mg/l in the jar test.

(iii) For all the samples tested both in plant and jar test:

(a) 10% gave unsatisfactory results in plant testing, while they were quite satisfactory in the jar test. Suspicion arose during those days when the alkalinity results between the plant and the jar test varied greatly (26th - 29th January 1993). The bigger than normal margin was attributed to excessive plant alum dose above that recommended by the laboratory technicians. The discrepancy was also observed in the morning and diminished during the day. It is believed that the night shift operators of that period intentionally increased the alum dose by night and adjusted to normal in the early hours of the morning, so as to be on the safe side, and so that they did not have to be vigilant.

(b) 90% gave satisfactory alkalinity results both in the jar test and plant testing, with 50% giving plant final alkalinity values less than observed in the jar test, and 40% giving higher values. 10% gave similar values both in plant and jar test. The alkalinity results for similar alum dosages in plant and jar test could not all tally. The difference could be attributed to various factors including:-

- Inaccuracy in plant dosing

- Variation of the raw water alkalinity with time.

Observations made during the field study revealed that:-

In practice at the water works, the alkalinity test was done once a week, even when turbidity changed drastically. No evidence was available to show that soda ash dosage prior to clarifier's alum dosage was based on any information concerning the presettled water alkalinity. While addition of soda ash at the clarification stage at any treatment works is aimed at increasing the natural alkalinity for purposes of effective coagulation, in the Sabaki Water Works this is done for pH correction. This is so because soda ash is applied whenever pH value of the final water was not satisfactory though this is done prior to clarification. On other occasions soda ash is applied on consequence of the drastic turbidity increase necessitating alum dose increase. While this might be beneficial at times, it should always be justified by the condition of the natural alkalinity present in the water.

As has been observed in the preceding section excessive alkalinity in the water renders alum less effective. Additionally, soda ash addition results in increased pH, with consequential reduction of the germicidal efficiency of the chlorine as indicated in Section 2.5.2 of this report. This implies that except for alkalinity correction, soda ash dosage should be applied after chlorination when necessary for pH correction.

On the basis of the foregoing results and discussion, it seems likely that there is no need of alkalinity addition at the clarification stage in the Sabaki Water Works. Hence taking into consideration that the testing was done during a critical period in the history of the Sabaki (when raw water turbidity reached an alarming level of 4,000 NTU), it is reasonable to conclude that the Sabaki raw water contains enough natural alkalinity for purposes of coagulation with alum in all seasons. As such soda ash addition prior to alum dosage at the clarification stage should be discontinued and applied only for pH correction after filtration and chlorination when necessary. However due to the limitations of the data in this study (having been conducted over a three month period), this conclusion should be taken as tentative. Thus action taken should only be precautionary. On the other hand to ensure that the results are given a wide and clear dissemination alkalinity tests should be conducted diligently on a daily basis for a period of not less than one year.

Meanwhile it is quite evident that soda ash application is not appropriately carried out. In order to realise greater cost savings both in purchasing of soda ash and alum, application of the former prior to clarification for purposes of natural alkalinity correction should strictly be applied only when the clarified water alkalinity falls below 20 mg/l as $CaCO_3$. This should be justified by measuring the alkalinity of the selected dose of the jar test. Otherwise, it should be dosed after filtration and chlorination for pH correction and corrosion control.

Table 5.2(c) Alkalinity Results (Extracted from Appendix A1 and A4).

Date	Raw Water		Final Water		Plant Dose		Jar Test Result for Similar Plant Dose		comments
	Tur	Alk	Tur	Alk	Alum	Soda	Tur	Alk	
16-11-92	650	110	2.6	80	130	50	-	-	O.K.
17-11-92	650	120	1.8	94	130	50	-	-	O.K.
17-11-92	600	120	2.4	88	130	-	-	-	O.K.
18-11-92	600	124	2.5	86	130	-	16	72	O.K.
19-11-92	1,800	132	2.4	100	120	-	40	88	O.K.
20-11-92	2,100	120	2.3	60	160	50		-	O.K.
21-11-92	1,500	100	1.4	56	210	-	54	40	O.K.
23-11-92	1,500	98	2.1	52	120	-	80	58	O.K.
24-11-92	1,200	100	1.5	52	120	-	20	58	O.K.
25-11-92	900	100	2.0	70	120	-	26	68	O.K.
26-11-92	800	116	1.8	70	112	-	30	80	O.K.
27-11-92	600	114	1.8	84	90	-	25	84	O.K.
28-11-92	600	114	2.0	90	100	-	25	70	O.K.
30-11-92	1,800	122	5.0	76	180	-	100	74	O.K.
01-12-92	1,700	120	2.4	74	180	-	25	74	O.K.
02-12-92	1,650	108	3.5	72	150	-	84	68	O.K.
03-12-92	3,600	100	180	70	150	-	800	84	N.O.K.
14-12-92	3,100	100	6.2	68	190	-	40	26	N.O.K.
15-12-92	4,000	82			200	-	40	26	O.K.
16-12-92	3,200	80	6.6	48	200	-	-	-	N.O.K.
26-01-93	1,400	86	4.5	18	150	-	30	44	N.O.K.
27-01-93	1,300	86	4.8	20	120	-	50	52	N.O.K.
28-01-93	1,200	90	6.5	30	120	-	70	60	N.O.K.
29-01-93	1,100	96	3.6	38	120	-	63	68	O.K.
01-02-93	2,800	-	2.4	62	150	-	48	88	O.K.
02-02-93	3,000	112	6.6	58	150	-	140	98	O.K.

O.K. Implies the results are satisfactory both in jar test and plant.

N.O.K. Implies the results are not satisfactory either in jar test or in plant.

5.3 Investigations into the Use of Alternative and Combinations of Coagulant

5.3.1 Alternative Coagulants

Investigations into the use of alternative coagulants in the Sabaki Water Works has been carried out in this study. Coagulants tested were alum, ferric chloride, catfloc T and superfloc C573. Jar test results of turbidity removal versus coagulant dosage for different raw waters of the Sabaki are given in Appendix A4. Selected examples of the data are presented graphically in Fig. 5.2(a) to Fig. 5.2(q).

In the present study, a comparative technical method based on equivalent performance that provides guidance in the selection of a coagulant has been adopted for analysis. In this, an empirical dosage ratio was found that resulted from identical performance for the coagulants. A residual turbidity of 50 NTU has been adopted to indicate equivalent performance for settled water in the jar test. Alum as the incumbent coagulant in the Water Works was taken as the basis of comparison. The dosage giving a residual turbidity of 50 NTU for each coagulant was obtained from the graphs, and the dosage ratio of each coagulant tested to alum obtained.

A summary of the empirical dosage ratio of each coagulant is presented in Table 5.3(a).

Table 5.3(a) **Empirical Dosage Ratio for Identical Performance of the Various Coagulants.**

Date	RWT (NTU)	Ferric: Alum	Catfloc: Alum	Superfloc: Alum
16/11/92	600	-	0.100	0.095
21/11/92	1,500	-	0.110	0.109
25/11/92	900	0.920	-	-
30/11/92	1,800	0.800	0.093	0.088
03/12/91	3,600	0.750	0.127	0.123
14/12/91	3,100	1.076	0.177	0.152
15/12/91	4,000	0.961	0.202	0.202
19/01/93	3,400	-	0.129	-
26/01/93	1,400	-	-	0.049
27/01/93	1,300	-	0.150	-
28/01/93	1,200	-	0.112	0.092
29/01/93	1,100	-	0.091	0.079
01/02/93	2,800	-	0.154	0.149
Average Values		0.901	0.131	0.114

From the dosage ratios obtained in Table 5.3(a) it can be observed that for all the coagulants tested, namely ferric chloride, catfloc T and superfloc C573, the coagulant - to - alum ratio are all less than unity except on 14/12/91. This implies that, on equidosage basis as mg/l, the polyelectrolytes and ferric chloride removed turbidity more efficiently than alum did. The average coagulant - to - alum ratios are shown in the last row of Table 5.3(a).

The effectiveness of the polyelectrolytes appears to become less pronounced as the raw water turbidity increases. This is so because, as the turbidity increases the dosage ratio increases. For example, the raw water turbidity of 4,000 NTU gave an empirical ratio of 0.202 for both the polyelectrolytes whilst 1,400 NTU resulted in 0.049. This indicates that the efficiency of the polyelectrolytes in relation to alum decreases as the raw water turbidity increases. The effectiveness of ferric chloride in relation to alum did not show any marked variation with raw water turbidity. This is expected as the chemical coagulation reactions involved are essentially the same for both metal ions. (Section 3.4.1).

A polyelectrolyte - to - alum empirical dosage ratio greater than 0.067 is not economically justifiable because on average polyelectrolytes costs about 15 times more than alum in Kenya (prices quoted are those prevailing in early March, 1993). Thus within the narrow range of variables investigated there are no economically justified reasons for summarily rejecting aluminium sulphate as the primary coagulant in the Sabaki Water Works. It is only on one occasion, 26/01/93 when a low value of 0.049 was obtained with superfloc.

However, based on visual observations during jar testing, and the data obtained in this study, when the coagulants were fed to the same raw water, each had its own advantages. From Figs. 5.2(a) to 5.2(q) it can be observed that ferric and alum reduces the turbidity to a lower minimum than the polyelectrolytes. These observation suggests that alum and ferric does a much better job of sweeping up the primary particles. The polyelectrolytes, on the other hand, formed large, strong flocs but was less efficient in picking up primary particles. This phenomenon was observed regularly. It was also noted that while the metallic coagulants produced a settled water of low turbidity, the polyelectrolytes produced less sludge volume.

The increasing stringent waste disposal standards worldwide coupled with the global environmental concern, would pose problems for metallic coagulants use, especially in regard to the treatment of highly turbid waters. As such measures being adopted in developed countries like the U.S.A. will become apparent in Kenya. Thus the volume and the quality of sludge produced by various coagulants will take a leading role in coagulant selection. The known characteristics of sludge volume reduction, easiness of handling and reasonable effectiveness would make polyelectrolytes workable substitutes for alum. Additionally, prices of polyelectrolytes would be expected to decrease with increase in demand. This is so because investors would be attracted to start polymer production locally.

However, comparison of all relevant costs including the subsequent management of sludge produced would be necessary to provide a complete quantified comparison.

From Figs. 5.2(a) to 5.2(q) it is noted that the aspect of restabilisation was not pronounced. In general, as the coagulant dose is increased, residual turbidity decreases, reaching a minimum and then increases. The increase in turbidity with increase in dosage is as a result of restabilisation. Its absence in this experiments could be attributed to reasons advanced by Amirtharajah and Mills (1982). The researchers emphasized two facts about restabilisation.

Firstly, it was generally observed only with dilute solutions. During the experimental work the Sabaki waters were colloidally concentrated with turbidities greater than 500 NTU. Secondly, significant concentration (>10 mg/l) of anions such as sulphate (SO_4^{2-}) could eliminate restabilisation. Almost all dosages were greater than 10 mg/l. However few cases though not pronounced were observed with all coagulants.

A notable observation is that for the same raw water turbidity but on different days, different optimum dosages were obtained for a given coagulant. On other occasions higher dosages were obtained for lower water turbidity. This can be attributed to the characteristics of the particulate matter. Though no effort was made to correlate suspended particle size distribution with turbidity, it is evident from previous investigations (Treeweek G.P. (1979) that turbidity is a complex function of the number of particles, their size, and refractive index. This made turbidity measurements limited in predicting the amounts of dosage needed to give a certain water quality, since turbidity measurements do not provide a direct measure of the particulate matter in the water and its size distribution. Thus the data cannot be extrapolated directly to all waters, nor can specific dosages be recommended for a given water without experimenting with it.

However, the observed trends provide useful information in coagulant selection, as well as in getting estimates or expected dosages.

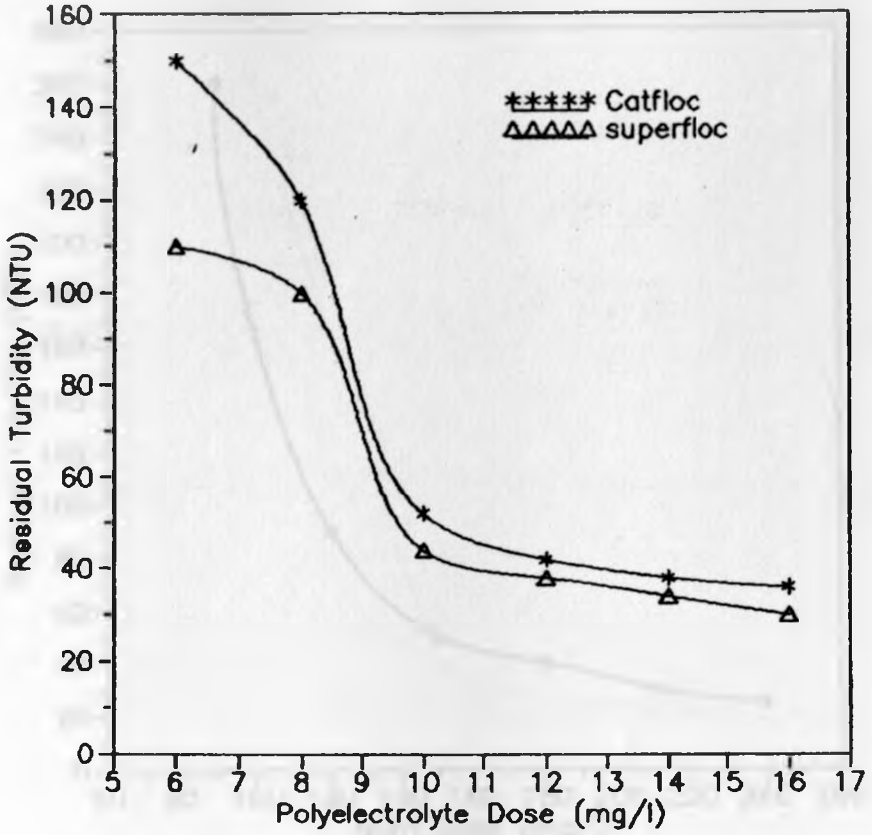


Fig. 5.2(a) Residual Turbidity Versus Dose
(RWT = 650, SD 16/11/1992.)

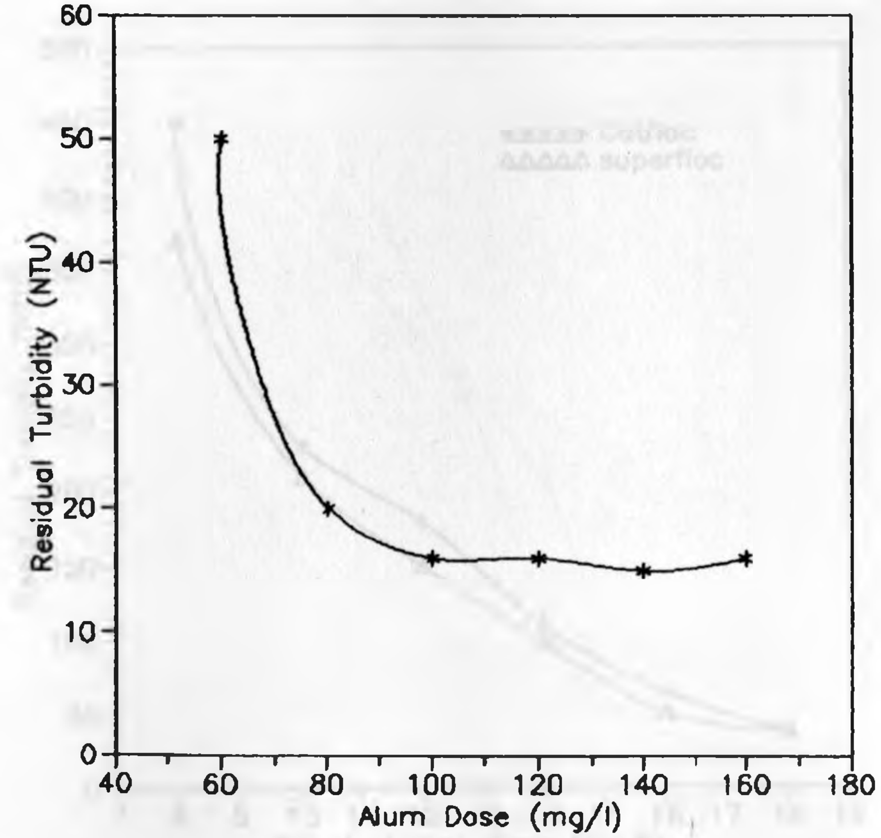


Fig. 5.2(b) Residual Turbidity Versus Dose
(RWT = 600, SD 18/11/1992.)

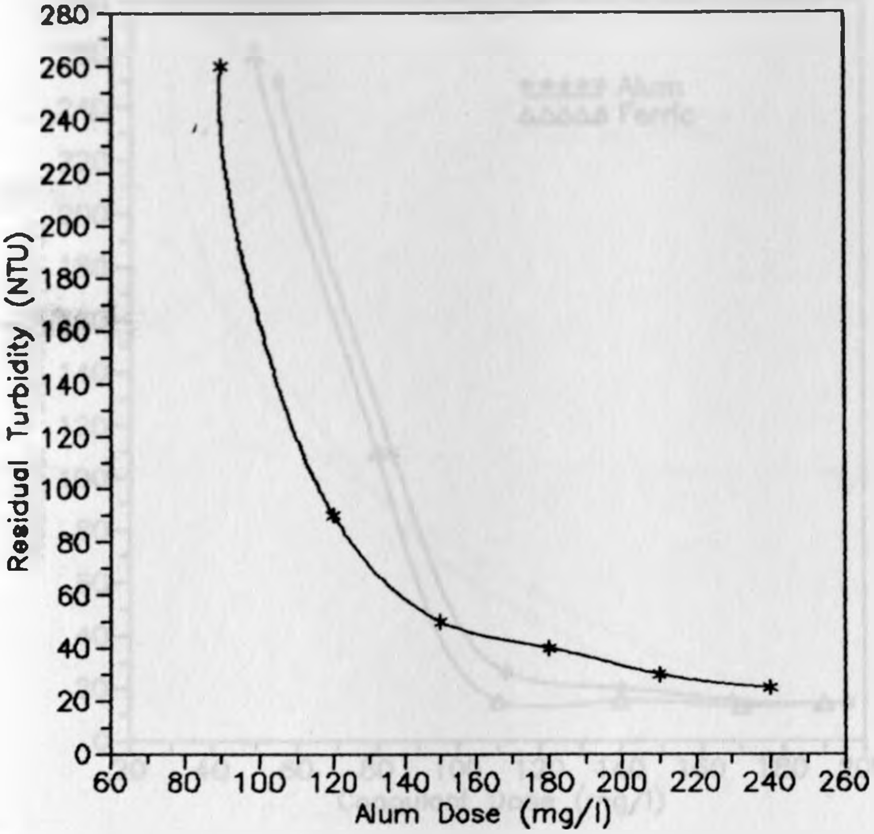


Fig. 5.2(c−1) Residual Turbidity Versus Dose
(RWT = 1500, SD 21/11/1992.)

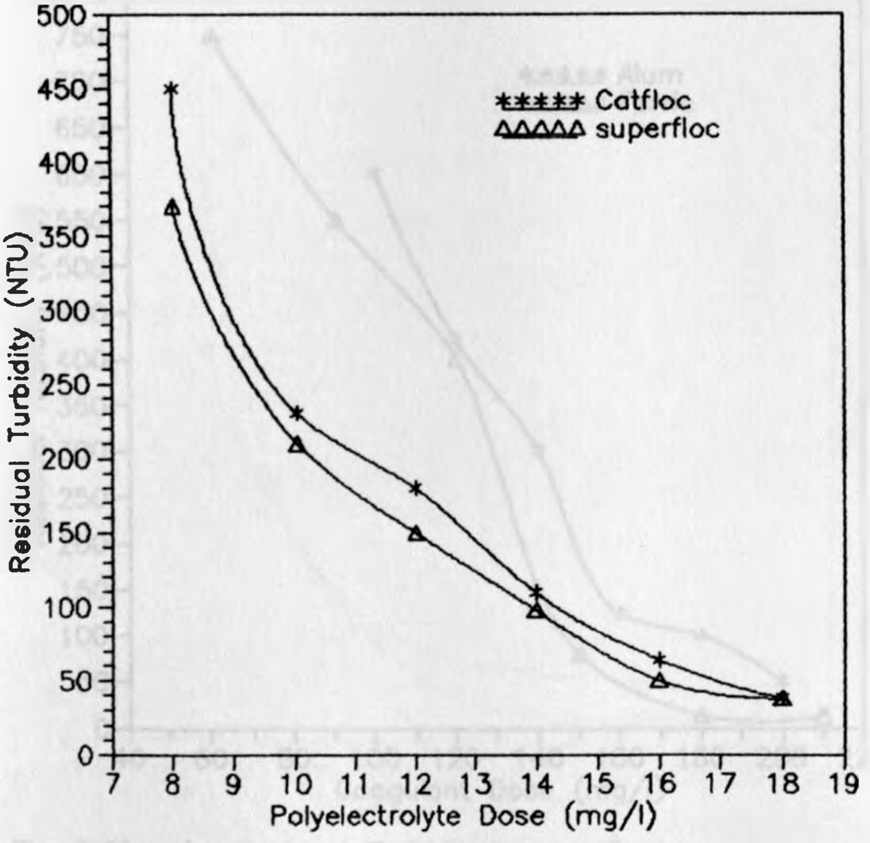


Fig. 5.2(c−2) Residual Turbidity Versus Dose
(RWT = 1500, SD 21/11/1992.)

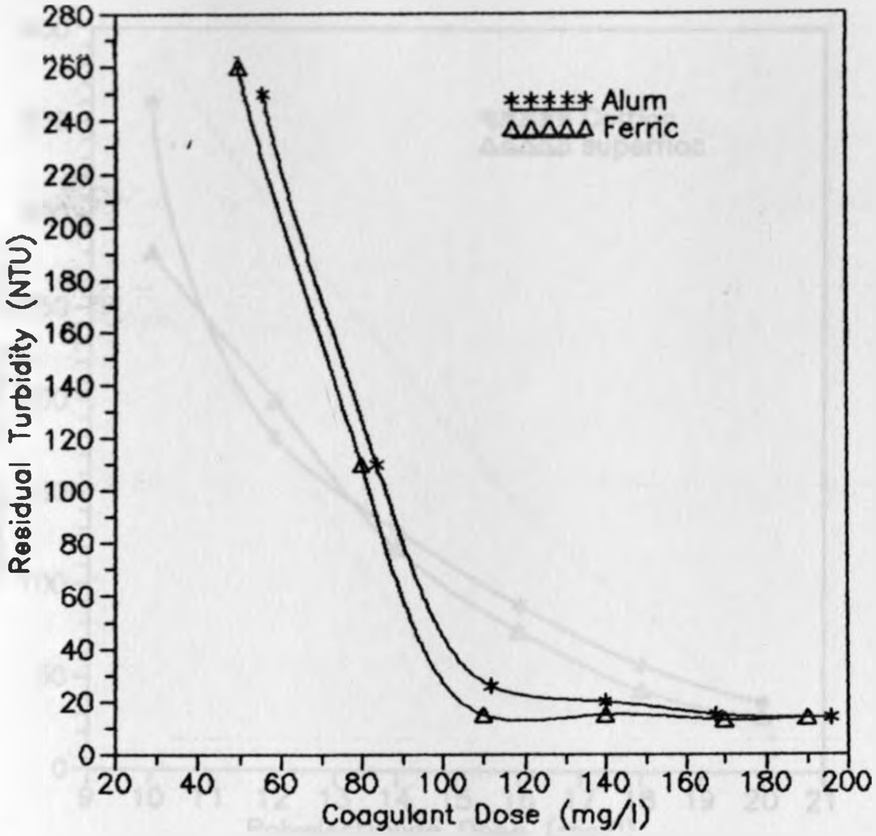


Fig. 5.2(d) Residual Turbidity Versus Dose (RWT = 900, SD 25/11/1992.)

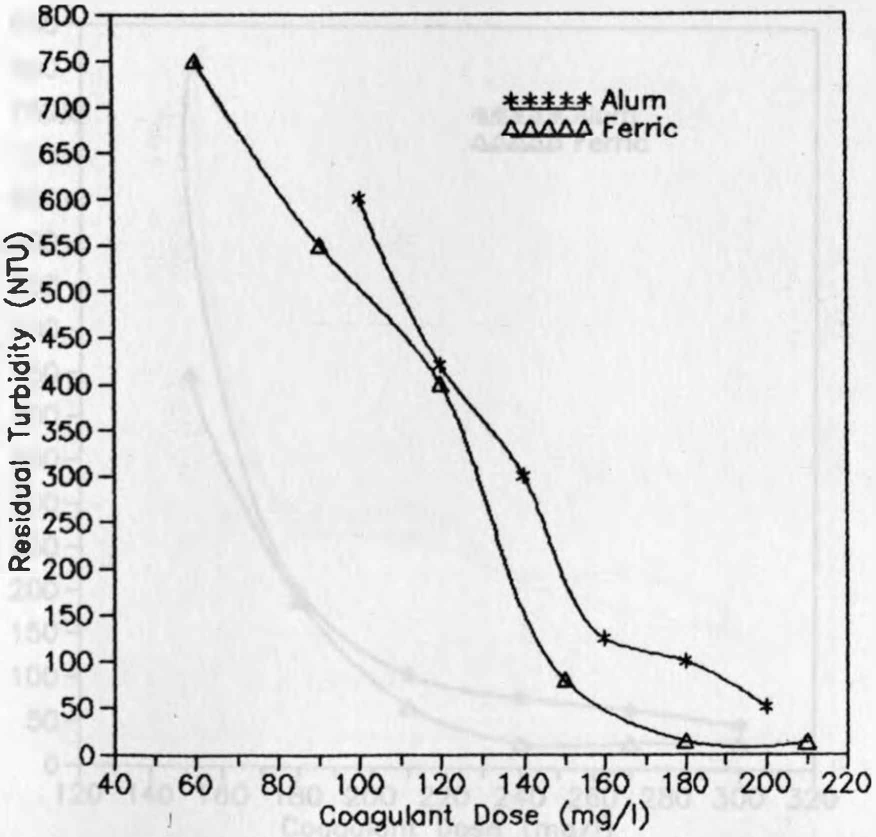


Fig. 5.2(e–1) Residual Turbidity Versus Dose (RWT = 1800, SD 30/11/1992.)

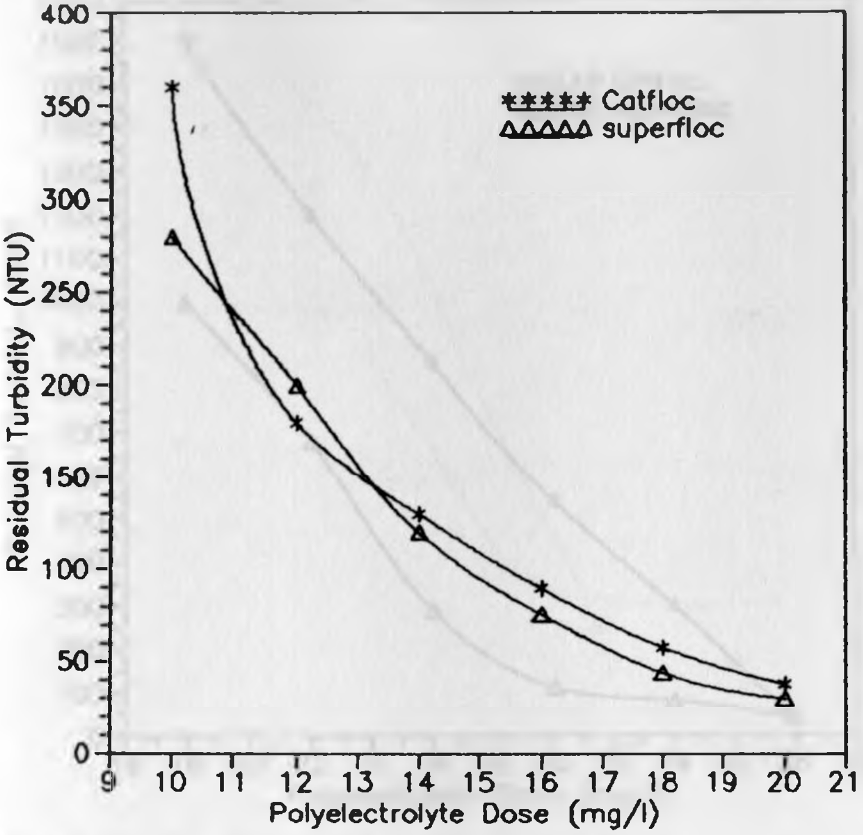


Fig. 5.2(e−2) Residual Turbidity Versus Dose
(RWT = 1800, SD 30/11/1992.)

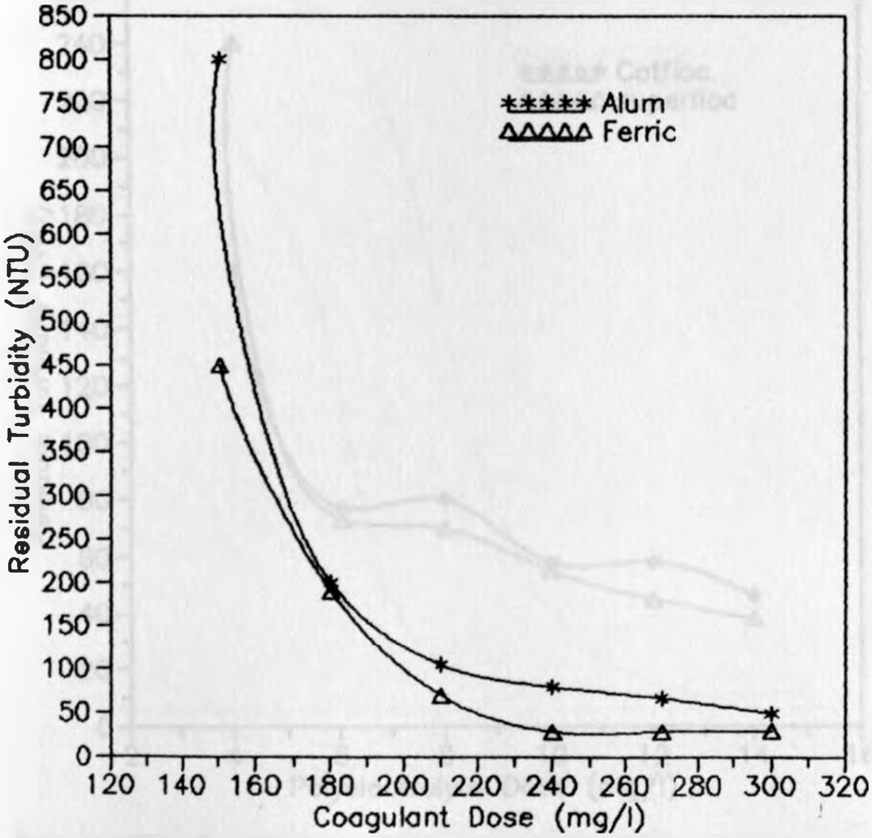


Fig. 5.2(f−1) Residual Turbidity Versus Dose
(RWT = 3600, SD 03/12/1992.)

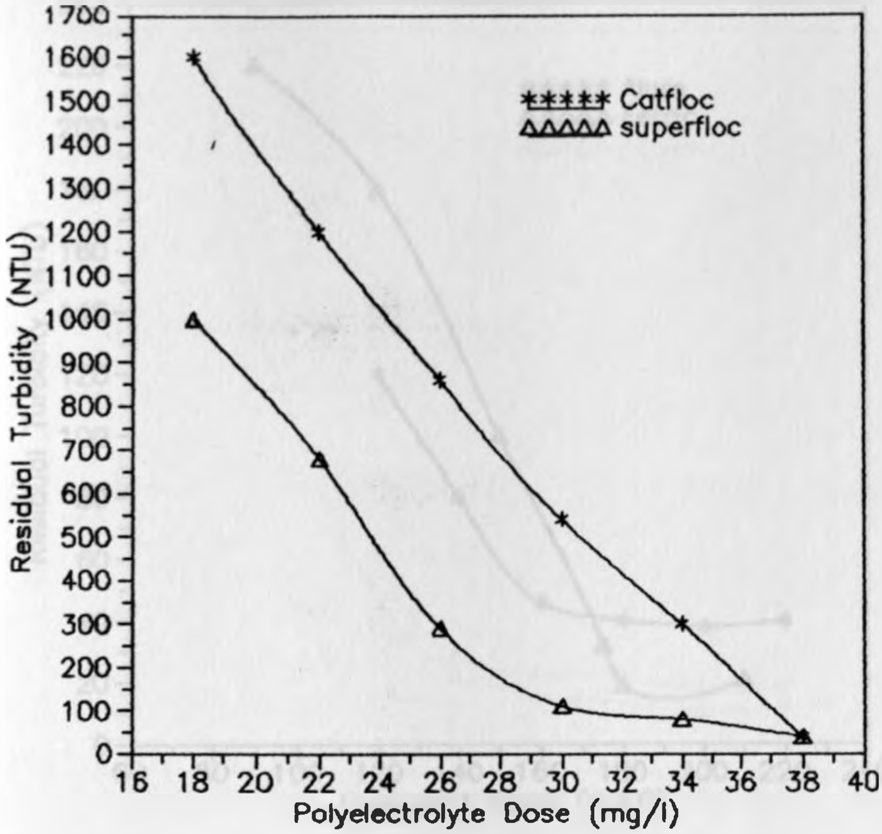


Fig. 5.2(f−2) Residual Turbidity Versus Dose
(RWT = 3600, SD 03/12/1992.)

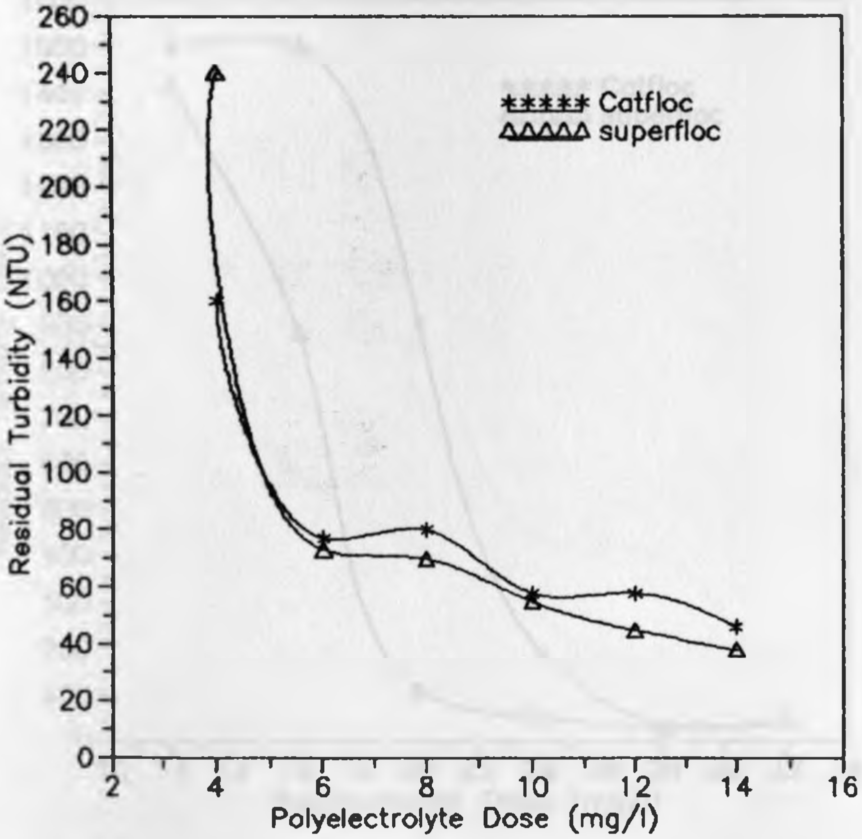


Fig. 5.2(g) Residual Turbidity Versus Dose
(RWT = 1300, SD 11/12/1992.)

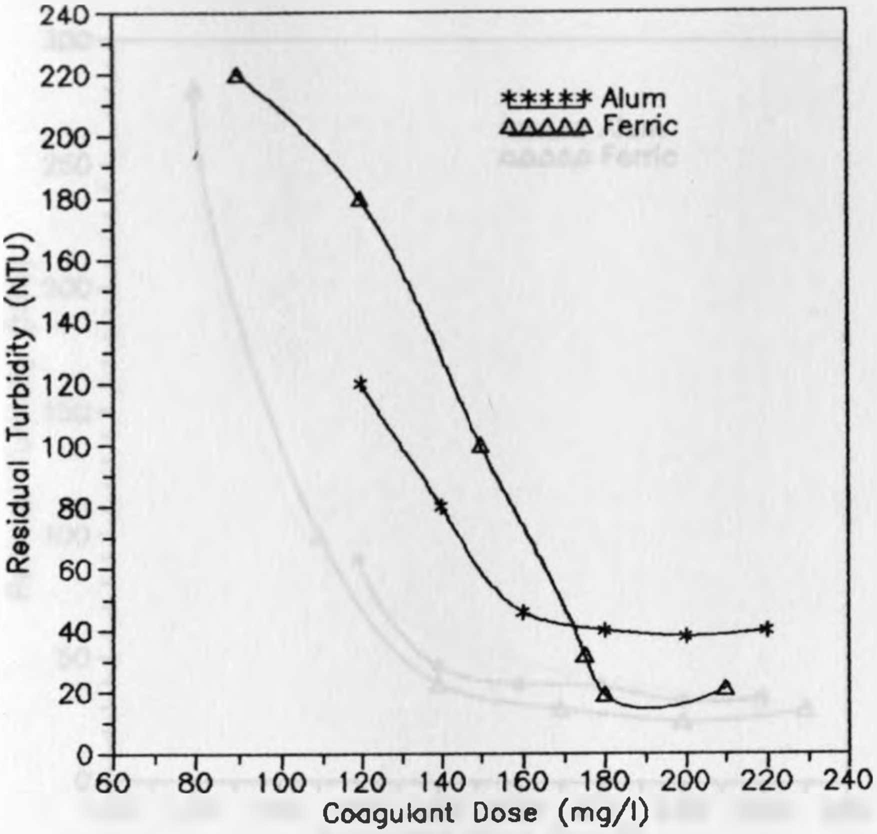


Fig. 5.2(h-1) Residual Turbidity Versus Dose
(RWT = 3100, SD 14/12/1992.)

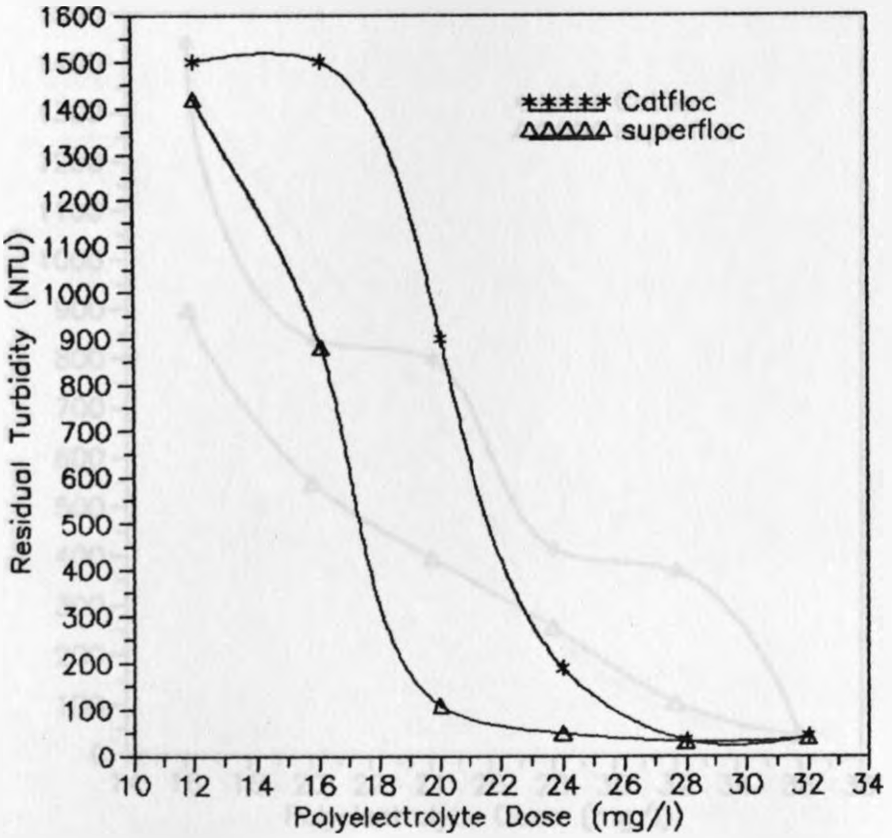


Fig. 5.2(h-2) Residual Turbidity Versus Dose
(RWT = 3100, SD 14/12/1992.)

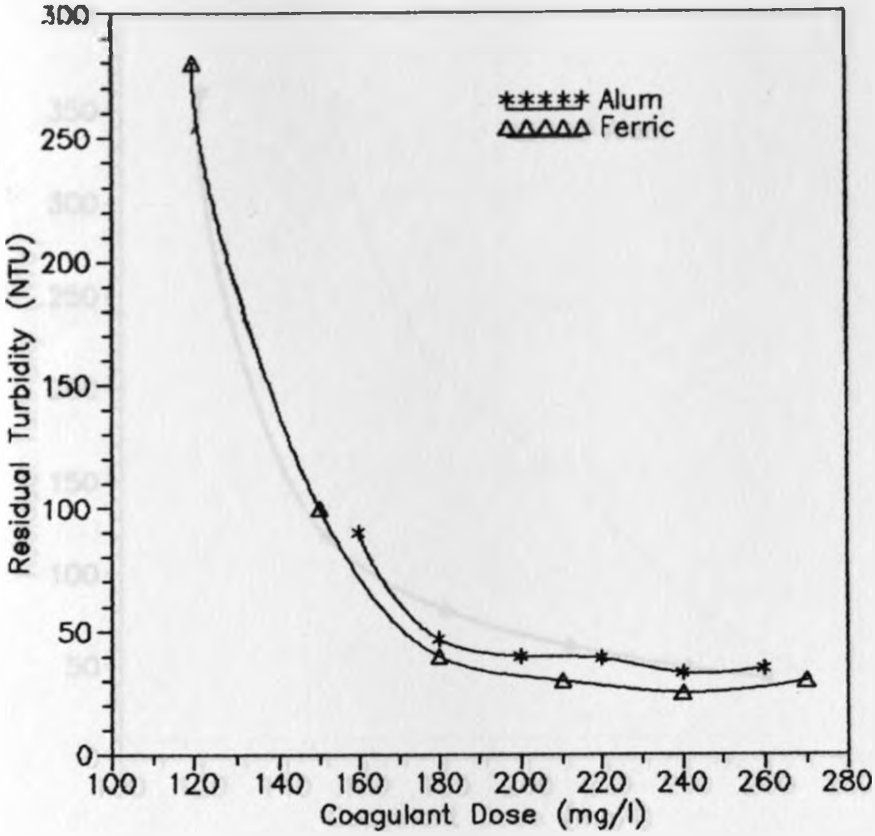


Fig. 5.2(J–1) Residual Turbidity Versus Dose
(RWT = 4000, SD 15/12/1992.)

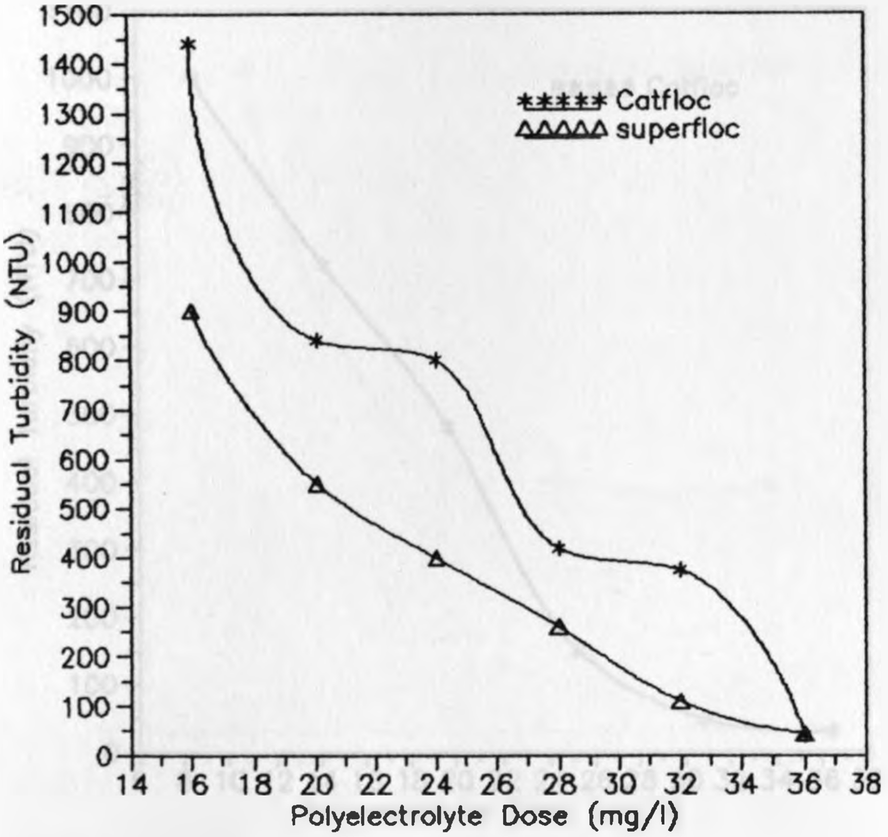


Fig. 5.2(J–2) Residual Turbidity Versus Dose
(RWT = 4000, SD 15/12/1992.)

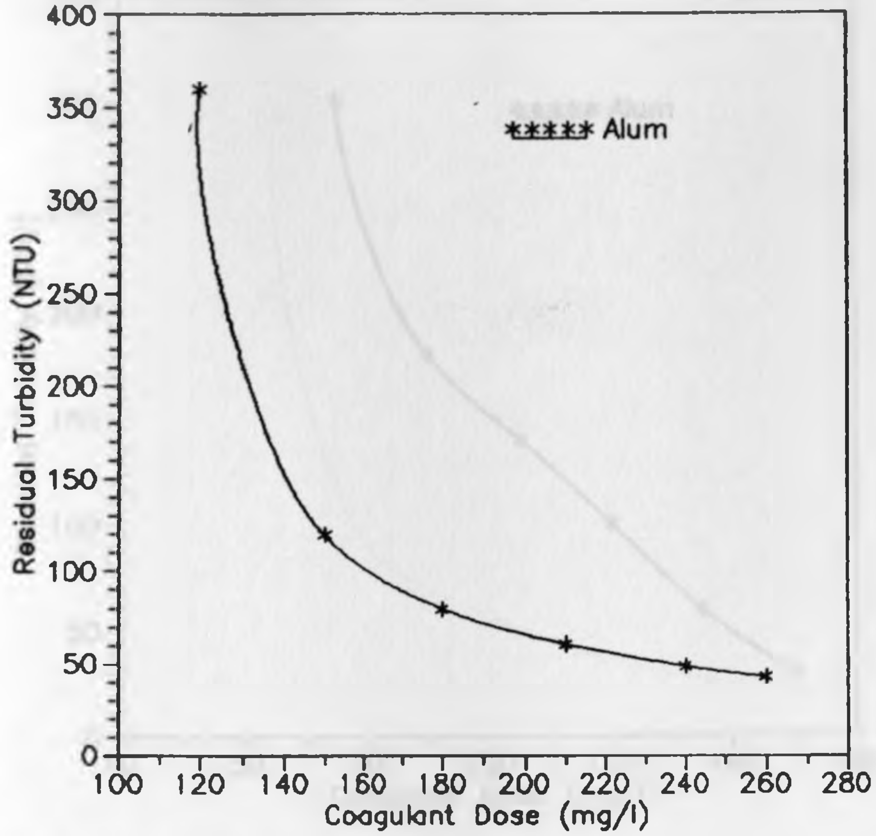


Fig. 5.2(K–1) Residual Turbidity Versus Dose
(RWT = 3400, SD 19/01/1993.)

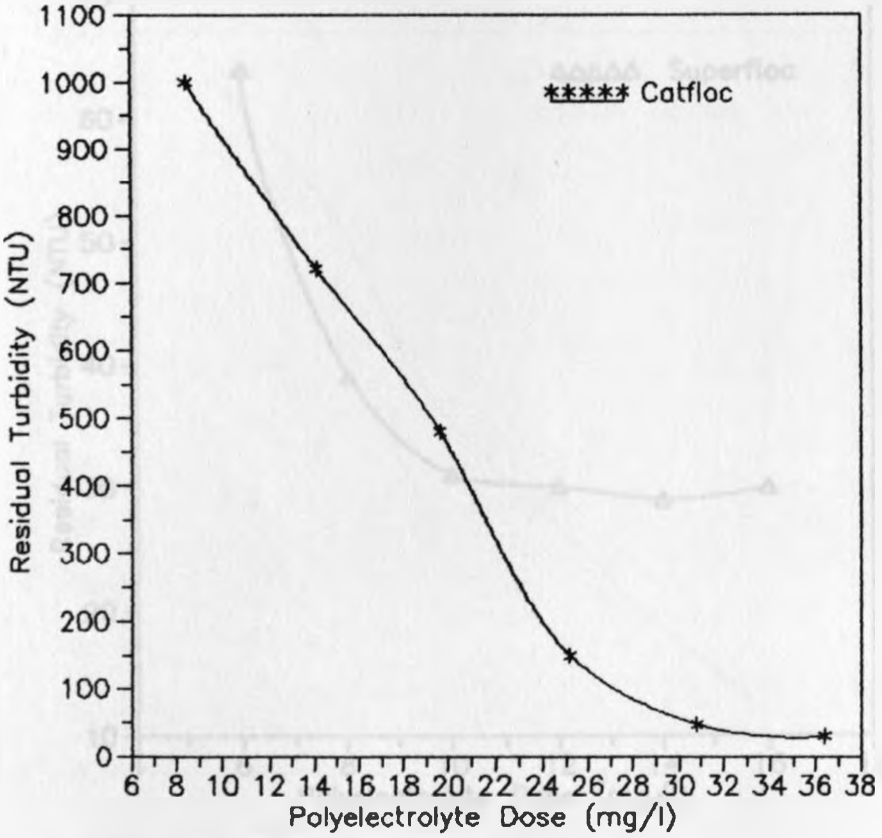


Fig. 5.2(K–2) Residual Turbidity Versus Dose
(RWT = 3400, SD 19/01/1993.)

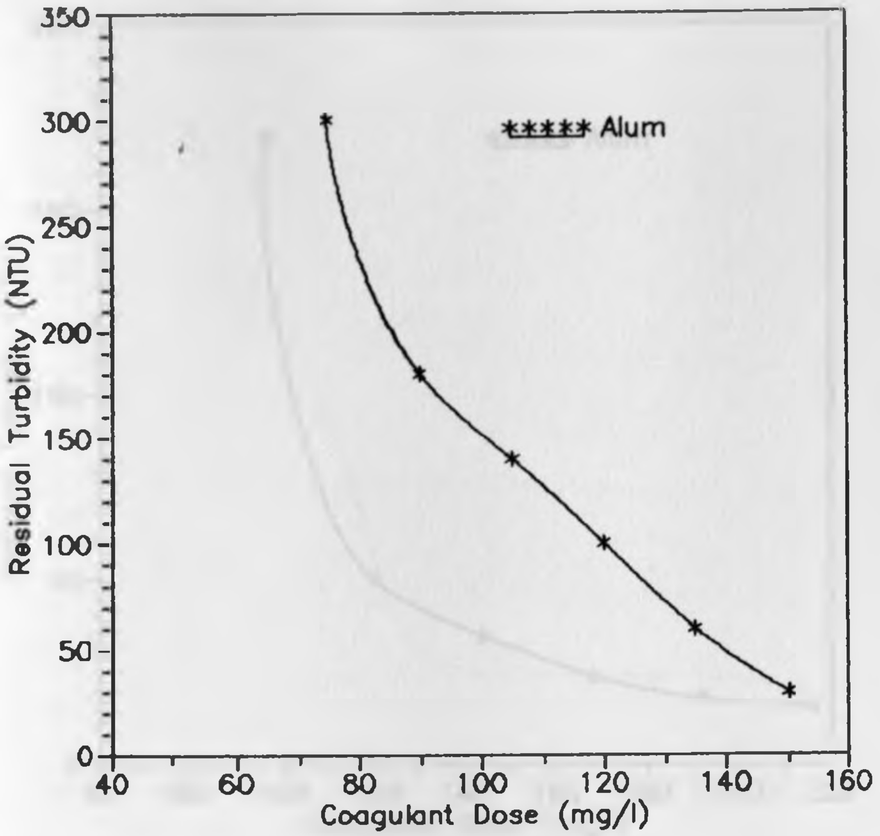


Fig. 5.2(L-1) Residual Turbidity Versus Dose (RWT = 1400, SD 26/01/1993.)

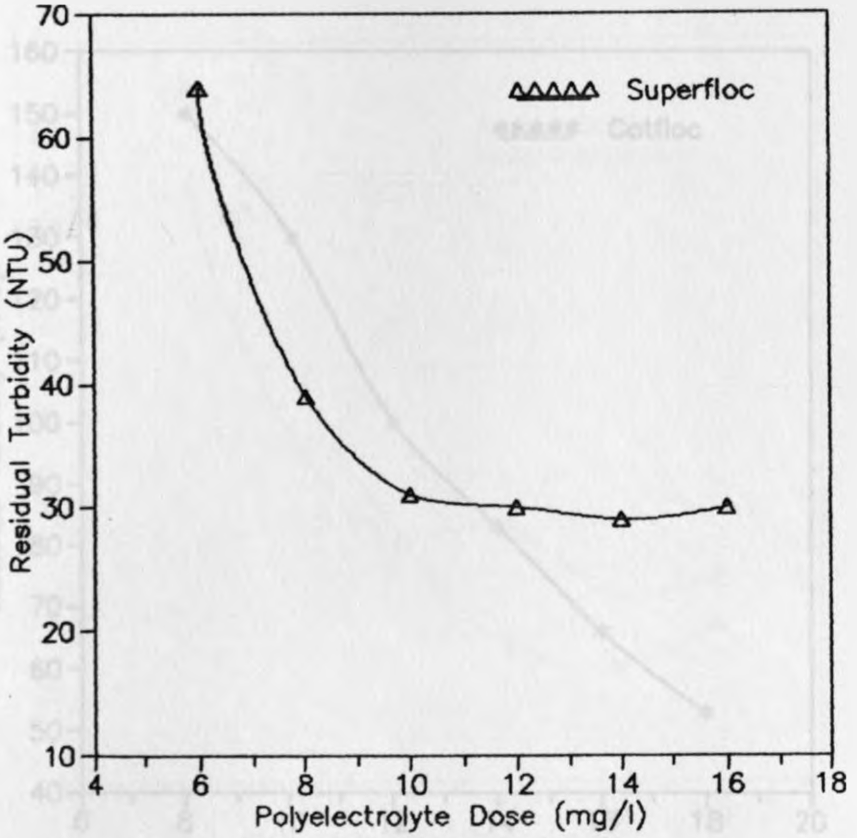


Fig. 5.2(L-2) Residual Turbidity Versus Dose (RWT = 1400, SD 26/01/1993.)

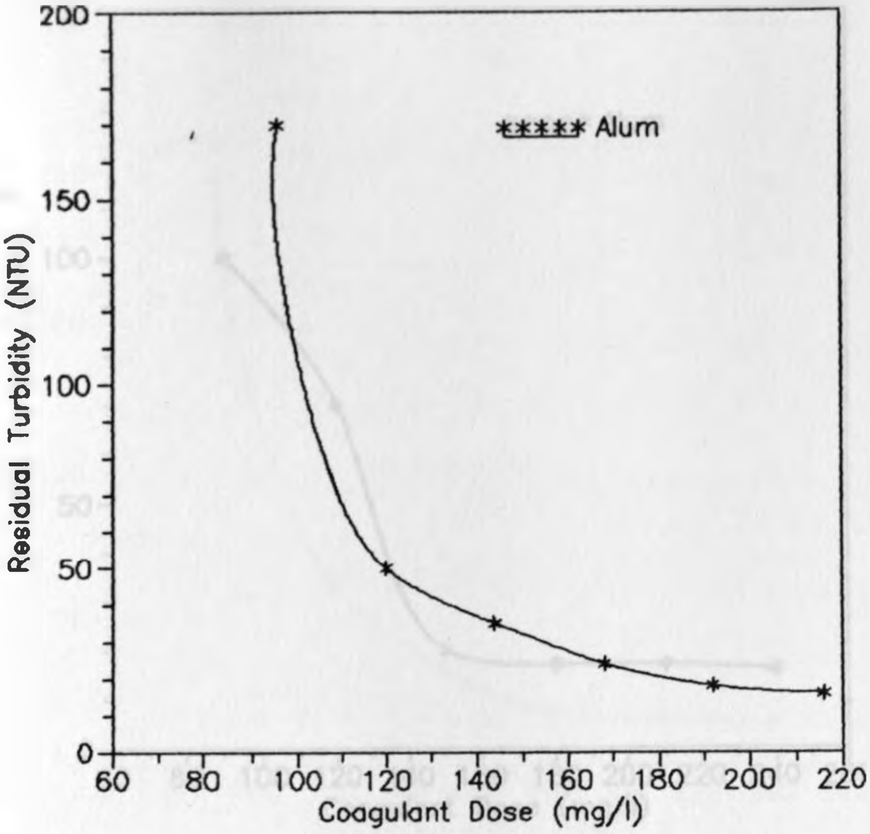


Fig. 5.2(m-1) Residual Turbidity Versus Dose
(RWT = 1300, SD 27/01/1993.)

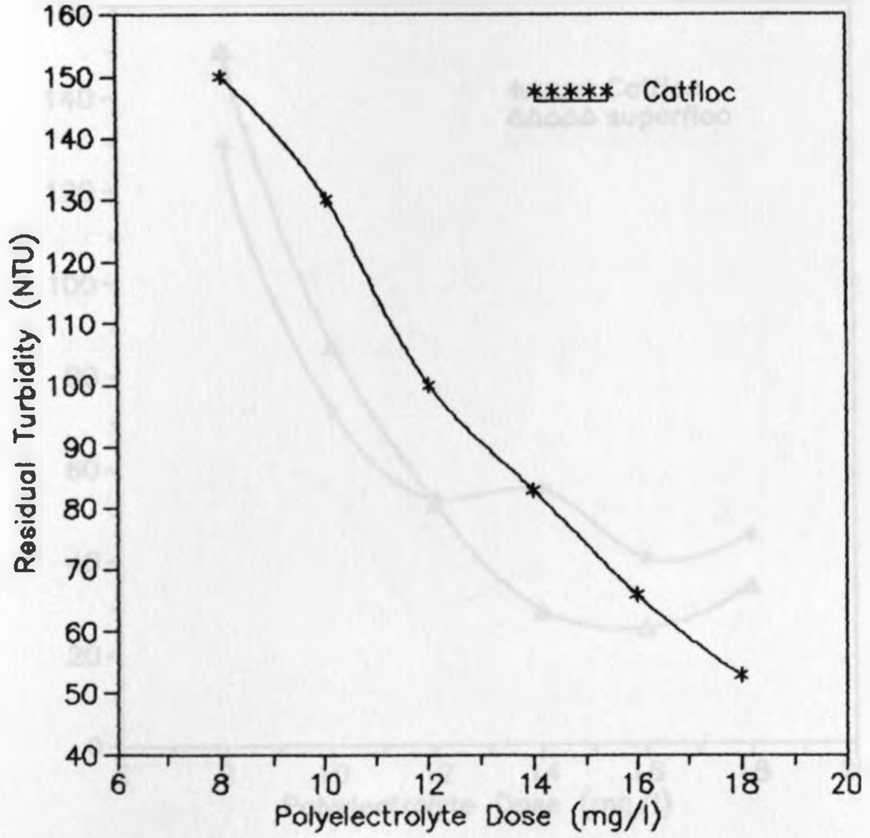


Fig. 5.2(m-2) Residual Turbidity Versus Dose
(RWT = 1300, SD 27/01/1993.)

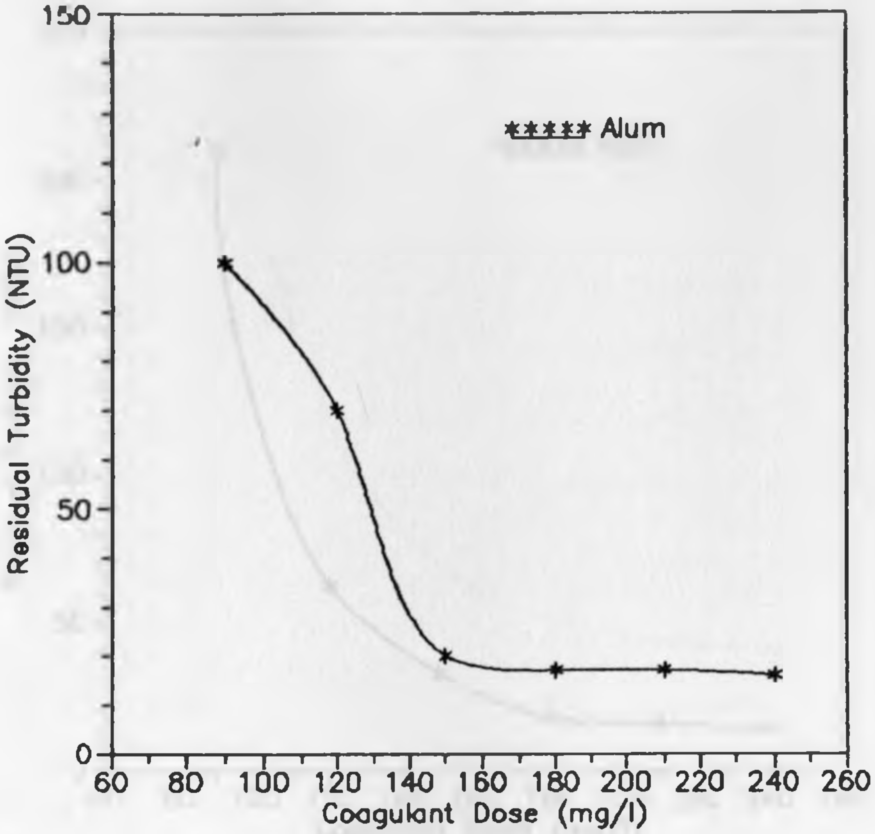


Fig. 5.2(n−1) Residual Turbidity Versus Dose
(RWT = 1200, SD 28/01/1993.)

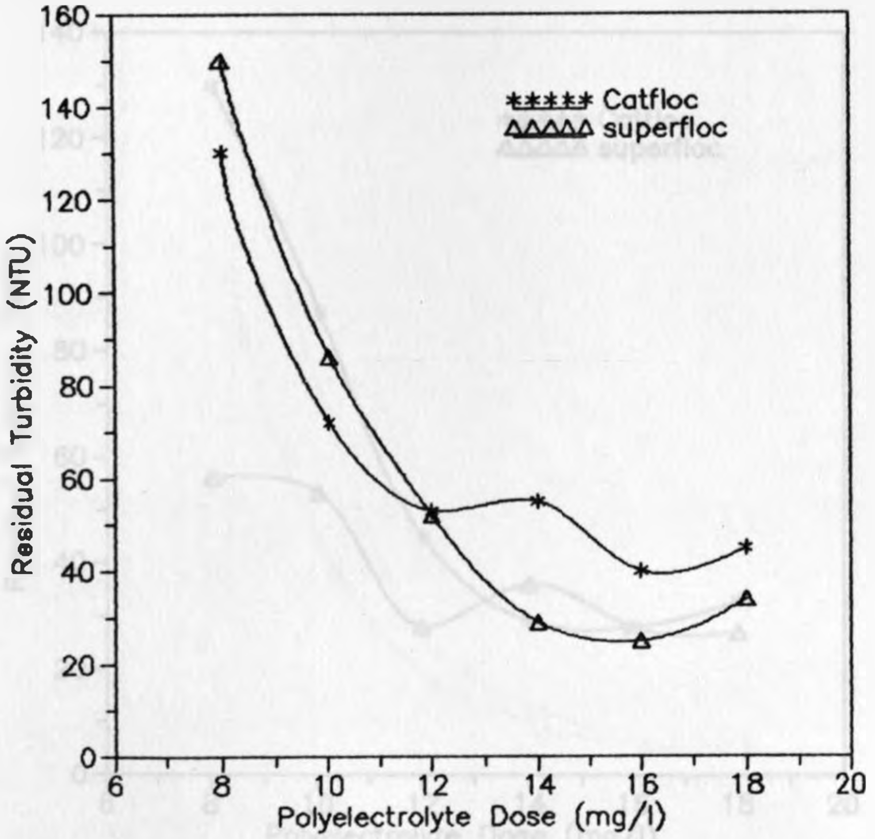


Fig. 5.2(n−2) Residual Turbidity Versus Dose
(RWT = 1200, SD 28/01/1993.)

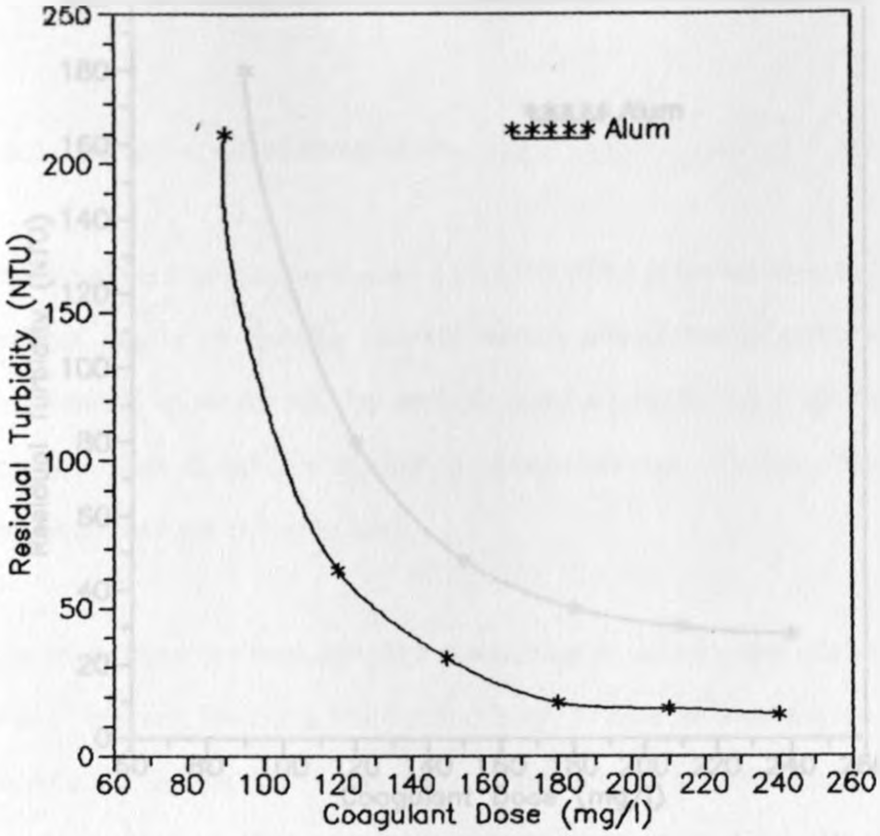


Fig. 5.2(p–1) Residual Turbidity Versus Dose
(RWT = 1100, SD 29/01/1993.)

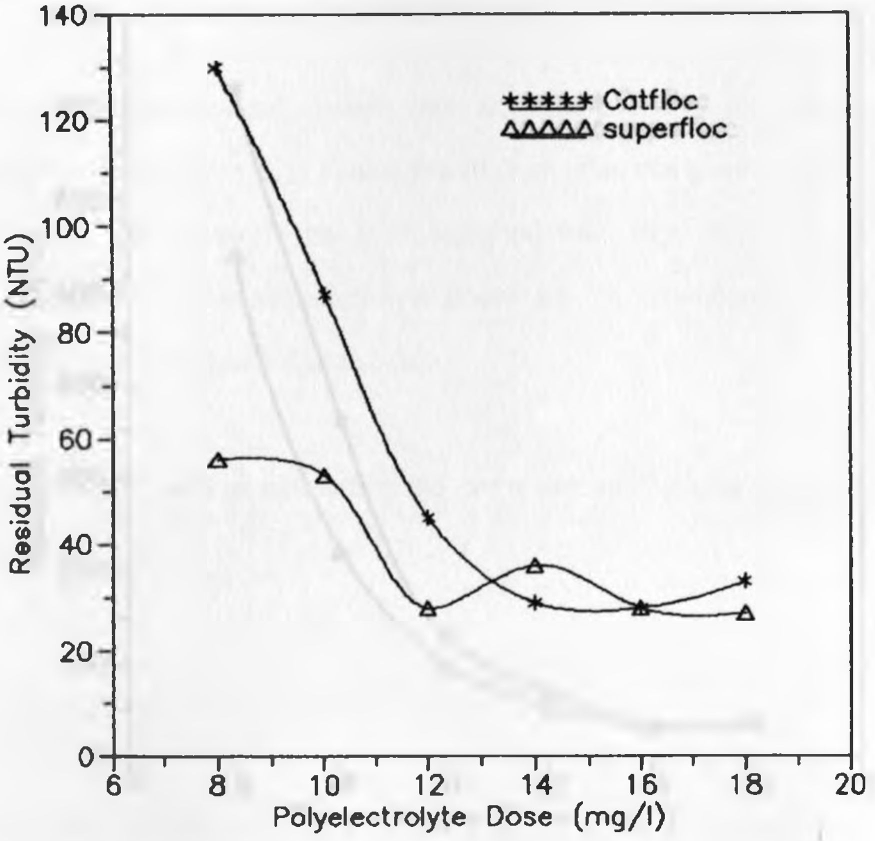


Fig. 5.2(p–2) Residual Turbidity Versus Dose
(RWT = 1100, SD 29/01/1993.)

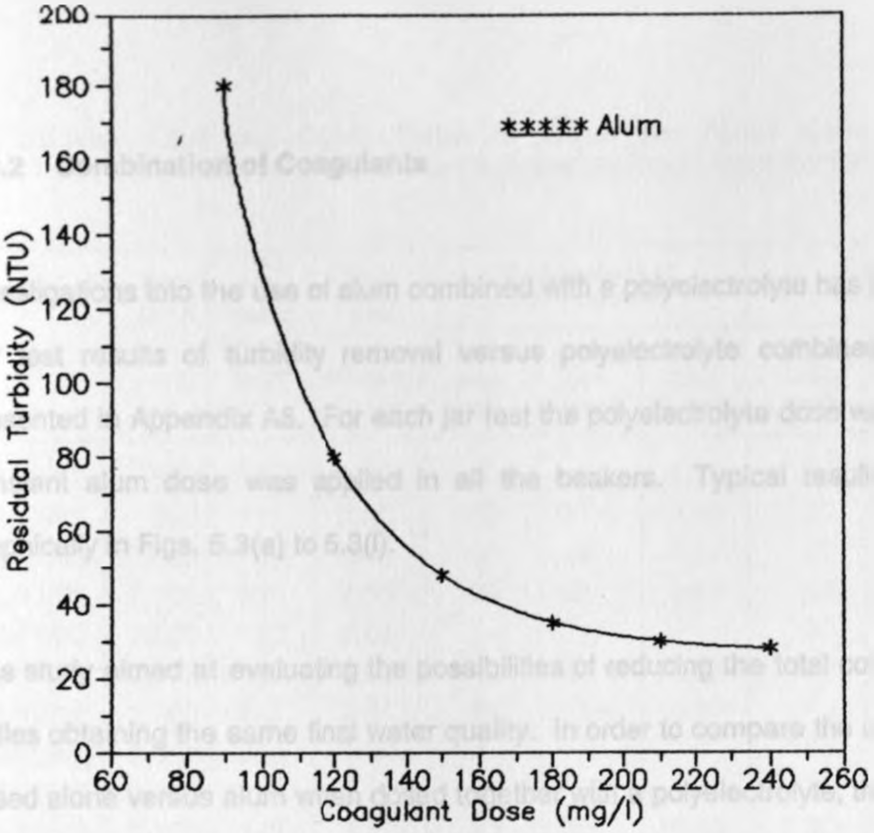


Fig. 5.2(q–1) Residual Turbidity Versus Dose
(RWT = 2800, SD 01/02/1993)

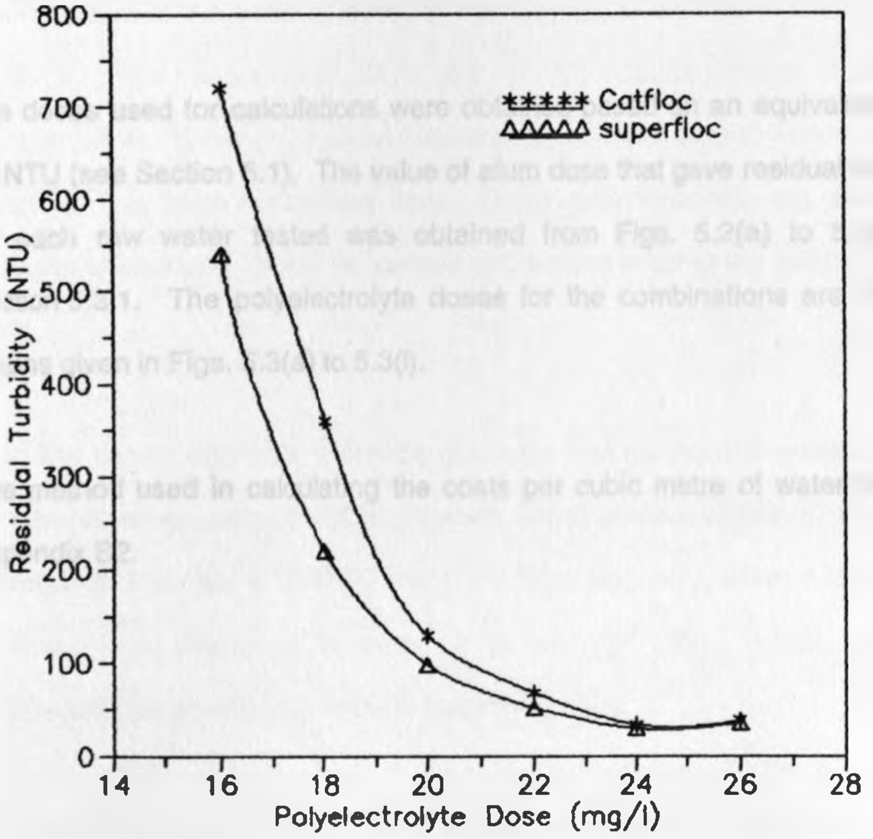


Fig. 5.2(q–2) Residual Turbidity Versus Dose
(RWT = 2800, SD 01/02/1993.)

5.3.2 Combination of Coagulants

Investigations into the use of alum combined with a polyelectrolyte has been carried out. Jar test results of turbidity removal versus polyelectrolyte combined with alum are presented in Appendix A5. For each jar test the polyelectrolyte dose was varied while a constant alum dose was applied in all the beakers. Typical results are presented graphically in Figs. 5.3(a) to 5.3(l).

This study aimed at evaluating the possibilities of reducing the total cost of coagulation, whiles obtaining the same final water quality. In order to compare the use of alum when dosed alone versus alum when dosed together with a polyelectrolyte, the cost of treating a cubic metre of water using alum alone, and using alum dosed together with a polyelectrolyte were calculated from the observed dosages. The summary of the costs are presented in Table 5.3(b).

The doses used for calculations were obtained based on an equivalent performance of 50 NTU (see Section 5.1). The value of alum dose that gave residual turbidity of 50 NTU for each raw water tested was obtained from Figs. 5.2(a) to 5.2(q) presented in Section 5.3.1. The polyelectrolyte doses for the combinations are obtained from the graphs given in Figs. 5.3(a) to 5.3(l).

The method used in calculating the costs per cubic metre of water treated is given in Appendix B2.

Table 5.3(b) Cost per Cubic Metre of Water for Alum alone Versus Alum Combined with Polyelectrolytes for Equivalent Performance

Date	RWT (NTU)	Alum Dosed Alone (mg/l)	Alum Cost (KShs/m^3)	Combinations of Alum & Catfloc			Combinations of Alum & Superfloc		
				Alum Dose (mg/l)	Catfloc Dose (mg/l)	Total Cost (Ksh/m^3)	Alum Dose (mg/l)	Superfloc Dose (mg/l)	Total Cost (KSh/m^3)
18/11/92	600	60	1.05	20	3	1.15	20	6.5	2.07
19/11/92	950	117	2.05	20	11.4	3.37	20	9.2	2.79
19/11/92+	1,500	150	2.63	40	18	5.47	40	19.5	5.87
20/11/92	2,100	160	2.80	60	32	9.53	60	30.8	9.21
21/11/92	1,500	150	2.63	-	-	-	30	17	5.57
30/11/92	1,800	200	3.50	30	30	8.48	30	20	5.83
01/12/92	1,700	145	2.54	45	18.4	5.67	45	16.5	5.16
03/12/92	3,600	330	5.78	-	-	-	60	36.2	10.64
11/12/92	1,450	-	-	10	4.9	1.48	10	6	1.77
15/12/92	3,100	178	3.12	60	32	9.53	60	25	7.68
22/01/93	3,000	-	-	120	32	2.95	120	1.1	2.39

A comparison of the costs obtained in Table 5.3(b) show that in this country using alum alone is more economical than any of the combinations of alum with each polyelectrolyte. However, it should be emphasised that only the costs of purchasing the chemicals has been considered here. Other considerations, e.g. sludge volume, and easiness of handling should be carried out, before a complete quantified comparison is made.

From the values obtained, it can be observed that as the raw water turbidity increases the difference between cost of alum when dosed alone and the combinations increases (For example, compare 18/11/92 and 03/12/93). Secondly, when a large amount of alum is dosed the difference is small (e.g. on 22/01/93). This suggests that the polyelectrolytes work better in lower turbidity ranges.

It should further be noted that in all the cases presented in Table 5.3(b), alum was dosed simultaneously with a polyelectrolyte. However, it should be emphasized that proper chemical application sequence is very important. This was illustrated by jar tests conducted on 22nd January and 2nd February 1993 (See Table 5.3(c)). The following three sets of experiments were conducted with each polyelectrolyte in combination with alum:

(i) Set one was done by dosing raw water with a polyelectrolyte first then alum followed after the rapid mixing of 2 min.

(ii) Set two was done by dosing alum first and then a polyelectrolyte after the rapid mixing of 2 min.

(iii) Set three was done by dosing both alum and polyelectrolyte simultaneously.

From the results in Table 5.3(c), it was noted that set two gave the best turbidity removal, while set one gave the worst results. This observation could be explained by the conclusion derived in Section 5.4 of this report, i.e. optimal polyelectrolyte dose is obtained at lower pH values. Thus on dosing alum first the solution pH is lowered (since alum is acidic) to pH ranges for optimal coagulation with polyelectrolyte.

With this in mind, then, the statement in Section 1.2 paragraph 2, which reads "The Sabaki Water Works was basically designed for initial removal of suspended solids in the presettlement tanks using a polyelectrolyte and then coagulation with alum at the clarifiers" is not justified. This is so because dosing alum first and then the polyelectrolyte proved more economical than vice - versa. Hence if a polyelectrolyte is used, it would be recommendable to dose it at the clarifiers and alum at the presettlement.

Once again, comparison of all relevant costs would be necessary to provide a complete quantified comparison.

Table 5.3(c) Results on Sequential Application of Alum Combined with the Polyelectrolytes (NB: Results on Catfloc were Conducted on 22nd January 1993, while those with Superfloc were Conducted on 2nd February 1993. In Both Cases the Raw Water Turbidity was 3000 NTU).

Alum Dose mg/l	Polyelectrolyte Dose (mg/l)		Residual Turbidity (NTU)					
			Set One		Set Two		Set Three	
	Catfloc	Superfloc	Catfloc	Superfloc	Catfloc	Superfloc	Catfloc	Superfloc
105	18	8	73	25	60	33	360	30
90	20	10	400	27	50	26	300	24
75	22	12	300	27	50	23	320	24
60	24	14	510	29	46	10	300	25
45	26	16	450	28	38	9	260	26
30	28	18	180	27	42	8	71	27

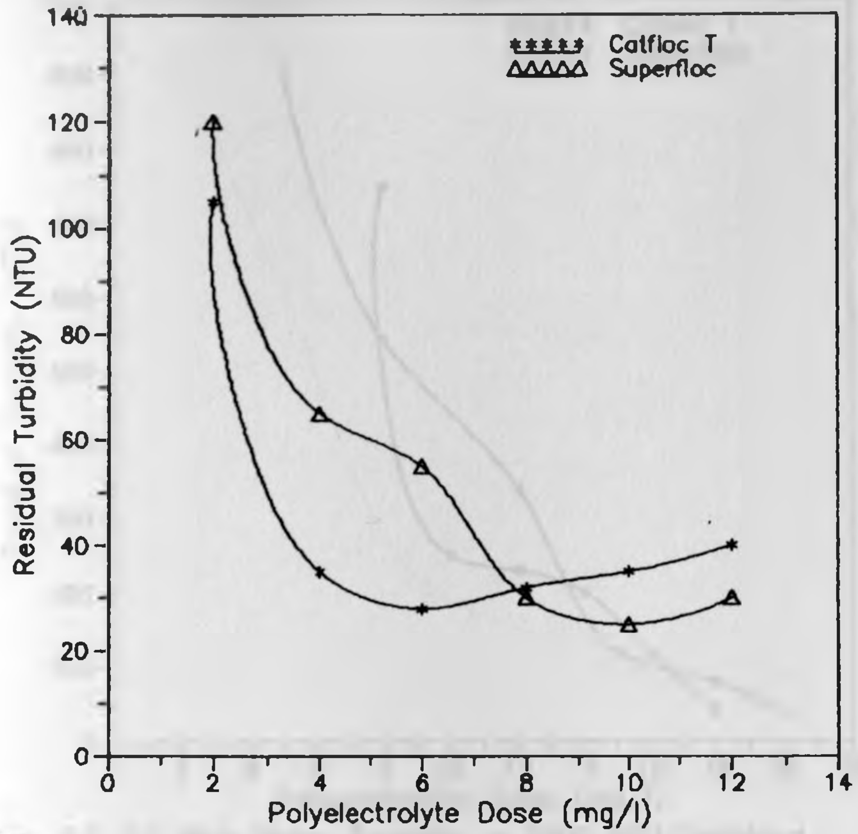


Fig. 5.3 (a) Raw Water Turbidity = 600 NTU.Combined with constant Alum dose of 20mg/l. (SD 18/11/1992)

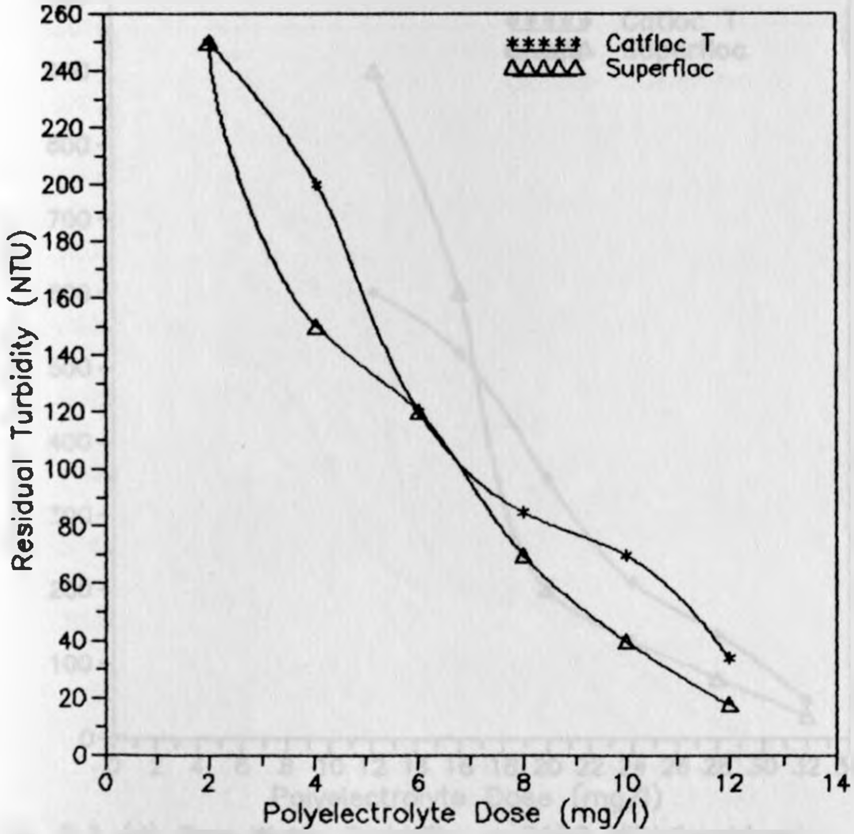


Fig. 5.3 (b) Raw Water Turbidity = 950 NTU.Combined with constant Alum dose of 20mg/l (SD 19/11/1992)

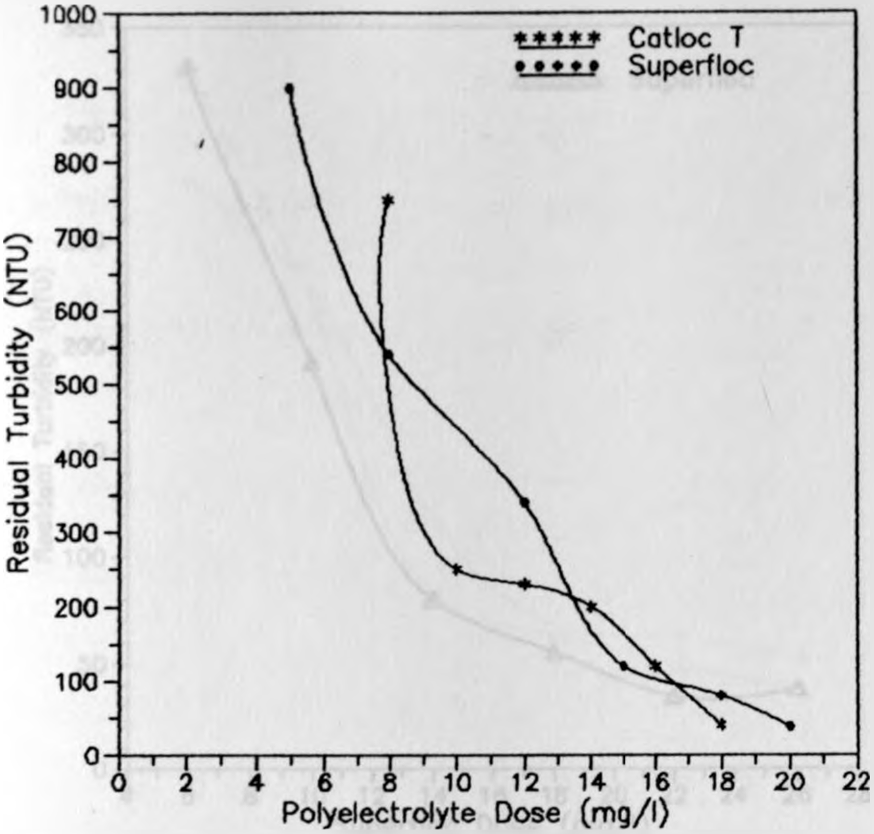


Fig. 5.3 (c) Raw Water Turbidity = 1800 NTU.Combined with constant Alum dose of 40mg/l. (SD 19/11/1992+)

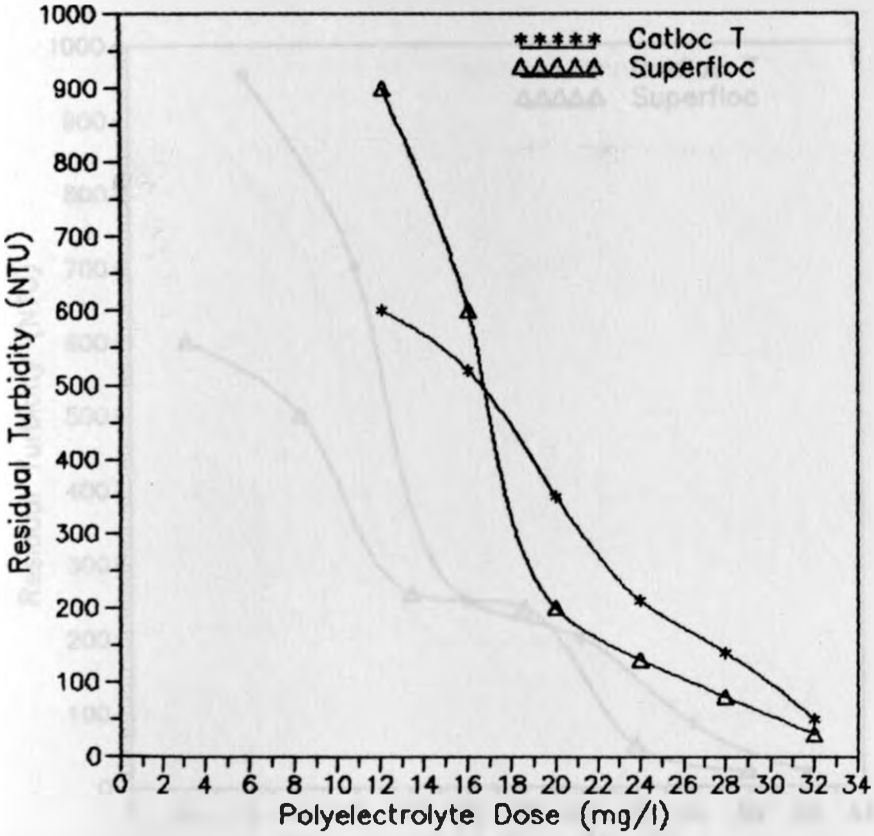


Fig. 5.3 (d) Raw Water Turbidity = 2100 NTU.Combined with constant Alum dose of 60mg/l. (SD 20/11/1992+)

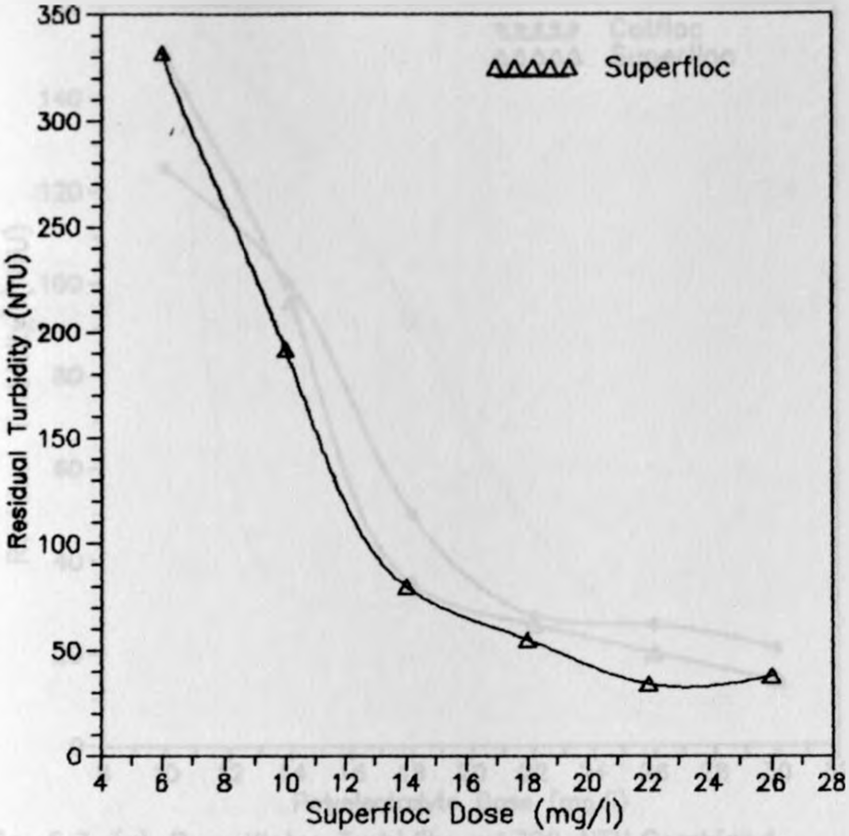


Fig. 5.3 (e) Raw Water Turbidity = 1500 NTU.Combined with constant Alum dose of 30mg/l. (SD 21/11/1992)

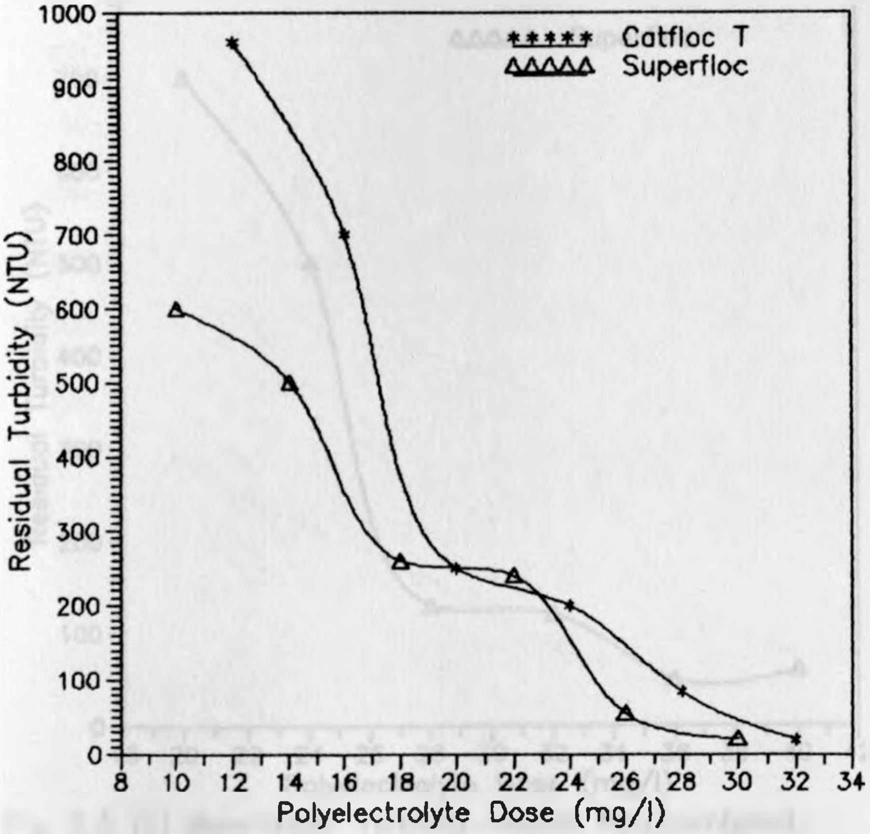


Fig. 5.3 (f) Raw Water Turbidity =1800 NTU.Combined with constant Alum dose of 40mg/l. (SD 30/11/1992)

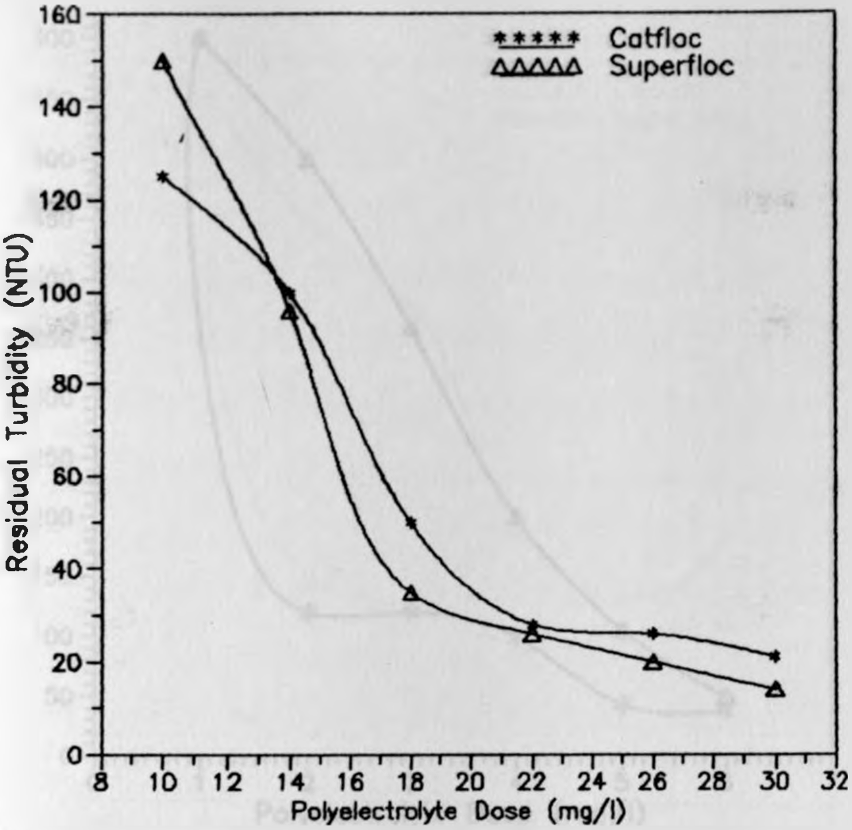


Fig. 5.3 (g) Raw Water Turbidity =1700 NTU.Combined with constant Alum dose of 45mg/l. (SD 01/12/1993)

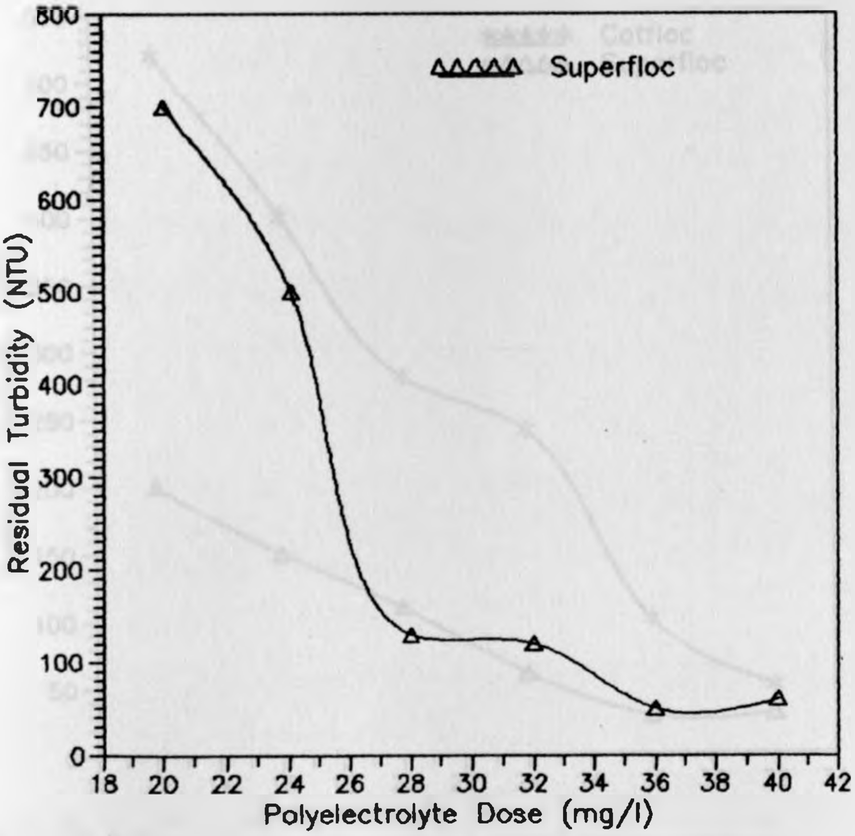


Fig. 5.3 (h) Raw Water Turbidity =3600 NTU.Combined with constant Alum dose of 60mg/l. (SD 03/12/1992)

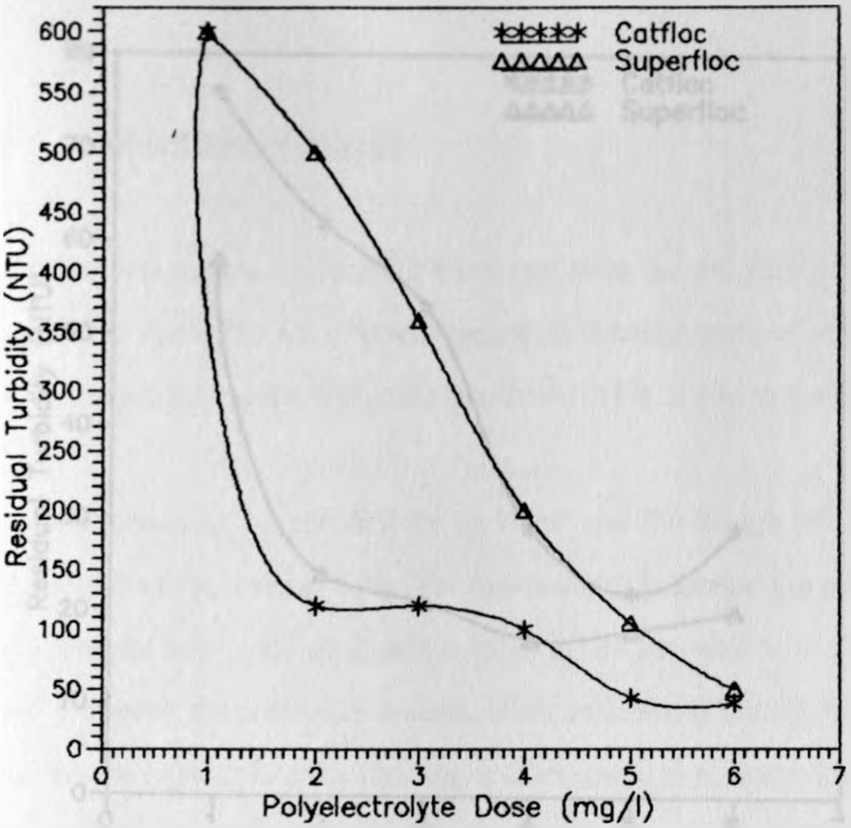


Fig. 5.3(J) Raw Water Turbidity =1450 NTU.Combined with constant Alum dose of 10mg/l. (SD 11/12/1992)

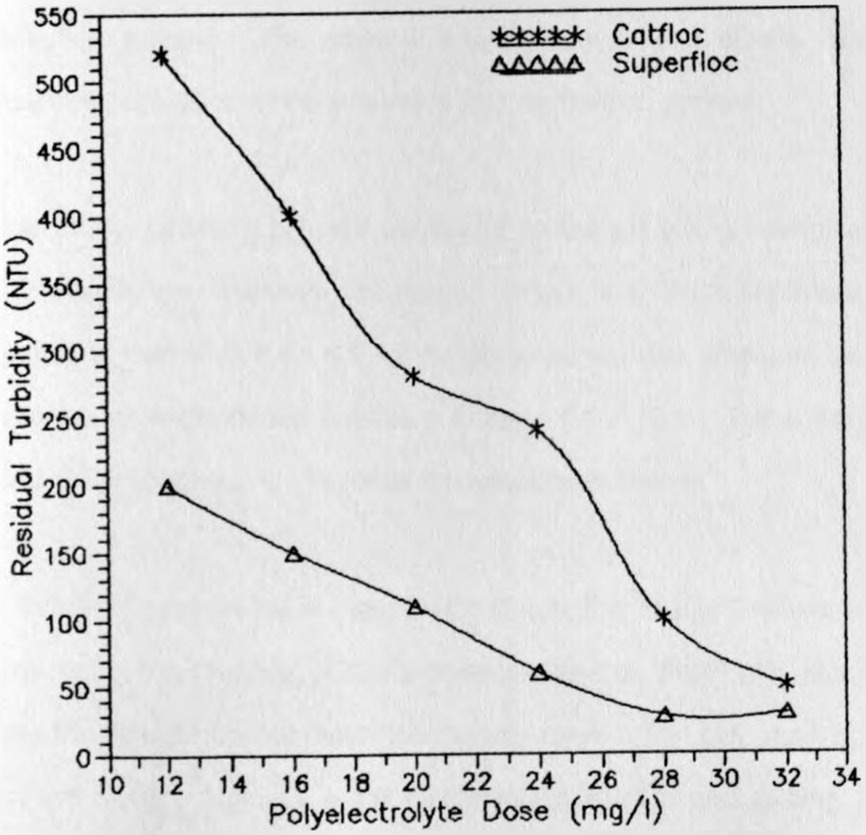


Fig. 5.3 (k) Raw Water Turbidity =3400 NTU.Combined with constant Alum dose of 60mg/l. (SD 15/12/1992)

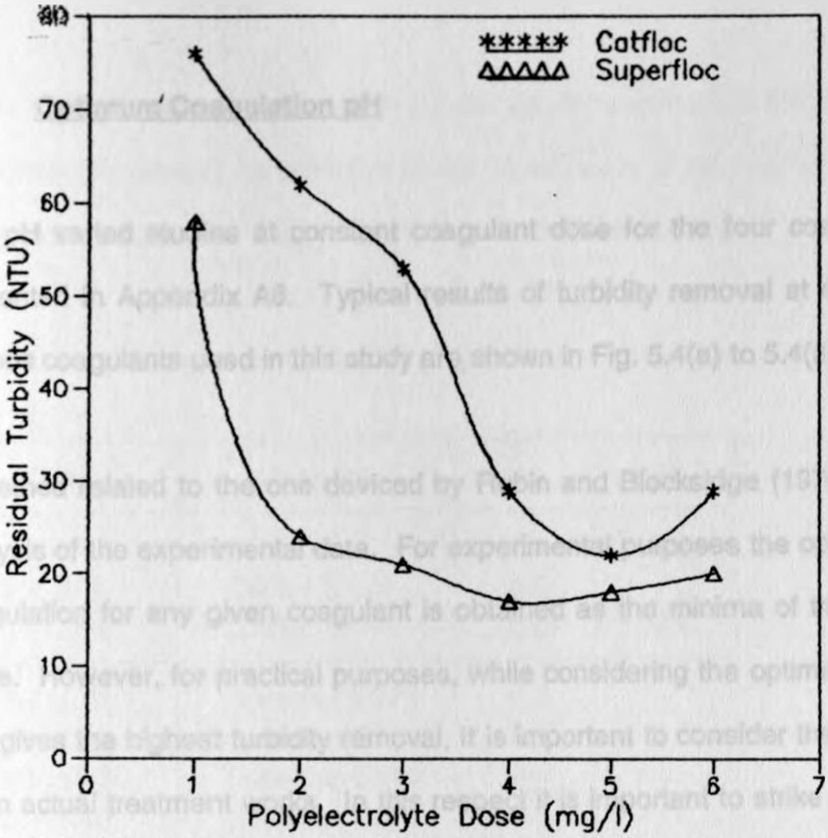


Fig. 5.3 (L) Raw Water Turbidity =3000 NTU.Combined with constant Alum dose of 120mg/l. (SD 22/01/1993)

5.4 Optimum Coagulation pH

The pH varied studies at constant coagulant dose for the four coagulants tested are presented in Appendix A6. Typical results of turbidity removal at different pH for the various coagulants used in this study are shown in Fig. 5.4(a) to 5.4(d).

A method related to the one deviced by Rubin and Blocksidge (1979) was adopted for analysis of the experimental data. For experimental purposes the optimum pH value for coagulation for any given coagulant is obtained as the minima of the turbidity removal curve. However, for practical purposes, while considering the optimum pH to be the pH that gives the highest turbidity removal, it is important to consider the applicability of the pH in actual treatment works. In this respect it is important to strike a balance between the optimum pH and the workable pH ranges. By workable pH range it means a pH range that would not adversely affect the consumers, the treatment units and the distribution system. The adverse effects may among others include health of the consumers, corrosion of the treatment and distribution system.

In this study, optimum pH was construed as the pH giving maximum turbidity removal while lying in the workable pH range. WHO, Vol. 2 (1984) whilst recommending a guideline pH value of 6.5 - 8.5 for supply to consumers, stresses that severe corrosion problems are experienced outside pH range 5.5 - 10.9. The experimental study thus varied the pH between 4 - 11 for all the coagulants tested.

For the results presented in Figs. 5.4(a) to 5.4(d) critical pH values were determined by extrapolating the steepest portions of each curve to obtain pH_L and pH_U, as the points where the straight line deviates the normal curve. The pH_L may be defined as a limit such that a slight decrease in pH results in aggregation and settling. pH_U is the solution pH limit such that a slight increase in pH produces a stable solution. Aggregation therefore occurs in the pH range below pH_L and above pH_U. This values were taken to define the optimum pH range as no substantial improvement in the removal of turbidity was observed beyond this deviation points. A summary of the optimum pH ranges of the coagulant tested for the Sabaki waters is given in Table 5.4(a).

Table 5.4 Summary of pH_L and pH_U Values

Date	Coagulant	pH_L	pH_U
18/11/92	Catfloc T	6.4	8.9
20/11/92	Catfloc T	6.0	-
01/12/92	Catfloc T	6.0	9.1
16/11/92	Superfloc C573	6.2	-
18/11/92	Superfloc C573	6.1	9.2
20/11/92	Superfloc C573	5.9	-
27/11/92	Superfloc C573	6.5	-
17/11/92	Alum	7.4	9.8
20/11/92	Alum	7.4	-
21/11/92	Alum	7.0	11.3
27/11/92	Alum	7.0	-
01/12/92	Alum	6.9	9.6
24/11/92	Ferric	4.3	7.7
28/11/92	Ferric	6.0	8.3
01/12/92	Ferric	6.5	-
14/12/92	Ferric	5.5	-

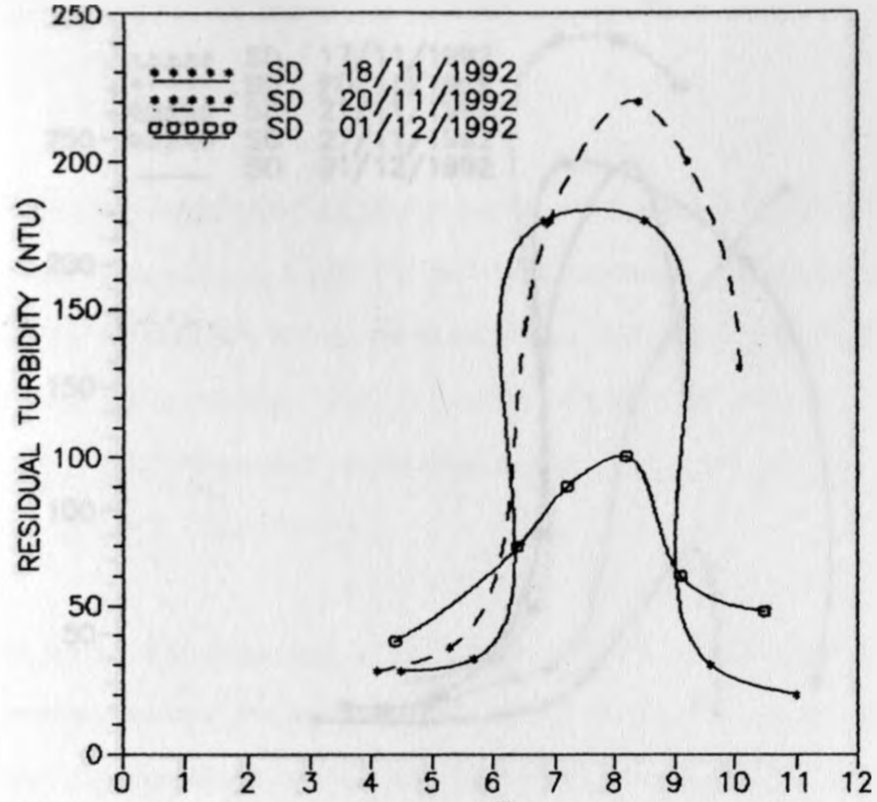


Fig. 5.4(a) Typical curves for catfloc T at constant doses with pH variation

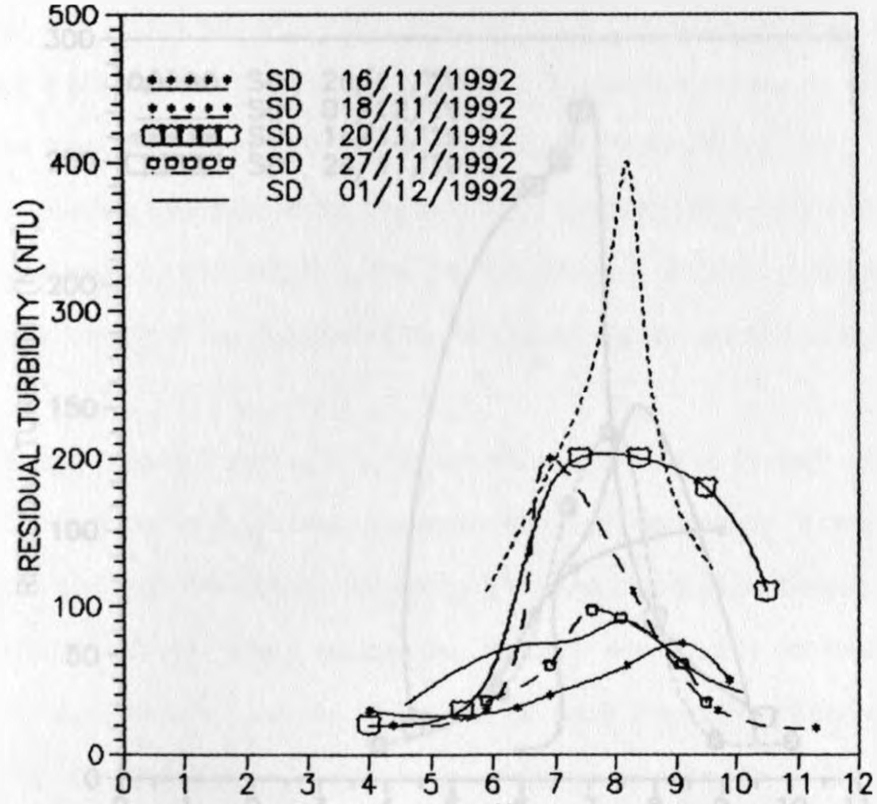


Fig. 5.4(b) Typical curves for superfloc C573 at constant doses with pH variation

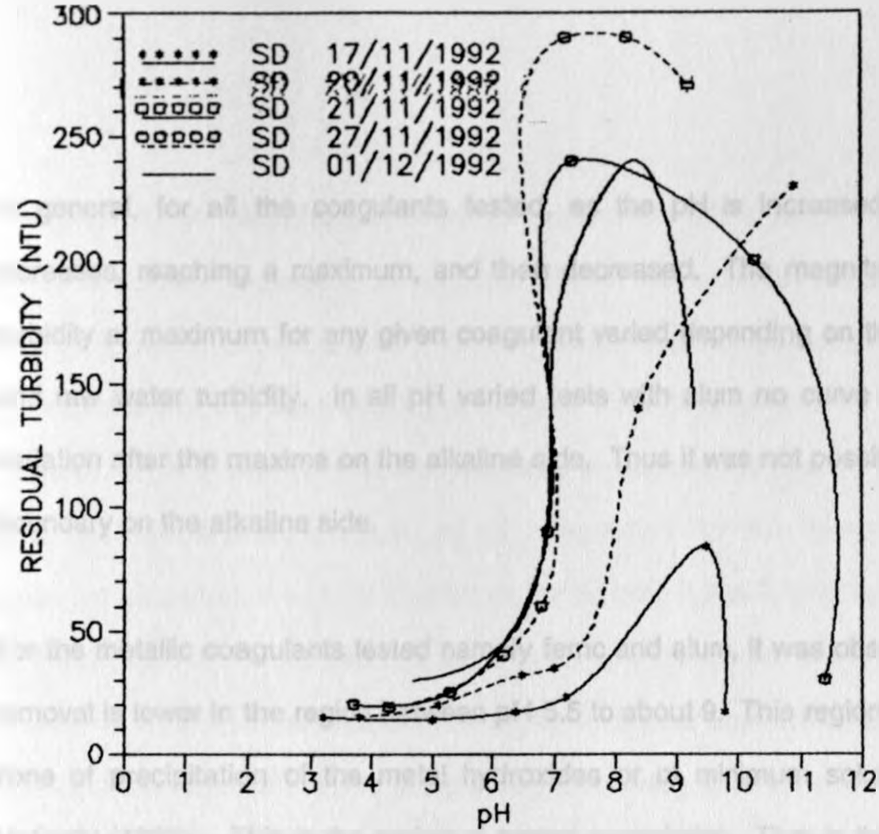


Fig. 5.4(c) Typical curves for alum at constant doses with pH variation

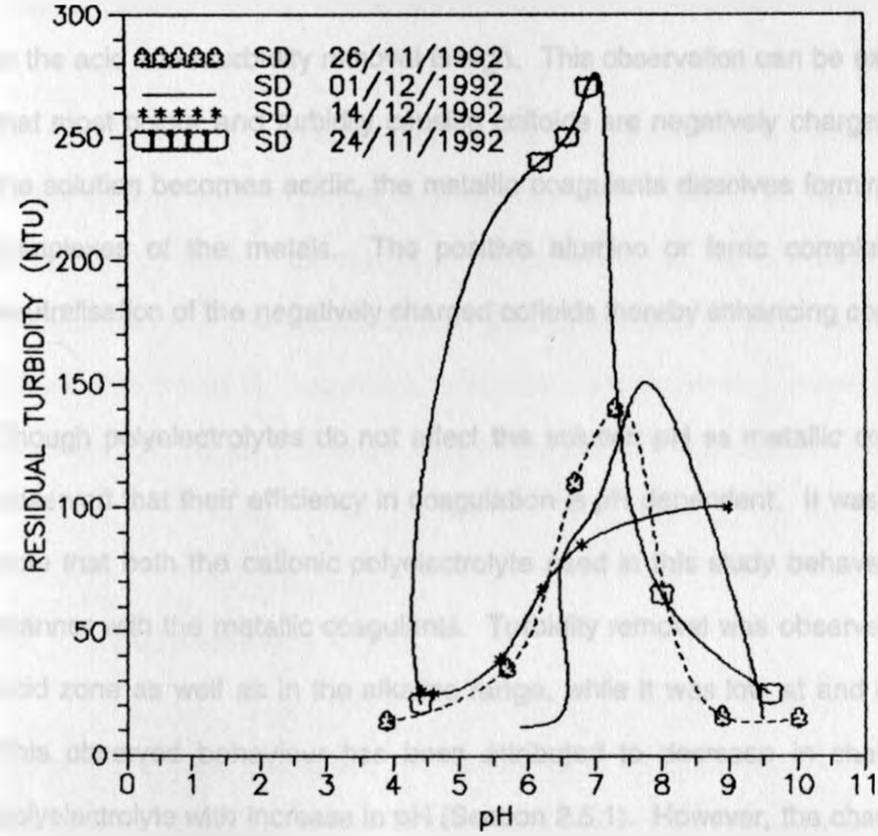


Fig. 5.4(d) Typical curves for ferric chloride at constant doses with pH variation

In general, for all the coagulants tested, as the pH is increased residual turbidity increases, reaching a maximum, and then decreased. The magnitude of the residual turbidity at maximum for any given coagulant varied depending on the amount of dose and raw water turbidity. In all pH varied tests with alum no curve showed a marked variation after the maxima on the alkaline side. Thus it was not possible to establish the boundary on the alkaline side.

For the metallic coagulants tested namely ferric and alum, it was observed that turbidity removal is lower in the region between pH 5.5 to about 9. This region coincides with the zone of precipitation of the metal hydroxides or of minimum solubility (Sawyer and McCarty (1967)). This is the region of sweep coagulation. That is the region where the colloids are enmeshed to the hydroxide and are removed as it settles.

In the acid zone turbidity removal is high. This observation can be explained by the fact that most colour and turbidity causing colloids are negatively charged. Additionally, as the solution becomes acidic, the metallic coagulants dissolves forming positive hydroxo complexes of the metals. The positive alumino or ferric complexes cause charge neutralisation of the negatively charged colloids thereby enhancing coalescence.

Though polyelectrolytes do not affect the solution pH as metallic coagulant do, it was observed that their efficiency in coagulation is pH dependent. It was quite surprising to note that both the cationic polyelectrolyte used in this study behaved in a comparable manner with the metallic coagulants. Turbidity removal was observed to be high in the acid zone as well as in the alkaline range, while it was low at and around neutral pH. This observed behaviour has been attributed to decrease in charge density of the polyelectrolyte with increase in pH (Section 2.5.1). However, the change in pH does not only alter the chemical and physical characteristics of the coagulants, but also the characteristics of the particulate matter in the water.

The complex interrelationship between pH, chemicals added and the water constituents makes it virtually impossible to precisely predict the optimum coagulation pH without performing some experimentation on the actual water to be tested. Hence only an approximation of the best working pH ranges have been presented here. In practice, therefore, a pH varied jar test, as described in Section 4.0 can be used to obtain the most effective and economical pH of coagulation for the given water. For the experimental period, the pH of the Sabaki varied from 7.7 to 8.5 with a mean value of pH 8.1 (Appendix A1). It is noted that the pH generally decreased with increase in turbidity. Increase in turbidity is associated with increase in river flow, which is in turn a result of increased storm runoff. From the existing monitoring data an average pH of 8.3 was obtained for the Sabaki waters. This value is slightly higher than for the experimental period. This can be explained by the fact that the whole of the experimental period was characterised by high turbidities which resulted from heavy downpour upstream.

The results of the experiments suggest that application of the metallic coagulants in the Sabaki waters would not require pH adjustments. This is so because, on dosing the appropriate amount of the coagulant (which are acidic) the pH would be lowered to the optimum range. The results further show that when polyelectrolytes are applied pH adjustments would be necessary. Alternatively when dosing polyelectrolytes combined with metallic coagulant, dose the metallic coagulant first and then the polyelectrolyte.

5.5 Field Experience

The purpose of this discussion is to demonstrate the importance of proper operation and maintenance of various units in a treatment plant. During the experimentation period, a number of observations were made pertaining to the operation, maintenance and staffing of the Sabaki Water Works. There is a tendency in the Sabaki to continue past practices because they seem to work, besides, the saying goes, "it always has been done this way". As a result this study intended to question a number of basic operating procedures and scrutinise various unit operations of the Water Works. Most operations, as expected were satisfactory, but a number of observations were made with regard to some routine aspects of water treatment.

The quality of the raw water entering a plant varies over time, to achieve the optimum condition, an operator must adjust coagulant dose in conjunction with this change. For the Sabaki Water Works it was observed that adjustments are made once every 24 hrs usually during the operators eight hours shift. During the entire 24 hrs time interval, however, significant changes in water quality were observed. This could cause overdosing or underdosing. Overdosing is attractive as it usually gives aesthetically pleasing water. This is greatly practiced in the Sabaki Water Works unknowingly and even intentionally as can be seen in the following examples:

(i) Intentional over dosing especially by the night shift operators as indicated in Section 5.1 was rampant.

(ii) On 31/07/91 and 01/08/91 (Appendix A3) an alum dose of 180 mg/l and 168 mg/l respectively both of which gave a residual turbidity of 40 NTU in the jar test were adopted for plant dosing. This dosages gave final water turbidity < 5 NTU (acceptable, WHO Vol. 2 (1984) in plant results (Appendix A2).

(iii) On 15/08/91 an alum dosage of 100 mg/l which gave a residual turbidity of 16 NTU in the jar test was adopted for plant dosing. Basing our argument on (ii) it would have been economical to adopt the lower dosages of either 80 or 60 mg/l which resulted in a residual turbidity of 24 NTU and 32 NTU respectively in the jar test. This is so because the same filters which managed to reduce 40 NTU in (ii) to acceptable limits would have even handled better the 32 NTU here.

(iv) 01/12/91 both alum dosages of 144 mg/l and 168 mg/l gave a settled water turbidity of 25 NTU in the jar test. Whilst the performance of both dosages was similar, the higher dosage of 168 mg/l was adopted for plant dosing. This is uneconomical. The lower dosage should have been adopted.

(v) On 16/08/91 an alum dosage of 100 mg/l which gave a settled water turbidity of 17 NTU in the jar test was adopted for plant dosing, while a dosage of 80 mg/l had given a settled water turbidity of 20 NTU in the jar test (Appendix A3). The reduction in turbidity by 3 units does not warrant the extra use of 20 mg/l of alum. At the current price KShs. 17.50/kg of alum, a daily misuse of 20 mg/l would incur a loss of about KShs. 8 million per annum on alum alone, when treating 2,400 m^3/hr of water.

From the foregoing discussion it is apparent that overdosing is rampant in the Sabaki Water Works. Secondly, there exist no specific set out criteria for influent turbidity loads to be allowed into the clarifiers or to the filters. Such controls should be fixed so that tangible saving could be realised. Until such values are fixed overdosing will continue to be experienced at the Sabaki. However, it should be emphasised that excessive overdosing, in addition to affecting the health of the consumers, leads to unnecessary added treatment costs, especially costs associated with sludge removal and pH adjustments.

During the field investigations it was noted that excessive accumulation of sludge both in the presettlement tanks and the clarifiers was rampant. On occasions the sludge accumulated to levels such that it could be felt by slightly dipping the hand a few inches.

Accumulation of excessive sludge reduces the capacity of the settlement tanks resulting in reduced retention time and also renders the sludge toxic. Accumulation of sludge was evidenced by the floc carry over observed in the presettled water channels. Bubbling observed in the settlement basins showed that the sludge was turning septic. The operators would at times interpret the carryover as due to insufficient alum dosage, hence increase it. This leads to overdosing. Such occurrences in the presettlement tanks was attributed to irregular sludge draining due to lack of a device to indicate the level of sludge as well as sludge height limit, indicating when desludging is necessary.

The performance of the clarifiers was frequently affected by the failure of the desludging system (described in Section 3.2.3) as well as by the thermal effects. Sludge draining was not regularly done, and accumulated to 2.5 metres of the top. Thermal effect during the hot hours was quite disturbing. Both these factors were evidenced by observed sludge carryover, and bubbling at the water surface. Bubbling indicated that sludge had accumulated to a thickness suitable for anaerobic digestion of the sludge. The bubbling was attributed to methane gas resulting from anaerobic digestion of the organic matter contained in the sludge. The effectiveness of cationic polyelectrolyte in treating potable water has been shown (Kawamura 1991). Whilst cationic polyelectrolytes aids in the formation of larger and heavier flocs, it also resulted in reduced sludge volume. Both this phenomena were observed during jar test as indicated in Section 5.3. Thus application of polyelectrolyte in the clarifiers would solve the problem of thermal effects, as well as reduce the frequency of desludging.

The performance of the filters at the Sabaki Water Works was satisfactory, though difficulties were noticed especially when the influent turbidity exceeded 50 NTU. The filters were backwashed at a frequency of once every 24 hrs. The frequency of backwashing did not change with change in filter influent quality. Whilst this may be acceptable, it should be justified by filter head loss measurements. Otherwise, this may result in under or over use of the filters. Apparently there are no headloss measurements currently being undertaken, as the automated mode described in Section 3.2.4 is not operational. Normal headloss gauge should be installed as poor filter effluent tempted the operators to increase alum dosage in the clarifiers.

An interesting observation was made as regards the quality of the filtered water and the final water for distribution. This is the general trend in the increase of the pH and turbidity of water after passing through the clear water sump (Appendix A1 and A2). Several reasons were advanced for this observed behaviour:

(a) A major omission of a washout for the clear water sump was made during design and construction of the Works. As such no cleaning of the sump has been done since its inception. Accumulation of particles bypassing the filters must then be expected. Carryover of this sludge (which would be alkaline in nature due to residue soda ash) could have an upward adjustment to the pH as well as increase in turbidity.

(b) Tropical Chloride of Lime (TCL) which is dosed after filtration, is used as the disinfectant. When TCL is dissolved in water it ionises to yield a hypochlorite ion which causes an increase in pH as shown in equation 5.5.1 and 5.5.2.

$$Ca(OCl)_2 + (H_2O) \rightleftharpoons Ca^{2+} + 2OCl^- \quad \ldots\ldots (5.5.1)$$

The hypochlorite ion establishes an equilibrium with the hydrogen ions in accordance to equation 5.5.2

$$OCl^- + H_2O \rightleftharpoons HOCl + OH^- \quad \ldots\ldots (5.5.2)$$

The OH^- ion produced causes the increase in pH.

During the field investigations, all flow measuring devices in the conveyance channels were out of order. Information was obtained that they have been out of operation for a long time. As a result flow measurements were estimated from raw water pumps performance curves supplied by the manufacturer. This is inaccurate as the pumps are old and have been subject to impact damage, wear and deterioration. Additionally serious leaks between units were evident from the continuous heavy flow observed in the drainage channels. For example most of the gates draining from the presettlement tanks were seriously leaking. This and others are signs of poor maintenance. Without accurate flow measurements it is highly doubtful whether exact chemical dosage can be applied. Exact dosage is particularly necessary if polyelectrolytes are to be used.

From the foregoing discussion it is apparent that proper training of the water works staff is essential if optimum treatment conditions are to be met. Unless they are qualified, it is unlikely that safe and economical water can be provided for public consumption. Whilst the selection of a mechanical engineer to head the plant (Section 3.4) appears to have been largely influenced by the overriding difficulty in keeping the mechanical plant operational, it is doubtful whether such an engineer would be capable of handling problems related to water treatment. A civil engineer would be best suited to head operations and the mechanical engineer to head maintenance.

On a closer examination at the organisation structure presented in Section 3.4, the most obvious shortcoming is the marked dependence on subordinate staff with no formal technical training and limited education. Only 32% of the staff are trained. Whilst it may be argued that the untrained staff have gained invaluable specific experience on the job, which other trained personnel may lack, and take time which may be viewed as unaffordable, it should be borne in mind that:

(i) untrained staff would not be in a position to deal with a situation that they have not previously encountered directly, which is a requirement for staff dealing with expensive and complicated plants

(ii) their lack of adequate formal education means that training and job advancement opportunities would not be open to them, unlike others, of whom they will be aware, who although performing similar work are more educated, leading to loss of morale and frustration on their part.

Being located in a remote area, to maintain qualified staff at the works, or even to mitigate against attempts by such staff to seek other employment opportunities, should be given full consideration. To do this the staffs' morale must be uplifted. This can be possible by providing sufficient entertainment, social and communal facilities. During the field investigation it was noted that the staffs' morale was low, thus there was high incidents of absenteeism and repeated efforts by many towards being transfered from Baricho.

Some members of staff were interviewed on what facilities they thought would make their stay at Baricho more comfortable and enjoyable. The following problems were cited in order of importance; lack of adequate schooling facilities for staff children; unavailability of adequate medical facilities nearby; shortage of means of transport; lack of shopping facilities; lack of recreation facilities and many other needs.

It is expected that if sustained efforts towards acting on social and personal needs of the staff is maintained, a disciplined, willing and capable workforce can be built up, greatly reducing the difficulties in operating the works. This too is a major step towards optimum chemical usage.

CHAPTER SIX

CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

The following conclusions were drawn from this study:

1. Alkalinity

   (a) In coagulation with alum, whilst boosting the natural alkalinity is aimed at ensuring effective and complete coagulation, excessive alkalinity addition was found to be counter-productive. In the event of abrupt turbidity increase or low final water pH in the Sabaki Water Works, soda ash is applied at a point prior to clarification stage. Application of soda ash at such a point may be beneficial or counter-produtive depending on the amount of natural alkalinity in the water.

   (b) The procedure used in applying soda ash in the Sabaki Water Works was found to be inappropriate, as it was not justified by alkalinity measurements. Such application could cause overdosing or underdosing, resulting in escalated operational costs.

2. Alternative Coagulants

   (a) Based on equivalent performance and the cost of purchasing the coagulants, there exists no economically justified reason for summarily rejecting alum as the primary coagulant in the Sabaki Water Works. However benefits arising from the use of polyelectrolytes (e.g. reduced sludge volume, better sludge quality, stronger and larger flocs, easiness of handling) have been identified. Cost quantification of these benefits would be required before making a complete comparison. Additionally, it was noted that with the growing global environmental concern, the selection of coagulants will to a great extent rely on the quality and quantity of sludge produced.

(b) From the literature review, the polyelectrolytes were found to be limited due to the uncertainty about their long range toxicity, carcinogenicity, and mutagenicity. As such those countries which use polyelectrolytes have fixed maximum dosages of the polyelectrolytes (e.g. USEPA has set a maximum dosage of 50 mg/l for catfloc T and 20 mg/l for superfloc C573). In order not to exceed such dosages, skilled labourers and appropriate dosing equipment would be required.

(c) The effectiveness of ferric chloride was found to be comparable with alum. An average empirical dosage ratio of ferric-to-alum was found to be 0.901. Certainly this shows ferric to be a more superior coagulant to alum. However, it was disqualified for application in the Sabaki due to its corrosive nature, combined with storage and feeding hazards. Its application would thus require the use of enormous amount of alkali (lime or soda ash) to give complete precipitation, as well as installation of expensive solution tanks and dosage equipments.

(d) When dosing combinations of alum with polyelectrolytes, the order of chemical application was found to play an important role. Optimal chemical dosage was obtained by dosing alum first and then the polyelectrolyte.

3. Optimum Coagulation pH

Optimum pH for alum coagulation was found to be in the range 5.5 - 7.4. This optimum pH zone favours alum coagulation in the Sabaki This is so because with the raw water pH range of 7.8 to 8.6 experienced in the Sabaki, alum addition lowers the solution pH to the optimum range for coagulation. Thus it is concluded that as long as alum remains the primary coagulant pH correction would not be necessary. However, the optimum pH range for the polyelectrolytes of pH $\leq$ 6.4, coupled with the fact that polyelectrolytes do not affect the solution pH, makes it necessary to correct the pH prior to dosage when using polyelectrolyte as primary coagulant. Alternatively dose alum first (to lower the pH as well perform coagulation) and then the polyelectrolyte. This concurs with conclusion number 2 (c).

4. <u>Other Factors Affecting the Efficiency of the Treatment Works</u>

(a) During the field study it was observed that overdosing and underdosing which could lead to chemical wastage in addition to affecting the health of the consumers was rampant. Possible causes of overdosing and underdosing include among others; inconsistency in dosage selection, lack of water flow measuring device, excessive sludge accumulation in the settlement basins, lack of proper training and morale of the workers.

(b) Controlled desludging and backwashing operations that will help to improve the performance of the treatment units and avoid wastage of water and chemicals are necessary. Desludging should be based on measurements of sludge depth in the settlement basins, while filter backwashing should be based on headloss measurements.

(c) Assessment of the social needs of the staff and development of training programmes at all levels to generate the required manpower is an immediate necessity if the Treatment Works is to register any appreciable measure of success. Lack of social facilities was found to greatly influence the morale of the workers. The principal objective of a training programme would be to provide each operator with information on which to base decision about water treatment problems. Capability for round the clock surveillance is important in detecting abrupt changes in raw water quality.

6.2 Recommendations

1. Soda ash dosage prior to clarification should be strictly applied only when the natural alkalinity of the coagulating solution fall below 20 mg/l. This should be justified by measuring the alkalinity of the selected dose of the jar test. Otherwise, it should be dosed only after filtration and chlorination if necessary for pH correction.

2. Before a conclusive decision is made on the use of polyelectrolyte further studies should be carried out to:

   (a) Thoroughly evaluate the health effects of using polyelectrolytes, and come up with allowable or maximum doses of each.

   (b) Evaluate the impact of using polyelectrolytes on the environment. In this assessment of the biodegradability of the sludge produced should be carried out.

   (c) Compare sludge volume produced with polyelectrolytes and alum, together with their consequential cost implications.

   (d) Investigate the possibility of alum recovery from the voluminous sludge by acidification, and its economic justification.

3. In the event of using polyelectrolytes in the Sabaki Water Works the following measures would be recommended:

   (a) All water treatment operators should be retrained on the use of polyelectrolytes. Emphasis being put on hazards related to overdosing of the chemicals.

   (b) Installation of more appropriate dosing equipments would be necessary for accurate dosing.

   (c) Equipment for assaying of purity of polyelectrolytes, residuals and impurities should be within reach.

   (d) The Ministry of Water Development should set standards for maximum contaminant levels of the monomers, as well as maximum dosing concentrations for the polyelectrolytes.

   (e) The use of polyelectrolytes in other industries such as paper and sugar in the upstream of the Treatment Works need to be looked into, with a view to controlling effluents entering the river.

   (f) When used in combination with alum, alum should be dosed prior to presettlement and the polyelectrolytes prior to clarification.

4. From field observations the following are recommended:

   (a) Quality standards for influent into the clarifiers and filters need to be set up to resolve inconsistencies in dosage selection and chemical wastage.

(b) Flow measuring device along the Treatment Works water channels need to be installed in order to achieve accurate chemical dosage.

(c) Sludge feeling mechanism in the presettlement basins, in order to regularise desludging and avoid excessive reduction of the retention period should be established.

(d) Headloss measuring device for the filters should be installed and recycling of filter backwash water attempted.

(e) Training programme to provide each operator with information on which to base decision about water treatment problems should be started.

(f) Two assistant engineers posts should be created. One, a mechanical engineer to assist in the installation and maintenance of the mechanical components of the Works, while the other, a civil engineer to oversee the smooth running of the treatment processes.

BIBLIOGRAPHY

American Water Works Association Inc. (1971): Water Quality and Treatment (A handbook of water supplies).

Amirtharajah, A. and Mills, K.M. (1982): Rapid-Mix Design for Mechanisms of Alum Coagulation. Journal of American Water Works Association, Vol. 74, Pg. 210

APHA-AWWA-WPCF (1975): Standard Methods for the Examination of Water and Waste Water. APHA, 1015 Eighteenth Street N W, Washington, DC.

Amirhor, P. and Engelbrecht, R.S. (1975): Virus Removal by Polyelectrolyte - Aided Filtration. Journal of American Water Works Association, Vol. 67, Pg. 187.

Babbitt, H.E. and Doland, J.J. (1955): Water Supply Engineering. Mc Graw-Hill, New York, U.S.A.

Barnes, D. and Wilson, F. (1983): Chemistry and Unit Operations in Water Treatment. Applied Science Publishers, London, UK.

Beardsley, J.A. (1973): Use of Polymers in Municipal Water Treatment. Journal of American Water Works Association, Vol. 65, Pg. 84.

Birkner, F.B. and Morgan, J.J. (1968): Polymer Flocculation Kinetics of Dilute Colloidal Suspensions. Journal of American Water Works Association, Vol. 60, Pg. 175.

Brossett, C., Biedermann, G. and Sillen, L.G. (1954): Studies on the Hydrolysis of Metal ions: XI. The Aluminium ion AL^{3+} Acta Chem. Scand. Vol. 8, Pg. 1917.

Carnduff, J.A. (1976): Treatment of the Metropolitan Toronto Water Supply Utilising Ferric Chloride. Journal of American Water Works Association, Vol. 68, Pg. 5.

Carol, R.J. and O'melia, C.R. (1982): Considering Sludge Production in the Selection of Coagulants: Journal of America Water Works Association, Vol. 74, Pg. 148.

Committee Report (1971): State of the Art of Coagulation. Journal of American Water Works Association, Vol. 63, Pg. 99.

Conley, W.R. and Evers, R.H. (1968): Coagulation Control. Journal of American Water Works Association, Vol. 60, Pg. 165.

Correl, N. and Robinson, Jr. (1974): Polyelectrolytes as Primary Coagulants for Potable Water Systems. Journal of American Water Works Associate, Vol. 66, Pg. 252.

Correl, N. and Robinson, Jr. (1979): Cationic Polyelectrolytes Reduce Organic Matters in Turbid Surface Waters. Journal of American Water Works Association, Vol 71, Pg. 226.

Costello, J.J. (1984): Post Precipitation in Distribution Systems. Journal of American Water Works Association, Vol. 76, Pg. 46.

Cox, C.R. (1969): Operation and Control of Water Treatment Process. Geneva (World Health Organisation): Monograph Series, No. 49.

Culp, G.L. and Culp, R.L. (1974): New Concepts in Water Purification. Van Nostrand Reinhold Ltd., New York, USA.

Davis, M.L. and Cornwell, D.A. (1991): Introduction to Environmental Engineering. Mc Graw-Hill, Inc. Newyork USA.

Dentel, S.K. and Gossett, J.M. (1988): Mechanisms of Coagulation with m Salts. Journal of American Water Works Association, Vol. 80, Pg. 187.

Ecknfelder, W.W. and Ford, D.L. (1970): Water Pollution Control. Jenkings, New York, USA.

Haarhoff, J. and Cleasby, J.L. (1988): Comparing Aluminium and Iron Coagulants for Inline Filtration of Cold Waters. Journal of American Water Works Association, Vol. 80, Pg. 168.

Habibian, M.T. and O'melia, C.R. (1975): Particles, Polymers and Performance in Filtration. Journal of Environmental Engineering Division - ASCE Vol. 101, Pg. 567.

Hahn, H.H. and Stumm, W (1967): Coagulation by Al (III). The Role of Adsorption of Hydrolysed AL (III) in the Kinetics of Coagulation. 154th Conf. Am. Chem. Soc. Chicago, September, 1967.

Hammer, M.J. (1986): Water and Waste Water Technology. 2nd Ed. John Willey and Sons, New York, USA.

Hanson, A.T. and Cleasby, J.L. (1990): The Effects of Temperature on Turbulence Flocculation; Fluid Dynamics and Chemistry. Journal of American Water Works Association, Vol. 82, Pg. 56.

International Agency for Research on Cancer (IARC) (WHO) (1985): Acrylamide. IARC Monographs, Vol. 39, Pg. 41.

Jeffcoat, W., Blake and Singley, J.E. (1975): The Effects of Alum Concentration and Chemical Addition Times on Coagulation. Journal of American Water Works Association, Vol. 67, Pg. 177.

Johnson, P.N. and Amirtharajah, A (1983): Ferric Chloride and Alum as Single and Dual Coagulants. Journal of American Water Works Association, Vol. 75, Pg. 232.

Kawamura Susumu (1976): Considerations on Improving Flocculation. Journal of American Water Works Association, Vol. 68, Pg. 328.

Kawamura Susumu, (1991): Effectiveness of Natural Polyelectrolytes in Water Treatment. Journal of American Water Works Association, Vol. 83, Pg. 88.

Kavanaugh Michael, C. (1978): Modified Coagulation for Improved Removal of Trihalomethane precursors. Journal of American Water Works Association, Vol. 70, Pg. 613.

Kirmeyer Gregory, J. and Logsdon, G.S. (1983): Principles of Internal Corrosion and Corrosion Control. Journal of American Water Works Association, Vol 75, Pg. 78.

La Mer, V.K. and Healey, T.W. (1953): Adsorption - Flocculation Reactions of Macro Molecules. Journal of Phys. Chem, Vol. 57, Pg. 584.

Lamont, I.K. (1981): Water Research Topics. Ellis Horwood Ltd., London, UK.

Leslie B, Rhead, M.M., Hill, D, and Keith, C.C.B. (1982): Qualitative and Quantitative Studies on the in situ Adsorption, Degradation and Toxicity of Acrylamide by the Spiking of the Waters of Two Sewage Works and a River. Journal of Water Research, Vol 16, Pg. 579.

Letterman, R.D., Tabatabaie, M and Ames, R.S. Jr. (1979): The Effects of the Bicarbonate Ion Concentration on Flocculation with Aluminium Sulphate. Journal of American Water Works Association, Vol. 71, Pg. 467.

Letterman, R.D. and Pero, R.W. (1990): Contaminants in Polyelectrolytes Used in Water Treatment. Journal of American Water Works Association, Vol. 84, Pg. 87.

Leu Rong-Jin and Ghosh, M.M. (1988): Polyelectrolytes Characteristics and Flocculation. Journal of American Water Works Association, Vol. 80, Pg. 159.

Licsko, I. (1976): Micro Processes in Coagulation. Journal of Water Research, Vol. 10, Pg. 143.

Loganathan, P and Maier, W.J. (1975): Some Surface Chemical Aspects in Turbidity Removal by Sand Filtration. Journal of American Water Works Association, Vol 67, Pg. 336.

Matijevic, E, Mathai, K.C. Otte Will, R.H., and Kerkner, M., (1961): Detection of Ion Hydrolysis by Coagulation (Aluminium (III)). Journal of Phys. Chem. Vol 65, Pg. 826.

Maudling, J.S. and Harris, R.H. (1968): Effect of Ionic Environment and Temperature on the Coagulation of Colour-Causing Organic Compounds with Ferric Sulphate. Journal of American Water Works Association, Vol. 60, Pg. 460.

Mc Ghee, Terence, J. (1991): Water Supply and Sewerage. 6th Ed. Mc Graw-Hill, Inc. New York, USA.

Moffet, J.W. (1968): The Chemistry of High-rate Water Treatment. Journal of American Water Works Association, Vol. 60, Pg. 1255.

Narkis, N. and Rebhun, M (1975): The Mechanism of Flocculation Process in the Presence of Humid Substances. Journal of American Water Works Association Vol. 67, Pg. 101.

Oehler, K.E. (1963): Flockung, Zetapotential and Flock-ungshilfsmittel in der Wasseranfbereitung. Vom Wass, 127.

Odira, P.M.A. (1985): Upflow Filters in Flocculation and Direct Filtration of Waters of High Turbidity. Tampere University of Technology (Finland), Publication 39.

Posselt Hans, S. Reidies Arno, H., and Weber Walter, J. Jr. (1968): Coagulation of Colloidal Hydrous Manganese Dioxide. Journal of American Water Works Association, Vol 60, Pg. 57.

Qureshi, N. and Malmberg, R.H. (1985): Reducing Aluminium Residuals in Finished Water. Journal of American Water Works Association, Vol. 77, Pg. 101.

Rausch, W.V. and Bale, H.D. (1964): Small Angle X-ray Scattering from Hydrolysed Aluminium Nitrate Solutions. Journal of Phy. Chem. Vol 40, Pg. 391.

Rubin, A.J. and Blocksidge, H., (1979): Coagulation of Montmorillonite Suspensions with Aluminium Sulphate. Journal of American Water Works Association, Vol. 71, Pg. 102.

Sawyer, C.N. and Mc Carty, P.L. (1967): Chemistry for Sanitary Engineers, 2nd Ed. Tokyo, Japan.

Sandell, L.S. and Luner, P. (1974): Flocculation of Microcrystalline Cellulose with Cationic Ionene Polymers. Journal of Applied Polymer Sci., Vol. 18, Pg. 2705.

Schock Michael, R. and Marvin, C.G. (1983): Plumbosolvency Reduction by High pH and Low Carbonate - Solubility Relationships. Journal of American Water Works Association, Vol. 75, Pg. 87.

Scott Wilson Kirkpatrick and Partners, (1982): Operation Manual, Mombasa and Coastal Water Supply, Sabaki Water Project.

Stovens, A.A., Slocum, C.J., Seeger, D.R. and Robert, G.G., (1976): Chlorination of Organics in Drinking Water. Journal of American Water Works Association, Vol 68, Pg. 615.

Stumm, W. and Morgan, J.J. (1962): Chemical Aspects of Coagulation. Journal of American Water Works Association, Vol. 54, Pg. 971.

Stumm, W. and O'melia, C.R. (1968): Stoichiometry of Coagulation. Journal of American Water Works Association, Vol. 60, Pg. 514.

Stump, V. and Novak, J. (1979): Polyelectrolytes selection for Direct Filtration. Journal of American Water Works Association, Vol. 71, Pg. 338.

Swift, D.L. and Freidlander, S.K. (1964): The Coagulation of Hydro Sols by Brownian Motion and Laminar Shear Flow. Journal of Colloid Science, Vol. 19, Pg. 621.

Tambo, H. and Hozumi, H., (1979): Physical Characteristics of Flocs. Journal of Water Research, Vol. 13, Pg. 421.

Treweek, G.P. (1979): Optimisation of Flocculation Time Prior to Direct Filtration. Journal of American Water Works Association, Vol. 71, Pg. 96.

WHO, (1984): Guidelines for Drinking-Water Quality. WHO, Geneval Vol. 2.

WHO, (1984): Guidelines for Drinking-Water Quality: WHO, Geneva, Vol. 3.

Yao, K.M., (1967): Particle Aggregation in Water Pretreatment (II). Wat. Sewerage Wks., Vol. 114, Pg. 295.

Yapijakis, C. (1982): Direct Filtration Polymer in Backwash Serves Dual Purpose. Journal of American Water Works Association, Vol. 74, Pg. 426.

APPENDICES

EXPERIMENTAL DATA

APPENDIX A1

SUMMARY OF TREATMENT WORKS MONITORING RESULTS

1. APPENDIX A1: SUMMARY OF TREATMENT WORKS MONITORING RESULTS

DATE	FLOW	RAW WATER				PRE	PRE-SETTLED				SODA	CLF	CLARIFIED				FILTERED				TREATED			
		PH	TUR.	ALK.	COL.	DOSE	PH	TUR.	ALK.	COL.	DOSE	DOSE	PH	TUR.	ALK.	COL.	PH	TUR.	ALK.	COL.	PH	TUR.	ALK.	COL.
14/11/92	2400	8.1	1020	108	>70		7.4	87	86	10			7.3	42	66	5	7.2	13	64	5	7.4	15	66	5
16/11/92	900	8.2	650	110	>70	100	7.4	56	78	10	50	30	7.3	14	74	5	7.4	1.4	78	<5	7.5	2.6	80	<5
17/11/92	2400	8.3	650	120	>70	100	7.3	55	80	10	50	30	7.3	17	100	5	7.4	0.7	94	<5	7.7	1.8	94	<5
17/11/92*	2400	8.5	600	120	>70	100	7.5	55	98	10		30	7.4	28	88	5	7.4	0.8	84	<5	7.7	2.4	88	<5
18/11/92	2400	8.3	600	124	>70	100	7.6	65	110	10		30	7.4	21	104	5	7.5	1.0	96	<5	7.6	2.5	86	<5
19/11/92	2400	8.2	950	126	>70	80	7.5	120	104	25		20	7.2	25	80	5	7.3	1.3	80	<5	7.6	1.1	80	<5
19/11/92+	2400	8.4	1800	132	>70	100	7.7	650	108	>70		20	7.4	65	100	30	7.5	2.2	96	5	7.6	2.4	100	<5
20/11/92	2400	8.1	2100	120	>70	120	7.4	850	90	>70	50	40	6.7	24	40	5	6.9	2.0	52	<5	7.3	2.3	60	<5
21/11/92	2400	8.2	1500	100	>70	150	7.3	280	72	>70		60	7.1	27	54	5	7.3	1.1	58	<5	7.5	1.4	56	<5
23/11/92	2400	8.4	1500	98	>70	100	7.9	600	64	>70		20	7.4	21	52	5	7.4	1.5	52	<5	7.5	2.1	52	<5
24/11/92	2400	8.5	1200	100	>70	100	7.5	100	72	3		20	7.3	17	54	5	7.3	1.2	54	<5	7.4	1.5	52	<5
25/11/92	2400	8.1	900	100	>70	100	7.3	113	78	30		20	7.2	17	72	5	7.2	1.8	64	<5	7.4	2.0	70	<5
26/11/92	2400	8.0	800	116	>70	90	7.1	75	96	15		22	6.9	18	70	5	7.0	1.5	70	<5	7.2	1.8	70	<5
27/11/92	2400	8.2	600	114	>70	70	7.1	68	100	15		20	6.9	18	92	5	7.3	1.7	88	<5	7.3	1.8	84	<5
28/11/92	2400	8.0	600	114	>70	80	7.2	52	98	15		20	6.9	16	90	5	7.3	2.5	88	<5	7.5	2.0	90	<5
30/11/92	2400	7.9	1800	122	>70	120	7.4	650	112	>70	50	60	7.1	55	94	10	7.1	6.1	80	<5	7.2	6.0	76	<5
30/11/92*	2400	8.1	1800	122	>70	120	7.3	600	98	>70		60	7.2	40	82	10	7.1	4.0	86	<5	7.2	7.0	82	<5

1. APPENDIX A1 (Cont'd)

DATE	FLOW	RAW WATER				PRE.	PRE-SETTLED				SODA	CLF	CLARIFIED				FILTERED				TREATED			
		PH	TUR.	ALK.	COL.	DOSE	PH	TUR.	ALK.	COL.	DOSE	DOSE	PH	TUR.	ALK.	COL.	PH	TUR.	ALK.	COL.	PH	TUR.	ALK.	COL.
01/12/92	2400	8.1	1700	120	>70	120	7.3	280	100	>70		60	7.1	28	80	5	7.2	1.0	76	<5	7.2	2.4	74	<5
02/12/92	2400	8.2	1650	108	>70	120	7.5	650	88	>70		30	6.8	25	74	5	6.7	3.5	72	<5	7.0	3.5	72	<5
03/12/92	2400	8.1	3600	100	>70	120	7.4	700	76	>70		30	7.1	77	68	15	7.2	440	70	>70	7.3	180	70	40
10/12/92	2400	8.1	1300	120		c50	8.1	59	118				8.2	42	120		8.0	12	116		8.0	15	116	
11/12/92	1620	8.1	1300	118	>70	c17	8.2	110	116	60			8.2	21	116	5	8.1	2.5	116	<5	8.1	2.2	118	5
14/12/92	2400	7.8	3100	100	>70	120	7.2	700	72	>70		70	7.1	30	40	5	7.3	2.9	60	5	7.3	6.2	68	15
15/12/92	2400	7.7	3400	84	>70	19.6	7.5	980	80	>70			7.3	105	80	60	7.2	45	70	20	7.2	51	68	20
16/12/92	2400	7.7	3200	80	>70	120	7.0	360	56	>70		80	6.9	90	40	40	7.1	5.8	44	<5	7.1	6.6	48	20
19/01/93	2400	8.3	3400	108	>70	120	6.9	240	74	>70		c8.4	6.9	25	74	5	6.9	6.5	74	<5	6.9	6.5	74	<5
20/01/93	2400	8.3	2800		>70	120	6.9	110		50		c8.4	6.9	20		5	6.9	1.8		<5	6.9	1.8		<5
21/01/93	2400	8.3	3000		>70	120	6.9	230		>70		c8.4	6.9	21		5	6.9	1.4		<5	6.9	2.5		<5
22/01/93	2400	7.8	3200	108	>70	120	6.8	180	68	>70		c8.4	6.8	25	68	10	6.8	3.5	68	<5	6.8	8.0	68	<5
26/01/93	1800	7.9	1400	86	>70	120	6.4	210	22	>70		30	5.9	13	2	<5	6.5	2.2	14	<5	6.6	4.5	18	<5
27/01/93	1800	7.9	1300	86	>70	100	6.4	160	60	>70		20	6.3	18	34	<5	6.4	3.8	26	<5	6.6	4.8	20	<5
28/01/93	1800	8.0	1200	90	>70	100	6.7	100	52	25		20	6.5	16	30	<5	6.5	3.2	30	<5	6.7	6.5	30	<5
29/01/93	2400	8.1	1100	96	>70	100	6.7	60	62	15		20	6.5	25	38	5	6.5	2.6	40	<5	6.7	3.6	38	<5
01/02/93	2400	8.1	2800		>70	120	6.9	120	80	35		30	6.7	18	52	5	6.7	2.0	60	<5	6.9	2.4	62	<5
02/02/93	2400	8.0	3000	112	>70	120	7.0	360	98	>70		30	6.5	32	50	5	6.6	4.5	52	<5	6.9	6.6	58	<5

APPENDIX A2

EXTRACT FROM PREVIOUS MONITORING DATA

2. APPENDIX A2: PREVIOUS MONITORING DATA

DATE	RAW WATER			PRESETTLED			CLARIFIED			FILTERED			FINAL		
	PH	TUR	COL	PH	TUR	COL	PH	TUR	COL	PH	TUR	COL	PH	TUR	COL
31/07/91	8.4	1600	>70	7.4	230	>70	6.9	26	5	6.9	1.8	<5	7.1	1.6	<5
01/08/91	8.4	1300	>70	7.2	90	20	6.8	18	<5	6.7	1.6	<5	6.9	1.5	<5
15/08/91	8.4	190	60	7.1	23	10	7.3	18	10	7.5	2.8	<5	7.5	3.0	<5
16/08/91	8.4	180	60	7.3	23	10	7.2	18	10	7.5	3.1	<5	7.5	2.8	<5
31/08/91	8.4	82	30	7.1	18	10	7.2	17	5	7.3	2.6	<5	7.5	2.5	<5
01/09/91	8.4	85	30	7.0	18	10	7.1	17	5	7.2	2.4	<5	7.3	2.3	<5
15/09/91	8.4	82	30	7.1	20	10	7.3	17	5	7.5	2.6	<5	7.6	3.0	<5
16/09/91	8.4	83	35	7.1	20	10	7.3	15	5	7.5	3.7	<5	7.5	3.2	<5
30/09/91	8.4	84	30	7.3	22	10	7.5	17	5	7.5	2.7	<5	7.6	2.6	<5
01/10/91	8.4	75	30	7.3	18	10	7.4	14	<5	7.5	2.3	<5	7.6	2.6	<5
15/10/91	8.4	55	25	7.5	15	5	7.5	13	<5	7.5	1.4	<5	7.6	1.5	<5
16/10/91	8.4	55	25	7.5	17	5	7.5	14	<5	7.6	0.9	<5	7.6	1.6	<5
31/10/91	8.4	82	35	7.4	16	5	7.5	13	<5	7.5	1.0	<5	7.7	1.2	<5
01/11/91	8.4	136	50	7.4	22	5	7.6	15	<5	7.6	1.3	<5	7.7	1.2	<5
15/11/91	8.4	95	40	7.3	18	5	7.5	13	<5	7.6	0.9	<5	7.7	0.8	<5
16/11/91	8.4	340	>70	7.3	27	10	7.5	20	<5	7.5	1.2	<5	7.6	1.4	<5
30/11/91	8.0	2100	>70	7.1	150	>70	6.8	23	10	6.8	1.2	<5	6.9	1.2	<5
01/12/91	8.0	1800	>70	6.9	160	>70	6.8	28	10	6.9	2.0	<5	6.9	1.5	<5
16/12/91	8.2	1700	>70	6.8	200	>70	7.3	25	5	7.1	17	<5	7.4	28	<5
17/12/91	8.1	1400	>70	6.9	120	40	6.8	70	5	6.9	14	<5	7.1	1.2	<5
24/12/91	8.4	2100	>70	7.0	230	>70	7.1	55	30	7.5	4.5	<5	7.6	5.5	<5
25/12/91	8.4	2400	>70	6.9	250	>70	7.0	45	30	7.3	100	50	7.3	130	50

2. APPENDIX A2 (Cont'd)

DATE	RAW WATER			PRESETTLED			CLARIFIED			FILTERED			FINAL		
	PH	TUR	COL	PH	TUR	COL	PH	TUR	COL	PH	TUR	COL	PH	TUR	COL
26/12/91	8.0	2400	>70	7.1	250	>70	6.7	50	30	6.7	4.0	<5	6.9	6.0	<5
27/12/91	8.1	2200	>70	6.8	130	>70	6.8	25	5	6.8	2.6	<5	6.9	6.5	<5
31/12/91	8.2	1500	>70	6.9	150	>70	6.8	20	5	6.7	3.5	<5	6.8	5.0	<5
01/01/92	8.4	1300	>70	7.0	240	>70	7.1	5.6	10	6.9	1.7	<5	7.3	2.4	<5
15/01/92	8.4	460	>70	7.4	24	5	7.5	21	5	7.5	2.0	<5	7.6	3.0	<5
16/01/92	8.4	420	>70	7.4	18	10	7.5	15	<5	7.5	2.0	<5	7.6	8.5	<5
31/01/92	8.4	94	60	7.3	16	5	74	14	<5	7.5	2.4	<5	7.6	2.5	<5
01/02/92	8.4	95	60	7.3	17	5	7.5	15	5	7.6	2.8	<5	7.6	3	<5
15/02/92	8.4	67	40	7.5	18	5	7.6	17	5	7.6	2.6	<5	7.7	2.8	<5
16/02/92	8.4	68	40	7.5	22	5	7.6	17	5	7.7	3.0	<5	7.7	3.8	<5
29/02/92	8.4	62	30	7.4	18	5	7.5	16	<5	7.7	3.8	<5	7.8	4.0	<5
01/03/92	8.4	58	30	7.5	15	5	7.6	14	<5	7.6	3.5	<5	7.8	3.6	<5
20/04/92	8.3	2000	>70	7.0	130	>70	6.8	26	5	6.9	1.4	<5	7.0	1.6	<5
21/04/92	8.3	2400	>70	6.9	150	45	6.7	30	5	6.9	1.4	<5	6.9	2.2	<5
22/04/92	8.3	1900	>70	6.9	150	45	6.7	25	5	6.8	1.4	<5	7.0	1.6	<5
30/04/92	8.3	1500	>70	7.3	170	55	6.8	25	5	7.2	1.8	<5	7.4	1.6	<5
01/05/92	8.3	2200	>70	7.1	250	>70	6.8	40	10	7.2	2.0	<5	7.3	1.8	<5
02/05/92	8.2	2800	>70	6.9	200	50	6.6	40	10	6.8	3.0	5	6.9	2.8	5
03/05/92	8.3	3000	>70	6.8	160	65	6.5	37	5	6.5	2.0	<5	6.8	2.4	<5
15/05/92	8.3	850	>70	6.9	70	15	6.7	20	5	6.7	1.3	<5	6.9	1.5	<5
16/05/92	8.3	800	>70	6.9	57	10	6.7	18	5	6.8	1.3	<5	7.1	1.4	<5
31/05/92	8.4	300	>70	7.1	30	10	7.3	20	5	7.4	1.8	<5	7.5	2.0	<5

2. APPENDIX A2 (Cont'd)

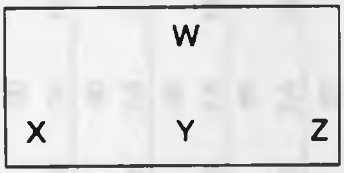
DATE	RAW WATER			PRESETTLED			CLARIFIED			FILTERED			FINAL		
	PH	TUR	COL	PH	TUR	COL	PH	TUR	COL	PH	TUR	COL	PH	TUR	COL
01/06/92	8.4	200	>70	7.3	30	10	7.3	25	5	7.4	1.6	<5	7.5	2.0	<5
15/06/92	8.5	160	35	7.1	30	10	7.3	25	5	7.5	3.0	<5	7.5	2.6	<5
16/06/92	8.4	160	35	7.2	32	10	7.3	23	5	7.5	2.0	<5	7.5	2.2	<5
30/06/92	8.4	90	30	7.0	23	5	7.3	18	5	7.6	1.6	<5	7.8	2.0	<5
01/07/92	8.4	95	30	7.5	35	5	7.5	30	5	7.6	7.0	<5	7.7	5.0	<5
15/07/92	8.4	96	25	7.6	24	5	7.6	20	5	7.5	2.1	<5	7.7	2.3	<5
16/07/92	8.4	95	25	7.3	21	5	7.5	20	5	7.6	2.1	<5	7.7	3.2	<5
31/07/92	8.4	70	20	7.3	21	5	7.7	18	5	7.8	3.0	<5	7.8	3.2	<5
01/08/92	8.4	70	15	7.7	30	5	7.8	26	5	7.8	3.6	<5	7.9	5.0	<5
15/08/92	8.5	75	15	7.4	22	5	7.5	18	5	7.6	3.6	<5	7.8	4.0	<5
16/08/92	8.5	75	15	7.5	23	5	7.5	20	5	7.6	3.0	<5	7.7	4.8	<5
31/08/92	8.5	70	10	7.5	21	5	7.5	15	5	7.5	1.0	<5	7.7	1.0	<5
01/09/92	8.5	70	10	7.3	17	5	7.4	14	<5	7.5	0.7	<5	7.6	1.0	<5
15/09/92	8.5	64	10	7.2	18	5	7.3	16	5	7.5	1.1	<5	7.7	1.3	<5
16/09/92	8.5	66	10	7.5	18	5	7.5	17	5	7.6	1.6	<5	7.7	2.0	<5
30/09/92	8.4	50	10	7.3	18	5	7.4	14	5	7.5	1.2	<5	7.7	1.3	<5
01/10/92	8.4	50	10	7.6	18	5	7.4	15	5	7.5	2.0	<5	7.8	2.5	<5
15/10/92	8.5	50	10	7.6	20	5	7.7	16	5	7.6	2.0	<5	7.7	2.4	<5
16/10/92	8.5	52	10	7.5	18	5	7.7	15	5	7.6	1.5	<5	7.8	2.0	<5
31/10/92	8.4	55	10	7.4	18	5	7.5	17	5	7.6	2.4	<5	7.8	2.5	<5
01/11/92	8.4	75	20	7.4	18	5	7.5	15	5	7.6	2.0	<5	7.7	2.0	<5

APPENDIX A3

EXTRACT FROM PREVIOUS JAR TEST RESULTS

How to Read the Data

This refers to all cells under the "DOSE" column.



W: Coagulant dosage (mg/l)
X: pH
Y: Turbidity (NTU)
Z: Alkalinity (mg/l as calcium carbonate)

3. APPENDIX A3: EXTRACT FROM PREVIOUS JAR TEST RESULTS

DATE	SODA	DOSE 1			DOSE 2			DOSE 3			DOSE 4			DOSE 5			DOSE 6			DOSE TAKEN	
	DOSE	TUR	PH	COL	TUR	PH	COL	TUR	PH	COL	TUR	PH	COL	TUR	PH	COL	TUR	PH	COL	PRE-SET	CLF
31/07/91	-		80			100			120			140			160			•180		140	40
		250	7.2	>70	240	7.1	>70	200	7.0	50	140	6.9	20	105	6.9	5	40	6.8	<5		
01/08/91	-		120			144			•168			192			216			240		140	28
		110	7.0	>70	65	6.9	30	40	6.7	10	22	6.5	5	22	6.4	<5	16	6.3	<5		
15/08/91	-		40			60			80			•100			120			140		100	0
		70	7.6	20	32	7.4	10	24	7.2	5	16	7.0	<5	15	6.9	<5	13	6.8	<5		
16/08/91	-		40			60			80			•100			120			140		100	0
		47	7.7	10	27	7.3	5	20	7.1	<5	17	6.9	<5	16	6.8	<5	15	6.7	<5		
31/08/91	-		40			60			•80			100			120			140		80	0
		45	7.8	15	21	7.5	10	16	7.3	<5	16	7.0	<5	15	6.9	<5	13	6.7	<5		
01/09/91	-		40			60			•80			100			120			140		80	0
		41	7.7	15	22	7.4	10	16	7.2	<5	15	7.0	<5	15	6.8	<5	13	6.6	<5		
15/09/91	-		40			60			•80			100			120			140		80	0
		42	7.6	15	18	7.3	10	16	7.1	<5	15	7.0	<5	14	6.7	<5	14	6.8	<5		
16/09/91	-		40			60			•80			100			120			140		80	0
		40	7.4	15	20	7.2	10	15	6.9	<5	14	6.8	<5	14	6.7	<5	13	6.7	<5		
30/09/91	-		40			60			•80			100			120			140		80	0
		43	7.6	15	30	7.4	10	17	7.2	<5	15	7.0	<5	14	6.8	<5	13	6.6	<5		
01/10/91	-		40			60			80			100			120			140		70	0
		43	7.6	15	18	7.4	10	14	7.3	<5	13	7.1	<5	12	7.0	<5	11	6.9	<5		
15/10/91	-		40			•60			80			100			120			140		60	0
		25	7.6	10	16	7.4	<5	14	7.3	<5	12	7.0	<5	11	6.9	<5	10	6.7	<5		
16/10/91	-		40			•60			80			100			120			140		60	0
		27	7.6	10	21	7.4	5	16	7.2	<5	15	7.0	<5	14	6.9	<5	12	6.8	<5		
31/10/91	-		40			•60			80			100			120			140		80	0
		32	7.5	10	18	7.3	5	14	7.1	<5	13	7.0	<5	13	6.9	<5	10	6.8	<5		

3. APPENDIX A3 (Cont'd)

DATE	SODA	DOSE 1			DOSE 2			DOSE 3			DOSE 4			DOSE 5			DOSE 6			DOSE TAKEN	
	DOSE	TUR	PH	COL	TUR	PH	COL	TUR	PH	COL	TUR	PH	COL	TUR	PH	COL	TUR	PH	COL	PRE-SET	CLF
01/11/91	-		60			80			100			120			140			160		80	0
		23	7.4	10	18	7.3	<5	15	7.1	<5	14	6.9	<5	12	6.8	<5	11	6.7	<5		
15/11/91	-		40			*60			80			100			120			140		80	0
		45	7.4	30	25	7.2	10	20	7.0	<5	13	6.9	<5	13	6.8	<5	12	6.7	<5		
16/11/91	-		40			60			80			100			120			140		90	0
		90	7.4	30	70	7.1	15	20	7.0	<5	14	6.8	<5	12	6.7	<5	13	6.7	<5		
30/11/91	64		144			168			192			216			240			264		132	60
		60	7.0	30	45	6.9	10	30	6.8	5	22	6.6	<5	20	6.5	<5	18	6.4	<5		
01/12/91	80		144			*168			192			216			240			264		128	40
		25	6.8	10	25	6.8	5	23	6.7	<5	21	6.6	<5	20	6.6	<5	17	6.5	<5		
16/12/91			80			100			120			140			160			180		90	40
	-	180	6.9	40	62	6.8	20	44	6.7	15	24	6.6	<5	20	6.5	<5	18	6.3	<5		
17/12/91	-		80			100			120			140			160			180		80	30
		58	6.9	10	26	6.8	<5	25	6.7	<5	21	6.5	<5	18	6.4	<5	16	6.2	<5		
24/12/91	64		80			100			120			140			*160			180		120	40
		230	7.3	>70	150	7.1	50	80	7.0	10	30	6.9	<5	21	6.7	<5	18	6.6	<5		
25/12/91	64		100			120			140			160			*180			200		120	60
		240	7.0	>70	120	7.0	50	60	6.9	5	28	6.8	<5	25	6.7	<5	15	6.5	<5		
26/12/91	80		120			140			160			*180			200			220		120	60
		280	7.2	>70	280	7.1	60	260	7.0	40	110	6.9	10	80	6.7	<5	28	6.5	<5		
27/12/91	64		120			140			160			*180			200			220		120	60
		280	7.6	>70	260	7.3	>70	160	7.1	50	80	6.9	5	50	6.8	<5	40	6.7	<5		
31/12/91	60		100			120			*140			160			180			200			
		130	7.2	>70	70	7.0	30	30	6.9	5	25	6.8	<5	20	6.7	<5	18	6.5	<5	100	40
01/01/92	60		80			100			*120			140			160			180			
		44	7.1	10	34	7.0	<5	25	6.9	<5	18	6.8	<5	18	6.7	<5	17	6.5	<5	80	40

* Dose selected for actual coagulation in the treatment works

APPENDIX A4

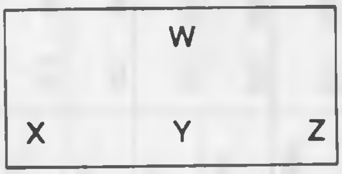
SUMMARY OF JAR TEST RESULTS ON ALTERNATIVE COAGULANTS

Legend

- *** Jar test performed on presettled water after dosing it with 120 mg/l of alum.**
- **+ Jar test performed on raw water which had been left to settle naturally for 3 hrs.**
- **! Jar test performed on presettled water which had been dosed with 100 mg/l alum.**

How to Read the Data

This refers to all cells under the "DOSE" column.



W: Coagulant dosage (mg/l)
X: pH
Y: Turbidity (NTU)
Z: Alkalinity (mg/l as calcium carbonate)

4. APPENDIX A4: SUMMARY OF JAR TEST RESULTS ON ALTERNATIVE COAGULANTS

DATE	COAGULANT	RAW WATER			DOSE 1			DOSE 2			DOSE 3			DOSE 4			DOSE 5			DOSE 6		
		PH	TUR.	ALK.	PH	TUR.	ALK.	PH	TUR.	ALK.	PH	TUR.	ALK.	PH	TUR.	ALK.	PH	TUR.	ALK.	PH	TUR.	ALK.
14/11/92	Superfloc					1.25			2.5			3.75			5							
		8.1	1020	108	8.1	350		8.1	350		8.1	350		8.1	210							
14/11/92	Catfloc					2			4			6			8			10			12	
		8.1	1020	108	8.1	620		8.1	370		8.1	360		8.1	300		8.1	150		8.1	120	
16/11/92	Superfloc					6			8			10			12			14			16	
		8.2	650	116	8.2	110	116	8.2	100	116	8.2	44	116	8.2	38	116	8.2	34	116	8.2	30	116
16/11/92	Catfloc					6			8			10			12			14			16	
		8.2	650	116	8.2	150	116	8.2	120	116	8.2	52	116	8.2	42	116	8.2	38	116	8.2	36	116
18/11/92	Alum					60			80			100			120			140			160	
		8.3	600	124	7.0	50	88	6.9	20	76	6.9	16	74	6.7	16	70	6.7	15	60	6.6	15	52
19/11/92	Alum					80			100			120			140			160			180	
		8.2	950	126	7.4	240	110	7.2	110	92	7.1	40	88	7.0	25	79	6.9	20	70	6.8	18	66
21/11/92	Alum					90			120			150			180			210			240	
		8.2	1500	100	7.5	260	78	7.3	90	64	7.1	50	54	7.0	40	46	6.8	30	40	6.6	25	26
21/11/92	Catfloc					8			10			12			14			16			18	
		8.2	1500	100	8.2	450	100	8.2	230	100	8.2	180	100	8.2	110	100	8.2	64	100	8.2	38	100
21/11/92	Superfloc					8			10			12			14			16			18	
		8.2	1500	100	8.2	370	100	8.2	210	100	8.2	150	100	8.2	98	100	8.2	50	100	8.2	38	100
23/11/92	Alum					90			120			150			180			210			240	
		8.4	1500	98	7.4	240	78	7.3	80	58	7.2	60	50	7.0	27	44	6.9	23	40	6.7	18	30
24/11/92	Alum					60			90			120			150			180			210	
		8.5	1200	100	7.5	320	82	7.3	70	72	7.2	20	58	7.0	18	50	6.9	16	40	6.8	16	36
25/11/92	Ferric					50			80			110			140			170			190	
		8.1	900	100	6.8	260	84	6.5	110	78	6.3	15	38	6.0	15	20	5.6	14	6	5.2	13	4
25/11/92	Alum					56			84			112			140			168			196	
		8.1	900	100	7.3	250	88	7.1	110	84	7.0	26	70	6.9	20	64	6.7	15	52	6.6	14	44
26/11/92	Alum					60			90			120			150			180			210	
		8.0	800	116	7.1	120	94	6.9	30	86	6.8	24	78	6.7	20	66	6.5	18	56	6.4	17	50
26/11/92	Ferric					10			20			40			60			80			100	
		8.0	800	116	7.5	420	112	7.3	306	104	7.1	170	92	6.9	104	78	6.7	18	66	6.5	13	46
27/11/92	Ferric					20			30			40			50			60			70	
		8.2	600	114	7.2	380	106	7.1	270	98	7.0	90	90	6.9	30	86	6.8	25	70	6.7	14	60
27/11/92	Alum					60			80			100			120			140			160	
		8.2	600	114	6.9	45	94	6.8	35	88	6.7	18	80	6.6	16	72	6.6	16	66	6.5	14	60
28/11/92	Alum					60			80			100			120			140			160	
		8.0	600	114	7.0	100	94	7.0	80	88	6.9	25	70	6.8	20	58	6.7	18	44	6.7	16	38

DATE	COAGULANT	RAW WATER			DOSE 1			DOSE 2			DOSE 3			DOSE 4			DOSE 5			DOSE 6		
		PH	TUR.	ALK.	PH	TUR.	ALK.	PH	TUR.	ALK.	PH	TUR.	ALK.	PH	TUR.	ALK.	PH	TUR.	ALK.	PH	TUR.	ALK.
30/11/92	Alum					100			120			140			160			180			200	
		7.9	1800	122	7.0	600	94	7.0	420	92	6.9	300	88	6.8	125	84	6.7	100	74	6.7	51	72
30/11/92	Ferric					60			90			120			150			180			210	
		7.9	1800	122	6.9	750	74	6.5	550	62	6.4	400	50	6.0	80	30	5.8	15	20	5.6	14	10
30/11/92	Catfloc					10			12			14			16			18			20	
		7.9	1800	122	7.9	360	122	7.9	180	122	7.9	130	122	7.9	90	122	7.9	58	122	7.9	38	122
30/11/92	Superfloc					10			12			14			16			18			20	
		7.9	1800	122	7.9	280	122	7.9	200	122	7.9	120	122	7.9	76	122	7.9	44	122	7.9	30	122
01/12/92	Alum					120			150			180			210			240			270	
		8.1	1700	120	6.8	100	90	6.8	40	82	6.6	25	74	6.6	20	66	6.5	19	60	6.5	17	50
01/12/92	Ferric					90			120			150			180			210			240	
		8.1	1700	120	6.8	170	76	6.6	21	62	6.3	12	38	6.1	11	24	5.5	12	8	4.9	14	2
02/12/92	Alum					120			150			180			210			240			270	
		8.2	1650	108	7.1	170	90	7.0	84	68	6.9	25	50	6.7	17	40	6.6	15	32	6.5	15	30
03/12/92	Alum					150			180			210			240			270			300	
		8.1	3600	100	7.0	800	84	6.9	200	66	6.8	105	60	6.7	80	50	6.6	67	42	6.5	50	40
03/12/92	Ferric					150			180			210			240			270			300	
		8.1	3600	100	6.7	450	46	6.6	190	32	6.4	70	22	5.8	29	12	5.1	29	6	4.6	29	0
03/12/92	Catfloc					18			22			26			30			34			38	
		8.1	3600	100	8.1	1600	100	8.1	1200	100	8.1	860	100	8.1	540	100	8.1	300	100	8.1	40	100
03/12/92	Superfloc					18			22			26			30			34			38	
		8.1	3600	100	8.1	1000	100	8.1	680	100	8.1	290	100	8.1	110	100	8.1	80	100	8.1	40	100
10/12/92	Superfloc					4			6			8			10			12			14	
		8.0	1300	120	8.0	300	120	8.0	76	120	8.0	33	120	8.0	27	120	8.0	26	120	8.0	30	120
11/12/92	Catfloc					4			6			8			10			12			14	
		8.1	1300	118	8.1	160	120	8.1	77	120	8.1	80	120	8.1	58	120	8.1	58	120	8.1	46	120
11/12/92	Ultrafloc					4			6			8			10			12			14	
		8.1	1300	118	8.1	200	120	8.1	56	120	8.1	45	120	8.1	39	120	8.1	36	120	8.1	40	120
11/12/92	Superfloc					4			6			8			10			12			14	
		8.1	1300	118	8.1	240	120	8.1	73	120	8.1	70	120	8.1	55	120	8.1	45	120	8.1	38	120
14/12/92	Alum					120			140			160			180			200			220	
		7.8	3100	100	6.7	120	60	6.7	80	46	6.6	46	34	6.6	40	28	6.4	40	24	6.3	38	22
14/12/92	Ferric					90			120			150			175			180			210	
		7.8	3100	100	6.5	220	44	6.4	180	32	6.3	100	26	6.1	32	14	6.0	21	10	5.0	19	8

4. APPENDIX A4 (Cont'd)

DATE	COAGULANT	RAW WATER			DOSE 1			DOSE 2			DOSE 3			DOSE 4			DOSE 5			DOSE 6		
		PH	TUR.	ALK.	PH	TUR.	ALK.	PH	TUR.	ALK.	PH	TUR.	ALK.	PH	TUR.	ALK.	PH	TUR.	ALK.	PH	TUR.	ALK.
14/12/92	Catfloc					12			16			20			24			28			32	
		7.8	3100	100	7.8	1500	100	7.8	1500	100	7.8	900	100	7.8	190	100	7.8	35	100	7.8	45	100
14/12/92	Superfloc					12			16			20			24			28			32	
		7.8	3100	100	7.8	1420	100	7.8	880	100	7.8	110	100	7.8	50	100	7.8	32	100	7.8	40	100
15/12/92	Alum					160			180			200			220			240			260	
		7.7	4000	82	6.8	90	44	6.6	47	32	6.5	40	26	6.3	39	22	6.2	35	22	6.0	33	18
15/12/92	Ferric					120			150			180			210			240			270	
		7.7	4000	82	6.7	280	32	6.4	100	18	6.1	40	14	5.5	30	10	5.0	30	0	4.6	25	0
15/12/92	Superfloc					16			20			24			28			32			36	
		7.7	4000	84	7.7	900	84	7.7	550	84	7.7	400	84	7.7	260	84	7.7	110	84	7.7	44	84
15/12/92	Catfloc					16			20			24			28			32			36	
		7.7	4000	84	7.7	1440	84	7.7	840	84	7.7	800	84	7.7	420	84	7.7	375	84	7.7	41	84
19/01/93	Alum					120			150			180			210			240			260	
		8.3	3400	108	7.0	360		6.8	120		6.7	80		6.6	61		6.5	49		6.3	43	
19/01/93	Catfloc					8.4			14			19.6			25.2			30.8			36.4	
		8.3	3400	108	8.3	1000	108	8.3	720	108	8.3	480	108	8.3	150	108	8.3	48	108	8.3	30	108
19/01/93	Catfloc*					2.8			5.6			8.4			11.2			14			16.8	
		7.0	300		7.0	27		7.0	25		7.0	24		7.0	26		7.0	26		7.0	28	
19/01/93	Alum*					30			45			60			75			90			120	
		7.0	300			25			23			21			16			16			15	
21/01/93	Alum					90			120			150			180			210			240	
		8.3	3000	108	6.6	700	50	6.5	400	46	6.4	220	40	6.2	50	28	6.1	24	22	6.0	25	20
21/01/93	Alum*					15			30			45			60			75			90	
		7.0	260	70	6.5	75	38	6.4	29	30	6.2	21	26	6.1	17	22	6.0	16	16	6.0	19	12
26/01/93	Alum					75			90			105			120			135			150	
		7.9	1400	86	7.0	300	68	6.9	180	64	6.8	140	60	6.6	100	54	6.5	60	48	6.4	30	44
26/01/93	Superfloc					6			8			10			12			14			16	
		7.9	1400	86	7.9	64	86	7.9	39	86	7.9	31	86	7.9	30	86	7.9	29	86	7.9	30	86
26/01/93	Alum+					30			45			60			75			90			105	
		7.9	1400	86	7.3	400	82	6.9	400	64	6.8	300	60	6.7	190	52	6.7	130	50	6.5	35	48

* Jar test performed on presettled water after dosing it with 120 ppm of alum

\+ Jar test performed on raw water which had been left to settle naturally for 3 hrs

4. *APPENDIX A4 (Cont'd)*

DATE	COAGULANT	RAW WATER			DOSE 1			DOSE 2			DOSE 3			DOSE 4			DOSE 5			DOSE 6		
		PH	TUR.	ALK.	PH	TUR.	ALK.	PH	TUR.	ALK.	PH	TUR.	ALK.	PH	TUR.	ALK.	PH	TUR.	ALK.	PH	TUR.	ALK.
27/01/93	Alum					96			120			144			168			192			216	
		7.9	1300	86	6.9	170	62	6.7	50	52	6.6	35	48	6.5	24	40	6.4	18	32	6.3	16	24
27/01/93	Catfloc					8			10			12			14			16			18	
		7.9	1300	86	7.9	150	86	7.9	130	86	7.9	100	86	7.9	83	86	7.9	66	86	7.9	53	86
27/01/93	Alum!					6			12			18			24			30			36	
		6.8	150	60	6.7	120	60	6.6	100	58	6.6	80	56	6.5	52	54	6.4	32	50	6.4	24	48
27/01/93	Catfloc!					2			4			6			8			10			12	
		6.8	150	60	6.8	18	60	6.8	17	60	6.8	18	60	6.8	18	60	6.8	18	60	6.8	18	60
28/01/93	Catfloc					8			10			12			14			16			18	
		8.0	1200	90	8.0	130	90	8.0	72	90	8.0	53	90	8.0	55	90	8.0	40	90	8.0	45	90
28/01/93	Superfloc					8			10			12			14			16			18	
		8.0	1200	90	8.0	150	90	8.0	86	90	8.0	52	90	8.0	29	90	8.0	25	90	8.0	34	90
28/01/93	Alum					90			120			150			180			210			240	
		8.0	1200	90	6.9	100	66	6.8	70	60	6.6	20	46	6.4	17	38	6.3	17	30	6.1	16	20
28/01/93	Alum!					0			7.5			15			22.5			30			37.5	
		6.8	92	64	6.8	85	64	6.7	60	60	6.6	24	54	6.5	18	52	6.5	17	50	6.4	17	46
29/01/93	Alum					90			120			150			180			210			240	
		8.1	1100	96	6.9	210	74	6.7	63	68	6.5	33	60	6.3	18	44	6.2	16	36	6.0	14	24
29/01/93	Catfloc					8			10			12			14			16			18	
		8.1	1100	96	8.1	130	96	8.1	87	96	8.1	45	96	8.1	29	96	8.1	28	96	8.1	33	96
29/01/93	Superfloc					8			10			12			14			16			18	
		8.1	1100	96	8.1	56	96	8.1	53	96	8.1	28	96	8.1	36	96	8.1	28	96	8.1	27	96
01/02/93	Alum					90			120			150			180			210			240	
		8.1	2800	90	7.0	180	88	6.8	80	90	6.7	48	88	6.5	35	76	6.5	30	70	6.4	28	66
01/02/93	Catfloc					16			18			20			22			24			26	
		8.1	2800	90	8.1	720	90	8.1	360	90	8.1	130	90	8.1	68	90	8.1	34	90	8.1	38	90
01/02/93	Superfloc					16			18			20			22			24			26	
		8.1	2800	90	8.1	540	90	8.1	220	90	8.1	98	90	8.1	52	90	8.1	30	90	8.1	36	90
01/02/93	Alum*					0			7.5			15			22.5			30			37.5	
		7.0	110	78	7.0	100	78	6.8	54	72	6.8	25	68	6.7	21	64	6.7	20	68	6.6	17	60
02/02/93	Alum					60			90			120			150			180			210	
		8.0	3000	112	7.4	460	108	7.2	280	104	7.1	180	102	6.9	140	98	6.9	95	98	6.8	65	96

* Jar test performed on presettled water after dosing it with 120 ppm of alum

! Jar test performed on presettled water which had been dosed with 100 mg/l alum

APPENDIX A5

SUMMARY OF JAR TEST RESULTS ON COMBINATIONS OF COAGULANTS

Legend

\+ Test done in the afternoon after raw water turbidity changed.

* Test done on presettled water (Tur = 540, Alk = 60, pH = 6.8) which had been dosed with 120 mg/l alum.

How to Read the Data

For all cells under the "DOSE" column.

V		W
X	Y	Z

V: Dosage for coagulant 1 (mg/l)
W: Dosage for coagulant 2 (mg/l)
X: pH
Y: Turbidity (NTU)
Z: Alkalinity (mg/l as calcium carbonate)

For all cells under the "COAGULANT" column.

C1
C2

C1: Coagulant 1
C2: Coagulant 2

5. APPENDIX A5: SUMMARY OF JAR TEST RESULTS ON COMBINATIONS OF COAGULANTS

DATE	COAGULANT	RAW WATER			DOSE 1			DOSE 2			DOSE 3			DOSE 4			DOSE 5			DOSE 6		
	(1/2)	PH	TUR.	ALK.	PH	TUR.	ALK.	PH	TUR.	ALK.	PH	TUR.	ALK.	PH	TUR.	ALK.	PH	TUR.	ALK.	PH	TUR.	ALK.
17/11/92	Catfloc				2		52	4		39	6		26	8		13						
	Alum	8.3	650	120	7.4	26	100	7.5	34	102	7.6	25	106	7.8	23	106						
17/11/92	Alum				28		50	108		50	130		50	156		50	182		50	208		50
	Soda ash	8.3	650	120	7.7	85	124	7.5	24	116	7.4	17	100	7.2	16	90	7.1	15	82	7.0	13	78
17/11/92	Superfloc				2		78	4		65	6		52	8		39	10		20	12		13
	Alum	8.3	650	120	7.1	12	84	7.1	13	86	7.3	14	90	7.4	16	96	7.4	16	100	7.7	15	104
18/11/92	Catfloc				2		20	4		20	6		20	8		20	10		20	12		20
	Alum	8.3	600	124	7.8	105	116	7.7	35	114	7.9	28	118	7.8	32	116	7.8	35	116	7.8	40	116
18/11/92	Superfloc				2		20	4		20	6		20	8		20	10		20	12		20
	Alum	8.3	600	124	7.7	120	116	7.6	65	114	7.7	55	116	7.7	30	116	7.7	25	114	7.7	30	116
19/11/92	Superfloc				2		20	4		20	6		20	8		20	10		20	12		20
	Alum	8.2	950	126	7.7	250	108	7.7	150	108	7.7	120	108	7.7	70	108	7.7	40	108	7.7	18	108
19/11/92	Catfloc				2		20	4		20	6		20	8		20	10		20	12		20
	Alum	8.2	950	126	7.6	250	108	7.6	200	108	7.6	120	108	7.6	85	108	7.6	70	108	6.6	34	108
19/11/92	Catfloc+				8		40	10		40	12		40	14		40	16		40	18		40
	Alum	8.4	1800	132	7.8	750	114	7.8	250	114	7.8	230	114	7.8	200	114	7.8	120	114	7.8	40	114
19/11/92	Superfloc+				5		40	8		40	12		40	15		40	18		40	20		40
	Alum	8.4	1800	132	7.7	900	114	7.7	540	114	7.7	340	114	7.7	120	114	7.7	80	114	7.7	38	114
20/11/92	Alum				150		50	180		50	210		50	240		50	270		50	300		50
	Soda ash	8.1	2100	120	7.4	230	146	7.3	180	140	7.2	80	136	7.1	55	84	7.0	48	80	6.9	40	68
20/11/92	Superfloc				12		60	16		60	20		60	24		60	28		60	32		60
	Alum	8.1	2100	120	7.7	900	96	7.7	600	96	7.7	200	96	7.7	130	96	7.7	80	96	7.7	30	96
20/11/92	Catfloc				12		60	16		60	20		60	24		60	28		60	32		60
	Alum	8.1	2100	120	7.7	600	94	7.7	520	96	7.7	350	96	7.7	210	94	7.7	140	96	7.7	50	96
21/11/92	Superfloc				6		30	10		30	14		30	18		30	22		30	26		30
	Alum	8.2	1500	100	7.8	332	88	7.8	192	88	7.8	80	88	7.8	55	86	7.8	34	88	7.8	38	88
27/11/92	Superfloc				2		10	4		10	6		10	8		10	12		10	14		10
	Alum	8.2	600	114	7.7	65	108	7.7	42	108	7.7	21	108	7.7	22	108	7.7	24	108	7.7	26	108
30/11/92	Superfloc				10		40	14		40	18		40	22		40	26		40	30		40
	Alum	7.9	1800	122	7.5	600	106	7.5	500	106	7.5	260	106	7.5	240	106	7.5	56	106	7.5	22	106
30/11/92	Alum				100		50	120		50	140		50	160		50	180		50	200		50
	Soda Ash	7.9	1800	122	7.5	680		7.4	600		7.3	350		7.2	150		7.1	130		7.0	30	
30/11/92	Catfloc				12		40	16		40	20		40	24		40	28		40	32		40
	Alum	8.1	1800	122	7.5	960	100	7.5	700	100	7.5	250	100	7.5	200	100	7.5	85	100	7.5	20	100

+ : Test done in the afternoon after raw water turbidity changed.

5. APPENDIX A5 (Cont'd)

DATE	COAGULANT	RAW WATER			DOSE 1			DOSE 2			DOSE 3			DOSE 4			DOSE 5			DOSE 6		
	(1/2)	PH	TUR.	ALK.	PH	TUR.	ALK.	PH	TUR.	ALK.	PH	TUR.	ALK.	PH	TUR.	ALK.	PH	TUR.	ALK.	PH	TUR.	ALK.
01/12/92	Superfloc				10		45	14		45	18		45	22		45	26		45	30		45
	Alum	8.1	1700	120	7.5	150	108	7.5	96	108	7.5	35	108	7.5	26	108	7.5	20	108	7.5	14	108
01/12/92	Catfloc				10		45	14		45	18		45	22		45	26		45	30		45
	Alum	8.1	1700	120	7.5	125	108	7.5	125	108	7.5	50	108	7.5	38	108	7.5	26	108	7.5	21	108
02/12/92	Superfloc				10		45	14		45	18		45	22		45	26		45	30		45
	Alum	8.2	2000	108	7.5	750	92	7.5	190	92	7.5	160	92	7.5	100	92	7.5	49	92	7.5	22	92
03/12/92	Alum				150		60	180		60	210		60	240		60	270		60	300		60
	Soda Ash	8.1	3600	100	7.7	1300	104	7.5	1000	98	7.4	450	90	7.3	80	86	7.2	40	82	7.1	30	70
03/12/92	Superfloc				20		60	24		60	28		60	32		60	36		60	40		60
	Alum	8.1	3600	100	7.6	700	88	7.6	500	88	7.6	130	88	7.6	120	88	7.6	50	88	7.6	60	88
11/12/92	Alum				10		1	10		2	10		3	10		4	10		5	10		6
	Catfloc	8.1	1450	100	7.8	600	80	7.8	120	80	7.8	120	80	7.8	100	80	7.8	43	80	7.8	38	80
11/12/92	Alum				10		1	10		2	10		3	10		4	10		5	10		6
	Superfloc	8.1	1450	100	7.8	600	80	7.8	500	80	7.8	360	80	7.8	200	80	7.8	105	80	7.8	100	80
15/12/92	Superfloc				12		60	16		60	20		60	24		60	28		60	32		60
	Alum	7.7	3400	84	7.2	200	68	7.2	150	68	7.2	110	68	7.2	60	68	7.2	28	68	7.2	30	68
15/12/92	Catfloc				12		60	16		60	20		60	24		60	28		60	32		60
	Alum	7.7	3400	84	7.2	520	68	7.2	400	68	7.2	280	68	7.2	240	68	7.2	100	68	7.2	50	68
19/01/93	Alum				90		5.6	120		8.4	150		11.2	180		14.0	210		16.8	240		19.6
	Catfloc	8.3	3400	108	6.9	110		6.8	55		6.7	35		6.6	25		6.5	25		6.3	20	
21/01/93	Alum				60		5.6	90		8.4	120		11.2	150		14	180		16.8	210		19.6
	Catfloc	8.3	3000	118	7.1	500		6.8	150		6.7	50		6.6	35		6.5	20		6.4	18	
22/01/93	Alum				30		28	45		26	60		24	75		22	90		20	105		18
	Catfloc	7.8	3000	108	7.5	360	90	7.4	300	88	7.3	320	80	7.3	300	72	7.2	260	68	7.2	71	62
22/01/93	Alum				120		1	120		2	120		3	120		4	120		5	120		6
	Catfloc*	7.8	3000	108	6.8	76	68	6.8	62	68	6.8	53	68	6.8	29	68	6.8	22	68	6.8	29	68
22/01/93	Alum				120		1	120		2	120		3	120		4	120		5	120		6
	Superfloc*	7.8	3000	108	6.8	58	68	6.8	24	68	6.8	21	68	6.8	17	68	6.8	18	68	6.8	20	68
22/01/93	Alum				60		5.6	90		8.4	120		11.2	150		14.0	180		16.8	210		19.6
	Catfloc	7.8	3000	108	6.9	280	68	6.7	150	56	6.6	55	44	6.5	35	38	6.4	25	32	6.2	16	30
02/02/93	Alum				30		18	45		16	60		14	75		12	90		10	105		8
	Superfloc	8.0	3000	112		25			27			27			29			28			27	
02/02/93	Superfloc				8		105	10		90	12		75	14		60	16		45	18		30
	Alum	8.0	3000	112	6.7	33	70	6.8	26	72	6.9	23	72	7.0	9.5	78	7.0	9.2	80	7.1	8.3	88
02/02/93	Catfloc				8		105	10		90	12		75	14		60	16		45	18		30
	Alum	8.0	3000	112	6.7	120	84	6.8	50	56	6.8	260	84	7.0	240	88	7.1	140		7.2	130	88

* Test done on presettled water (Tur. =540, Alk. =68, PH =6.8) which had been predosed with 120 ppm alum

APPENDIX A6

SUMARY OF JAR TEST RESULTS ON pH OPTIMISATION

6. APPENDIX A6: SUMMARY OF JAR TEST RESULTS ON pH OPTIMISATION

DATE	COAGULANT	DOSE	RAW WATER			TEST 1			TEST 2			TEST 3			TEST 4			TEST 5			TEST 6		
			PH	TUR	ALK.	PH	TUR.	ALK.	PH	TUR.	ALK.	PH	TUR.	ALK.	PH	TUR.	ALK.	PH	TUR.	ALK.	PH	TUR.	ALK.
16/11/92	Superfloc	10	8.2	650	116	4.0	30	0	6.4	32	52	6.9	40	90	8.2	60	110	9.1	75	130	9.9	50	150
17/11/92	Alum	91	8.4	600	120	3.2	15	0	5.0	14	10	6.4	17	48	7.2	23	82	9.5	84	152	9.8	17	230
18/11/92	Superfloc	4	8.4	750	124	4.4	20	4	5.9	30	18	6.9	200	80	8.3	110	244	9.7	30	518	11.3	18	700
18/11/92	Catfloc	4	8.4	750	124	4.5	28	6	5.7	32	16	6.8	180	76	8.5	180	260	9.6	30	510	11.0	20	680
20/11/92	Alum	210	8.4	2310	108	3.8	15	0	5.1	20	4	6.5	32	32	7.0	35	48	8.4	140	110	10.9	230	418
20/11/92	Superfloc	24	8.4	2310	108	4.0	20	0	5.5	30	10	7.4	200	74	8.4	200	108	9.5	180	132	10.5	110	226
20/11/92	Catfloc	24	8.4	2310	108	4.1	28	0	5.3	36	8	6.9	180	68	8.4	220	108	9.2	200	128	10.1	130	218
21/11/92	Alum	90	8.2	1500	100	3.7	20	0	5.3	25	4	6.9	90	48	7.3	240	78	10.3	200	240	11.4	30	600
24/11/92	Ferric	60	8.1	1125	100	4.4	21	0	6.2	240	32	6.6	250	62	6.9	270	72	8.0	65	106	9.6	25	172
26/11/92	Ferric	50	8.0	800	116	3.9	14	0	5.7	35	38	6.7	110	64	7.3	140	84	8.9	16	126	10	15	246
26/11/92	Alum	60	8.2	770	116	6.1	26	30	6.8	110	44	7.0	140	70	7.4	170	100	9.4	140	126	10.3	30	252
27/11/92	Alum	60	8.1	660	118	4.3	19	0	6.2	40	20	6.8	60	38	7.2	290	56	8.2	290	120	9.2	270	190
27/11/92	Superfloc	4	8.1	660	118	5.9	36		6.9	60		7.6	96		8.1	92		9.1	61		9.5	35	
30/11/92	Alum	180	7.9	1800	122	6.2	54	38	6.6	85	62	6.7	99	66	6.8	120	74	7.5	350	104	8.1	450	126
01/12/92	Ferric	105	8.0	1600	126	5.9	12	18	6.3	13	40	6.6	85	56	6.8	90	116	7.7	150	116	9.5	15	178
01/12/92	Superfloc	20	8.0	1600	126	4.6	34	1	6.5	74	52	7.4	78	110	8.1	90	126	9.3	56	168	10.1	42	248
01/12/92	Catfloc	20	8.0	1600	126	4.4	38	0	6.4	70	50	7.2	90	100	8.2	100	130	9.1	60	158	10.5	48	260
01/12/92	Alum	120	8.0	1600	126	4.7	30	4	6.2	45	24	6.9	95	74	7.2	192	90	8.3	200	126	9.3	140	168
02/12/92	Superfloc	20	8.2	2000	108	5.9	110		7.0	200		7.6	260		8.2	400		9.1	160		9.6	125	
14/12/92	Ferric	150	7.7	3100	100	4.4	26	0	4.6	25	0	5.6	39	12	6.2	67	20	6.8	85	72	9.0	100	134
14/12/92	Alum	140	7.7	3100	100	5.0	31	2	6.0	51	10	6.7	54	28	7.2	68	40	7.7	160	65	9.1	1400	125
15/11/92	Alum	170	7.7	4000	82	4.9	26	0	5.5	27	10	6.5	42	18	7.0	60	32	7.7	500	76	9.1	1900	138
16/12/92	Catfloc	24	7.7	3200	80	5.0	31		6.1	100		6.6	500		7.7	650		8.5	750		9.8	1350	
16/12/92	Superfloc	24	7.7	3200	80	5.1	25	0	5.7	60	8	6.2	180	30	7.7	280		8.8	1200		9.8	1500	

APPENDIX B1

METHOD FOR CALCULATING ALKALINITY CONSUMPTION VALUES

APPENDIX B1

METHOD FOR CALCULATING ALKALINITY CONSUMPTION VALUES

The values of alkalinity in mg/l as $CaCO_3$ consumed per 1.0 mg/l alum dosed for each jar test was calculated as follows:

$$AC_X = \frac{RA - A_X}{AD_X}$$

where AC_X = Alkalinity consumption in mg/l as $CaCO_3$ per mg/l alum dose for dose X

RA = Raw water alkalinity for dose X

A_X = Alkalinity in mg/l as $CaCO_3$ for dose X

AD_X = Alum dose in mg/l for dose X

$$AC = \frac{AC_1 + AC_2 + AC_3 + AC_4 + AC_5 + AC_6}{6}$$

where AC = Average alkalinity consumption in mg/l $CaCO_3$ per mg/l alum.

Typical examples for data obtained on 27/11/1992 (Appendix A4).

$$AC_1 = \frac{RA - A_1}{AD_1}$$

where RA = 114

A_1 = 94

AD_1 = 60

$$AC_1 = \frac{114 - 94}{60} = 0.33 \text{ mg/l as } CaCO_3 \text{ per mg/l alum.}$$

Similarly the values for doses 2, 3, 4, 5 and 6 have been obtained as:

$AC_2 = 0.33$
$AC_3 = 0.34$
$AC_4 = 0.35$
$AC_5 = 0.34$
$AC_6 = 0.34$

This gives the average alkalinity consumption value for the day as:

$$AC = \frac{0.33 + 0.33 + 0.34 + 0.35 + 0.34 + 0.34}{6}$$

$$= 0.34 \text{ mg/l as } CaCO_3 \text{ per mg/l alum}$$

APPENDIX B2

COST CALCULATIONS FOR COMBINATIONS OF COAGULANTS

APPENDIX B2

COST CALCULATIONS FOR COMBINATIONS OF COAGULANTS

Cost calculations presented in Table 5.3(b) were obtained based on the following prices prevailing in early March 1993.

(i)	Cost of alum	(KShs/kg) = 17.50	(Kel Chemicals, Thika)
(ii)	Cost of superfloc	(KShs/kg) = 265	(AMSCO Chemicals Ltd.)
(iii)	Cost of catfloc	(KShs/kg) = 265	(Aquatec Chemicals Ltd.)

To illustrate how cost of treating cubic unit of water was obtained, a typical example shall be presented here using jar test results obtain on 18/11/1992 (See Table 5.3(b)). On this date for the same raw water of 600 NTU, an equivalent performance of 50 NTU residual turbidity resulted from:

(i) Alum dose of 60 mg/l

(ii) Alum dose of 20 mg/l combined with catfloc dose of 3 mg/l

1. Cost of Alum Dosed Alone

60 mg/l is equivalent to

$$\frac{60 \text{ mg/l} \times 1.000 \text{l/m}^3}{10^6 \text{ mg/kg}} = 60 \times 10^{-3} \text{ kg/m}^3$$

Cost of treating cubic metre of water with this dose

$$= \quad 60 \times 10^{-3} \text{ kg/m}^3 \times \text{KShs } 17.50/\text{kg}$$

$$= \quad \underline{\text{KShs. } 1.05/\text{m}^3}$$

all the values in column 4 table 5.3(b) are obtained similarly.

2. Cost of Alum Combined with Catfloc

(i) Catfloc dose in kg/m^3 $= \dfrac{3\ mg/l \times 1{,}000\ l/m^3}{10^6\ mg/kg}$

$= 3 \times 10^{-3}\ kg/m^3$

Cost of catfloc per metre cubed of water

$= 3 \times 10^{-3}\ kg/m^3 \times 265\ KShs/kg$

$=$ KShs 0.80/m^3

(ii) Alum dose in kg/m^3 $= \dfrac{20\ mg/l \times 1{,}000\ l/m^3}{10^6\ mg/kg}$

$= 20 \times 10^{-3}\ kg/m^3$

Cost of alum per cubic metre of water

$= 20 \times 10^{-3} \times 17.50$

$=$ KShs. 0.35 m^3

Total cost for the combined case

$=$ Cost of alum + cost of superfloc

$= 0.35 + 0.80 =$ KShs. 1.15/m^3

All values in column 7, and 10 of Table 5.3(b) are obtained similarly.