INVESTIGATION OF TURBIDITY AND CHLORINE DISINFECTION IN SOUTH AFRICAN WATERS

by

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DECLARATION OF CANDIDATE

I, Ubendra Moodley, declare that unless indicated, this dissertation is my own work and that it has not been submitted for a degree at another University or Institution.

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ABSTRACT

Investigation on Turbidity and Chlorine Disinfection in South African Waters

All natural waters containing particulate matter, such as clay, silt, colloidal particles, plankton and other microscopic organisms, are referred to as turbid. Turbidity can be considered as a measure of the degree of contamination of natural waters, with particular regard to the dangerous presence of pathogenic micro-organisms. Although problems relating to poor water treatment have resulted in devastating outcomes in the past, South Africa's water treatment plants currently implement clarification processes that are effective in the removal of impurities that are resistant to chemical disinfection.

The abovementioned clarification processes, which are normally used to remove the complex mixture of dispersed insoluble particulate matter, include coagulation, flocculation, sedimentation and filtration. Nevertheless, there is a need to improve the treatment efficiency of potable waters and ensuring the employment of low cost appropriate technology. Whereas physical clarification is not sufficient, chemical disinfection is employed as a final polishing treatment. However, there is evidence in literature that the efficiency of chlorine disinfection is negatively affected by high turbidity levels. The phenomenon is correlated with poor operational practice of conventional water treatment plants. In order to investigate the relationship between disinfection and turbidity, with the aim of developing a code of best practice for efficient treatment operations, two typical water treatment plants were visited to investigate this relationship. These were considered representative of the standard of water treatment in South Africa. The correlation between turbidity and chlorine disinfection was monitored over a period of time and in relation to variable parameters. The results obtained for each plant were analysed independently and sparked the need for further investigation. The abovementioned relationship was therefore, examined by means of experimental investigations. An operational protocol for water treatment plants was presented as a final outcome of the investigation.

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CHAPTER 1 - INTRODUCTION

An abundance of unwanted organic and inorganic organisms are contained within the earth's natural environment. Of particular importance to this study however, are natural water bodies, which contain contaminants that prevail in varying degrees. These contaminants include both soluble and insoluble substances, which exists in either an organic or inorganic state. The presence of insoluble, suspended substances is the main cause of turbidity.

Turbidity refers to the optical property of water[1], which causes light to be scattered and absorbed rather than transmitted in straight lines through the sample. The scattering of light within a water sample is due to the occurrence of both coarse suspended matter which settles readily in water, as well as very small colloidal material that remains suspended in water indefinitely. The instrument that utilises this light scattering phenomenon as a means of evaluating the turbidity of a sample is known as a nephelometer.

Turbidity is primarily the result of silt or sedimentation[2], which has settled out of eroding water flows, leaving small solid particles that are continuously carried by the moving water. These particles include clay materials, microscopic organisms, flocculated particles and other types of amorphous matter. Of primary importance however, is the persistent presence of pathogenic micro-organisms that are refractory to mechanical treatment processes, referred to as clarification. Literature shows that disinfection is also affected by turbidity[4]. There is therefore, a need to understand the nature and polluting potentials of suspended matter in water, so to optimise the treatment techniques, with particular focus on final disinfection.

The primary objective of this research is to identify the nature of those substances that constitute turbidity in water with the purpose of assessing their pathogenic potential. If a consistent correlation between pathogens and turbidity is identified, a simple analytical protocol could be developed to improve clarification and disinfection operations in treatment plants. In particular, the main hypothesis of this research is that: if there is a direct correlation between disinfection efficiency and turbidity, and therefore a consequent direct correlation between turbidity and pathogens, the efficiency of the latter can be improved or controlled by acting directly on the turbidity, rather than on other parameter indicators. This would constitute a great advantage in operational/analytical procedures currently employed at treatment plants in South Africa and worldwide.

A literature review on state-of-the-art water treatment methods was conducted in order to assess the influence of turbidity on the various processes. The nature of pollution in potable water with particular reference to suspended material was also investigated. Available technology and legislation regarding water treatment in South Africa was also assessed by examining the disinfection techniques employed by two of South Africa's well-established water treatment plants. The aim of the experimental component of this research was to develop a direct relationship between disinfection and turbidity, as a means of formulating a more efficient solution to disinfection.

The two plants that were identified and compared, include the Wallmannsthal Bulk Water Treatment Works and the Umgeni Water Treatment Plant. These plants are referred to as well-established and representative of treatment operations in South Africa, as the Wallmannsthal Bulk Water Treatment Works is responsible for supplying consumable water to the entire Pretoria North region, and the Umgeni Water Treatment Plant is responsible for supply to the Durban central area. The disinfection techniques adopted by both plants were of a similar nature, where chlorine was preferred as their choice of disinfectant. The parameters that were investigated include the turbidity value and the amount of chlorine already present in the water prior to being dosed with the disinfectant, and the subsequent amount of chlorine left over at the end of the disinfection cycle, together with the resulting turbidity value. It was evident at the end of the disinfection cycle that a significant amount of disinfectant was being wasted. Copies of these test results were not provided for inclusion in this study, however, the results were discussed with the relevant personnel to understand the reasons behind the procedures that were being adopted. In general, both plants adopt the policy whereby, as long as there is free available chlorine at the end of the disinfection cycle, then the water is safe for drinking. This policy is not an ideal one, as although the safety aspect is being achieved, the cost-effective aspect is subsequently compromised. The experimental investigation was therefore undertaken to contribute toward the identification of a more cost-effective solution for efficient disinfection, by establishing a link between disinfection efficiency and turbidity. The aim of the experimental investigation was to formulate a graphical relationship for the dosage of disinfectant that is required to obtain a desired turbidity value.

The literature review that comprises chapter two of this study, aims at identifying and examining those substances that constitute turbidity in water, as well as the mechanical and chemical treatment processes that are utilized at water treatment plants to produce an end-product that is suitable for consumption. The procedures that were used to conduct the experimental component of this investigation are explained in chapter three, with discussion

of the results and formulation of the relationship between disinfection efficiency and turbidity being illustrated in chapter four. The subsequent conclusions and recommendations to this study are outlined in chapter five.

CHAPTER 2 - LITERATURE REVIEW

2.1 PRINCIPLES OF COLLOIDAL MATTER IN WATER

Thomas Graham discovered that certain substances could be separated from other substances by a process known as dialysis (dialysis is the separation of smaller molecules from larger ones, or of dissolved substances from colloidal particles in a solution by the selective diffusion through a semi-permeable membrane). Those substances that did not diffuse through the semi-permeable membrane were referred to as colloids, while the name crystalloid was given to those substances which diffused to form a true solution.

Colloids consist of particles lying in size between the dissolved state, and particles which readily sediment out of solution (refer to illustration shown in figure 2.1).

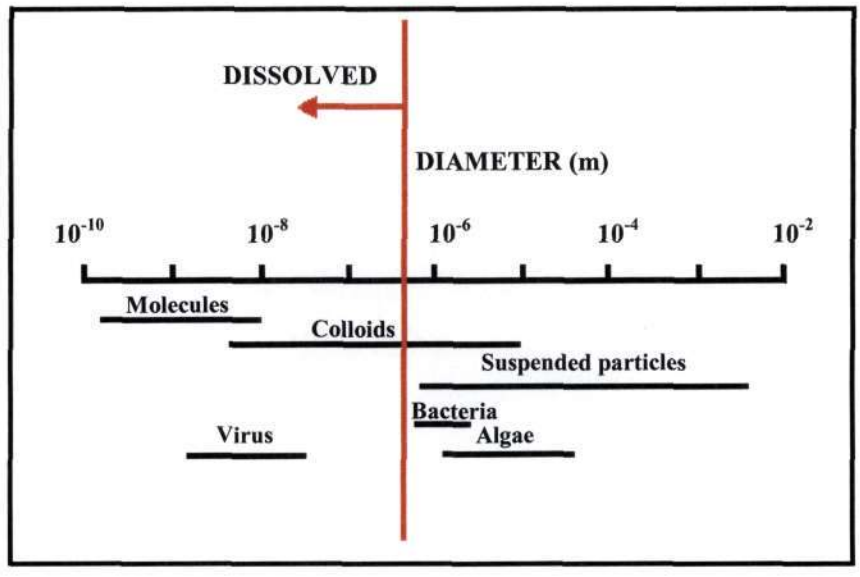

Figure 2.1: Relative sizes of dissolved and sediment particles[4]

Natural waters are likely to contain dissolved organic and inorganic substances, bacteria, plankton and coarse suspended matter, as well as substances in a state of colloidal suspension. The heterogeneous mixture of insoluble particulate matter has widely varying sizes, shapes and chemical composition, and variations in the relative occurrence of these materials are widespread.

A visual example of turbid water can be seen in Figure 2.2[5] - A stream running muddy during high flow due to a high concentration of suspended sediments.

Figure 2.2: Stream containing a high concentration of suspended solids

As a means of understanding the phenomenon of turbidity and its effect on disinfection, one must first understand the science of colloidal substances that constitute turbidity. Sub-sections 2.1.1 to 2.1.5 have therefore been compiled to provide the reader with a thorough insight into the physical and chemical properties that govern colloids.

2.1.1 CLASSIFICATION OF COLLOIDAL MATTER

Colloids can be defined[6] as a mixture in which one substance is divided into minute particles (called colloidal particles) and dispersed throughout a second substance. There are both natural as well as artificial processes giving rise to a suitable dispersion of one substance in another and in general, a colloid or colloidal dispersion is a two-phased[7] system of matter, which contains mixture types that are intermediate between homogeneous and heterogeneous substances. The dispersed phase consists of particles that are of extremely small dimension, and the continuous phase or dispersion medium, is where these particles become uniformly distributed in a manner that prevents them from being filtered easily, or settled rapidly (refer to Figure 2.1).

Colloidal particles are larger than molecules but too small to be observed directly with a microscope, however, their shape and size can be determined by electron microscopy. In a true solution, the particles of a dissolved substance are of molecular size and are thus smaller than colloidal particles; and in a coarse mixture (e.g. a suspension), the particles are much larger than colloidal particles. Although there are no precise boundaries in the size of particles in mixtures, colloids or solutions, colloidal particles are usually in the order of 10^{-7} to 10^{-5} cm in size. Dispersions where the particle sizes are within this range are referred to as colloidal aerosols, colloidal emulsions, colloidal foams or colloidal suspensions.

One way of classifying colloids is to group them in accordance with the three phases i.e. solid, liquid or gas. These classifications however, must include both the dispersed substance as well as the medium of dispersion. In this regard, typical examples of the abovementioned are indicated in table 2.1[7].

Table 2.1 Classification of colloidal matter

		DISPERSED PHASE		
		GAS	**LIQUID**	**SOLID**
DISPERSING PHASE	**GAS**	None: all gases are soluble	Liquid aerosol, Examples: fog, mist	Solid aerosol, Examples: Smoke, dust
	LIQUID	Foam, Examples: Whipped cream	Emulsion, Examples: Milk, mayonnaise, hand cream	Sol, Examples: Paint, pigmented ink
	SOLID	Solid foam, Examples: Styrofoam, Pumice	Gel, Examples: Gelatine, jelly, cheese, Opal	Solid sol, Examples: Ruby glass

In addition to this, further distinctions are also made in the case of dispersed solids. In some cases, e.g. a dispersion of sulphur in water, the colloidal particles have the same internal structure as the bulk of the solid. In other cases, e.g. a dispersion of soap in water, the particles are an aggregate of small molecules and do not correspond to any particular solid structure. In still other cases, e.g. the dispersion of a protein in water, the particles actually form large singular molecules. A different distinction, usually made when the dispersing medium is a liquid, is between lyophilic and lyophobic systems. The particles in a lyophilic system have a great affinity for the solvent, and are readily solvated (combined, chemically or physically, with the solvent) and dispersed, even at high concentrations. In a lyophobic system the particles resist solvation and dispersion in the solvent, and the concentration of particles is usually relatively low.

Particulate matter can be classified into specific categories with respect to their physical, chemical and biological characteristics:

Classification of Colloids According to Size – Particle size is commonly used as the parameter for determining whether or not a dispersion is a colloid. Particles smaller than 0.01 μm are normally classified as dissolved[4], while insoluble material is often defined as any particle from 0.01 μm up to 200 μm in size and includes both colloidal and suspended particles of an inorganic, organic or bio-organic nature. Particles larger than 200 μm will be found suspended in water only with a high velocity current, or when they are free-swimming or buoyant bio-organic particles.

Hydrophilic, Hydrophobic and Association Colloids – According to studies conducted by Manahan[8], colloids can actually be categorised into three distinguishable groups, namely, hydrophilic, hydrophobic and association colloids. The common element between the three classes of colloids is the fact that they are held in suspension by electrostatic interactions with water molecules. However, the difference between the three classes is that their chemical compositions are dissimilar from one another.

Hydrophilic colloids are large molecules that contain, as an integral part of their structure, functional groups that can hydrogen bond with water molecules. Hydrophilic colloids have solutes with structural groups that are exposed on their surface, and are able to hydrogen bond with water. Proteins and a number of synthetic polymers are typical examples of hydrophilic colloids (refer to figure 2.3).

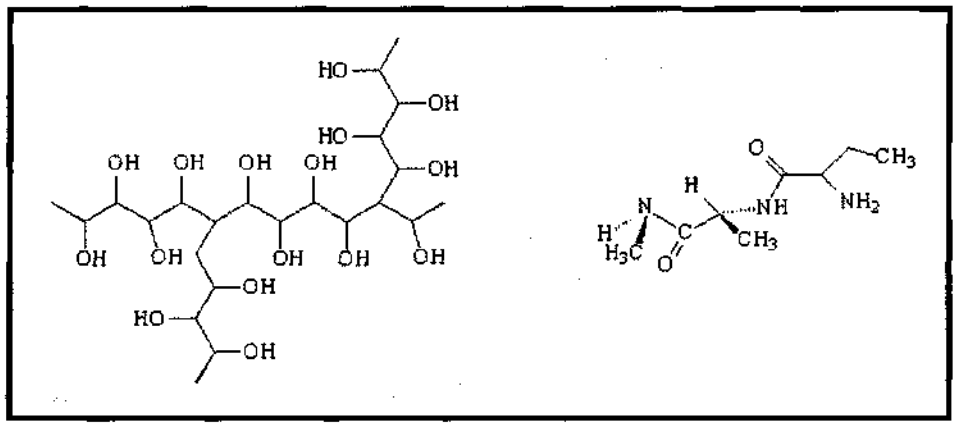

Figure 2.3: Examples of compounds that can form hydrophilic colloids

Hydrophobic colloids also contain solutes with surface groups that cannot hydrogen bond, and typically involving groups that can only interact via dispersion forces. Clays form a negative charge on their surface when placed in water, and remain in suspension by the electrostatic interaction between the negative surface charge and the positive charges from

cations present in the water. Figure 2.4 below, illustrates colloidal clay particles that are suspended in solution by these electrostatic interactions.

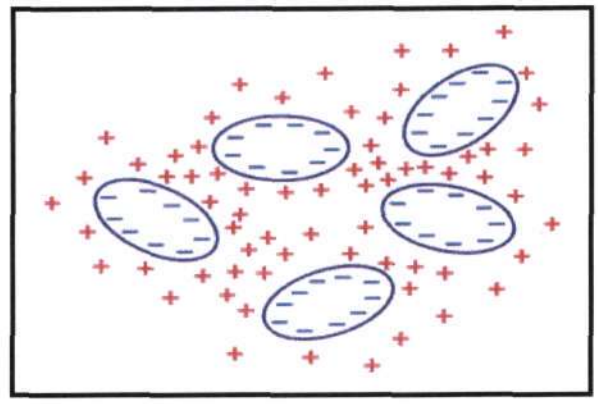

Figure 2.4: Electrostatic interactions between colloidal clay particles

The formation of hydrophobic colloids will not take place unless a method of chemical alteration is applied to the solute. The methodologies of facilitating this process are:

- If the solute can adsorb ions onto its surface, then it will be able to interact strongly enough with water. (Note: adsorb means to stick to the surface).
- By combining the solute with another molecule that has two distinct ends to it. One end being hydrophobic in nature and the other being hydrophilic. The head groups interact strongly with the water whilst the hydrophobic tails group together away from the water (refer to Figure 2.5).

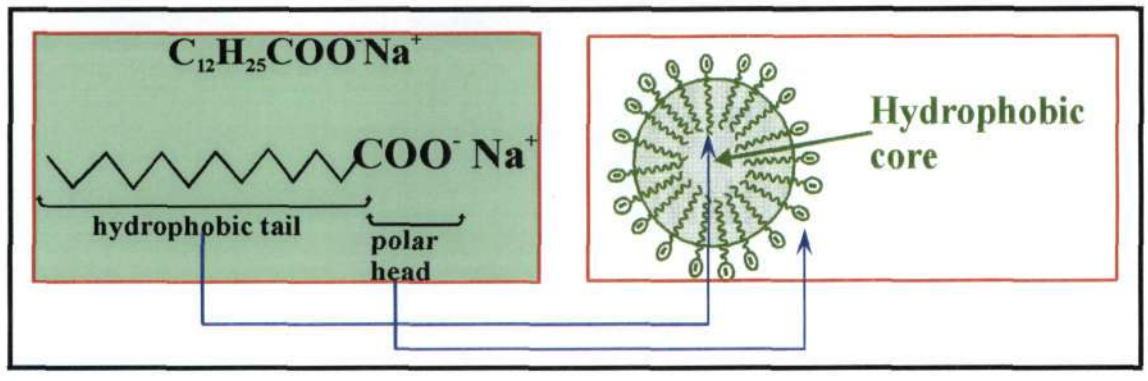

Figure 2.5: Hydrophobic colloids in water

Table 2.2 illustrates some of the general properties, summarised by Ross[4], which compares hydrophilic and hydrophobic colloids.

Table 2.2 Properties of colloids

PROPERTY	TYPE OF COLLOID	
	HYDROPHILIC	HYDROPHOBIC
COAGULATION	Results in a gel.	Results in granules.
CONCENTRATION	High concentration of disperse phase frequently stable.	Only low concentration of disperse phase stable.
DESICCATION	Residue will take up water immediately after desiccation.	Residue will not become de-coagulated.
ELECTROLYTIC	Unaffected by small amounts of electrolytes; salted out by large amounts.	Very easily precipitated by electrolytes.
STABILITY	Governed by electric charge and solvation.	Governed by electric charges of the particle only.
TYNDALL EFFECT	Usually yields a weak Tyndall beam.	Tyndall beam and light scatter is marked.

The third type found in colloidal systems[8], is the association colloids. These are molecules that have two parts to their molecular structure, a hydrophobic part and a hydrophilic part. Soaps and detergents form association colloids when mixed with water. Their molecular structures are similar to the illustration below (refer to figure 2.6), where the carboxylic acid group is the hydrophilic portion and the hydrocarbon chain is the hydrophobic part of the molecule.

When placed in water, these molecules form a structure where the hydrocarbon tails collect into tiny oil droplets and the charged carboxylate groups interact with the water through an electrostatic interaction to keep the droplet suspended. Figure 2.7 below, illustrates association colloids in suspension.

The importance of comprehending the chemical interactions that occur between various substances in water, is to facilitate ones understanding of how these substances become entwined in one another, thereby strengthening the chemical structure of the newly-formed molecules. These newly-formed molecules are of particular concern in instances where pathogenic substance are involved, e.g. most pesticides and herbicides are not water soluble,

however, they aggregate with humic and fulvic acids, which are natural breakdown products of cellulose. Humic and fulvic acids form hydrophilic colloids in water, transporting pesticides and herbicides in the process.

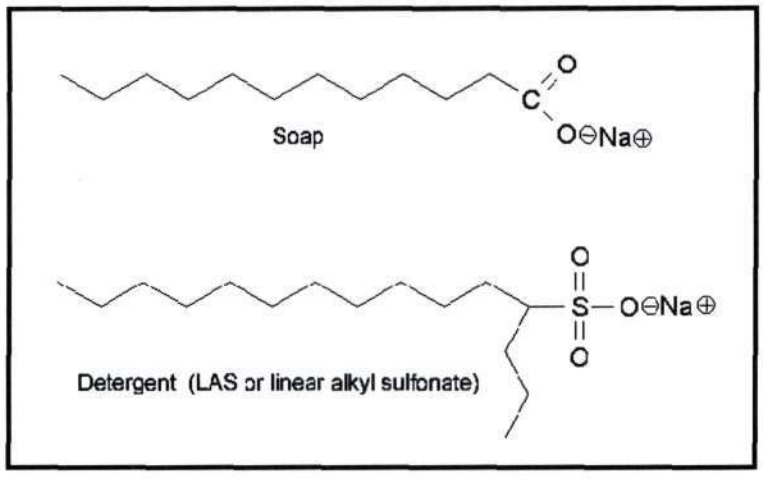

Figure 2.6: Sodium salt of a carboxylic acid [soap] and of linear alkyl sulfonate [detergent], form association colloids when placed in water

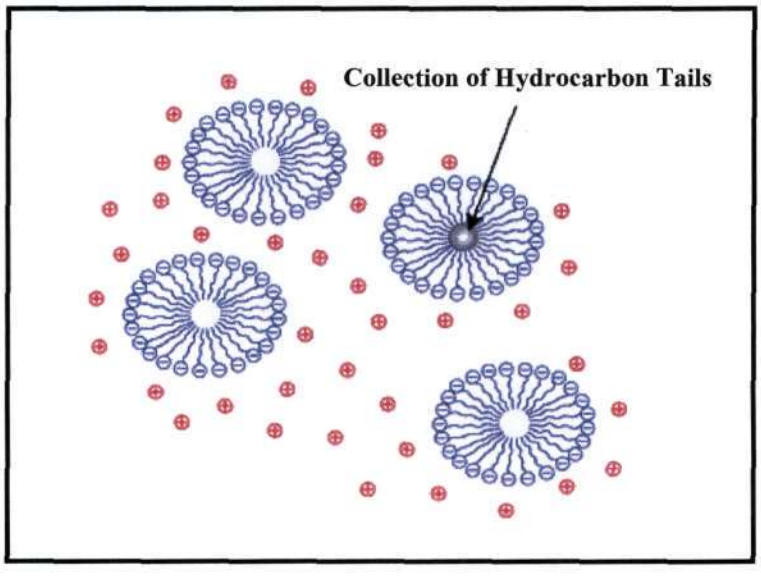

Figure 2.7: Electrostatic interaction between water and the hydrocarbon tails

Turbidity and Colour Colloids – Turbidity and colour are expressions of the optical property of a colloidal dispersion[9]. Photo electric measuring methods are therefore based either on the measurement of the transparency i.e. on absorption of the transmitted light, or on the intensity of the lateral scattered light reflected by particles in suspension, i.e. the Tyndall effect.

A homogeneous solution does not disturb the propagation of light, except to change its phase velocity to $v = c/n$, where c is the speed of light in a vacuum and n is the index of refraction. In a gas, light scattering is made possible by the density fluctuations, which are a natural result of the free movement of the molecules. Scattering is the emission of light in all directions, which decreases the intensity of the ordered beam, while absorption is the conversion of light to other forms of energy.

A colloidal system need not always be visibly turbid, e.g. a gel may be quite transparent when the particles are small therefore, slight turbidity may not be noticed until a beam of light is passed through. The turbidity causes scattering so that the path of the light beam, which maintains the appearance of a cone (known as the Tyndall cone), can be clearly seen.

The Tyndall effect is a common atmospheric phenomenon, where Tyndall cones are evidence of lyophobic sols. If the sol is composed of transparent particles with an index of refraction considerably different from that of the external phase, and if they are present in sufficient concentrations, the sol will become opaque and white, which is the limit of turbidity. If the particles have the same index of refraction, the Tyndall effect will be small.

The substances that normally produce turbidity or opalescence, are clay minerals with an associated quantity of organic matter. The size range covers particles both small enough to possess the long term stability associated with colloidal particles, and large enough to settle appreciably under the action of gravity.

Bio-organic and Inorganic Colloids – The term bio-organic[10] is normally used to cover biological organisms or detritus of biological organisms with a density less than 1.9 g/cm^3 while the terms inorganic or clay mineral, are used to describe particles with a non-carbon structure that have a density greater than 2 g/cm^3.

2.1.2 PROPERTIES OF COLLOIDS

As indicated above, a key property of colloid systems[6] that distinguishes them from true solutions is that colloidal particles scatter light. If a beam of light, such as that from a flashlight, passes through a colloid, the light is reflected by the colloidal particles and the path of the light can therefore be observed. When a beam of light passes through a true solution (e.g., salt in water) there is so little scattering of the light that the path of the light cannot be seen and the small amount of scattered light cannot be detected except by very sensitive instruments. When an ultramicroscope is used to examine a colloid, the colloidal

particles appear as tiny points of light in constant motion, called Brownian movement, which helps keep the particles in suspension.

The particles of a colloid selectively absorb ions and acquire an electric charge. All of the particles of a given colloid take on the same charge (either positive or negative) and therefore repel one another. If an electric potential is applied to a colloid, the charged colloidal particles move toward the oppositely charged electrode, however, if the charge on the particles is neutralized, they may precipitate out of the suspension.

A colloid may be precipitated by adding another colloid with oppositely charged particles, where the particles that are attracted to one another, coagulate and precipitate out. The addition of soluble ions may precipitate a colloid, e.g. the ions in seawater precipitate the colloidal silt dispersed in river water, forming a delta. Particles in a lyophobic system are readily coagulated and precipitated, and the system cannot easily be restored to its colloidal state. A lyophilic colloid does not readily precipitate and can be restored by the addition of a solvent.

Thixotropy is a property exhibited by certain gels (semisolid, jellylike colloids). A thixotropic gel appears to be solid and maintains a shape of its own until it is subjected to a shearing (lateral) force or some other disturbance, such as shaking. It then acts as a sol (a semi-fluid colloid) and flows freely. Thixotropic behaviour is reversible, and when allowed to stand undisturbed the sol slowly reverts to a gel. Common thixotropic gels include oil well drilling mud, certain paints and printing inks, and certain clays.

2.1.3 TYPES OF COLLOIDAL MATTER PRESENT IN WATER PRIOR TO DISINFECTION

Prior to identifying the different types of colloidal matter present in water, it is of interest to understand the crystalline structure[11] that constitutes the various types of solids that prevail in water. The reason for this is to understand how a strong molecular structure adds the resistance of certain solids to chlorine disinfection. In this regard, solids can be categorised into four major groups, namely:

Ionic Solids (Figure 2.8[11]) - Substances that have a definite melting point and contain ionic bonds.

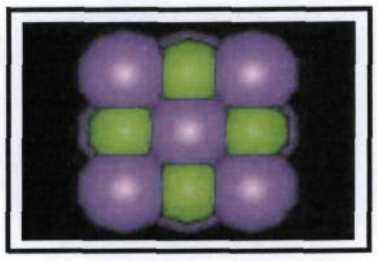

Figure 2.8: Crystalline structure of ionic solids

Covalent solids (Figure 2.9[11]) - Substances that appear as a single giant molecule made up of an almost endless number of covalent bonds.

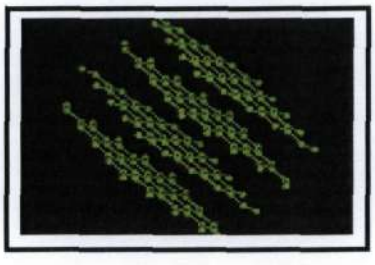

Figure 2.9: Crystalline structure of covalent solids

Molecular solids (Figure 2.10[11]) - Represented as repeated, molecular units.

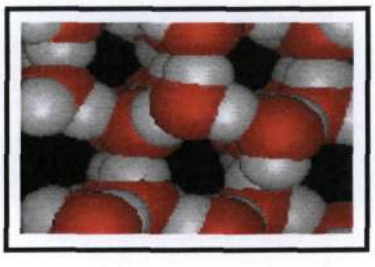

Figure 2.10: Crystalline structure of molecular solids

Metallic solids (Figure 2.11[11]) - Are repeating units made up of metal atoms.

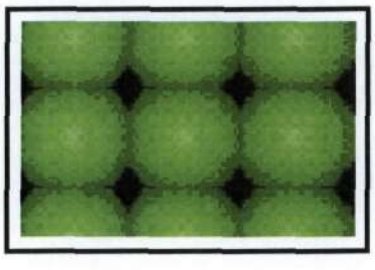

Figure 2.11: Crystalline structure of metallic solids

Depending on the mode, degree and efficiency of the clarification processes, the influent to the chlorination contact tank will contain particulate substances that vary in size, shape, density and surface characteristics, and consist largely of the following:

CLAY MINERALS – Clays[8] are the most common form of hydrophobic colloids in natural waters and due to their chemical compositions, clays have a strong tendency to absorb chemical species from water. A number of substances posses the ability to escape the solids removal processes that form part of the water treatment cycle, by dissolving in the water. The presence of clays however, assists the removal process in that instead of becoming dissolved, the chemical substances tend to absorb to the clay surface. They are then removed from the water together with those clay particles that settle under gravity within the sedimentation tanks (the sedimentation process is elaborated upon in section 2.6.3). The water leaving the sedimentation tanks must now undergo the filtration process (refer to section 2.6.4), where the chemical substances which have dissolved in the water are unlikely to be removed. The removal of these chemical substances together with the clay materials during the sedimentation process, therefore ensures that the filtered water has been effectively clarified, thus contributing toward the efficiency of the disinfection process. To grasp the manner in which the abovementioned absorption and removal process is facilitated, it is important to first familiarise oneself with the physical and chemical composition of clays in general.

Clay is a generic term used to describe a class of secondary minerals produced from the weathering of aluminium silicate rocks. Clays are flat sheets of alternating layers of silicon oxides and aluminium oxides, held together by ionic attraction for cations sandwiched between the sheets. Figure 2.12[8], is an example of kaolinite clay, illustrating the alternating sheets of silicon oxides and aluminium oxides. The negative surface charge of clay particles results when an aluminium (+3) or silicon (+4) is replaced with a sodium (+1), potassium (+1) or ammonium (+1) ion, giving an overall negative charge to the particle.

Both organic and inorganic materials can be trapped between the sheets of aluminium and silicon oxides, providing an effective mechanism for transporting materials in an aqueous environment. These properties of clays therefore make them useful agents for cleaning contaminated water. Furthermore, due to their ability to retain pollutants, clay liners are placed at the bottom of landfills, preventing pollutants from getting into the groundwater.

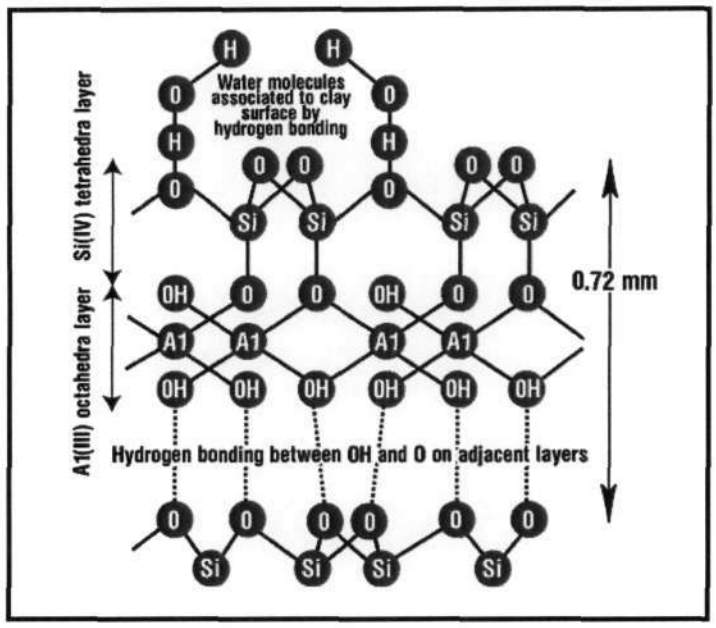

Figure 2.12: Ionic interactions in kaolinite clay

Clays can be divided[11] into four major groups, indicated and briefly described in table 2.3.

Table 2.3 Major clay groups

TYPE OF CLAY	CHARACTERISTICS / PROPERTIES
KAOLINITE	This group has three members namely, kaolinite, dickite and nacrite.
MONTMORILLONITE / SMECTITE	This group is composed of several minerals that differ in chemical content, e.g. pyrophyllite, talc, vermiculite, sauconite, saponite, nontronite and montmorillonite.
ILLITE / CLAY-MICA	This group is basically a hydrated microscopic muscovite, with illite being a significant rock forming mineral.
THE CHLORITE GROUP	This group is not always considered a part of the clays and is sometimes left alone as a separate group within the phyllosilicates.

FLOCCULATED PARTICULATE MATTER - In wastewater treatment operations[12], the processes of coagulation and flocculation are employed to separate suspended solids from water. Finely dispersed solids (colloids) suspended in wastewaters are stabilized by negative electric charges on their surfaces, causing them to repel each other. Since this prevents these charged particles from colliding to form larger masses, called flocs, they do

not settle. To assist in the removal of these particles from a suspension, chemical coagulation and flocculation are required. These processes (as briefly explained below), are usually done in sequence, and constitutes both physical and chemical procedures where chemicals are mixed with the impure water to promote the aggregation of the suspended solids into particles large enough to settle or be removed.

Coagulation (elaborated upon in section 2.6.1) – Is the destabilization of colloids by neutralizing the forces that keep them apart. Cationic coagulants provide positive electric charges to reduce the negative charge (zeta potential) of the colloids. As a result, and with the facilitation of rapid mixing to disperse the coagulant throughout the liquid, the particles collide to form larger particles (flocs). Care must also be taken not to overdose the coagulants as this can cause a complete charge reversal and restabilize the colloid complex.

Flocculation (elaborated upon in section 2.6.2) – Is the action of polymers to form bridges between flocs to bind the particles into large agglomerates or clumps. Bridging occurs when segments of the polymer chain adsorb on different particles and help particles aggregate. An anionic flocculant will react against a positively charged suspension, adsorbing on the particles and causing destabilization either by bridging or charge neutralization. In this process it is essential that the flocculating agent be added by slow and gentle mixing to allow for contact between the small flocs and to agglomerate them into larger particles. The newly formed agglomerated particles are quite fragile and can be broken apart by shear forces during mixing. Care must also be taken to not overdose the polymer as doing so will cause settling/clarification problems. Anionic polymers themselves are lighter than water and as a result, increasing the dosage will increase the tendency of the floc to float and not settle.

WATER-BORNE MICRO-ORGANISMS - Micro-organisms[3] can be found commonly in nature and although being invisible to the naked eye, micro-organisms are present in soils, air, food and water. Once exposed to micro-organisms, they will remain as an integral part of our bodies and due to being mostly harmless, they will assist the body by contributing to a number of vital processes such as the metabolism. Pathogenic micro-organisms have specific properties which distinguish them from chemical contaminants where, although being living organisms, they do not dissolve in water but will coagulate or attach themselves to both colloids and solids present in water. Furthermore, pathogenic micro-organisms found in domestic waste waters can be divided into three categories, namely: bacteria, viruses and parasitic protozoa.

AMORPHOUS MATTER - Amorphous solids[7] are undefined materials that are located in a phase that is intermediate between solids and liquids. The atoms in an amorphous solid are aligned in a rigid disorderly structure, where they do not have definite melting points nor do they have regularly repeated units. An amorphous solid does not have a long-range order (i.e. physical systems in which remote portions of the same sample exhibit correlated behaviour) for the position of its atoms. Most classes of solid materials can be found or prepared in an amorphous form, e.g. a window glass is an amorphous ceramic, many polymers (such as polystyrene) are amorphous, as well as foods such as cotton candy.

Amorphous materials are commonly prepared by rapidly cooling molten material, where the cooling reduces the mobility of the material's molecules before they can pack into a more thermodynamically favourable crystalline state. Amorphous solids can exist in two distinct states, the rubbery state and the glassy state, where the temperature at which they transition between the glassy and rubbery states is called their glass transition temperature.

2.1.4 DENSITY AND SEDIMENTATION COEFFICIENT OF COLLOIDS

A distinct physical characteristic of colloidal particles is their long term ability to remain suspended in water. This is basically a function of both size and density, and these parameters can be used to calculate the sedimentation coefficient or rate of movement in a given gravitational field using the following equation[4]:

$$S = \frac{d^2(Pp - Pm)x10^{13}}{18\eta}$$

Where S = Sedimentation coefficient, Svedberg units (S)
d = particle diameter, cm
Pp = particle density, g/cm^3
Pm = suspending solution density, g/cm^3
η = viscosity of solution, poise

Understanding the mobility trends of colloidal particles in water is of utmost importance in implementing effective coagulation, flocculation and sedimentation processes. The aim of the coagulation and flocculation processes is to promote the formation of flocculants that are dense enough to settle within the sedimentation tanks (see section 2.6.3). The water, which contains the floc particles, is held in the sedimentation tanks for a specific amount of time to allow the particles to settle under the influence of gravity at the bottom of the sedimentation

tanks, from where it is then removed. A particle with a sediment coefficient[4] of 2 x 10^8S will settle 1 metre in water in 6.55 hours, and a 2 x 10^4S particle will settle 1 metre in water in 655 hours. To obtain the desired level of sediment removal, it is therefore imperative that accurate settling calculations are made using the above equation, to determine the amount of time that is required for the floc particles to settle at the bottom of the sedimentation tank.

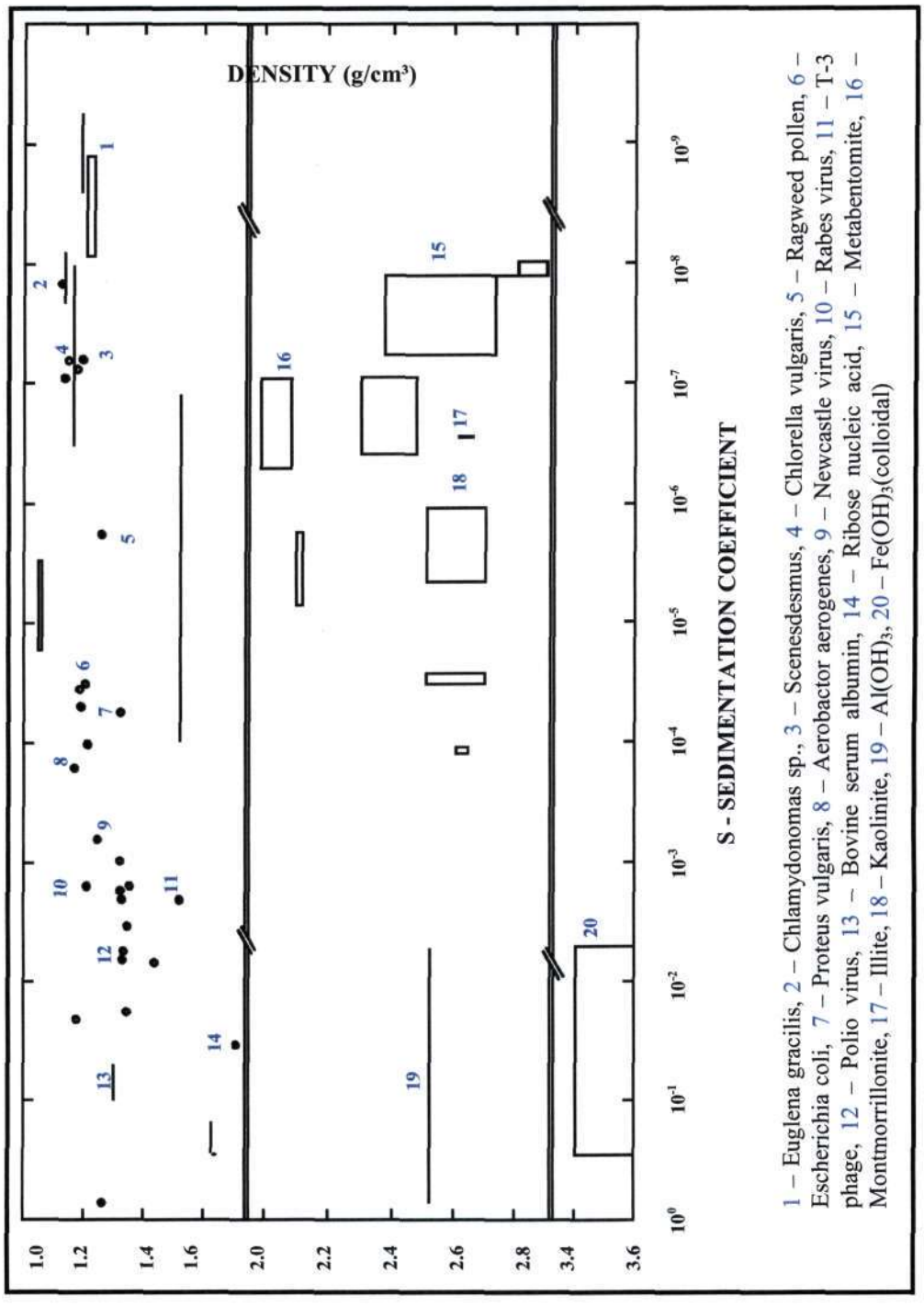

Figure 2.13: Relationship between sedimentation coefficient and density for selected bio-organic and inorganic particles found in natural water

Figure 2.13 above, illustrates the relationship[4], between sedimentation coefficient and density for selected bio-organic and inorganic particles found in natural water.

2.1.5 ENMESHMENT PHENOMENON OF COLLOIDAL MATERIAL

Simply stated, this phenomenon involves the enmeshment of pathogens within other forms of turbidity-constituting matter. During the water treatment cycle, the detrimental effects posed by such a relationship, is that these enmeshed pathogenic materials are offered a level of protection during the disinfection process. In this regard, the level of contact between the disinfectant and pathogens is subsequently decreased.

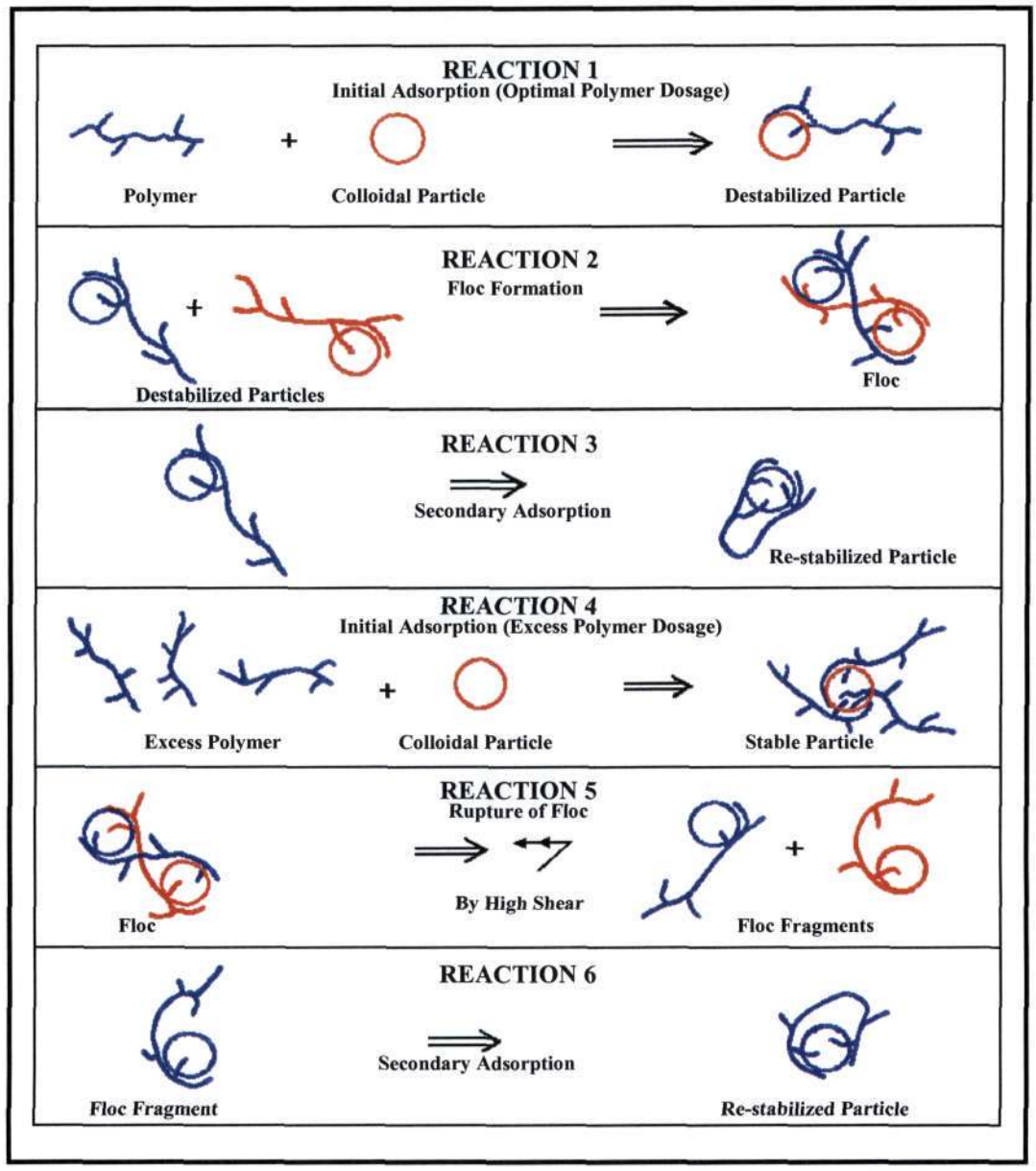

Figure 2.14: Schematic representation of the bridging mechanism in the coagulation of colloids using polymers

During the treatment of water, enmeshment predominantly occurs when massive amounts of coagulants are added to the water, which leads to the formation of various hydrous polymers[13]. As these polymers form, the colloids become trapped within the floc formations. Aluminum sulphate is used in most treatment plants and serves as a typical example of a substance that promotes the coagulation of colloidal particles into flocs. In water treatment plants, this mainly happens through three different mechanisms: charge neutralization through adsorption of oppositely charged ions, inter-particle bridging where the coagulant forms a polymer chain and precipitate enmeshment where particles are trapped when colloidal flocs form.

Polymeric flocculants have proven to be beneficial in aggregating particles to a settleable size and increasing the shear strength of the floc against hydraulic break-up[4]. Simply stated, polymer molecules attach themselves to the surfaces of suspended particles, where the free end of the molecule is able to absorb onto another suspended particle when contact is made, thus forming a bridge or link between two particles. The progressive linking of more and more particles results in an ever increasing size of a floc, whose eventual size is limited by its ability to withstand the hydraulic shear gradient imposed upon it by agitation or turbulence. A schematic representing this phenomenon is shown in Figure 2.14[4].

2.2 TEST METHODS FOR OPERATORS

2.2.1 TYPES OF WATER TESTING PROCEDURES

A variety of test procedures[14] and methods are available for use by water and wastewater operators. They range from colorimetric, titrimetric, electrometric (meter & probe), turbidimetric, nephelometric, and demonstrative methods. Often, more than one of these methods can be utilized to measure a single unknown (parameter), e.g. chlorine residual can be measured colorimetrically, titrimetrically, or electrometrically. The key aspects that require consideration when deciding on the method best suited to ones objective include:

a) accuracy
b) cost (initial & cost per test)
c) skill level
d) repeatability
e) portability
f) decision-making information obtained

A summary of the most common test procedures utilized in water and waste water operations is listed below.

2.2.1.1 Colorimetric Methods

Defined as the measurement[14] of a parameter where its concentration is directly proportional to colour development and intensity after the addition of a known volume of reagent(s) (chemicals). In cases like chlorine residual, the reaction is almost immediate, and results can be determined right away. Other tests like nitrates and phosphates may require 5 to 10 minute waiting periods before full colour development is obtained.

Some unique colorimetric tests react in reverse, i.e. the greater the colour development, the lower the concentration of a particular parameter. Typical examples of experimental procedures that observe this rationale include fluoride, and a number of ozone test methods. To determine the concentration, the colour developed in the sample is either compared visually with the manufacturer's supplied standards (colour comparator) or inserted into a photometer, colorimeter, or spectrophotometer to give results directly on a meter scale, or digitally via an electronic readout. The results obtained are expressed as parts per million (ppm), milligrams per litre (mg/L), grains per gallon (gpg), etc.

2.2.1.2 Titrimetric Methods

A sample is taken[14], and reagents are added to produce a colour. In this case the reagent is known as an indicator reagent and the titrant is added drop by drop until a colour change occurs. The point at which the colour change is observed is known as the endpoint.

Titration methods are generally quite inexpensive, and are the preferred method in many instances. Typical tests for acidity, alkalinity, carbon dioxide, hardness, dissolved oxygen, and chlorine are among the most common. Here too, convenient packaging and simplicity is the key to their portability and accuracy. This method is preferred in determining corrosion in water supplies, and offers the operator an easy, inexpensive approach in meeting lead/copper requirements.

2.2.1.3 Electrometric Methods

This is one of the more commonly used methods[14], where an electrode is inserted into the water sample. A small current or voltage is produced and electronically amplified whilst

being read on a meter scale. Typical tests include the measurement of pH and conductivity, but a variety of parameters using ion specific electrodes (ISE) can also be measured, e.g., calcium, nitrates, chlorine, etc.

Nearly every electrometric procedure requires meter calibration and/or sample pre-treatment, e.g., 4, 7 & 10 pH buffers are normally used to calibrate pH meters. In general, electrometric methods have higher initial costs and require a higher degree of care and maintenance due to the electrode systems.

2.2.1.4 Nephelometric Methods

This method has been used during my practical investigation and is specific to water turbidity where the suspended matter within a sample is utilized by means of the scattering effect[15] that suspended solids have on light: the higher the intensity of scattered light, the higher the turbidity.

The turbidity is measured via a specially designed meter that sends a focused light beam through the water sample. The suspended solids, dirt and silt causes the light beam to scatter, with the amount of scatter being measured by a photodiode at a 90° angle incident to the light source. Results here are expressed as Nephelometric Turbidity Units (NTUs).

During periods of low flow, many rivers that possess low turbidity levels (usually less than 10 NTU) have a clear green appearance, while during rainstorms, particles from the surrounding land are washed into the river making the water a muddy brown colour, and therefore, indicating a highly turbid water. Furthermore, during high flows, water velocities are faster and water volumes are higher, which can more easily stir up and suspend material from the stream bed, causing higher turbidities. Figure 2.15[15] shows, from left to right, comparative samples of turbid water extracted from a river before a rainstorm, during a mild storm and during a severe storm.

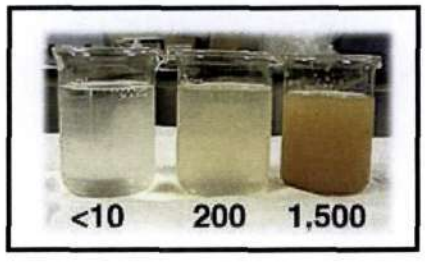

Figure 2.15: Comparative samples of turbid water

A handheld turbidity meter (refer to Figure 2.16[15]) can be used for on-site applications, while state-of-the-art turbidity meters (refer to Figure 2.17[15]) are being installed in rivers to provide instantaneous turbidity readings. Both turbidity meters require calibration prior to being used. This is done using the standard samples which are provided by the meter manufacturers (typical standard samples are shown in Figure 2.18[15]).

Figure 2.16: Handheld turbidity meter

Figure 2.17: Modern (state-of-the-art) turbidity meter

Figure 2.18[15] shows three glass vials that indicate turbidity standards of 5, 50, and 500 NTUs. Once the meter is calibrated to correctly read these standards, the instrument can be used for measurement thereafter.

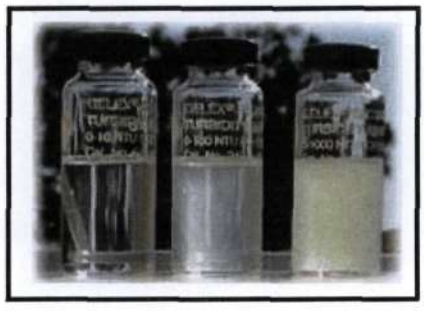

Figure 2.18: Turbidity standards - (from left to right) 5, 50, and 500 NTUs

2.2.2 ELABORATION ON THE NEPHELOMETRIC METHOD

Historically, the standard method[16] for determination of turbidity has been based on the Jackson Candle Turbidimeter, however, the lowest turbidity value that can be measured on this device is 25 Jackson Turbidity Units (JTU). Due to the turbidity of water treated by conventional fluid particle separation processes usually falling within ranges lower than 25 units, secondary methods using electronic nephelometers are being utilized as the preferred instruments for turbidity measurement, where the results are expressed at Nephelometric Turbidity Units (NTU's).

Most commercial turbidimeters designed for measuring low turbidities, give comparatively good indications of the intensity of light scattered in one particular direction, predominantly at right angles to the incident light. Turbidimeters with scattered-light detectors located at 90° to the incident beam are called nephelometers. Nephelometers are relatively unaffected by small differences in design parameters and are therefore, specified as the standard instrument for measurement of low turbidity.

A standard reference suspension having reproducible light-scattering properties is specified for nephelometer calibration, namely Formazin. A clear comparison, which can be observed by the naked eye, between the different Formazin Turbidity Standards (illustrated in Figure 2.19[5]), and the variations in turbidity associated with matter pertaining to the natural environment, are shown in Figures 2.20[5] (Turbidity of Clay Suspensions), 2.21[17] (Turbidity Due to Algae) & 2.22[17] (Turbidity Due to Sediment).

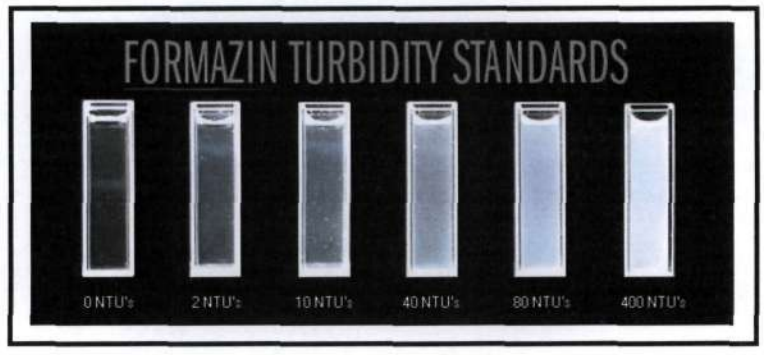

Figure 2.19: Nephelometer calibration suspensions – Formazin Turbidity Standards

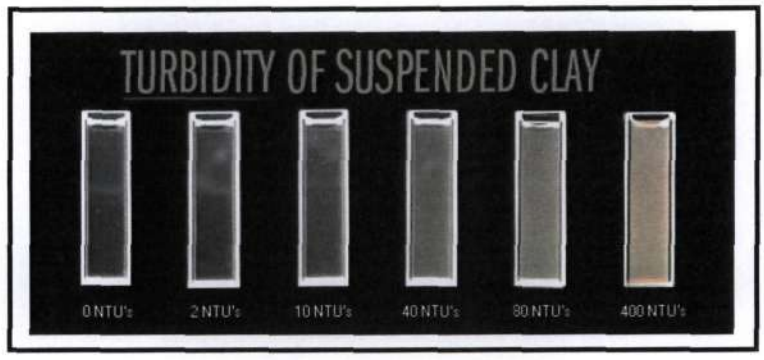

Figure 2.20: Turbidities associated with clay suspensions

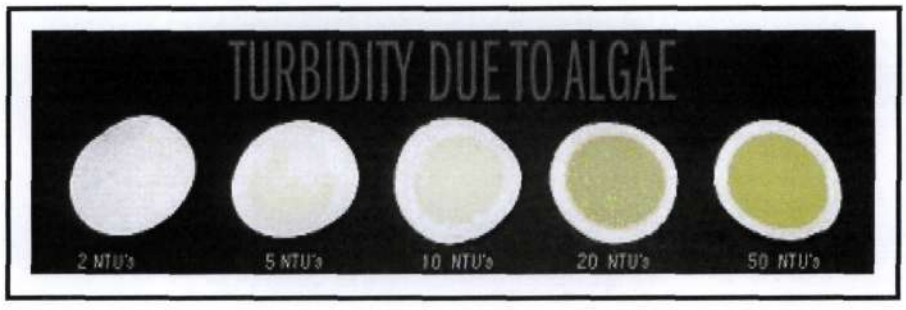

Figure 2.21: Turbidities associated with algae

Figure 2.22: Turbidities associated with sediment

2.2.3 FUNCTIONALITY OF A BASIC NEPHELOMETER

The single beam design[18] configuration, shown in Figure 2.23[18], is the most basic nephelometer design, which uses only one light source and one photodetector located at 90 degrees from the incident light. The single beam design is the oldest of the modern nephelometers and is typically used with a polychromatic tungsten filament lamp. The design is still in wide use today and yields accurate results for turbidities under 40 NTU.

As turbidity increases and the amount of scattered light increases, multiple scattering occurs when light strikes more than one particle in the sample fluid. The result is that the intensity of the scattered light which reaches the 90 degree detector can diminish as the instrument effectively "goes blind." For this reason, a single beam design does not typically demonstrate a stable measurement capability at high turbidities.

With the above in mind, the single beam design still illustrates the basic rationale that is used in all types of nephelometers, ranging from the most basic to the most advanced, and its functionality is illustrated in Figure 2.23.

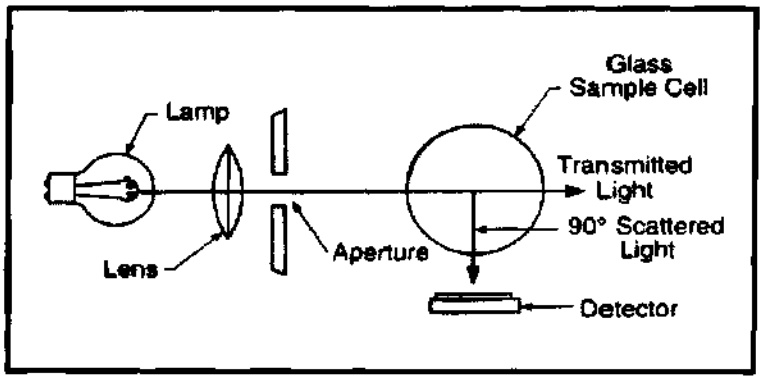

Figure 2.23: Schematic illustrating the functionality of a single beam nephelometer

2.2.4 SHORTCOMINGS OF THE NEPHELOMETRIC METHOD

A comparison between turbidity and total particle concentration measurements normally reveals no obvious correlation between the two parameters, primarily because the intensity of scattered light reflected by particles in suspension depends not only upon the number of particles, but also upon the size, distribution, shape, colouring, refractive index and composition of the materials within the sample[4]. These characteristics do also however, affect both microscopic and electronic particle count measurements.

Although modern turbidimeters have high stability and accuracy, their drawback is that none can measure in the very low range interval of below 0.01 units. Another limitation is the fact that turbidimeters are incapable of measuring black particles due to the particles having insufficient light scattering power for stray light measurement.

William R. Ross set forth[4] a unified concept whereby the direct microscopic count procedure for estimating the presence of plankton and amorphous matter, may be applied to the performance evaluation of potable water unit treatment processes. This method was

especially suitable where turbidity values of less than 5 units are experienced. The direct microscopic count procedure[19] is defined as a determination of the number of micro-organisms found within a demarcated region of a slide holding a known volume of culture.

As illustrated in Figure 2.24[4], a wide range of microscopic values can occur over a narrow range of turbidity values. This diagram includes comparative results for turbidity, total microscopic count, amorphous matter, plankton and algae in an average monthly variation accumulated over a 20 year period in untreated surface water samples.

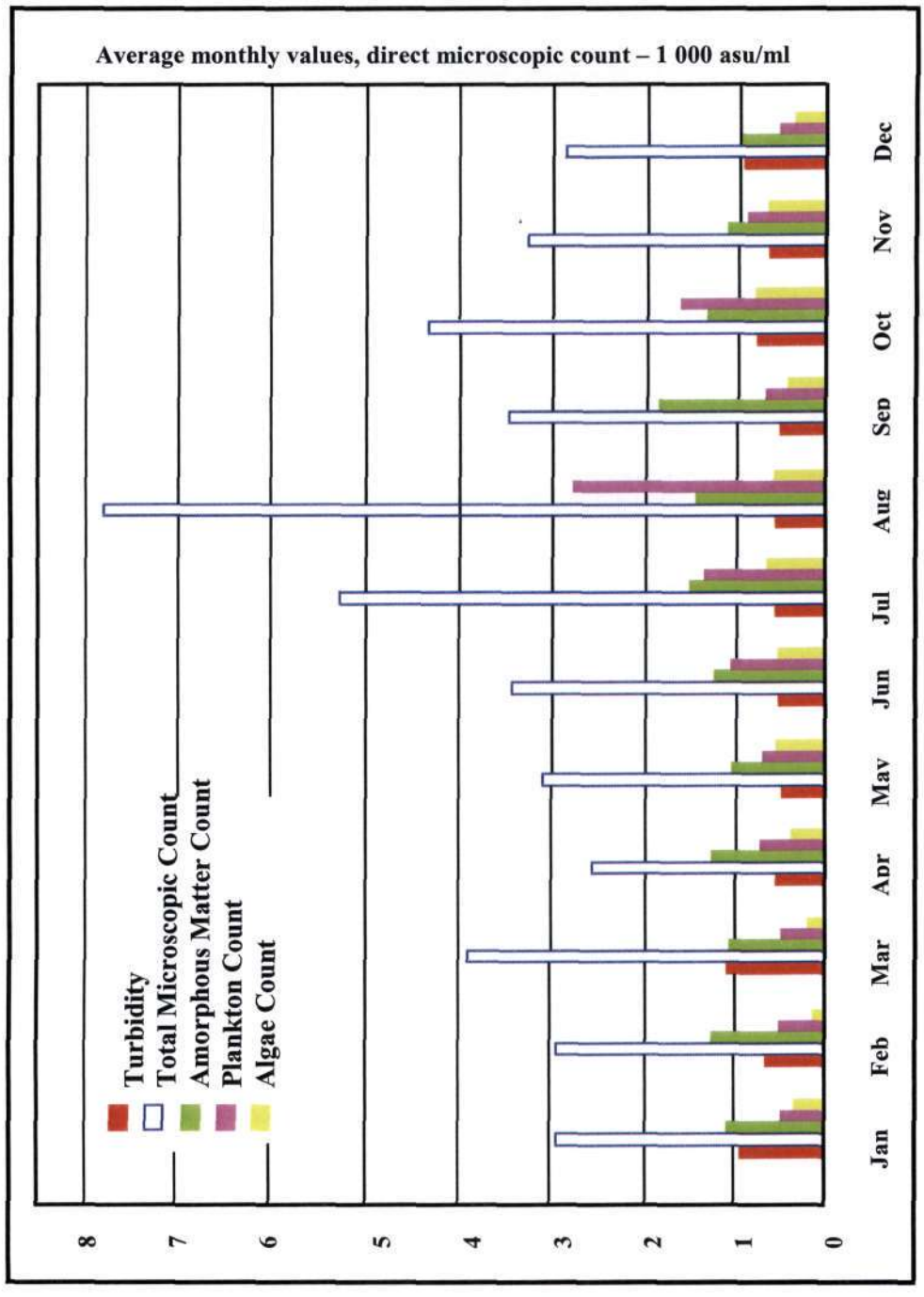

Figure 2.24: Results for turbidity, total microscopic count, amorphous matter, plankton and algae in an average monthly variation accumulated over a 20 year period in untreated surface water samples

2.3 CHARACTERISTICS OF WATERBORNE MICRO-ORGANISMS

Of particular concern to this study, were those micro-organisms that promoted the spread of infectious diseases. The interactions[20] between waterborne pathogens and their hosts involve complex and diverse processes at the genetic, biochemical, phenotypic, population, and community levels, while the distribution and abundance of micro-organisms in nature and their microbial processes are affected by both biotic and abiotic factors that act at different scales. Many micro-organisms that are pathogenic to humans and animals enter ambient waters after import from various point and diffuse sources.

The review included in this section, illustrates the basic principles of ecology for waterborne viruses, bacteria, protozoa, yeasts and moulds, which are of public health concern, as a means of better understanding how selective forces may alter one's ability to assess the microbial quality of water.

2.3.1 EFFECTS OF ENVIRONMENTAL CHANGE

Environmental change at all scales, from local to global, influences microbial populations and indicator organisms. Large scale or global changes in weather or climate are predicted to have major effects on waterborne diseases[21]. Past and continued alteration of forested areas (e.g. deforestation) and natural waters (e.g. water diversions such as dams and drainages of lakes, river diversions), road construction, commercial and residential development, change the ecological conditions of waterways. These changes often favour the introduction of organisms at all levels of biological organization and can also result in changes in microbial diversity, as well the introduction of new or increased levels of pathogens and indicator organisms. This subsequently increases the opportunity for human exposure to pathogens native to that environment via water and other routes and therefore, increases the exposure of humans to disease-causing micro-organisms.

2.3.2 SIZE OF MICRO-ORGANISMS

The sizes of water-borne bacteria and viruses have been presented in Tables 2.4[4] and 2.6[4]. form this, it is evident that viruses are not only much smaller than bacteria[4], but are generally smaller than the particulate matter associated with turbidity in water. Viruses would therefore appear to have more opportunity to become enmeshed in a protective coating of turbidity-contributing materials, and are thus allowed more opportunity to escape disinfecting actions.

2.3.3 VIRUSES

2.3.3.1 Introduction to Viruses and Their Properties

Virus-host interactions are fundamental to the biology and ecology of viruses due to them being intracellular parasites. Viruses are inert beings[23], since they are not capable of capturing autonomously the energy from the environment to redirect it toward specific metabolic processes or toward definite functions, for example reproduction. In this section, the ecology and evolution of viruses are considered, specifically for waterborne viruses that are human and animal pathogens, or bacterial viruses that are potential indicators of faecal contamination.

2.3.3.2 Virus Composition, Basic Properties and Diversity

Viruses are among the smallest microbes[24], consisting of one or more molecules of DNA or RNA, which contain the virus's genes surrounded by a protein coat or capsid. Viruses range from about 0.02 to 0.1 μm in size, with the capsid functioning not only as a protective layer, but also as the structure for host cell attachments that lead to infections. The reason for this is that the capsid contains specific chemical structures that recognize receptor sites on the host cell. Some viruses, although usually not the ones transmitted by faecally contaminated water, also possess an outermost lipoprotein membrane called the envelope. The envelope is usually a virus-modified host cell membrane that contains virus-specific glycoproteins, which is acquired as the virus exits the cell. Some of these glycoproteins in enveloped viruses are the chemical structures for attachment to host cell receptors.

Viruses are also obligate parasites and do not multiply outside of living susceptible cells, and these numbers decrease even in a nutritional environment constituted by domestic waste. A variety of the morphological characteristics of enteroviruses and of phage is shown in Table 2.4[4].

Table 2.4 Morphological characteristics of water-borne enteroviruses and phage

VIRUS	SHAPE AND FORM	SIZE (Mμ)
Adeno		30
Coxsackie A, B.	Sphere with dense core of 15 mμ; no outer membrane.	28
ECHO	Sphere with nucleoid of 13 mμ; no outer membrane.	24 – 25
Infectious	Polyhedral; no membrane or protein.	40 – 150

Hepatitis		
Poliomyelitis	Cubical; 42 capsomeres in 5:3:2: Symmetry; no outer membrane.	25
REO	Cubical with nucleoid of 35 mμ; 92 Capsomeres; no outer membrane.	60 – 90
Bacteriophage	Polyhedral head and cylindrical tail, like tadpole.	Head dia. 100 – 150 Tail length 100 - 150

2.3.3.3 Viral Replication, Virus-Host Interactions and Viral Evolution

The replication and evolution of viruses and their interactions with their hosts are strongly related to host fitness as both viruses and hosts co-evolve[25]. The ability of a virus to infect a particular host cell is primarily a function of the availability of the appropriate chemical structures on the surface of the virus and the host cell that allows for attachment to, and penetration of the cell. These receptor-dependent interactions determine the virus host range, tissue tropisms (i.e. ability to infect cells of a particular tissue, such as intestinal, liver, or neurological tissues) for human and animal hosts, and thus the ability to cause certain kinds of infections and diseases. Despite the importance of cell surface receptors in the susceptibility of different cells or tissues to viral infection, the outcomes of viral infection, especially diseases, are often mediated by other molecular interactions during virus replication. Several outcomes of viral infection of host cells are possible, namely:

- Virus multiplication leading to many progeny viruses with resulting cell lysis and subsequent death.
- Virus multiplication leading to many progeny viruses but cell survival.
- Development of a stable relationship (at least temporarily) with the host cell with little or no virus multiplication, either as a discrete intracellular genetic element, or as an integrated part of the host cell's genetic material.

Hosts that recover from virus infections are immune to future infections, either temporarily or perhaps indefinitely. In the case of rotaviruses, immunity is transient, only partially protective, and even less protective against different rotaviruses that possess considerable levels of diversity[26]. In the case of polioviruses, infection is likely to result in long-lasting

immunity that is protective against paralytic disease and mortality, however, enteric infections that are sub-clinical or mild, still occur in persons with immunity.

2.3.3.4 Viruses in Human and Animal Wastes and in the Aquatic Environment

Enteric viruses found in human and animal faeces[25], sewage, and faecally contaminated water include not only enteric pathogens but also viruses that infect bacteria residing in the intestinal tracts of humans and other warm-blooded mammals, and are called enteric bacteriophages. Some faecal viruses are respiratory pathogens, which were swallowed with respiratory exudates that actually infected the enteric tract. The aquatic environment also contains many other viruses that infect a variety of aquatic and terrestrial life ranging from prokaryotes to protozoa to plants and animals. The viruses shed in faeces and present in sewage, belong to a diverse range of taxonomic groups that have different genetic, morphological, and functional properties. Of the human enteric viruses, some belong to taxonomic groups containing single-stranded RNA (enteroviruses, caliciviruses, hepatitis A and E viruses, astroviruses, and coronaviruses); double-stranded, segmented RNA (reoviruses and rotaviruses); bi-segmented and double-stranded RNA (picobirnaviruses); single-stranded DNA (parvoviruses); or double-stranded DNA (adenoviruses). The bacteriophages found in faeces, sewage, and ambient water, while not pathogenic, are genetically and morphologically diverse.

2.3.3.5 Stability, Survival, Effects of Physical and Chemical Agents, and the Transport of Viruses

Some of the important properties of enteric viruses and bacteriophages[27] that influence their environmental behaviour and natural history include their small size, stability over a wide temperature and pH range, resistance to various chemical agents such as oxidants and proteolytic enzymes, and propensity to aggregate and adsorb to particles and surfaces. These properties allow enteric viruses in faeces and sewage to survive conventional sewage treatment processes and persist in environmental waters and their associated sediments.

Conventional sewage treatment systems employing primary and secondary treatment reduce enteric viruses by about 90 to 99 percent in the treated effluent. Many of the viruses removed from the effluent remain infectious in the resulting sludge or bio-solids, which must be treated further to reduce the viruses and other pathogens. Chemical and physical disinfection processes vary greatly in their ability to inactivate enteric viruses. Appreciable virus reduction in sewage is achieved only once an effluent is disinfected with chlorine,

ozone, high doses of UV radiation, or when viruses are physically removed or inactivated by certain advanced wastewater treatment processes, such as membrane filtration or chemical coagulation. Due to municipal sewage often being disinfected by chlorine alone, which is a relatively weak oxidant, the discharged sewage effluents often still contain relatively high concentrations of viruses[28].

Furthermore, as a result of on-site wastewater treatment systems such as septic tanks and subsurface drain fields, which inadequately reduces viruses, the wastes of feral, domestic, and agricultural animals either being untreated or inadequately treated, can deliver substantial numbers of enteric viruses and other pathogens to ground or surface waters. In fact, enteric viruses have been found on occasion in both surface and ground waters, which were used as drinking water sources and for recreation.

2.3.4 BACTERIA

2.3.4.1 Introduction to Bacteria and Their Properties

Bacterial waterborne pathogens and indicators vary in size from 0.2 - 2 μm and can be categorised into two major groups:

- Native opportunistic pathogens such as the Aeromonas spp. and the Mycobacterium spp.
- Introduced pathogenic bacteria that are not "normally" found in a particular water system (e.g. Shigella) or other bacteria often found only at relatively low concentrations in natural waters and other environmental media (e.g. Legionella and Clostridium).

Under certain environmental conditions some of the waterborne bacteria have the ability to form endospores, which have no metabolic activity but are specialized cells capable of surviving extended periods of time in the environment.

The natural densities of pathogens are difficult to ascertain since most systems receive imports of bacteria through surface runoff from precipitation events, atmospheric dry-fall, vertebrate and arthropod transport, and human activities. In highly disturbed systems, such as agriculture or water treatment discharges, imports of pathogenic bacteria would be expected to be much higher e.g. Lalitha and Gopakumar[29] in a study of freshwater and brackish sediments, shellfish, and native fish found that 21 percent of all sediment samples

contained Clostridium botulinum, 22 percent of the shellfish harboured C. botulinum, and between 2 and 8 percent of indigenous fish had C. botulinum on their surfaces.

Although some pathogenic bacteria exclusively inhabit humans, most also have environmental biotic reservoirs (referred to as zoonotic), and these reservoirs can be important in the transmission of pathogens to other hosts. Both C. jejuni and C. coli are human gastrointestinal pathogens that are the major cause of bacterial diarrhoeal illness in many developed countries, and such outbreaks can be waterborne or food borne. Waterborne outbreaks have been associated with community water supplies or untreated spring water, in which Campylobacter cells can survive for months.

Aerobic Gram-negative bacteria, frequently found in water sources, are a common cause of hospital infection, particularly in intensive care units. Of particular concern are resistant Pseudomonas, Enterobacter, Acinetobacter, Klebsiella, and Stenotrophomonas[30,31]. These micro-organisms are widespread in aquatic environments and may be introduced into hospitals by patients, staff or visitors and become established in microenvironments such as sinks, showers and ice machines.

Furthermore, bacteria also possess at least three novel evolutionary mechanisms that can facilitate their rapid response to many environmental changes through alteration of their genetic composition:

- Conjugation (refer to Figure 2.27[34])
- Transduction (refer to Figure 2.27[34])
- Transformation (refer to Figure 2.27[34])

2.3.4.2 Biological Interactions: Environmental Reservoirs

Critical to understanding the ecology of waterborne pathogens and indicator organisms, is the knowledge of various niches and habitats that promote or safeguard these micro-organisms while they reside in a water body. Recent studies have identified unique biological interactions between certain prokaryotic and eukaryotic pathogens and other proto- and metazoans[32].

Free-living amoebae, which are well adapted to harsh or changeable environments such as desiccation, elevated temperatures and disinfectants, harbour bacteria intracellularly. Some bacteria can thus prevent intracellular destruction and can grow and survive within protozoa,

finding both protection from adverse environmental conditions and protected modes of transportation. This interaction may also enhance their infectivity in mammals, e.g. endosymbiotic or parasitic relationships between Legionella bacteria (see Figure 2.25[33]) and their free-living algal and protozoan hosts allow not only for bacterial proliferation but also for protection from disinfection, which thereby increases their survival and ability to reach human hosts through drinking, recreational and cooling tower waters.

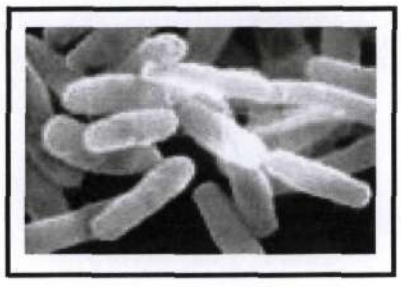

Figure 2.25: Legionella bacteria

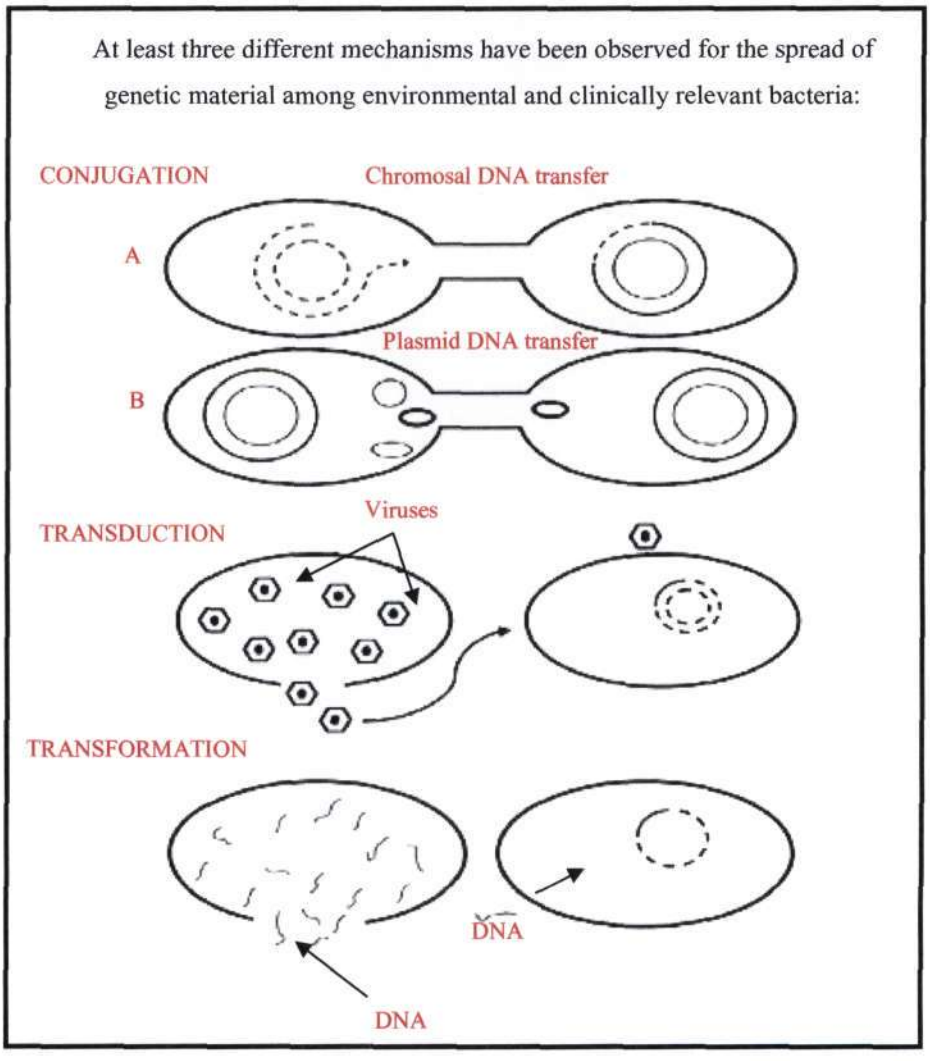

Figure 2.26: Evolutionary mechanisms for bacteria

2.3.4.3 Ecology of Plasmids

Bacteria in nature can acquire and lose genetic material through a variety of evolutionary mechanisms (see Figure 2.26[34]). Pathogenic bacteria introduced into aquatic systems could in theory, and do in practice, alter their genetic composition using mechanisms as illustrated in Figure 2.26.

2.3.5 PROTOZOAN PARASITES

2.3.5.1 Parasites and Population Ecology

Parasites, both protozoa and helminths (worms and flukes), have a complex biological population[35] that reflects their diverse species and strains, their hosts and the environment in which the parasites and the hosts reside. Parasite population ecology is described based on a nested hierarchy that identifies infrapopulations (all of the parasites of a single species in one host); suprapopulations (all of the parasites of a given species, in all stages of development, within all hosts of an ecosystem); and component populations (all of the infrapopulations of a species of parasite within all hosts of a given species in an ecosystem). The complexity of these associations is further complicated by the genetic diversity of the parasites where many so called "species" have genetic and phenotypic differences that are not reflected in the current taxonomy of a single genus and species.

2.3.5.2 Introduction to Protozoa and Their Properties

The protozoa are an ancient group of unicellular organisms (single celled eukaryotes that are between 3-30 μm in size), which were probably derived from unicellular algae. The movement of protozoa[36] is accomplished through one of three modes: flagellae, ameboid locomotion, or cilia. Although there are numerous free living protozoa, some can be obligate parasites of humans as well as animals (referred to as zoonotic - spread from animals to humans), and often spread via the faecal-to-oral route. As such, these are important organisms from a public health perspective and are associated with waterborne disease worldwide.

Parasitic protozoa have both a trophozoite (ameboid) and a sporozoite stage within the host. Sporozoites, which are the only stage that can survive outside a host, are called either cysts or oocysts depending on the taxonomic level. Cysts are the sporozoa of parasitic protozoa that reproduce by asexual cell division, whereas oocysts are sporozoa that have both sexual

and reproductive stages. For enteric protozoa, cysts or oocysts are the only stages that can survive outside a host and are excreted in the faeces of infected individuals. Another important parasitic group is the Microsporidia, which comprise obligate spore-forming parasites.

Although several species of waterborne protozoa are of public health concern, this section focuses on the ecology, evolution and basic biology of the following groups and genera:

- The free living amoebae Naegleria and Acanthamoeba.
- The enteric protozoa Giardia, Cryptosporidium and Toxoplasma.
- A relatively newly recognized group in human infections, the Microsporidia.

2.3.5.3 Sources, Stability and Survival

The environmental route of transmission for many protozoan parasites has made it necessary to develop new methods for their early and repeated detection[37]. These parasites pose new and emerging threats because of their ability to survive in a variety of moist habitats including surface waters.

The parasitic protozoa are of particular interest in this chapter because they may have significant environmental reservoirs that harbour the oocysts, including the free living forms in fresh and marine waters. Furthermore, since ingestion is required for most diseases to develop, knowledge of potential vectors or sources is critical.

Species of the genus Naegleria are found in stagnant bodies of freshwater such as lakes, slow moving rivers, ditches, and non or poorly chlorinated swimming pools. Naegleria are known to be thermophilic, and the incidence of infection follows a seasonal pattern occurring mostly in the summer months when water temperatures rise. They have been isolated from environments with temperatures between 26.5 and 28°C and become more virulent between 30 and 37°C. Acanthamoeba spp. are omnipresent and have been isolated from many different environments including ocean sediment and even dust. Their growth however, is more prolific at lower temperatures (25 to 35°C) than Naegleria.

The ecology of Toxoplasma gondii oocysts is diverse and varied. While cats are regarded as the primary source for Toxoplasma, oocysts from terrestrial land animals (e.g. feral cats) have also found their way into surface waters, resulting in major documented outbreaks in humans such as in the Greater Victoria area of British Columbia, Canada[38].

The ability of Toxoplasma to survive under extremely broad environmental conditions has prompted research into the ranges of tolerance of different variables including temperature. The infectivity of T. gondii oocysts showed no loss at 10, 15, 20, and 25°C for 200 days, and the oocysts also remained infective up to 54 months at 4°C and for 106 days at –5 and –10°C.

Very little is known about the sources of Microsporidia. In France during the summer of 1995, a waterborne outbreak of Microsporidia occurred with approximately 200 cases of disease. The causative species identified was Enterocytozoon bieneusi and although faecal contamination of the drinking water was never detected, contamination from a nearby lake was suspected. There is minimal data on the occurrence of human strains of Microsporidia in surface waters, however, Dowd et al. (1998b[39], 1999[40]) described a polymerase chain reaction (PCR) method for detection and identification of Microsporidia (amplifying the small subunit ribosomal DNA of Microsporidia). They found isolates in sewage, surface waters and ground waters. The strain that was most often detected was Enterocytozoon bieneusi, which is caused by diarrhoea being excreted from infected individuals into wastewater. Microsporidia spores have been shown to be stable in the environment and remain infective for days to weeks outside their hosts. As a result of their small size (1 to 5 μm), they may be difficult to remove using conventional water filtration techniques, and there is a concern that these micro-organisms may have an increased resistance to chlorine disinfection similar to Cryptosporidium.

In contrast to Microsporidia, much is known about sources and survivability of Cryptosporidium and Giardia in the environment, especially the aquatic environment where their oocysts can survive for weeks or months. Both Cryptosporidium and Giardia are well adapted to environmental extremes, being able to survive temperatures ranging from 4 to 37°C and environments ranging from homeothermic animal bodies to thermally and chemically variable freshwater. Species of Giardia exhibit a high degree of host specificity and as such have been named based on their normal host (e.g. G. lamblia inhabits humans, G. muris inhabits rodents and G. ardeae inhabits birds).

2.3.6 YEASTS AND MOULDS

2.3.6.1 Introduction and Background

Yeasts and moulds are collectively called fungi as a group and possess defined nuclear membranes that contain the chromosomes of the cells[41]. There are more than 100,000

species of known fungi, although only a few are known to be human pathogens. Fungi are more than 10 to 100 times larger than bacteria. Moulds are multicellular, complex organisms that produce sexual and asexual spores. They appear as cottony and fuzzy growth in food and other materials due to the growth of hyphae and mycelium, and many are spoilage organisms. Some moulds are beneficial to humans because of their production of important antibiotics and fermentation of foods, while others may cause a variety of human diseases ranging from "athlete's foot" to aspergillosis.

Yeasts are single-celled fungi that are usually oval in shape and divide asexually by budding or sexually through the production of spores. They are important in food fermentation, food spoilage and several human diseases, especially Candida albicans, the common cause of various "yeast infections." Yeasts and moulds are omnipresent in the environment, including air, soil, food and water.

2.3.6.2 Ecology and Evolution of Fungi and Their Role as Human Pathogens

Humans are continuously exposed to fungi from various environmental sources and often, are colonized with fungi. On rare occasions, some fungi cause human infection and illness and most of these illnesses occur in immuno-compromised hosts. Fungal infections or mycoses are classified according to the degree of tissue involvement and the mode of entry into the host. These categories are:

- Superficial (local in skin, hair, and nails)
- Subcutaneous (infection of the dermis, subcutaneous tissue, or adjacent structures)
- Systemic (deep infections of internal organs)

For a fungus to cause serious disease it usually has to actively invade tissues, especially deeper tissues, and become disseminated throughout the body (systemic). Fungal infections can also be categorized as frank (can infect healthy, immuno-competent hosts) or opportunistic (can infect only the immuno-compromised) pathogens.

The pathogenic mechanisms of fungi tend to be highly complex. This is due to them arising, in large part, from adaptations of pre-existing characteristics of the organisms' non-parasitic life-styles[41]. Most of the human pathogenic fungi are dimorphic (i.e. able to reversibly transition between yeast and hyphal forms). This dimorphism is an important attribute of fungi because the morphogenic change from one form to the other is often associated with host invasion and disease.

2.3.6.3 Fungi and Waterborne Pathogens

Of the fungal colonies isolated on agar plates from water, typically about half are yeast and the other half mould colonies. Moulds from the families Oomycetes and Chytridiomycetes can virtually always be found in fresh and saline water in the environment. While these moulds are not generally pathogenic to humans, they can infect animals and cause disease[42].

2.3.7 SUMMARY: CONCLUSIONS AND RECOMMENDATIONS

The ecology and evolution of waterborne pathogens have important implications for the emergence and re-emergence of those pathogens that are of public health concern due to inadequately treated water supplies. Table 2.5[43] illustrates some of the diseases that are of major concern, together with the microbial agent, sources and the accompanying symptoms.

Table 2.5 Waterborne diseases

DISEASE	MICROBIAL AGENT	SOURCES	SYMPTOMS
Amebiasis	Entamoeba hystolytica	sewage, untreated drinking water, flies in water supply	abdominal discomfort, fatigue, weight loss, diarrhoea, gas pains
Campylo-bacteriosis	Campylobacter jejeuni	poultry, livestock manure, municipal water-line breakdown, chlorine contamination, or other disinfectant contamination	fever, abdominal pain, diarrhoea
Cholera	Vibrio cholerae	untreated water, sewage, poor hygiene, crowded living conditions with inadequate sewage facilities	watery diarrhoea, vomiting, occasional muscle cramps
Cryptos-poridiosis	Cryptospo-ridium parvum	collects on water filters and membranes that cannot be disinfected, animal manure, seasonal runoff of water	diarrhoea, abdominal discomfort
Hemorrhagic diarrhoea	E.coli / H0157:H7	poultry, livestock manure, underground well water,	hemorrhagic diarrhoea, cramps,

		inadequately treated drinking water and sewage	nausea, low-grade fever
Giardiasis	Giardia lamblia	untreated water, poor disinfection, pipe breaks, leaks, groundwater contamination, campgrounds in which humans and wildlife use same source of water (beavers and muskrats act as a reservoir for Giardia)	diarrhoea, abdominal discomfort, bloating, gas and gas pains
Hepatitis	Hepatitis	A raw sewage, untreated drinking water, poor hygiene, ingestion of shellfish from sewage-flooded beds	fever, chills, abdominal discomfort, jaundice, dark urine
Shigellosis	Shigella species	sludge, untreated wastewater, groundwater contamination, poorly disinfected drinking water	fever, diarrhoea, bloody stools
Typhoid fever	Salmonella typhi	raw sewage (carried and excreted in faeces by humans), water supplies with surface water source	fever, headache, constipation, appetite loss, nausea, diarrhoea, vomiting, abdominal rash
Legionnaire's disease	Legionellaceae and L. cincinnatus	cooling towers, showers through inhalation of vapours; raw sewage, stagnant clean drinking water in water tanks or towers, construction sites near rivers, lakes	flu and pneumonia-like symptoms: malaise, fever, chills, headache, nausea, dizziness, coughing, chest congestion, chest pain, pressure, possible vomiting
Pontiac fever	Legionellaceae	same sources as Legionnaire's disease	milder form of Legionnaire's disease;

			pneumonia-like symptoms but without fever; illness of shorter duration
Viral gastroenteritis	Viruses, including Norwalk and rotavirus family	sewage, contaminated water, inadequately disinfected drinking water (mostly surface-water sources)	repeated vomiting and diarrhoea over 24-hour period, gastrointestinal discomfort, headache, fever

When humans have prolonged exposures to pathogens, such as in disaster situations or changes in personal hygiene habits, the pathogens tend to become opportunistic[43]. The concept of using indicators for waterborne pathogens implies that certain characteristics of micro-organisms such as genes and gene products remain constant under varying environmental conditions. The effectiveness of indicator technologies that are based on the detection of some aspect of the biology or chemistry of a living organism (whether a pathogen or an indicator micro-organism) may decrease over time because of evolutionary changes in the target organism. Natural and artificial selection may alter the structure, function and production of biological molecules or cause other changes in the organism that affect the ability of the indicator to detect it. Therefore, it is important to understand the effects of the environment on these targets and organisms.

Existing and candidate indicator organisms should have ecologies and responses to environmental variations similar to those of the pathogenic organisms that they are supposed to be indicating. Furthermore, environmental changes may lead to changes in selective pressures resulting in new strains of pathogens with different traits. Understanding the ecology and evolution of pathogens will provide insights into their pathways of transmission, modes of distribution, potential to re-emerge in the future, or emergence in other environments.

The following is recommended as a means improving the understanding of the ecology and evolution of waterborne pathogens and the development of new and effective indicators of microbial contamination:

- The natural background density of waterborne pathogens should be established to differentiate between native opportunistic pathogens and introduced pathogens.
- Efforts should be made to differentiate between indicators and pathogens that are native to the environment and those that are introduced from external sources, such as human and animal wastes.
- Because some waterborne pathogens or indicator organisms may survive and replicate in various environmental reservoirs independently of each other, an improved understanding of the ecology and natural history of microbial indicators and pathogens and the mechanisms of their persistence, proliferation and dispersal should be sought.
- Advanced analytical methods should be used to help distinguish between introduced pathogenic and naturally occurring non-pathogenic strains of waterborne micro-organisms, and to characterize the emergence of new strains of pathogens as a result of genetic change.
- Bacteria, viruses and protozoa have evolved mechanisms that facilitate their rapid response to environmental changes. These mechanisms may influence the infectivity of the organism. Therefore, additional research is needed on microbial evolutionary ecology to address long-term public health issues.

2.4 THE RISK OF NOT CHLORINATING: MICROBIAL DISEASE

Waterborne diseases, led by cholera, typhoid and dysentery, were a top health problem in 1900[44]. With the introduction of filtration and disinfection systems during the last century, the risk of disease from drinking water in wealthier countries has been substantially reduced. Despite the enormous progress that has been made however, there are still significant numbers of disease cases resulting from contaminated drinking water.

It has[44] been estimated that only half of waterborne disease outbreaks in community water systems and about one third of those in non-community systems are detected, investigated and reported. Microbes in tap water may be responsible for as much as one in three cases of gastrointestinal illness.

Groundwater supplies are also a subject of increasing concern, because enteric viruses and other organisms can leach into the groundwater system from the land application or burial of sewage sludge and other treatment wastes. Although the "traditional" bacterial diseases of cholera and typhoid have largely been brought under control in this country, other micro-

organisms are constantly being identified and connected to waterborne illness, e.g. the Legionnaires hemophile bacteria, the cause of legionnaires' disease.

The microbial agent most commonly identified and implicated in outbreaks of waterborne disease in recent years is the protozoan cyst Giardia lamblia, which is found in water as a result of the deposition of faecal material from both humans and animals. Surveys of various water supplies indicate that 26 to 43 percent of surface water is contaminated with Giardia cysts ranging in concentrations from 0.3 to 100 cysts per one hundred litres. Giardia strains are known to cause infection even at low doses, and outbreaks of disease have been associated with Giardia levels of 0.6 to 21 cysts per 100 litres.

The health risks associated with these types of micro-organisms have been well established. The primary risks involve intestinal and gastroenteric diseases, such as diarrhoeal infections and dysentery. As touched upon in section 2.3, Giardia, for example, causes symptoms that are flu like in appearance but are usually more severe, such as diarrhoea, nausea and dehydration that can last for months in some cases. The bacteria Legionella invoke severe pneumonia-like symptoms, especially in a less resilient population such as the elderly. Other health risks are present as well, such as hepatitis A or poliomyelitis from waterborne viral infections. In most instances, the adverse effects are acute, immediate and readily apparent.

While many cases of waterborne disease are short term and relatively minor, some are fatal and others drag on for months and can be chronically debilitating. The effects are particularly serious for the more vulnerable groups of the population, such as the very young, the very old, and those already weakened from other health problems. People with suppressed immune systems, such as those undergoing therapy for cancer or AIDS, for example, can be burdened with waterborne illnesses for many months, with often devastating fluid loss.

The infectious dose for waterborne micro-organisms varies tremendously (see Table 2.6[44]). The risk of infection for some of the viruses and protozoa is estimated to be 10 to 1000 times greater than for the bacterial organisms at a similar level of exposure. In general, viral and protozoan pathogens, such as Giardia, appear to be highly potent, with small numbers of the organism being capable of causing infection and disease in susceptible human hosts. Furthermore, many of the protozoa and viral agents are more resistant to disinfection than pathogenic bacteria, requiring larger quantities of chlorine and other disinfecting agents to successfully reduce their numbers in the water supply.

Table 2.6 Probability of Infection from Waterborne Micro-Organisms

MICRO-ORGANISM	PROBABILITY OF INFECTION FROM EXPOSURE TO 1 ORGANISM	NUMBER OF ORGANISMS FOR 1% LIKELIHOOD OF INFECTION
Salmonella (bacteria)	2.3×10^{-3}	4.3
Salmonella typhi (bacteria)	3.8×10^{-5}	263
Shigella (bacteria)	1.0×10^{-3}	10
Vibrio cholerae classical (bacteria)	7.0×10^{-5}	1428
Poliovirus 1 (virus)	1.5×10^{-2}	0.67
Entamoeba histolytica (protozoa)	2.8×10^{-1}	0.04
Giardia lamblia (protozoa)	2.0×10^{-2}	0.5

In addition to primary infection from direct ingestion of water laden with microbial contaminants, there is also the inherent risk with these pathogens of secondary or tertiary infection. Disease may be spread by person to person contact from infected individuals or by contamination of other materials, such as food, which can then expose previously non-infected members of the population.

Chemical disinfecting agents, most commonly chlorine, have been used successfully to combat waterborne micro-organisms since the early 1900s. Presently, chlorine is the most widely used disinfectant and has become the predominant disinfecting agent for all types of potable water treatment operations in locations ranging from small rural communities to major municipal centres.

The addition of chlorine to the water supply is economical, convenient and effective in virtually eliminating the transmission of bacterial and viral diseases from drinking water. Not only is it successful in destroying pathogenic micro-organisms during the treatment process (the primary reason for using a disinfectant), but also due to its persistence in the water distribution system, chlorine helps to prevent the re-growth of nuisance micro-organisms. In addition, chlorine is also effective at reducing noxious odours and tastes in the water supply. The addition of chlorine has markedly expanded the "drinkability" of the nation's water resources by permitting the use of water not considered pristine and protected.

The water treatment process involves a series of different steps. Some of the major steps include flocculation and coagulation (the joining of small particles of matter in the water into larger ones that can more readily be removed), sedimentation (the settling of suspended particles in the water to the bottom of basins from which they can be removed), and filtration (the filtering or straining of the water through various types of materials to remove much of the remaining suspended particles), as well as chemical disinfection. Chlorination is usually performed at several stages of the treatment process. Pre-chlorination may be performed in the initial stages to combat the algae and other aquatic life that may interfere with the treatment equipment and later steps. The major chlorination stage however, occurs in the final treatment step after the completion of the other major processes, where the concentration and residual content of the chlorine can be closely monitored. In this post-chlorination phase, the chemical is more effective in the filtered water, and less contact time is required for the chemical to disinfect the water supply.

Chlorination can deactivate micro-organisms by a variety of mechanisms, such as damage to cell membranes, inhibition of specific enzymes, destruction of nucleic acids and other lethal effects to vital functions. The effectiveness of the chlorination process depends upon a variety of factors, including chlorine concentration and contact time, water temperature, pH value and level of turbidity. Disinfectant concentrations and contact times used by different water utilities vary widely, usually depending on the characteristics of the water being treated.

2.5 MEASURING PRINCIPLES

2.5.1 TURBIDITY

Turbidity is defined as[14] an "expression of the optical property that causes light to be scattered and absorbed rather than transmitted in straight lines through the sample." Simply stated, turbidity is the measure of relative sample clarity. Figure 2.27[14] shows the interaction of a light beam and undissolved, finely distributed particles known as suspended solids.

When the light beam passes through the sample of fluid, the suspended solids scatter the light in all directions (360°spherically). A reduction in the intensity of the light beam is primarily caused by the suspended solids scattering the light, however, absorption (colour)

from dissolved substances can also reduce the intensity and should be taken into consideration by manually or automatically subtracting its effect.

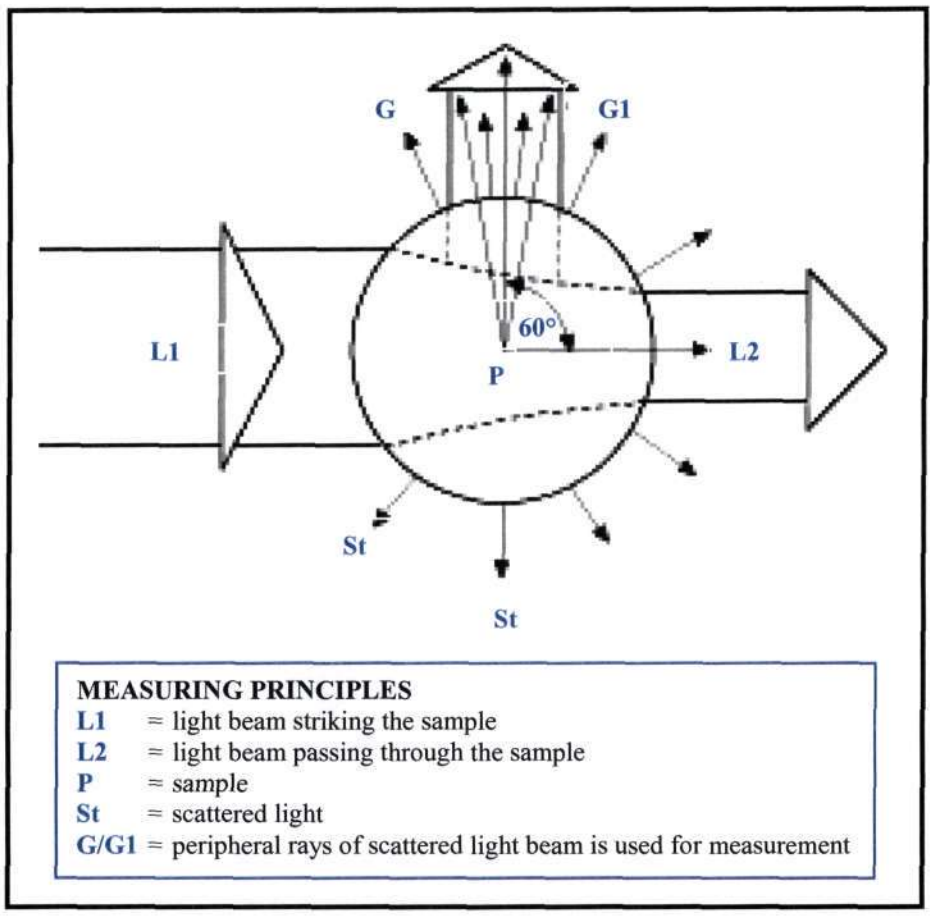

Figure 2.27: Interaction of a light beam with suspended solids

Low quantities of suspended solids are normally monitored by measuring the scattered light effect rather than the absorption effect due to the fact that with scattered light, the photocell detects small changes in light intensity with respect to a dark background. The disadvantage occurs at higher suspended solids levels where multiple scattering restricts the amount of light received by the photocell. This condition results in a lower-than-actual turbidity reading. At suspended solids concentrations above 2000 ppm, alternate measurement methods such as absorption must be used in place of the turbidity measurement as a result of turbidity measurements providing a reading of the amount of scattered light and cannot be directly related to a gravimetric equivalent unless a working curve for the specific sample is created. The intensity of this scattered light is affected by many variables including wavelength, particle size, colour and shape (refer to Figure 2.28[14]).

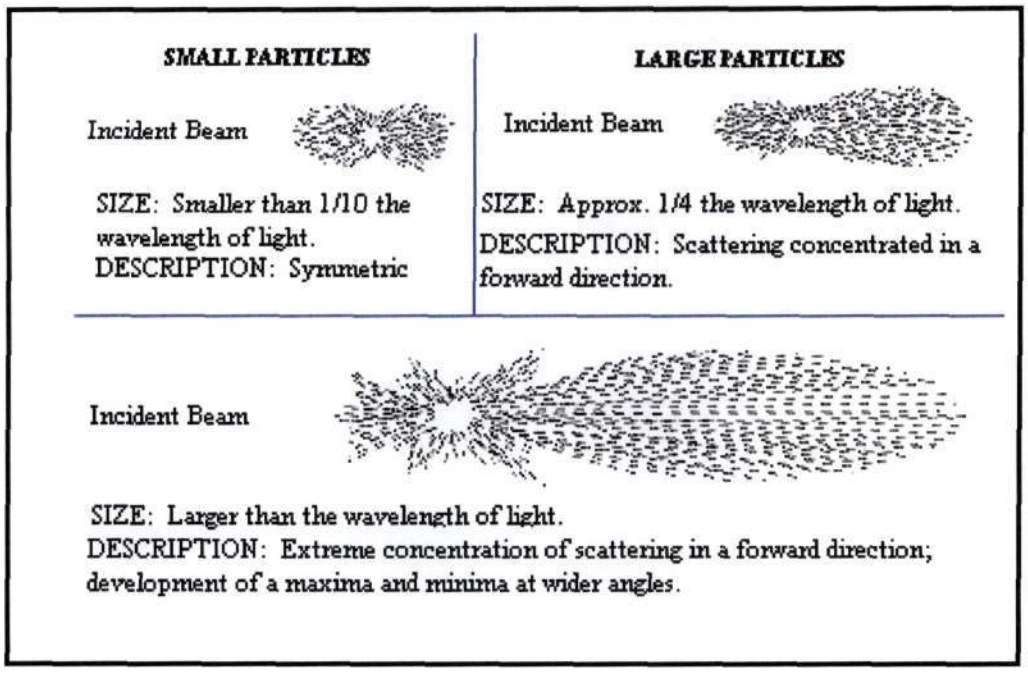

Figure 2.28: Intensity of scattered light

2.5.2 pH

The term pH is derived from "p" meaning power and "H" for the element hydrogen and literally means "power of hydrogen". The importance of pH as a parameter for monitoring is reflected by potential impacts to the life cycle stages of aquatic macro-invertebrates and certain salmonids that can be adversely affected when pH levels above 9.0 or below 6.5 occur. The mobility of metals is also enhanced by low pH, with arsenic being an exception due to being mobilized at higher pH. Thus, pH can play a significant factor in impacts to water bodies located in areas contaminated by heavy metals, e.g. mining. Estimating/computing the toxicity of ammonia, aluminium and some other contaminants requires accurate pH values as metadata. Temporal causes of a variation in pH can range from the primary production by fauna and flora (diurnal and seasonal), to fractionation during snowmelt, changes in runoff processes and changes in atmospheric deposition (monthly and/or seasonal)[45].

pH is measured to determine the acid/base characteristics of water and is controlled by interrelated chemical reactions that produce or consume hydrogen ions[46]. It is defined as the hydrogen ion concentration in moles per litre (Moles L^{-1}) and is represented as the negative log (base 10) of the hydrogen ion concentration (-log $[H^+]$), although in effect it is the activity of hydrogen ions and not their actual concentration that determines pH. The pH scale can range over 14 orders of magnitude although extremely acid pH (negative) of

natural waters has been reported. Natural waters can fall in the range of 0 (highly acidic) to 14 (highly basic) but most commonly fall in the range of 4 to 9, with their pH being a function of the relative activities of H^+ and OH^- ions they contain. Generally, dissolution of carbon dioxide is the most important buffering system (carbonate system) in extremely fresh natural waters to affect pH (~ pH of 6), in the absence of some other site-specific conditions. However, most natural waters are slightly basic (~pH of 8) due to the presence of carbonates (CO_3^{2-}) and bicarbonates (HCO_3^-).

The instrument utilised in the measurement of a solution's pH, consists of a sensing electrode that is attached to a meter (see Figure 2.29[47]), which manipulates the data that is transmitted by the sensing electrode to calculate the pH reading of the test sample.

Figure 2.29: pH meter

2.5.3 CHLORINE CONTENT

Most waters contain chlorine compounds that persist in varying doses. In order to determine the disinfecting requirements of a water body requiring treatment for household use, the initial chlorine content in the water needs to be determined. This is done so that not too much (wastage which may lead to unnecessary financial implications over time), nor too little (incomplete/partial disinfection will only be achieved) of the disinfecting agent is utilised in the disinfection process. The amount of chlorine present in a water body prior to disinfection can therefore, be easily ascertained by the use of a chlorine photometer (see Figure 2.30[49]).

Figure 2.30: Chlorine photometer

The photometer allows[50] to measure the concentration of free or total chlorine in a grab sample of water. This instrument is a simple apparatus which works with the principle of transmitting ultraviolet light through a water sample, where the data drawn is in turn converted to provide an output for the chlorine concentration present in the test sample.

2.6 FACTORS INFLUENCING TURBIDITY REMOVAL

The effective treatment of water to produce an end product that is free from infectious micro-organisms includes a series of mechanical and chemical processes, of which, coagulation, flocculation, sedimentation, filtration and disinfection can be regarded as the five major unit processes or operations. Figure 2.31[4] is a flow diagram, which represents the major unit operations that are carried out during the purification of water.

In water treatment plants, the mechanical processes play a vital role in the removal of impurities that vary in chemical character from inorganic clays and salts, to micro-organisms and other naturally occurring and synthetic organic compounds. Should all the processes prior to disinfection, i.e. coagulation, flocculation, sedimentation and filtration, be properly applied, the removal of 95 – 99 percent or more of the bacterial and viral content of the water can be achieved.

The abovementioned mechanical and chemical processes are therefore explained in more detail in the sections to follow. Aside from the general function of each specific process, particular emphasis has also been placed on the factors that influence such processes, and the need for them.

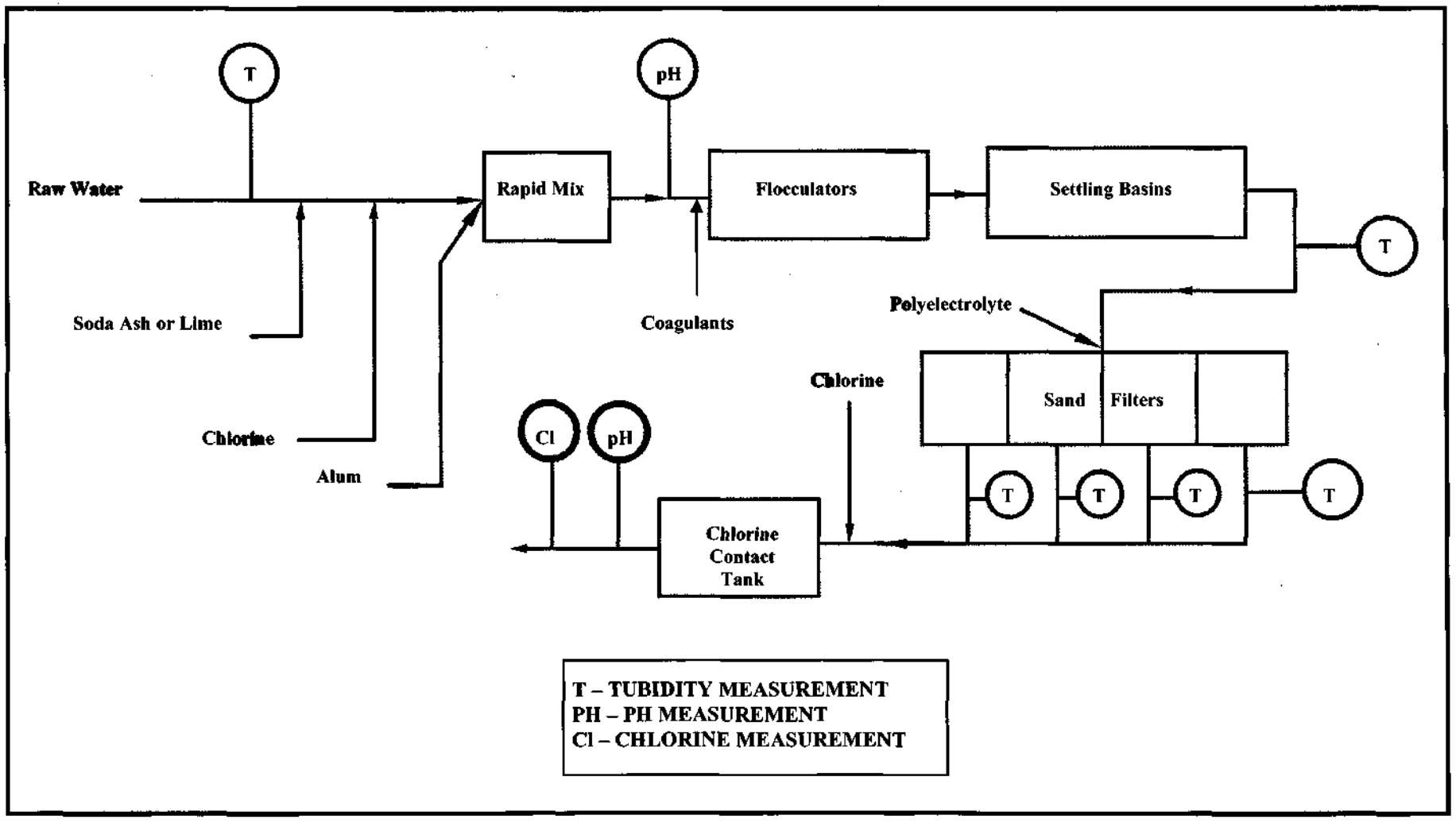

Figure 2.31: Schematic illustrating the process operations on a water treatment plant

2.6.1. COAGULATION

2.6.1.1 Purpose of Coagulation

Untreated surface waters[52] contain clay, minerals, bacteria, inert solids, microbiological organisms, oxidized metals, organic colour producing particles and other suspended materials. Some of the microbiological organisms can include Giardia cysts, pathogenic bacteria and viruses, while the inclusion of iron and manganese comprises the oxidized metals category. All of these materials can inhibit disinfection, cause problems in the distribution system and leave the water cloudy rather than clear. The purpose of coagulation in the treatment cycle is to remove these particles from the water.

The ability of particles to remain suspended in water is a function of both the particle size and specific gravity. Particles which are greater than one micron in diameter are considered silt, and settle out due to their relatively large size and density, without the need to coagulate, in a matter of seconds or minutes. Colloidal material ranges in size from 0.001 to one micron in diameter, where these materials require days to months for complete settling to occur. Since detention times in the water treatment process are generally less than twelve hours, the rate of settling of these colloidal particles must be increased in the water treatment process. This is accomplished in the coagulation process when tiny particles agglomerate into larger, denser particles which will settle more quickly.

2.6.1.2 The Coagulation Process

Coagulation is accomplished by the addition of ions having an opposite charge to that of the colloidal particles[52]. Since the colloidal particles are almost always negatively charged, the ions which are added should be positively charged. The coagulating power of an ion is dependent on its valency or magnitude of charge. A bivalent ion (+2 charge) is 30 to 60 times more effective than a monovalent ion (+1 charge). A trivalent ion (+3 charge) is 700 to 1000 times more effective than a monovalent ion.

Typically, two major types of coagulants are added to water, i.e. aluminium salts and iron salts. The most common aluminium salt is aluminium sulphate, or alum. On my visit to both the Wallmannsthal Bulk Water Treatment Works and the Umgeni Water Treatment Plant, it was observed that aluminium sulphate was selected as the preferred choice of coagulant. When aluminium sulphate is added to water, the aluminium ions enter into a series of complicated reactions. The aluminium ions become hydrated, meaning that water

molecules attach themselves to the aluminium ions. In addition, anions present in the water, such as hydroxide and sulphate ions can attach to the aluminium ions. These reactions result in large, positively charged molecules having aluminium ions at their centre, and having charges as high as +4. Following these reactions, a second type of reaction occurs, called Olation. This reaction involves the bridging of two or more of these large molecules to form even larger, positively charged ions. A typical molecule can contain eight aluminium ions, twenty hydroxide ions, and will have a +4 charge. Iron salts behave in a similar manner when added to water.

Once these large polymeric aluminium or iron compounds are formed, the magnitude of their high positive charge allows these species to rapidly move toward the colloid, where they are adsorbed onto the negatively charged surface of the turbidity particle. The coagulant compounds can penetrate the bound water layer because of their high positive charge. This rapid adsorption results in the compression of the electrical double layer, and results in the colloid becoming coated with the coagulant compounds. The net result of this process is that the electrical charges on the particles are reduced. The suspension is now considered to be destabilized, and the particles can be brought together through, among other forces, Brownian Movement, and will be held together by the Van der Waals forces.

Furthermore, an additional process also occurs that assists this process. As the coagulant continues to undergo the hydrolyzation and olation reactions, progressively larger masses of flocculent material are formed. These compounds can become large enough to settle on their own, and tend to trap turbidity particles as they settle. This is commonly referred to as sweep floc.

As the coagulation reactions and destabilization are occurring, the Zeta Potential at the surface of the colloid is also found to be reducing. Typically, the Zeta Potential for a naturally occurring water may be in the range of -10 to -25 millivolts. As the reactions occur, this Zeta Potential will be reduced to approximately -5 millivolts. These figures are only examples of what might be considered as typical waters. Since all waters exhibit a specific set of characteristics, these numbers will vary. It is interesting to note that the Zeta Potential does not have to be reduced to zero in order for coagulation to occur due to the forces of attraction becoming predominant before complete destabilization occurs.

2.6.2. FLOCCULATION

Following the dispersal of the coagulants[52] into the water and the completion of the destabilization reactions, Van der Waals forces will act to join the colloids if sufficient collisions of the destabilized colloids can occur. The purpose of the flocculation step is to create a gentle agitation to encourage collisions of the colloids to form larger floc particles. In the flocculation step, much less power dissipation is required than in the rapid mix step. If rapid mixing continues for too long, or if the flocculation is too violent, the floc will shear apart as it forms, and no adequate floc formation will occur.

As such, flocculation is generally accomplished by gentle agitation, often using large horizontal or vertical slow moving paddles in vessels much larger than a vessel containing a mechanical mixer. The water moves from the flash mixer[53] to the flocculation basins (see Figure 2.32[53]), which contains the horizontal paddle systems. These basins provide a gentle, constant mixing of the microfloc formed during coagulation and after about 20 to 30 minutes, the floc particles are usually visible and will look like tiny tufts of cotton or wool, separated by clear water. Once the flow is of a sufficient size and density to be settled, the water moves into the sedimentation or settling basins.

Figure 2.32: Flocculation basins

However, virus and bacteria removals often parallel the removal of turbidity, and an example of this phenomenon is presented in Figure 2.33[4].

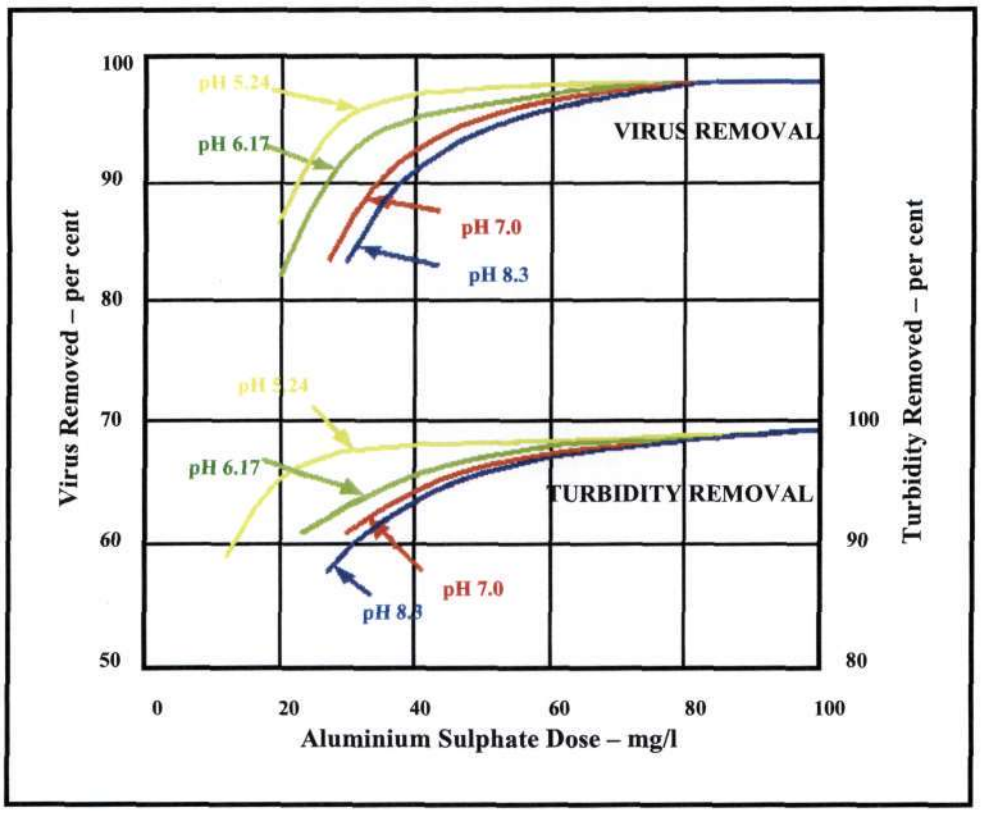

Figure: 2.33 Removal of bacteriophage T4[4] and clay turbidity by coagulation and flocculation

2.6.3. SEDIMENTATION

Sedimentation has been used as a tool[52] in chemistry for quite a long time. Its purpose is to provide sufficient time to allow gravity to act on matter more dense than the liquid the matter is suspended in. Gravity will force the more dense matter to settle at the bottom of the container. The sedimentation basins (see Figure 2.34[54]) are designed to hold large volumes of water for several hours and to give a smooth, even flow. This design allows the velocity and turbulence of the water to be decreased to the point that the water will no longer transport the flocculated solids and they will settle to the bottom of the basin. The bottom of basin is usually sloped to allow the sludge to collect at a singular point, hence facilitating removal.

Figure 2.34: Sedimentation basins

Depending on the turbidity[55] of the water arriving at the Rand Water Treatment Plant, between 95% and 97% of the suspended particles are removed during sedimentation. Between 500 and 1300 tons of dry sludge are produced each day during the purification process. This is removed from the sedimentation tanks (see Figure 2.35[55]) at Zuikerbosch and Vereeniging in thin slurry containing 3% mass by volume of dry sludge.

Figure 2.35: Removal of sludge from Rand Water's sedimentation tanks

Typical floc settling curves[4] which may be obtained by optimum and incomplete coagulation and flocculation procedures are presented in Figure 2.36[4].

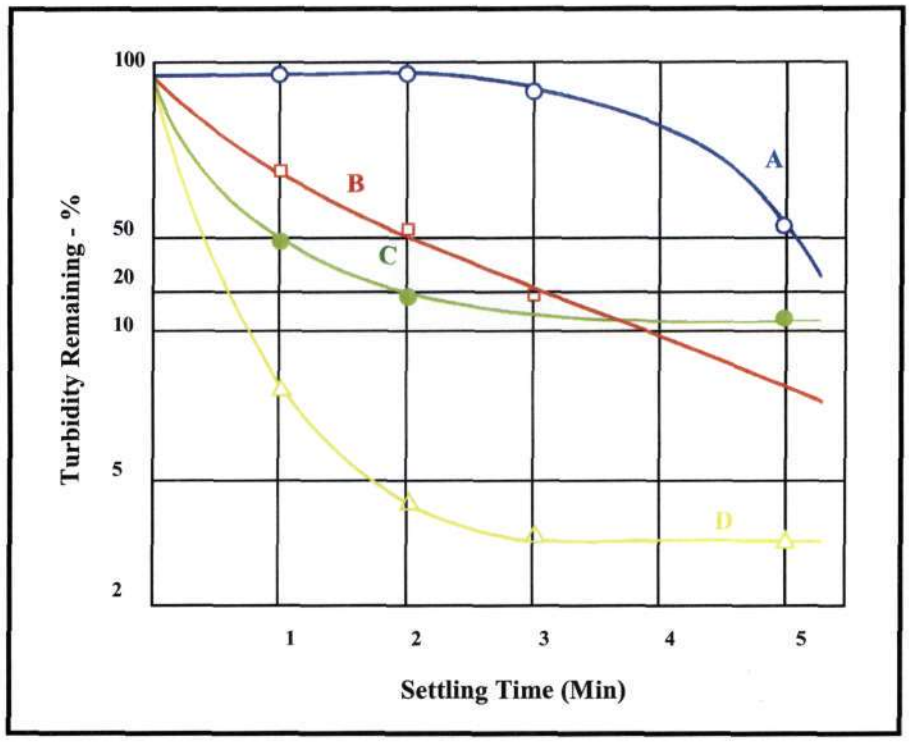

Figure 2.36: Typical floc settling[4] curves

Curve A indicates a coagulation which produced a uniformly fine floc, so small that at the end of 1 to 2 minutes settling, the supernatant had a turbidity equal to that of the starting water due, in part, to the fine floc which did not settle. Settling was slow and the final turbidity was excessive. Curve B represents the most common type of settling rate obtained. During the first 5 minutes, the settling rate was practically a straight line on a semi-log plot. Settling was rapid and clarification was satisfactory. The coagulation represented by curve C shows that a mixture of large rapid settling floc and small, slow-settling particles was obtained. Settling was rapid for the first two minutes, but with little further clarification after that. High residual turbidity may also have resulted from incomplete coagulation. Curve D represents the ultimate in coagulation. Practically all of the floc particles were so large and dense that 97% settled within three minutes. Sedimentation was essentially complete within that time since only 0.5% additional floc settled in the next 27 minutes. Final clarity of the supernatant was entirely satisfactory. This coagulation was obtained with a coagulant aid.

2.6.4. FILTRATION

2.6.4.1 Filtration of Surface Water Supplies

After the coagulation, flocculation and sedimentation processes are complete[52], the raw water is much clearer, but is not yet potable. Some residual iron, manganese, clay, inert solids, bacteria and other constituents are still present in the water. Even in a high quality unfiltered treated water having a total suspended solids concentration of 0.1 mg/l, approximately 200 million particles are present per litre. Therefore, filtration of the water is essential in further reducing the concentration of these constituents.

Traditionally, filtration has been designed and used to remove suspended material, such as colloidal river silt, iron and manganese from drinking water supplies. It has been desirable to remove these constituents because, if they are found in finished water, they can harbour bacteria and interfere with the disinfection process. More recently however, filtration facilities are being designed to remove aquatic organisms, primarily Giardia cysts. These cysts, along with other constituents such as nematodes, algae, diatoms, mites and flagellated protozoans, are being found in rural sources of drinking water. Since the presence of Giardia cysts in water supplies can result in waterborne outbreaks of Giardiasis, filtration is necessary to completely remove these organisms.

Filtration is the process of passing a properly treated water through a bed of some type of media for the purpose of reducing the particle concentration present in the water (refer to Figures 2.37 & 2.38[53] for a diagrammatic representation of a typical filtration mechanism together with a simplistic view of its method of operation).

Figure 2.37: Filtration tanks

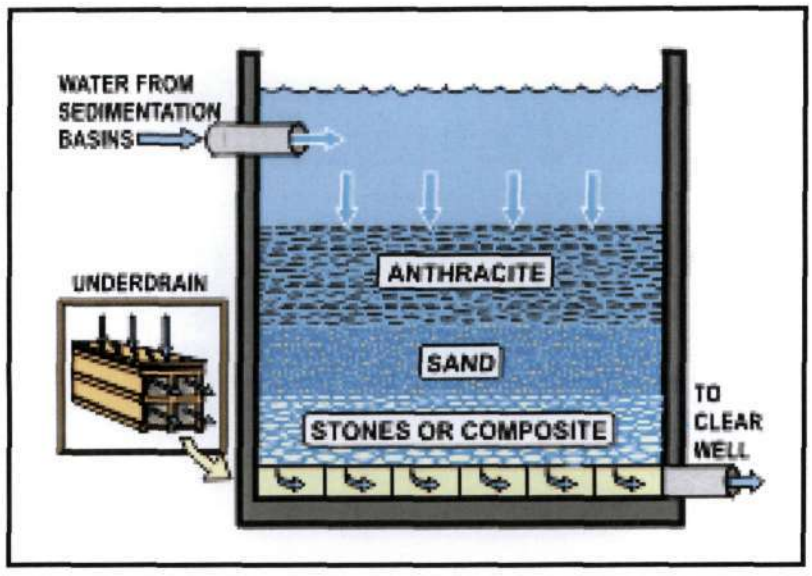

Figure 2.38: Schematic representing the basic operation of[53] a filtration tank

2.6.5. DISINFECTION

2.6.5.1 Primary Disinfection

The water leaving the purification works[55] is disinfected with chlorine to kill micro-organisms, bacteria and any viruses that may be present in the water. The required concentration of chlorine is determined so that the number of colony forming micro-organisms per millilitre, as determined by the standard plate count technique after 48 hours incubation at 37°C, is less than 10 after 20 minutes contact with chlorine.

The chlorine dosage must be between 1.5 and 4.0 mg/l depending on the raw water quality to ensure that there is minimal re-growth of any micro-organisms during the 6 to 8 hours that the water travels to the booster pumping stations. The free residual chlorine at these dosages will vary between 1.0 and 2.5 mg/l after 20 minutes of contact time. There are no chlorine contact chambers and the mixing takes place in the pipelines (refer to Figure 2.39[55]).

2.6.5.2 Secondary Disinfection by Chloramination

Chlorine, although an excellent disinfectant, does not remain active for much longer than 6 to 8 hours. Disinfection needs to be repeated but this time with a less powerful agent that will remain active for long periods so that the water may be protected right up to the end

consumer. This is achieved by dosing chlorine and ammonia at the booster pumping station in the correct mass ratio of not less than 4:1 and forming the monochloramine in-situ (refer to Figure 2.39). The monochloramine, although less active than chlorine, then protects the water against bacterial action for periods of up to 8 days.

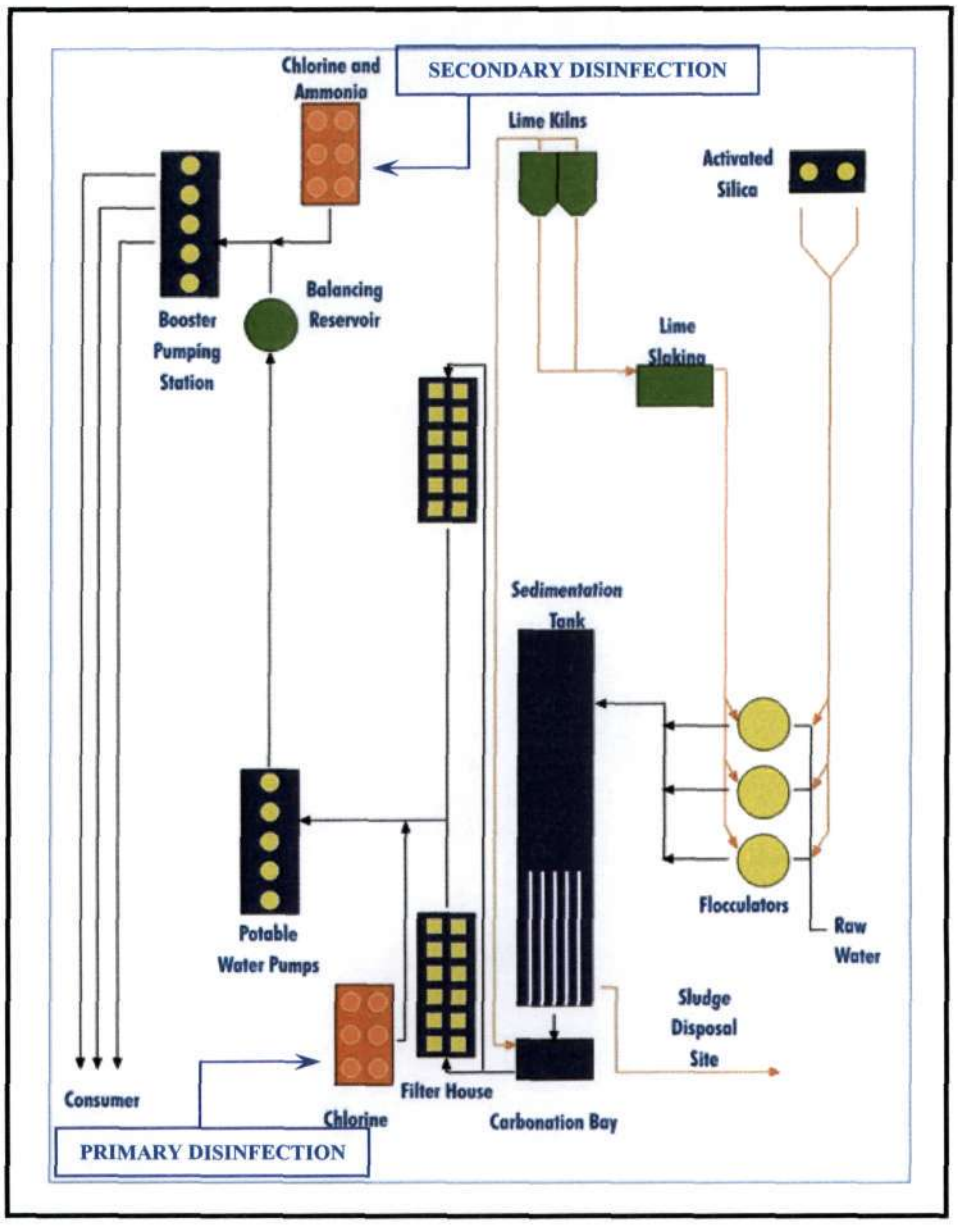

Figure 2.39: Schematic illustrating the process of disinfection

2.7 CHLORINATION CHEMISTRY

2.7.1 BACKGROUND INFORMATION

In 1774, Swedish pharmacist Carl Wilhem Scheele released a few drops of hydrochloric acid onto a piece of manganese dioxide, and within seconds, a greenish-yellow gas arose. The following equation[58] represents the chemical reaction that ensued.

$$MnO_2 + 4\ HCl \rightarrow Cl_2 + MnCl_2 + 2\ H_2O$$

At that time however, Carl Wilhem Scheele had no idea that he had just discovered chlorine. The fact that the greenish-yellow gas was only recognized several decades later by English chemist Sir Humphrey Davy. Until that time, people were convinced that the gas was a compound of oxygen. In 1890, Davy suggested the name "chloric gas" or "chlorine" for this newly discovered element.

Chlorine is now used as one of the most effective and economical germ-killers, where its powerful disinfectant qualities come from its ability to bond with and destroy the outer surfaces of bacteria and viruses.

2.7.2 GENERAL PROPERTIES OF CHLORINE

Chlorine is commonly found in nature[57], but due to it being highly reactive, it is almost always in combination with other elements such as sodium, potassium and magnesium. Chlorine's structure makes it very reactive (its outer shell is missing just one electron), which makes it attractive to other atoms and molecules. As a result of its high reactivity, chlorine is regarded as a very useful substance, and when combined with other chemical building blocks, chlorine can change the nature of a substance, and build or improve a product.

When isolated as a free element, chlorine exists as a greenish yellow gas, which is 2.5 times heavier than air. It turns to a liquid state at -34°C, and it becomes a yellowish crystalline solid at -103°C. Chemists began experimenting with chlorine and chlorine compounds in the 18th century where they've learnt that chlorine has an extraordinary ability to extend a chemical bridge between various elements and compounds that would not otherwise react with each other.

Of particular interest, was the use of chlorine in the studying and synthesizing of organic compounds, i.e. compounds that have at least one atom of the element carbon in their molecular structure (all living organisms, including humans, are composed of organic compounds). To be rendered useful however, chlorine must first be separated from all other elements with which it is combined. Manufacturers use a process known as "electrolysis," which breaks down salt water into its basic components by passing an electrical current through the salt water, which splits the solution into the positive sodium, and negative chloride ions. Since opposite charges attract one another, the negative chloride ions gather at the positive poles to form molecular chlorine gas. The gas is then dried, chilled and pressurized, or alternatively, it is converted to a liquid form for storage and shipping. In other words:

2NaCL	+	$2H_20$	(electricity) →	Cl_2	+	2NaOH	+	H_2
Salt		Water		Chlorine		Caustic Soda		Hydrogen

2.7.3 CHEMICAL REACTION OF CHLORINE WITH WATER

When chlorine is used in water treatment systems[59] it is added in either a gaseous or liquid form of chlorine (Cl_2). When it combines with water (which solution is called Chlorine Water), chlorine produces hypochlorous acid and hydrochloric acid. The chemical equation for this reaction is:

Cl_2	+	H2O	→	HOCl	+	**HCl**
Chlorine		Water		Hypochlorous Acid		Hydrochloric Acid

The hydrochloric acid is not very stable, and on being exposed to sunlight, it readily decomcomposes, yielding oxygen. Hypochlorous acid however, experiences partial dissociation, whereby the HOCl is broken down to form H^+ and OCl^- ions. As the pH varies in a system, so too does the concentration of hypochlorous acid (HOCl) versus the concentration of hypochlorite (OCl^-) ions (refer to Figure 2.40[3]). This dissociation reaction clearly shows that the ratio of $OC1^-$ to HOCl increases as the pH increases. When the pH value of the chlorinated water is around 7.5, 50 % of the chlorine concentration present will be undissociated hypochlorous acid (HOCl), while the other 50 % will be hypochlorite ions

(OCl^-). The higher the pH values, the greater will be the concentration of OCl^- ions, while the amount of HOCl becomes proportionately less.

Both HOCl and OCl^- are good disinfecting agents although HOCl does tend to be slightly more effective. Hypochlorous acid is the active[60], killing form of chlorine and is what does the real sanitizing work. The chlorine molecule or ion kills micro-organisms by slashing through the cell walls and destroying the inner enzymes, structures and processes. When this occurs, the cell has been deactivated, or oxidized. The hypochlorous molecule continues this slash & burn until it combines with a nitrogen or ammonia compound, becoming a chloramine, or it is broken down into its component atoms, becoming de-activated itself.

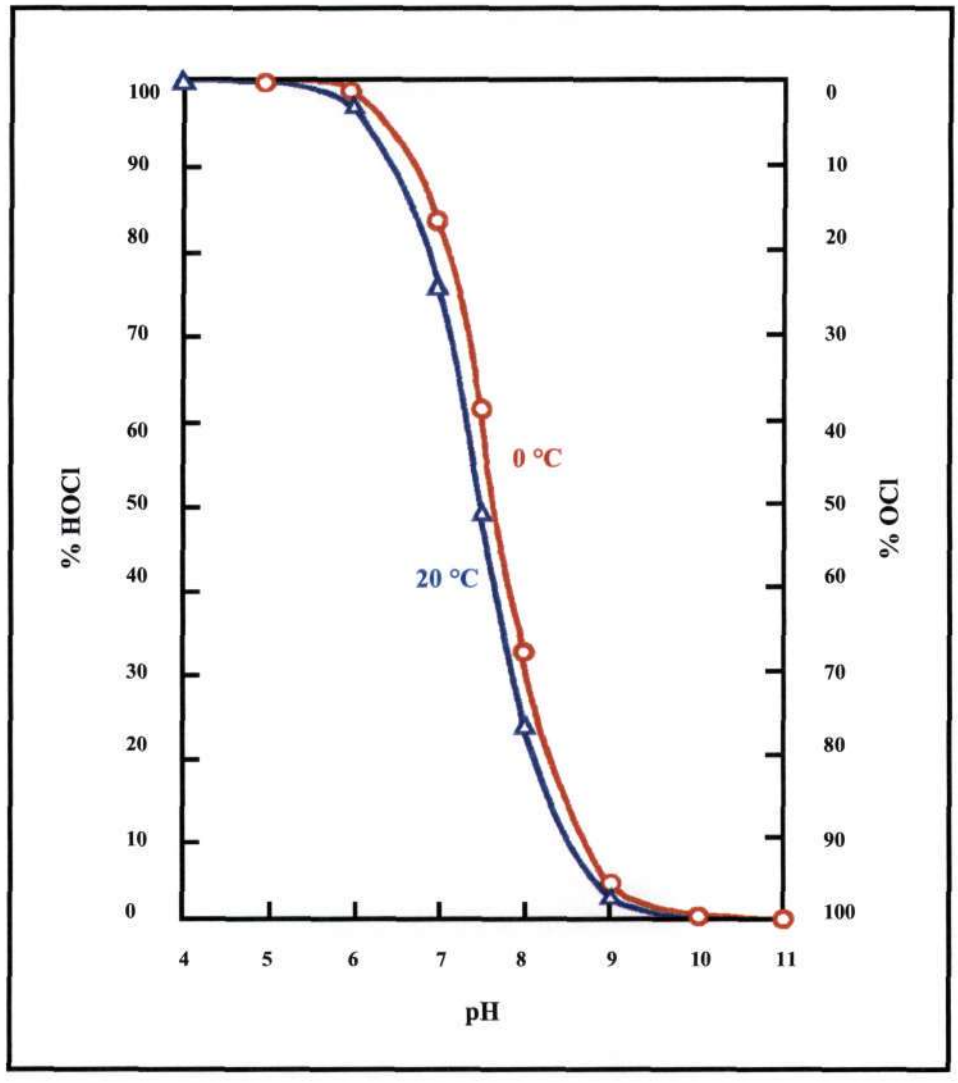

Figure 2.40: Dissociation[3] of hypochlorous acid versus pH

2.7.4 USABLE OPTIONS FOR CHLORINE IN ITS THREE STATES (SOLID, LIQUID AND GAS)

In its elemental state[60], chlorine exists as a gas. Gas is the purest form of chlorine, with no binders or carriers, thus allowing the % of available chlorine to be 100%. However, due to chlorine gas being extremely acidic, it is also considered as being extremely dangerous and as a result, is restricting in its use.

Liquid chlorine is another type, which is created by bubbling the chlorine gas through a solution of caustic soda. The yellow liquid (stronger, but chemically identical to bleach) has 10 - 15% of available chlorine, and has a pH on the other end of the scale, i.e. at 13. Liquid Chlorine is called sodium hypochlorite (NaOCl) and because it is already in solution, sodium hypochlorite produces hypochlorous acid instantly when it comes into contact with water.

Trichlor is a tablet form of chlorine, and is short for trichloro-s-triazinetrione, a stabilized form of chlorine that has achieved a great amount of use in the last ten years. "Stabilized" means that it has cyanuric acid pressed into the tablet. Cyanuric, also called stabilizer or conditioner, is like sunscreen for the chlorine molecule. Trichlor is created by combining the salts of cyanuric acid and chlorine gas into a tablet or stick, and has 90% of available chlorine with a pH of 3.

Another member of the chlorinated iso-cyanurate family is dichlor, short for sodium dichloro-s-triazinetrione. Dichlor is made in roughly the same manner as trichlor, however, the product is much different. The pH is a very acceptable 7, and it is manufactured in the form of granules, so it dissolves rapidly and goes right to work on contaminants. Dichlor has less chlorine, only 62% of available chlorine, however, as a result of containing cyanuric acid, it lasts longer than other unstabilized forms of granular chlorine. Dichlor's main drawback is its cost per kg of available chlorine. It is perhaps the most expensive form of chlorine available.

There are two other types of granular chlorine on the market, i.e. the hypochlorites. Lithium hypochlorite, like dichlor, is a very expensive product with only 35% available. It takes almost 3 kg of lithium to equal 1 kg of trichlor, however, it does have its advantages in that it is calcium free, and so it won't contribute to hardness levels; it's also dust free and non-flammable.

Calcium hypochlorite is commonly available in its granular form, but can also be purchased in tablet form. Calcium hypochlorite is a commonly used shock treatment in that it has a quick kill rate and has 65% of available chlorine. The popularity of calcium hypochlorite is due primarily to its availability and low price despite a high pH value of nearly 12, and the calcium binders used which contribute to higher hardness levels. Calcium hypochlorite is more dangerous and unstable than other forms in that it is very dusty and becomes contaminated easily by foreign substances which can cause combustion.

2.7.5 CHARACTERISTICS OF CHLORINE RELATED DISINFECTANTS

Water disinfection can be accomplished[3] by the use of a vast number of chemical disinfectants (chemical disinfectants are chemical substances that are used to kill or deactivate pathogenic micro-organisms). The following chemical disinfectants are regarded as being the four most effective chlorine decontaminants:

- Chlorine
- Sodium hypochlorite
- Chlorine dioxide
- Chloramines

2.7.5.1 Chlorine

As already indicated, chlorine is one of the most commonly used disinfectants for water disinfection. Chlorine can be applied for the deactivation of most micro-organisms and it is also relatively cheap[3].

Chlorine atoms contain 17 negative electrons (negatively charged particles), which move around the heavy core of the atom in three shells (see Figure 2.41[3]). Within the inner shell there are two electrons, within the middle shell there are eight and within the outer shell there are seven. The outer shell has space available for one other electron, which causes free, charged atoms, called ions, to form.

Chlorine Applications

Chlorine is a very reactive element that is applied on a massive scale[3]. Chlorine has the ability to form compounds with other substances, including those substances that do not normally react with one another. When chlorine bonds to a substance that contains carbon

atoms, organic substances are formed, e.g. plastic, solvents and oils, as well as several human body fluids. When chlorine chemically binds to other elements, it often replaces hydrogens atom during a so called substitution reaction. Multiple hydrogen atoms in the same molecule can be replaced by chlorine atoms, causing new substances to form one after another.

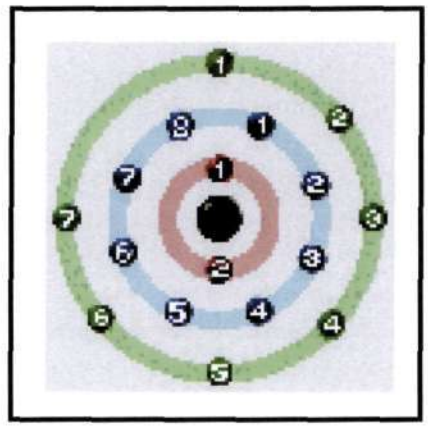

Figure 2.41: Ionic representation of a chlorine atom

Of particular interest to this study however, is the application of chlorine in water treatment processes. The amount of time that chlorine is present during treatment is called the contact time and is related to the 'Ct' value[61]. Ct values are calculated to determine the amount of time that a disinfectant must be present in the system to achieve a specific kill of micro-organisms, for a given disinfectant concentration. A large Ct value means that disinfection alone will not be sufficient for treatment and additional methods will also be necessary to eliminate the micro-organisms. The contact time is directly related to the chemicals' efficiency in eliminating bacteria and viruses from the water. The chart below, Figure 2.42[61], indicates the amount of time that HOCl, OCl^- and NH_2Cl need to be present in the treatment system in order to achieve a 99% kill of E.coli.

Furthermore, an increased contact time for chlorine subsequently increases the chlorine demand. Depending on the amount of organic material and free chlorine residual present in the water, the probability of producing disinfection by-products, such as trihalomethanes, may increase.

Chlorine as a Disinfectant

Chlorine is one of the most widely used disinfectants[3], which is extremely effective for the

deactivation of pathogenic micro-organisms. Chlorine can be easily applied, measured and controlled and is fairly persistent while being relatively cheap.

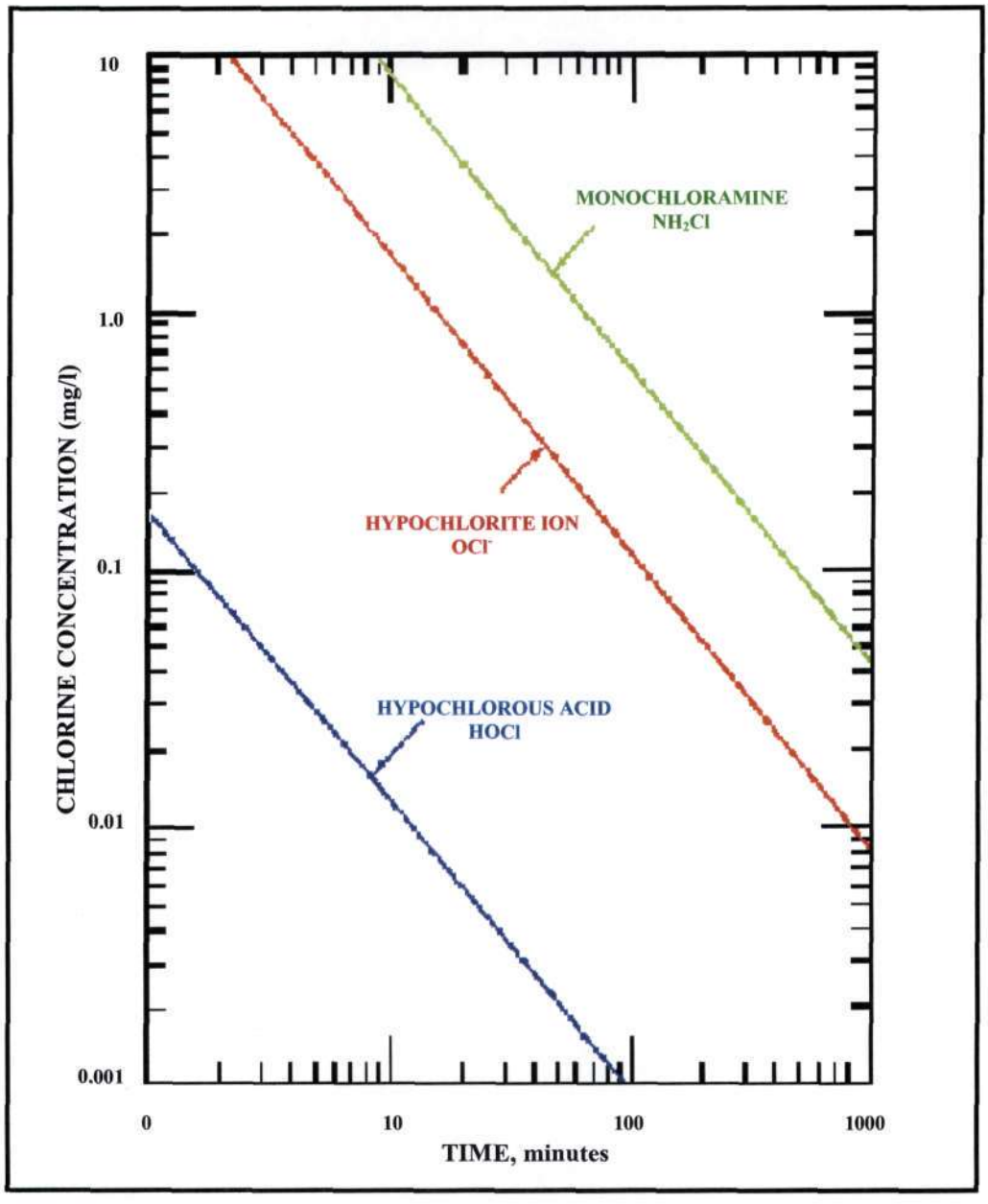

Figure 2.42: Representation[61] of the amount of time required for HOCl, OCl^- and NH_2Cl to be present in the treatment system in order to achieve a 99% kill of E.coli

Chlorine has been used for more than two hundred years in applications such as the deactivation of pathogens in drinking water, swimming pool water and wastewater, for the disinfection of household areas and for textile bleaching. When chlorine was first discovered, it was unknown that diseases were caused by micro-organisms. In the nineteenth century however, doctors and scientists discovered the contagious nature of

diseases, and that the spread of diseases can be prevented by the disinfection of hospital areas. Very soon afterward however, chorine had been experimenting with as a disinfectant. In 1835 doctor and writer Oliver Wendel Holmes advised midwifes to wash their hands in calcium hypochlorite ($Ca(ClO)_2.4H_2O$) to prevent the spread of midwifes fever. However, the use of chlorine as a disinfectant on a wider scale only began in the nineteenth century, after Louis Pasteur discovered the disease-spreading capabilities of micro-organisms.

How Chlorine Disinfection Works

Chlorine kills pathogens such as bacteria and viruses by breaking the chemical bonds in their molecules[3]. Disinfectants that are used for this purpose consist of chlorine compounds which can exchange atoms with other compounds, such as enzymes in bacteria and other cells. When enzymes come into contact with chlorine, one or more of the hydrogen atoms in the molecule are replaced by chlorine, which causes the entire molecule to change shape or fall apart. When enzymes do not function properly, a cell or bacterium will die.

When chlorine is first added to water, hypochlorous acids form:

$$Cl_2 + H_2O \rightarrow HOCl + H^+ + Cl^-$$

Depending on the pH value, hypochlorous acid partly expires to hypochlorite ions:

$$Cl_2 + 2H_2O \rightarrow HOCl + H_3O + Cl^-$$
$$HOCl + H_2O \rightarrow H_3O^+ + OCl^-$$

This then falls apart to form chlorine and oxygen atoms:

$$OCl^- \rightarrow Cl^- + O$$

Hypochlorous acid (HOCl, which is electrically neutral) and hypochlorite ions (OCl^-, electrically negative), will form free chlorine when bound together, which results in disinfection. Both substances have a very distinctive behaviour, with hypochlorous acid being more reactive and a stronger disinfectant. Hypochlorous acid is subsequently split into hydrochloric acid (HCl) and oxygen (O). The oxygen atom is a powerful disinfectant, in that the disinfecting properties of chlorine in water are based on the oxidising power of the free oxygen atoms, and on chlorine substitution reactions.

The cell wall of pathogenic micro-organisms is negatively charged by nature (see Figure 2.43[3]). As such, it can be penetrated by the neutral hypochlorous acid, rather than by the negatively charged hypochlorite ion. Hypochlorous acid can penetrate slime layers, cell walls and protective layers of micro-organisms and effectively kills pathogens as a result. The micro-organisms will then, either die or suffer from reproductive failure.

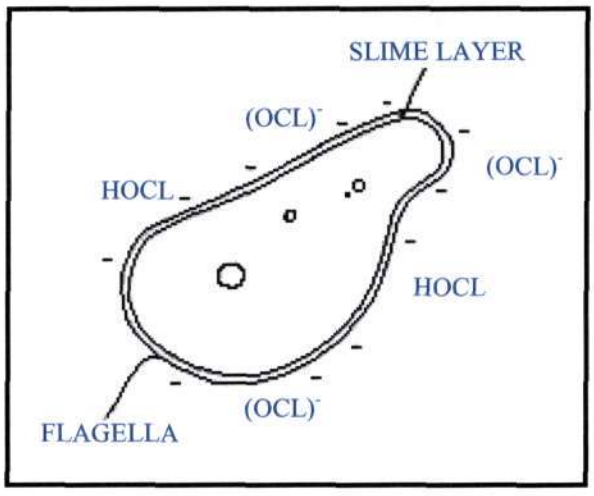

Figure 2.43: Charge distribution along a pathogenic micro-organism's cell wall

Free and Bound Active Chlorine

When chlorine is added to water for disinfection purposes, it usually starts reacting with dissolved organic and inorganic compounds in the water[3]. Chlorine can then no longer be used for disinfection, due to forming other products. The amount of chlorine that is used during this process is referred to as the 'chlorine enquiry' of the water. Chlorine can react with ammonia (NH_3) to produce chloramines, i.e. chemical compounds which contain chlorine, nitrogen (N) and hydrogen (H). These compounds are referred to as 'active chlorine compounds' (contrary to hypochlorous acid and hypochlorite, which are referred to as 'free active chlorine') and are responsible for water disinfection, however, these compounds also react much slower than free active chlorine.

Breakpoint Chlorination

Breakpoint chlorination is accomplished[3] by increasing the chlorine dosage to a point at which all ammonia compounds in the water are completely oxidized and removed by chlorine reaction, after which point all dissolved chlorine exists as free available hypochlorous acid (HOCL) or hypochlorite ion (OCL^-). The amount of chlorine required to

reach breakpoint depends upon the amount of ammonia present. In order to reach the breakpoint, super-chlorination is applied. To achieve this, one uses chlorine concentrations which largely exceed the 1 mg/l concentration required for disinfection.

A breakpoint curve on the water to be chlorinated is obtained by determining the total chlorine residual for various chlorine dosages, after sufficient contact time has elapsed for the reactions to go to completion. The breakpoint curve is characterised by a hump and a dip (refer to Figure 2.44[4]), where the breakpoint refers to the position of the dip on the breakpoint curve. The breakpoint can be seen at the point where the $NH_3 - N$ is reduced to zero, free available chlorine is detected and the total chlorine residual is minimised. The breakpoint value is thus the amount of chlorine dosage required to obtain the breakpoint (dip) on the breakpoint curve.

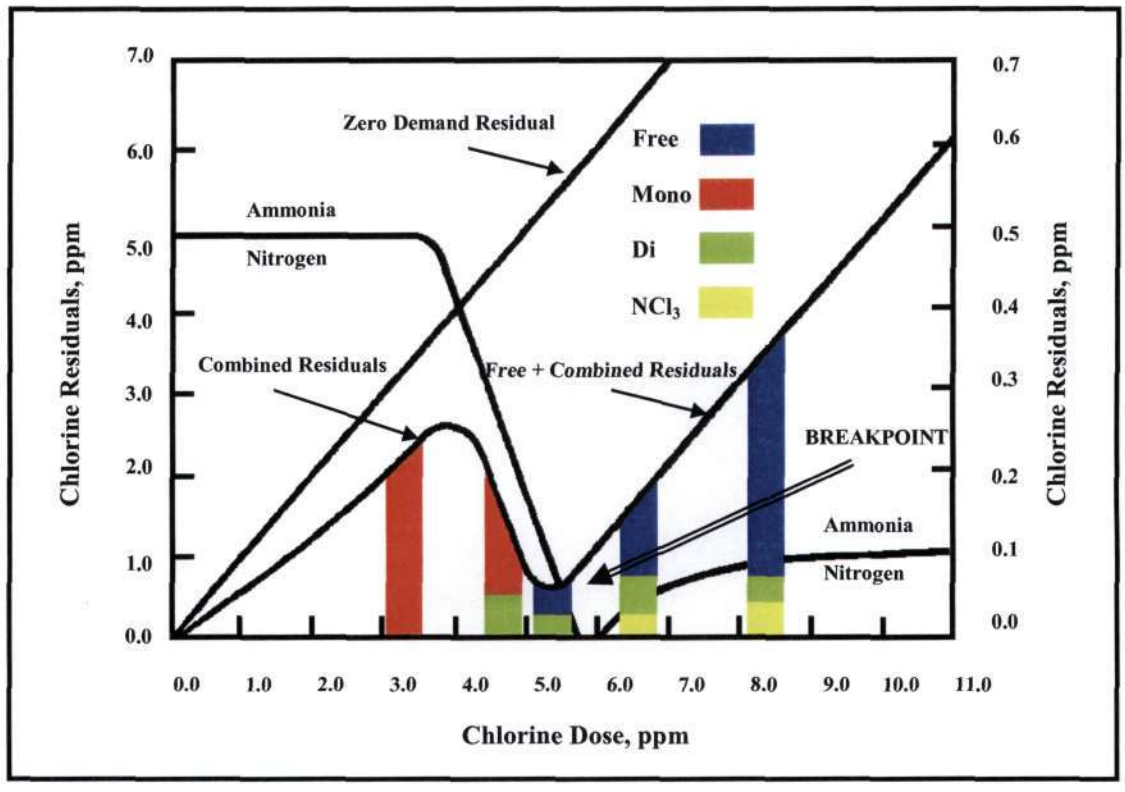

Figure 2.44: Representation of[4] a breakpoint curve

Factors That Determine the Effectiveness of Chlorine Disinfection

Factors which determine chlorine disinfection effectiveness[3] include:

- Chlorine concentrations
- Contact time

- Temperature
- pH
- Number and types of micro-organisms
- Concentrations of organic matter in the water

A typical breakdown of the duration of disinfection for faecal pollutants are shown in Table 2.7[3], where several different types of pathogenic micro-organisms are disinfected using chlorinated water that contains a chlorine concentration of 1 mg/l (1 ppm) when the pH = 7,5 and T = 25 °C.

Table 2.7 Breakdown of the duration of disinfection for faecal pollutants

DISINFECTION TIME OF FAECAL POLLUTANTS USING CHLORINATED WATER	
E.coli 0157 H7 bacterium	< 1 minute
Hepatitis A virus	about 16 minutes
Giardia parasite	about 45 minutes
Cryptosporidium	about 9600 minutes

Health Effects of Chlorine

The reaction of the human body to chlorine depends on the concentration of chlorine present in air[3], and on the duration and frequency of exposure. Effects also depend on the health of an individual and the environmental conditions during exposure.

When small amounts of chlorine are breathed in during short time periods, this can affect the respiratory system, where the effects vary from coughing and chest pains, to fluid accumulation in the lungs. When chlorine enters the body it is not very persistent, because of its reactivity. Pure chlorine is very toxic, even small amounts can be deadly. Chlorine is much denser than air, and during World War I chlorine gas was used on a large scale to hurt or kill enemy soldiers by allowing a toxic fume to form above the soil. Chlorine gas affects the mucous membrane (nose, throat, eyes) by dissolving them, causing the chlorine gas to end up in the blood vessels.

2.7.5.2 Sodium Hypochlorite

Sodium hypochlorite (NaOCl) is a compound that can be effectively used for water purification. It is used on a large scale for surface purification, bleaching, odour removal and water disinfection.

Characteristics of Sodium Hypochlorite

Sodium hypochlorite is a clear, slightly yellowish solution with a characteristic odour[3]. As a bleaching agent for domestic use, it usually contains 5% of sodium hypochlorite (with a pH of around 11). Should this concentration increase to about 10-15% (with a pH of around 13), it tends to become very corrosive and burns.

Sodium hypochlorite is unstable however, with chlorine evaporating at a rate of 0.75 grams of active chlorine per day from the solution. When sodium hypochlorite comes into contact with acids, sunlight, certain metals and poisonous and corrosive gasses, the sodium hypochlorite disintegrates.

Production of Sodium Hypochlorite

Sodium hypochlorite can be produced in two ways[3]:

1. By dissolving salt in softened water, which results in the production of a concentrated brine solution. The solution is electrolyzed and forms a sodium hypochlorite solution in water. This solution contains 150 g of active chlorine (Cl_2) per litre, and during this reaction the explosive hydrogen gas is also formed.

2. By adding chlorine gas (Cl_2) to caustic soda (NaOH). When this is done, sodium hypochlorite (NaOCl), water (H_2O) and salt (NaCl) are produced according to the following reaction:

$$Cl_2 + 2NaOH \rightarrow NaOCl + NaCl + H_2O$$

Applications of Sodium Hypochlorite

Sodium hypochlorite is used on a large scale[3], e.g. in agriculture, chemical industries, paint and lime industries, food industries, glass industries, paper industries, pharmaceutical

industries, synthetics industries and waste disposal industries. In the textile industry, sodium hypochlorite is used to bleach textiles. It is sometimes added to industrial waste water to reduce odours i.e. hypochlorite neutralizes sulphur hydrogen gas (SH) and ammonia (NH_3). It is also used to detoxify cyanide baths in metal industries, to prevent algae and shellfish growth in cooling towers, to disinfect water in water treatment plants and in households for the purification and disinfection of the house.

How Sodium Hypochlorite Disinfection Works

By adding hypochlorite to water, hypochlorous acid (HOCl) is formed:

$$NaOCl + H_2O \rightarrow HOCl + NaOH^-$$

Hypochlorous acid is divided into hydrochloric acid (HCl) and oxygen (O). The oxygen atom is utilized as a very strong oxidator.

Health Effects of Sodium Hypochlorite

There is no threshold value for sodium hypochlorite exposure, however, various health effects occur after exposure[3], where exposure is predominantly caused by the inhalation of aerosols. This causes coughing and a sore throat, and after swallowing sodium hypochlorite, the effects include stomach aches, a burning sensation, coughing, diarrhoea, a sore throat and vomiting. Sodium hypochlorite is also poisonous for water organisms and is very toxic when coming into contact with ammonium salts.

Advantages and Disadvantages of Using Sodium Hypochlorite[3]

Advantages - Sodium hypochlorite as a disinfectant can be transported and stored with relative ease when produced in-situ, dosages are simple to administer, and it is as effective as chlorine gas for disinfection.

Disadvantages - Sodium hypochlorite is a dangerous and corrosive substance and while working with it, safety measures have to be taken to protect workers and the environment. To avoid disintegration, sodium hypochlorite should not come in contact with air. Both sodium hypochlorite and chlorine do not deactivate Giardia Lambia and Cryptosporidium.

2.7.5.3 Chlorine Dioxide

The quest for the disinfectant replacement of chlorine resulted in several possible candidates. Although no disinfectant is perfect, chlorine dioxide is a very good alternative due to its characteristics.

Stabilised Chlorine Dioxide

Like ozone and chlorine[3], chlorine dioxide is an oxidizing biocide and not a metabolic toxin. This means that chlorine dioxide kills micro-organisms by disrupting the transport of nutrients across the cell wall, but not by the disruption of the metabolic process itself. Stabilised chlorine dioxide is ClO_2 buffered in an aqueous solution. Adding an acid to the required concentration activates the disinfectant.

How Chlorine Dioxide Works

Of the oxidizing biocides, chlorine dioxide is the most selective oxidant[3]. Both ozone and chlorine are much more reactive than chlorine dioxide, and will be consumed by most organic compounds. Chlorine dioxide however, reacts only with reduced sulphur compounds, secondary and tertiary amines, and some other highly reduced and reactive organics. This allows much lower dosages of chlorine dioxide to achieve a more stable residual than either chlorine or ozone. Chlorine dioxide, generated properly (all chlorine dioxide is not created equally), can be effectively used in much higher organic loading than either ozone or chlorine because of its selectivity.

Effectiveness of Chlorine Dioxide

The effectiveness of chlorine dioxide is at least as high as chlorines (although at lower concentrations)[3]. Furthermore, there are also other important advantages:

- The bactericidal efficiency is relatively unaffected by pH values between 4 and 10.
- Chlorine dioxide is clearly superior to chlorine in the destruction of spores, bacteria's, viruses and other pathogen organisms on an equal residual base.
- The required contact time for ClO_2 is lower.
- Chlorine dioxide has better solubility.
- No corrosion is associated with high chlorine concentrations (reduces long term maintenance costs).

- Chlorine dioxide does not react with NH_3 or NH_4^+.
- ClO_2 destroys phenols and has no distinct smell.
- It is better than chlorine is removing iron and magnesium compounds.

Applications of Chlorine Dioxide

Chlorine dioxide can be used in two ways[3]. The first is the in-situ generation through a special process and the second is the possibility to order chlorine dioxide in its stabilised form (SCD).

SCD is activated on site whenever its usage is desirable. It can be dosed into an existing or new process where disinfection is required, which makes it an easy to use, safe and versatile disinfectant. The dosing system is also compact, safe, flexible and low on maintenance.

Chlorine dioxide is applied in instances where biofilm exists within the piping. The biofilm protects Legionella from most types of disinfectants, however, chlorine dioxide removes the biofilm and kills the bacteria, spores and viruses.

Potable Water Disinfection

Chlorine dioxide has been used for years in potable water disinfection[3]. The need arose when it was discovered that chlorine and similar products formed some dangerous disinfection by-products like THM (trihalomethanes). Since then, a number of water companies have started using ClO_2. There are however, more reasons to use chlorine dioxide since:

- The bactericidal efficiency is relatively unaffected by pH values between 4 and 10.
- Chlorine dioxide is clearly superior to chlorine in the destruction of spores, bacteria, viruses and other pathogenic organisms.
- The required contact time for ClO_2 is lower.
- Chlorine dioxide has better solubility.
- No corrosion is associated with high chlorine concentrations, which also reduces long term maintenance costs.
- Chlorine dioxide does not react with NH_3 or NH_4^+.
- It destroys THM precursors and increases coagulation.
- ClO_2 destroys phenols and has no distinct smell.

- It is also more effective than chlorine in the removal of iron and magnesium compounds.

2.7.5.4 Chloramines

Drinking water odour and flavour has improved by the application of chloramines from the beginning of the twenty-first century. Eventually chloramines were also used for disinfection.

Properties of Chloramines

Chloramines are formed[3] during a reaction between chlorine (Cl_2) and ammonia (NH_3). Chloramines are amines which contain at least one chlorine atom, which is directly bond to the nitrogen atoms (N). Inorganic chloramines are formed when dissolved chlorine and ammonia react. During this reaction, three different inorganic chloramines are formed, namely, monochloramine (NH_2Cl), dichloramine ($NHCl_2$) and trichloramine (NCl_3). Inorganic chloramines, free chlorine and organic chloramines are chemically related and can change into one another easily. Inorganic chloramines are not very persistent; however, these compounds are still more persistent than freely available chlorine compounds.

Production of Chloramines

Chloramines are frequently produced by adding ammonia to water that contains free chlorine (HOCl or OCl, depending on the pH)[3]. The ideal pH value for this reaction is 8.4, which implies that the water is slightly alkaline. The reaction mechanism is as follows:

$$NH_3\,(aq) + HOCl \rightarrow NH_2Cl + H_2O$$

When this reaction takes place, three kinds of inorganic chloramines can be formed, with the pH value dictating which of the three types is to be produced (see Figure 2.45[3]). Trichloramines are formed mainly when the pH value is 3 or below. When the pH value is 7 or above, dichloramine concentrations are the highest. The amounts of chlorine and ammonia in the water also influence the origination of chloramines, with the chlorine:ammonia rate being ideally 6:1. During chloramine production, the rate is usually 3-5:1. When ammonia concentrations are higher, more di- and trichloramines are formed. Organic chloramines can also be formed during these reactions, however, the organic

chloramines cannot be distinguished from other chloramines using standard chloramine analysis methods.

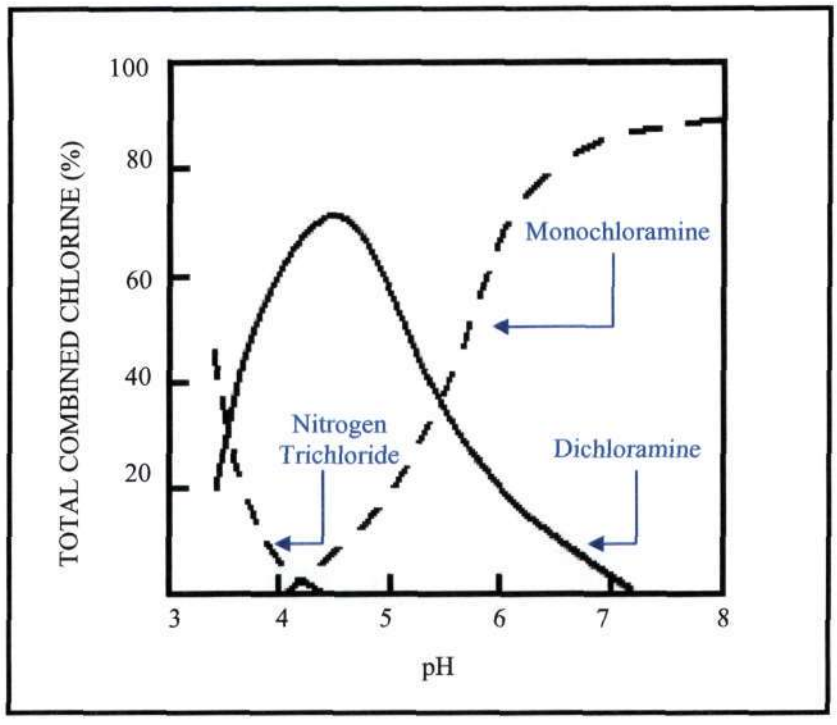

Figure 2.45: Representation[3] of the production of chloramines in relation to pH

Table 2.8[3] illustrates the various types of chloramines and their properties.

Table 2.8 Description of chloramine types

APPEARANCE	NAME	MOLECULAR WEIGHT	PREFERRED PH VALUE	BIOCIDATING EFFECT
NH_2Cl	monochloramine	52	> 7	good
$NHCl_2$	dichloramine	85	4 - 7	tolerable
NCl_3	trichloramine	119	1 - 3	average
RNHCl	organic chloramines	varies	unknown	bad

Applications of Chloramines

Chloramines can be used as bleach, disinfectants and oxidators[3]. Organic disinfectants slowly give off chlorine, causing a slower and less aggressive disinfection than that with

hypochlorite (OCl^-). Chloramines can be used to improve odour and flavour of the water when chlorine is being used as a disinfectant. Chloramines are also used for the disinfection of drinking water and wastewater and to resist biofouling in cooling water systems.

Water Disinfection with Chloramines

When chloramines are used as a disinfectant, ammonia is added to the chlorine-treated water[3]. Chloramines are as effective as chlorine for the deactivation of bacteria and other micro-organisms; however, the reaction mechanism is slower. Chloramines, like chlorine, are oxidators and are capable of killing bacteria by penetration of the cell wall, which results in a blockage of the metabolism. Monochloramine is the most effective disinfectant, in that it reacts directly with amino acids in the bacterial DNA. During the deactivation of micro-organisms, chloramines function by destroying the shell which protects a virus. The pH value does not interfere with the effectiveness of chloramines, however, when the pH value is 7 or higher, monochloramine is the most abundant chloramine.

Using chloramines to Disinfect Drinking Water

In the United States of America[3], chloramines are applied more and more often as an alternative for chlorine during the secondary disinfection of drinking water. In the year 2002, 20% of the US drinking water production companies used chloramines. The main reason for the transfer from chlorine to chloramines is that chloramines react with organic matter less often than chlorine. Little to no trihalomethanes (THM) and other disinfection by-products are formed during chloramine disinfection. Chloramines prevail for long periods of time before being broken down and will therefore, remain actively within the plumbing for a long time. Furthermore, chloramines do not give off any taste or smell and are relatively safe.

Removal of Chloramines from Water

Like other molecules, chloramines contribute to the total amount of dissolved solids in the water[3]. Like chlorine however, chloramines are selectively reactive and may have damaging effects when they remain in the water for too long.

When chloramines are present, there are usually trace amounts of ammonia and hypochlorite in the water as well. Chloramines are hardly ionic, and as a result and because of the low molecular weight, chloramines, mainly monochloramine, are difficult to remove

from water by reverse osmosis (RO) or water softening. Boiling, distillation and substances that are used for chlorine removal also cannot be used for the removal of chloramines, however, sunlight and aeration can prove to be a useful aid in chloramine removal.

Chloramines can be removed by means of a granular active carbon filter. This filter brings down chloramine concentrations from 1-2 ppm to less than 0,1 ppm. One must make sure that the active carbon comes into contact with chloramines for a significant amount of time. It should be noted however, that an active carbon filter is a selective, which means that it also removes other compounds, such as chlorine (reduction to chloride), hydrogen sulphide, organic compounds, THM, pesticides and radon. When these compounds are present in water, this will influence the capacity of the filter. The amount of chloramines in the water can be determined by measuring the 'total chlorine' residual, i.e. measuring the 'total amount of chlorine' or the 'amount of chlorine compounds'.

Benefits and Drawbacks of Using Chloramines[3]

Benefits:

- **Few disinfection by-products** - Using chloramines instead of chlorine has its benefits, in that, organic compounds (e.g. trihalomethanes) and other possibly carcinogenic by-products (e.g. halogenic acetic acid) are formed.

- **Chloramines remain active for a long time** - Chloramines remain in the water longer than chlorine. Monochloramines are most effective when the pH value is 7 or higher. When the pH value exceeds 7, the water becomes alkaline, with benefit of which being that the water is less corrosive than acid water. When the pH value is high, chlorine can be found in the water as hypochlorite ions (OCl^-). These ions have a higher oxidation potential than hydrochloric acid, however, as a disinfectant it is a hundred times less effective.

- **Chloramines increase taste and smell of the water** - Chloramines do not alter the pH of the water, however, they provide a better taste and smell than chlorine. Chloramines are often applied to prevent a chlorine taste or smell.

Chloramine disinfection can be improved by raising temperatures.

Drawbacks:

- **Formation of organic chloramines** - When large amounts of organic matter are present in the water, organic nitrogen causes the formation of organic chloramines, which do not possess the same disinfection properties as inorganic chloramines. This situation occurs when organic matter contents exceed the 3 ppm boundary.

- **Reaction rate of chloramines** - The drawback of chloramines is that they are less reactive than chlorine, and a portion of the disinfectant remains in the water, where it will be consumed by bacteria or broken down. This process can take weeks and contrary to chlorine, chloramines do not perish when the water lies still for a few days. As a result chloramines need to be removed from water, which can be done by using granular active carbon or acetic acid.

- **Effectiveness of chloramines** - In Massachusetts, research has been carried out to bring to light the death causes of people that used water disinfected by chlorine or chloramines. When the water was disinfected by chloramines, people were more likely to die from pneumonia or flues, which indicates that chloramines are less effective than chlorine for the elimination of pathogenic micro-organisms.

- **Formation of nitrates** - High amounts of ammonia serve as nutrients for nitrifying bacteria in water, which can cause nitrate levels in the water to rise. Nitrate is converted to nitrite in the stomach, and can react with proteins in fish to form N-nitrosamines. These compounds may be carcinogenic however, where young children are extremely susceptible. When children are younger than 5 months, they cannot drink nitrate-rich water due to the nitrites causing the oxygen level in the blood to fall (Blue Baby Syndrome). It is advised to feed babies with water that has a nitrate content of below 25 μg/l.

- **Corrosion** - When chloramines are chemically removed, ammonia may then be released. The toxic effect that ammonia has on fish can be prevented by the application of biological filters, natural zeolites and pH control. Ammonia causes corrosion of lead and copper, and nowadays, most waterworks are made using lead or copper. To prevent corrosion however, orthophosphates are added.

Health Effects of Chloramines

Water that is disinfected by chloramines does not cause a health threat[3]. It can be used for drinking, bathing and washing and is suitable for several daily domestic purposes.

2.7.6 WHAT IS TOTAL, COMBINED AND FREE CHLORINE

These are the states of existence for the chlorine molecule[60]. If a molecule is free, it has not bonded with or combined with another compound and is therefore available for sanitizing. When free chlorine molecules encounter and destroy a nitrogen or ammonia containing compound, they combine with them to create a combined chlorine compound, or a chloramine. The chloramine is no longer available to sanitize anything, and it floats around in the water, blocking the path of other useful free chlorine molecules. If a strong smell of chlorine is experienced, the reason for this is attributed to the high combined chlorine levels. This level can also be tested with a DPD test kit which measures total and free levels separately and allows the tester to determine combined levels by subtracting the two. Total chlorine is therefore, simply the sum of combined and free levels.

The graph shown below, Figure 2.46[61], depicts the chlorine residual (free chlorine) as a function of increasing the chlorine dosage.

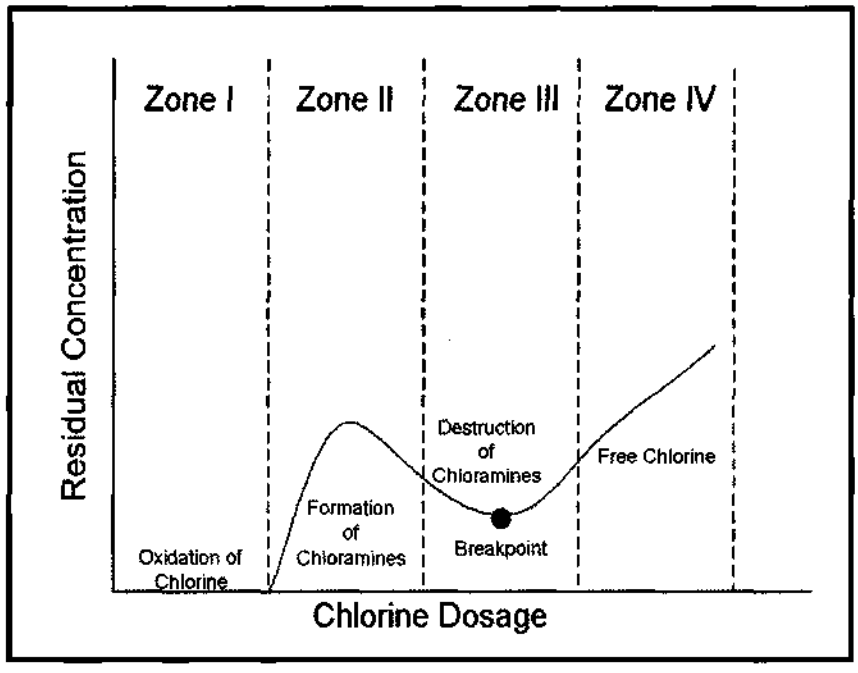

Figure 2.46: Representation of chlorine[61] residual (free chlorine) as a function of increasing the chlorine dosage

Zone I: Chlorine is reduced to chlorides.

Zone II: Chloramines are formed.

Zone III: Chloramines are broken down and converted to nitrogen gas which leaves the system (Breakpoint).

Zone IV: Free residual.

2.7.7 SUPERCHLORINATION

Is usually applied in cases where undesirable organic substances have to be destroyed. The chlorine dosage should be sufficient to satisfy the chlorine demand, i.e. to react chemically with, and destroy the organic substances which produce tastes and odours, and thereafter, to provide a residual of free available chlorine. When the breakpoint is reached, the chlorine demand has been satisfied and the chlorine which is subsequently added remains in solution as free residual chlorine and not as chloramines or other forms of combined available chlorine.

2.8 CASE STUDIES ILLUSTRATING THE INFLUENCE OF TURBIDITY ON THE DISINFECTION OF WATER

The following case studies are presented to illustrate the nature of work that has been carried out with regard to the chlorination of turbid waters, together with the assumptions that have been made. Most of these cases focus on instances whereby chlorination was applied to waters that were not adequately clarified.

2.8.1 The performance of the activated sludge process is often determined by the gravity separation between the treated water and the sludge in the final clarifier[62]. The proliferation of filamentous bacteria in the microbial community of the sludge, referred to as "filamentous bulking," has often been reported to hamper this solid-liquid separation. Filamentous bulking results in less dense and less settleable sludge flocs and in severe cases, the operation of the plant can be totally compromised. The addition of disinfectants (mostly chlorine based) to the sludge to selectively kill off the causative filamentous bacteria is often used in practice as a short-term and cost-effective solution.

Sludge chlorination was adopted as a method of choice in the United States to combat filamentous bulking. Using chlorine, bulking caused by filamentous

bacteria at full-scale treatment plants were successful controlled. However, along with success, occasions of partial success and sometimes failure have also occurred, e.g. Microthrix parvicella bacteria have been found, in certain instances, to be only partially eliminated at high chlorine dosages. The Microthrix parvicella bacteria were observed as being intact in batch tests at very high chlorine doses, while the microbial flocs were completely destroyed. In a recent survey in Italy, it was discovered that the use of chlorination was successful in only 63% of the cases. In most of these cases, no relevant explanation was offered for these unsuccessful cases of sludge chlorination.

2.8.2 Ross[4] studied a situation in which river water containing suspended solids was first chlorinated and then filtered for use in a dairy. An outbreak of paratyphoid fever was traced through the milk back to the water supply, notwithstanding the fact that a chlorine residual had been maintained at all times. An analysis of the available information, lead the authors to conclude the following as the most probable course of events. The initial dose of chlorine applied to the raw water was rapidly converted to the relatively much less active chloramines, whilst pathogens encased in particulate matter were sufficiently protected as to escape elimination. Some active organisms were therefore carried into the small service tank, which was sometimes dangerously near to being empty, and directly into the milk bottles whilst the chloramines were still acting upon them. Before the organisms were killed however, milk was filled into the bottles, the residue of available chlorine neutralised, and the organisms provided with a favourable environment for proliferation.

2.8.3 On 19 July 1991, The North Carolina Department of Environment, Health and Natural Resources (DEHNR), was notified that an outbreak of acute upper respiratory illness had occurred at a summer camp[63]. On August 2, the DEHNR was notified of a similar outbreak during a second session at the camp. The epidemiologic investigation, initiated by the DEHNR on August 7, identified the cause as pharyngoconjunctival fever (PCF), associated with adenovirus type 3.

The first camp session (June 16 - July 12) was attended by 768 boys and 300 counsellors. On July 12, the first-session campers returned home, but counsellors remained at the camp for the second session (July 14 - August 9), which 800 boys attended. Approximately 700 persons swam each day in a 1-acre, manmade pond that had a maximum depth of 3 metres. Well water was continuously pumped into

the pond at multiple sites through pipes located 0.3 metres below the surface of the water. An automatic chlorination system treated the water before it entered the pond, which however, was significantly turbid with plants growing at the bottom. In the first session, 226 persons who had visited the camp infirmary, showed symptoms of upper respiratory illness. During the second session, 369 campers and 86 staff members visited the infirmary with the same upper respiratory manifestations noted. A sample of 181 campers from the second session and 40 staff members at the camp were interviewed. A case of PCF was defined as a combination of two of four possible symptoms, namely, sore throat, fever, coughing and red eyes. The attack rate for those surveyed was 52% with the duration of illness being unknown for five persons. Every camper swam at least once during the 4 weeks; 158 of 175 (90%) swam one or more times per day. The attack rate for campers who swam daily; 74 of 153 (48%) did not differ significantly from that for campers who swam less than once per week; 11 of 17 (65%). The attack rate for infrequent swimmers (i.e. those who swam once per week or less), was 6 of 8 (75%); and for frequent swimmers (i.e., those who swam three or more times per week), was 4 of 5 (80%). A concentrated sample of the pond water was drawn approximately 1.5 metres below the surface which yielded the presence of adenovirus serotype 3 with no residual chlorine. One week after the end of the second session, the pond was drained and the result being that no further outbreaks were reported.

The illness described in this outbreak is consistent with PCF, a syndrome caused by adenovirus (especially serotypes 3 and 7). Because of the turbidity of water in soil-bottom reservoirs, chlorination is ineffective. Turbid water contains organic molecules (e.g. humic and fulvic acids from plant decay) that react with chlorine, generating trihalomethanes (THM), especially chloroform (i.e. THM molecules which have no antiviral activity). Viruses may attach or embed themselves in suspended particles present in turbid waters. From here the virus-containing particles precipitate into the sediment where they remain viable in the cooler temperatures until agitated by swimmers.

2.8.4 In the aftermath of the Midwest, Illinois Flood of 1993, public health officials were monitoring for waterborne illnesses, especially in communities where drinking and wastewater treatment plants were off-line for a period of time[64].

At the time of the flood, the floodwaters churned up huge amounts of debris from the river bottoms and carried loads of organic and inorganic materials to the surface. Alternating turbulence and stagnation of river waters also created hospitable conditions for the growth and movement of many pathogenic (disease causing) micro-organisms.

The post storm illnesses arising as a result of the pathogenic material agitated during the storm was due to the occurrence of various bacteria, viruses and protozoa, which still remained in the drinking water subsequent to being treated. As in most cases where illnesses prevail as a result of pathogenic micro-organisms, those affected individuals experienced symptoms that ranged from fever and malaise to the better known gastro-intestinal symptoms such as diarrhoea and stomach aches. Normally, the human intestinal tracts contain many types of harmless bacteria that the body routinely eliminates. However, in this case the affected parties were subjected to prolonged exposures to the pathogens, where pathogens then tend to become opportunistic and lead to illnesses.

2.8.5 Ross reported[4] on studies pertaining to an impounded water supply which received no treatment other than chlorination. The concentration of free residual chlorine in samples collected from household taps after a minimum of 30 minutes contact, varied from 0.1 to 0.5 mg/l and the total residual chlorine was between 0.7 and 1 mg/l. Samples for bacteriological examination collected at the same time, consistently yielded confirmed coliform organisms. Chemical and microscopic examination of these tap samples indicated that the turbidity varied from 3.8 to 84 units. These results were yielded because of the presence of iron rust that occurred due to the mains being corroded; and therefore biological organisms of 2000 standard units were often found.

The author stated that viruses, being much smaller than bacteria, would appear to have more opportunity to become enmeshed in a protective coating of turbidity-contributing materials and thus more opportunity to escape disinfecting action. They also pointed out that data on the effectiveness of chlorine disinfection as determined by laboratory studies conducted under favourable conditions is not applicable to turbid waters. Seldom, if ever, is a natural water as free from contaminants as the chlorine demand-free water used in the laboratory. It is therefore essential to treat water by coagulation and filtration to nearly zero turbidity if chlorination is to be regarded as an effective process.

CHAPTER 3 - LABORATORY PROCEDURES

3.1 OBJECTIVE OF INVESTIGATION

To recap on the information included in the introduction, the primary objective of this research was to identify the nature of those substances that constitute turbidity. The aim of the experimental component of this research was to formulate a graphical relationship for the dosage of disinfectant that is required to obtain a desired turbidity value. The primary objective thereto, is to contribute toward the identification of a more cost-effective solution for efficient disinfection, by establishing a link between disinfection efficiency and turbidity. In this regard, a simple analytical protocol could be developed to improve disinfection operations, thereby contributing to the improvement in operational/analytical procedures currently employed at treatment plants in South Africa and worldwide.

3.2 METHODOLOGY OF INVESTIGATION

The primary step in investigating the effect of turbidity on the efficiency of chlorine disinfection is to define the interactions of the main variables involved in the system, namely, chlorine, micro-organisms, turbidity and the aqueous medium (refer to Figure 3.1).

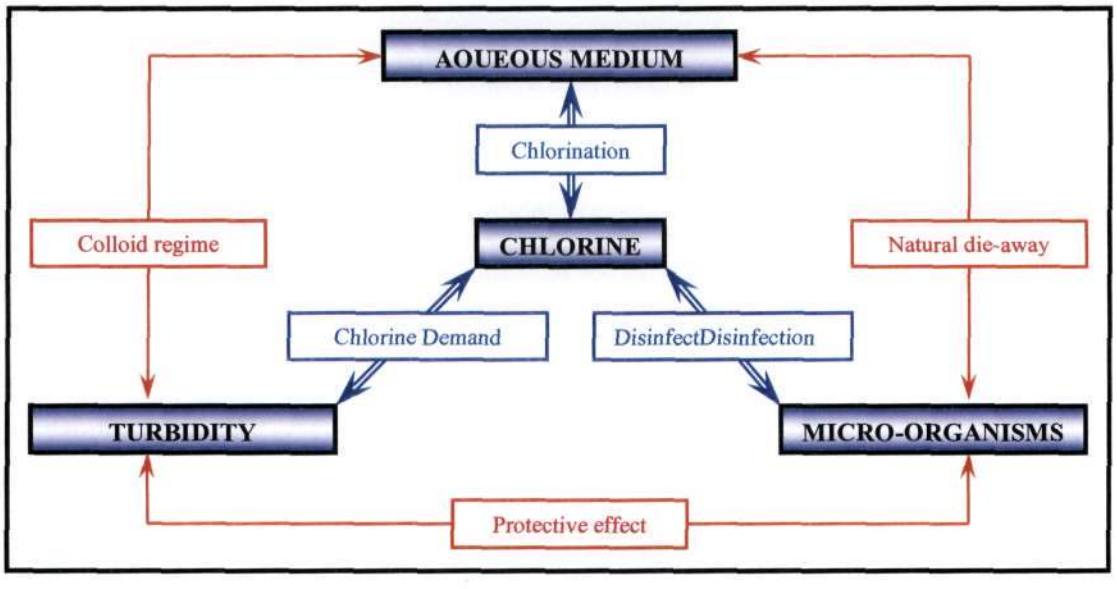

Figure 3.1 : Overview of relationship between turbidity and chlorine disinfection

Emphasis has also been placed on the types and general properties of particulate matter that constitute turbidity in water, together with their interaction with micro-organisms by means of adsorption, bridging and enmeshment. Most treatment plants use a sizeable portion of their investment costs on facilities for the removal of turbidity, and it is therefore of much significance to discuss the factors influencing the clarification of water in the various unit processes and operations, so as to provide a basis for improved operation. The literature review provides a detailed description of chlorination chemistry (section 2.7) and the aspects that influence the disinfection of water.

The laboratory procedures were conducted at the Wallmannsthal Bulk Water Treatment Works (see figure 3.2), with all materials and equipment being made available by personnel employed on the abovementioned plant. As a means of obtaining results that were as accurate as possible, actual plant operating conditions have been simulated wherever possible.

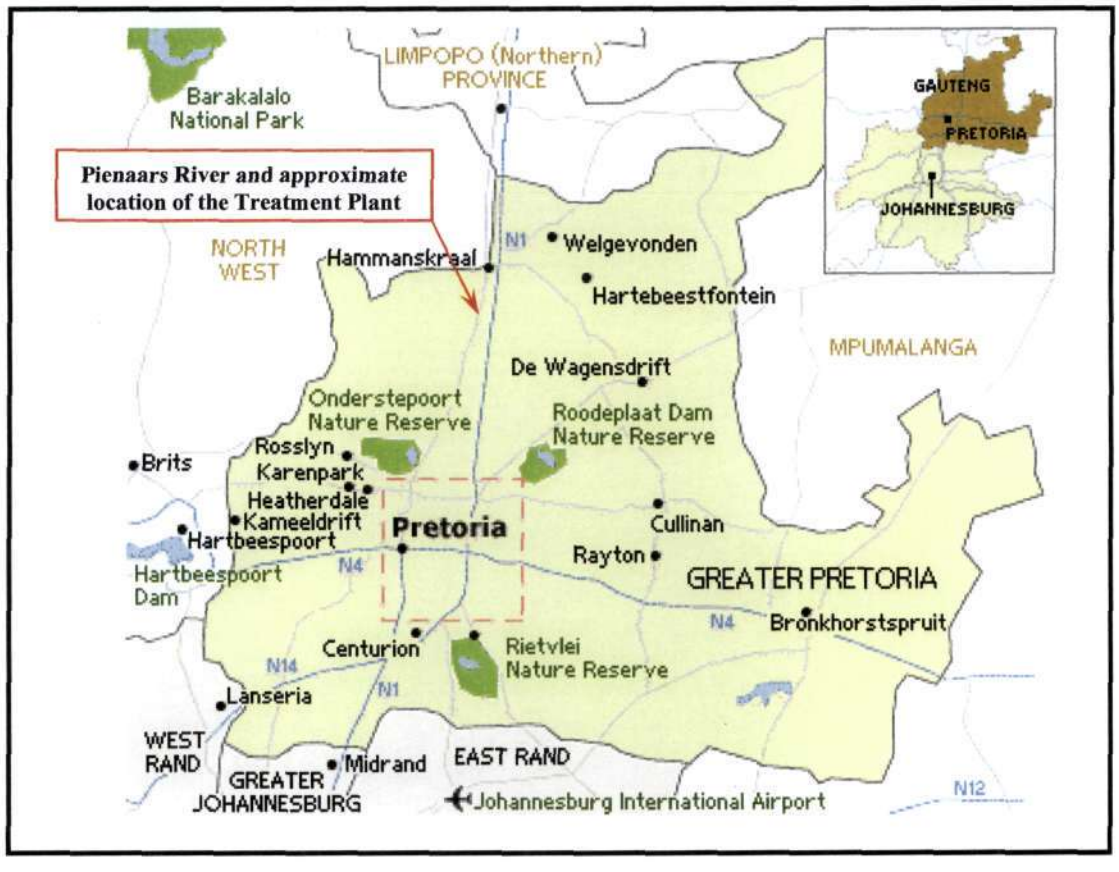

Figure 3.2 : Map showing the route of the Pienaars River and approximate location of the Wallmannsthal Bulk Water Treatment Plant

3.3 EXPERIMENTAL SYSTEM

3.3.1 DISINFECTANT AND SAMPLING TECHNIQUES

Although gas chlorination techniques are predominantly practiced on water treatment plants, solid chlorine compounds can also be used to obtain the desired effects. The key is to prepare a higher concentrate of chlorine solution so that a chlorine dosage equivalent to 100 % gas chlorine can be obtained. Calcium Hypochlorite, $Ca(OCl)_2$, which is the disinfecting compound that was used in the laboratory experiments, has a chlorine concentration that is equivalent to 70 % of the gas chlorine utilized in the Wallmannsthal Bulk Water Treatment Plant.

The logic employed in formulating the most effective sampling technique, was to establish a test system that would provide a wide range of comparative data. Bearing in mind the processes that comprise the water treatment cycle, it would be ideal to identify sample extraction points where the water was the most turbid, where the water was the least turbid (but prior to it being disinfected), as well as an additional extraction point that was intermediately located between the other two. In this regard, and while taking cognisance of the abovementioned logic, it was decided that the optimum method of sampling was to extract a water sample from the raw water entering the treatment plant (Pienaars River), a clarified water sample (intermediate) and a filtrate water sample (last point before disinfection). The result of obtaining samples at three different stages of the water treatment cycle, was that each sample type exuded characteristics that were distinctly different from the other two (characteristics listed in Chapter 4)

At each extraction point, a pair of 800 ml beakers was filled with the water occurring at these extraction points, providing two quantities of each sample type, thus provided a total of six samples in all (refer to Section 3.4.2 for further elaboration). In each pair of sample types, one was used as a control system for monitoring the testing environment, and the other was dosed with the chlorine disinfectant (elaborated upon in Chapter 4). The control system served as an indicator to identify whether the properties of the test solutions were being altered by external conditions, e.g. a change in temperature alone has the potential to affect the properties of the test solutions. By constant measurement of the turbidity and pH of the control system to identify any significant property changes, it was possible to ascertain whether the characteristics of the test solutions were also being altered.

3.3.2 EXPERIMENTAL PROCEDURE

The disinfection solution was prepared (refer to section 3.4.2) and stored in a closed measuring cylinder together with the six test samples that were placed on the jar test apparatus, where mixing for 15 minutes at 100 rpm took place. Only three of the six test samples, one from each control point, were dosed with the disinfection solution while the remaining three served as a control system, thus providing a comparison to ensure the correctness of the measuring equipment at all times. The samples' pH, turbidity and initial amount of chlorine present were measured prior to the addition of the Calcium Hypochlorite disinfectant.

The amount of disinfectant added to each test sample had to be sufficient to ensure that chlorine residual remained in each sample after the chlorine demand had been satisfied. Keeping the above in mind, a 2.5 ml pipette was used to transfer the disinfectant to the test samples. After doing this, simulation of the retention time applicable to the Wallmannsthal Treatment Plant oxidation process was then attempted. On addition of the disinfectant solution, the samples were again stirred but on this occasion, it was for 30 minutes at 100 rpm.

On close inspection of the solutions, the formation of flocs was visible in the clarified water sample. The coagulation process, initiated by the stirring apparatus, promoted the formation of tiny flocs, which therefore indicates the presence of the ion exchange phenomena that occurs in water.

After the 30 minutes had elapsed, two 50 ml samples was drawn from each beaker and covered so that no interference or evaporation of the chlorine residual, which was now assumed to be present, would take place. The pH, turbidity and chlorine residual were once again measured, and an analysis comparing the information before and after the addition of the Calcium Hypochlorite disinfectant, was subsequently performed.

3.4 MATERIALS

3.4.1 PREPARATION OF CHLORINE DOSAGE SAMPLE

The chlorine compound that was selected (Calcium Hypochlorite or $Ca(OCl)_2$), is the same disinfectant that is used in pools i.e. hth.

As a consequence of gas chlorination methods being used on the Wallmannsthal Bulk Water Treatment Plant, and the objective of trying to replicate these treatment procedures, the hth was converted to a concentration that was similar to that being used in the gas chlorinators.

A ratio of one part per million (1 ppm) was sought after and should pure chlorine be used, as used in gas chlorination systems, a simple dosage of 0.1 gram of pure chlorine per 100 ml of test solution would be required. As a result of collecting 800 ml of each test solution, and bearing in mind the required ratios that must be obtained, a chlorine dosage of 0.8 grams of pure chlorine was required. In this situation however, calcium hypochlorite which only comprises 70 % of pure chlorine was to be used, and therefore, the following conversion factor had to be incorporated:

$$0.8g \times \frac{100}{70} = 1.14 \text{ grams of } Ca(OCl)_2 \text{ per 800 ml of test solution}$$

The 1.14 grams of $Ca(OCl)_2$ was then emptied into a measuring cylinder and mixed with distilled water to produce a litre of chlorine disinfectant solution.

3.4.2 SELECTION OF WATER SAMPLES

As introduced in Section 3.3.2, three points occurring along the water treatment cycle were strategically identified as the sample extraction points. The six samples that were obtained, which constituted two quantities of each sample type, include:

- The Pienaars River from where two raw water samples were drawn.
- The sedimentation tank outflow point from where two samples of the clarified water was collected.
- The filtration tank from where two samples of the filtrate were also drawn.

3.4.3 PREPARATION OF TEST SOLUTIONS

All glassware that was used in the disinfection tests had to first be treated in order to satisfy any chlorine demand thereof. The beakers, into which the test solutions were poured, were washed

thoroughly with a neutral soap agent and rinsed first in tap, and then distilled water. The test samples were drawn at points on the treatment plant where chlorine addition had already taken place, therefore, the amount of chlorine present in each test sample prior to proceeding with any of the experimental procedures were first measured (these values were used as the "zero reference" for further chlorine addition). The beakers were then placed on the Jar Test Apparatus where it was stirred for 15 minutes at 100 rpm.

3.4.4 CHLORINE INDICATOR

Due to the reasons outlined in Section 3.4.3, all six of the test samples mentioned in Sections 3.3.1 and 3.4.2, had to be tested to reveal the amount of chlorine present before any experimental procedures could take place. The frequency of sampling, included two quantities of each sample type, and the frequency of testing was twice, i.e. both of the samples obtained at each of the extraction points were tested prior to the addition of the chlorine disinfectant to ensure the accuracy and consistency of the measured results. Upon addition of the chlorine disinfectant, the control system for each extraction point (see Section 3.3.1), as well the two corresponding 50 ml test systems (as indicated in Section 3.3.2), were subjected to chlorine tests.

The chlorine indicator used in the laboratory experiments was the N-diethyl-p-phenylenediamine (DPD) indicator. The principle of using DPD is based on the fact that free available chlorine reacts instantly with the N, N-diethyl-p-phenylenediamine (DPD) indicator in the absence of iodide ions to produce a red colour.

This DPD indicator was readily available in sachets that were added to a specific amount of each test sample i.e. 50 ml of each water sample. An initial red colour is the first indication that chlorine is present and confirmation of this can then be received by placing the 50 ml sample in a chlorine metre (photometer) where UV light is passed through the sample and the measure of the amount of chlorine present in the water is thus indicated.

3.5 INSTRUMENTATION

Various instruments including the pH meter, nephelometer and chlorine photometer were used to monitor the experimental systems and to compare the related parameters. It should also be

noted that each of the abovementioned experimental procedures were repeated for all three test samples and were administered before and after the addition of the chlorine disinfectant.

3.5.1 NEPHELOMETER

CALIBRATION

Formazin was selected as the calibration standard for the laboratory work. Its reproducibility was relatively simple and involved the following key steps:

1) **Reagent water:** Distilled water was passed through a 0.45µ pore size membrane filter.

2) **Stock standard suspension (Formazin):**

- 1 g of hydrazine sulfate, $(NH_2)_2.H_2SO_4$, was dissolved in reagent water and diluted to 100 ml in a volumetric flask.
- 1 g of hexamethylenetetramine was dissolved in reagent water and diluted to 100 ml in a volumetric flask.
- In a separate 100 ml volumetric flask, 5 ml of each of the above two solutions were added and then allowed to stand for 24 hours after which, the flask was filled with 90 ml of reagent water to produce 100 ml of solution (referred to as the stock standard suspension).

3) **Primary calibration standards:** 10 mL of the stock standard suspension was then diluted and mixed with reagent water to produce 100 ml of solution. The turbidity of this suspension is defined as 40 NTU.

Due to the turbidity trends of the Pienaars River (the raw water source entering the Wallmannsthal Treatment Works) already being known, the calibration range of up to 40 NTU was sufficient for measurement requirements. The 40 NTU sample was then measured using the nephelometer. The meter reading deviated slightly from the desired result, however, the reading was still within the allowable 5% deviation tolerance.

USE DURING EXPERIMENTATION

The instrument used during the turbidity measurements was of a good quality as it is designed to minimize stray light from reaching the detector in the absence of turbidity, and to be free from significant drift after a short warm-up period. Furthermore, in order to obtain readings that were as accurate as possible, the following design criteria were adhered to:

- Light source – A tungsten filament lamp was used.
- The distance traversed by the incident light and scattered light within the sample tube did not exceed 10 cm.
- The angle of light acceptance by the detector – Was centred, as accurately as possible, at 90 degrees to the incident light path.
- Clear and colourless glass beakers were used, which were devoid of any large scratches or etching.
- The samples were agitated by rapid mixing via the jar test apparatus to break up large flocs and sediments.
- The beakers were also cleaned by thorough washing with laboratory soap inside and out, followed by multiple rinses with distilled water. The beakers were then left to air-dry and careful consideration was taken to handle these beakers only by the top to avoid dirt and fingerprints within the light path.

3.5.2 pH METER

CALIBRATION

The first step was to clear the pH meter of its existing standardization. The "pen-like" electrode, which was immersed in a bottle of storage solution, was then rinsed off with distilled water. The electrode was then immersed in a pH 7 buffer solution, while gently swirling the solution to ensure that the electrode had been fully saturated with the buffer. The standardization button was then pressed to enable a reading of the pH 7 buffer solution to be taken. After a stable reading was taken the meter would automatically return to the "measure screen". The electrode is then removed from the pH 7 buffer solution and rinsed once again with distilled water. The electrode is thereafter immersed in the pH 10 buffer solution (the solution has a blue appearance), which was swirled yet again. The standardization button was

pushed again for calibration with the second buffer solution. Once a stable reading was drawn, the meter would display a calibration slope and return to the "measure screen", which serves to indicate that the meter has been calibrated and is ready to measure the pH of any solution.

USE DURING EXPERIMENTATION

The electrode was simply immersed in the sample solution, where the value of the sample's pH was then provided by the digital meter, which is connected to the electrode. The electrode serves as the sensing mechanism that transfers the sample's level of alkalinity to the transmitting unit (digital meter).

3.5.3 PHOTOMETER

CALIBRATION

The photometer used in this investigation is a portable apparatus that functions with the principle of passing ultraviolet light through a water sample, where the nature of the light that exits the sample is analysed by this instrument to reveal the chlorine concentration of the sample.

Similar to the above two calibration processes, a sample containing a chlorine concentration of 2 mg/l (2 PPM) was used to confirm the accuracy of the apparatus (the procedure for measurement is indicated in section 3.2.4). The reading indicated by the photometer corresponded with the chlorine concentration prevailing in the calibration sample, i.e. 2 mg/l and was therefore, deemed suitable for the experimental procedure at hand.

Should the situation arise whereby the meter reading differs significantly from the calibration sample, the apparatus would then be regarded as being unusable, as it is not possible for the end user to make the necessary adjustments to the instrument.

USE DURING EXPERIMENTATION

A 50 ml cylindrical glass tube (cuvette) was half filled with water samples that were drawn at the three selected control points. To ensure the accuracy of all readings, careful consideration

was also placed on the handling of the cuvettes to make sure that the transmitting surface of the tube remains clean and scratch-free. The tubes were placed individually in the photometer (in a compartment known as the optical well) with the cover of the sensing compartment being closed to ensure that the UV light remains unaffected by any external sources. Upon placement in the optical well, the instrument is zeroed and the sample is then removed from the optical well. The N-diethyl-p-phenylenediamine (DPD) indicator is then dispensed and mixed thoroughly with sample. The sample was then allowed to stand for approximately 2 minutes to allow for the completion of the chemical reaction between the sample and the reagent. The read button was then pressed and the chlorine concentration was subsequently displayed via the digital meter read-out.

CHAPTER 4 - RESULTS AND DISCUSSION

The results of all experiments performed are discussed below, together with the appropriate tabulations.

4.1 INITIAL PH, TURBIDITY AND CHLORINE CONTENT

All samples were first tested to identify the possibility of chlorine compounds already existing prior to the addition of the Calcium Hypochlorite, $Ca(OCL)_2$ disinfectant. The chlorine content of each sample was as follows:

- The raw water sample contained 0.19 mg/l
- The clarified sample contained 0.05 mg/l
- The filtrate contained 0.02 mg/l

It should be noted that the control points that were selected, were done so as a means of obtaining water samples that were dissimilar in their chemical composition. In this regard, the variation in the results obtained applicable to the existing chlorine concentrations of the three test samples prior to disinfection, was the intended aim. In simple terms, the greater the disparity between the test samples, the more magnified are the results.

The abovementioned chlorine concentrations were used in the establishment of a 'common reference point' for developing comparisons between the results received for the various test samples (elaborated upon in section 4.4.1). Tables 4.1, 4.2 and 4.3, indicates the values that were measured with reference to the pH, turbidity and chlorine addition, prior to the addition of $Ca(OCL)_2$.

Table 4.1 Recordings for the raw water sample prior to the addition of $Ca(OCL)_2$

	RAW WATER	
	SAMPLE 1	**SAMPLE 2 (CONTROL)**
pH	8	8
TURBIDITY (NTU)	16	16
CHLORINE CONTENT (mg/l)	0.19	0.19

Table 4.2 Recordings for the clarified water sample prior to the addition of $Ca(OCL)_2$

	CLARIFIED WATER	
	SAMPLE 3	SAMPLE 4 (CONTROL)
pH	8.38	8.38
TURBIDITY (NTU)	1.97	1.97
CHLORINE CONTENT (mg/l)	0.05	0.05

Table 4.3 Recordings for the filtrate water sample prior to the addition of $Ca(OCL)_2$

	FILTRATE	
	SAMPLE 5	SAMPLE 6 (CONTROL)
pH	8.01	8.01
TURBIDITY (NTU)	0.64	0.64
CHLORINE CONTENT (mg/l)	0.02	0.02

4.2 FINAL PH, TURBIDITY AND CHLORINE RESIDUAL

Following the addition of the $Ca(OCl)_2$ disinfectant, the samples were placed in the jar test apparatus to ensure that the disinfectant was thoroughly mixed with the existing sample constituents. As indicated in section 3.4.2, each test sample was then transferred into two 50 ml beakers, giving two test quantities of each sample type, where the pH, turbidity and chlorine concentrations of each sample were then measured. The results of these measurements are indicated in Tables 4.4, 4.5 and 4.6.

Also included in Tables 4.4 to 4.6, are the mean or average[65] values, which have been calculated using the following equation:

$$\bar{x} = \frac{1}{N}\sum_{i=1}^{N} x_i = \frac{x_1 + x_2 + \ldots + x_N}{N}$$

Where $\bar{x}$ = Mean or average

$x_1 + x_2 + \ldots + x_N$ = The measured parameters for each individual test sample

N = The number of parameters that were measured

Table 4.4 Recordings for the raw water sample after adding $Ca(OCL)_2$

	RAW WATER			
	SAMPLE 1a (50 ml)	SAMPLE 1b (50 ml)	AVERAGE	SAMPLE 2 (CONTROL)
pH	8.06	8.05	8.055	8
TURBIDITY (NTU)	14.87	14.91	14.89	16
CHLORINE RESIDUAL (mg/l)	0.45	0.47	0.46	0.19

Table 4.5 Recordings for the clarified water sample after adding $Ca(OCL)_2$

	CLARIFIED WATER			
	SAMPLE 3a (50 ml)	SAMPLE 3b (50 ml)	AVERAGE	SAMPLE 4 (CONTROL)
pH	8.40	8.40	8.40	8.38
TURBIDITY (NTU)	1.68	1.67	1.675	1.97
CHLORINE RESIDUAL (mg/l)	0.89	0.88	0.885	0.05

Table 4.6 Recordings for the filtrate water sample after adding $Ca(OCL)_2$

	FILTRATE			
	SAMPLE 5a (50 ml)	SAMPLE 5b (50 ml)	AVERAGE	SAMPLE 6 (CONTROL)
pH	8.15	8.17	8.16	8.01
TURBIDITY (NTU)	0.55	0.54	0.545	0.64
CHLORINE RESIDUAL (mg/l)	0.98	1.01	0.995	0.02

As a means of evaluating the accuracy of the test results, the pH, turbidity and chlorine residual measurements for each individual test sample were compared to their respective averages (averages included in Tables 4.4 to 4.6). Although the test results appeared to be relatively close to their respective averages, accuracy checks were conducted by means of tabulating the standard deviation of each sample from its respective average value (see Section 4.3 below).

4.3 STANDARD DEVIATIONS

As indicated above, all deviations from the average or mean value was calculated using the following Standard Deviation Equation[65]:

$$s = \sqrt{\frac{1}{N-1}\sum_{i=1}^{N}(x_i - \bar{x})^2}$$

Where s = Standard Deviation

x_i = The measured parameters for each individual test sample

$\bar{x}$ = Mean or average

N = The number of parameters that were measured

RAW WATER

The standard deviations for the raw water samples are included in Table 4.7. Due to the average being calculated for only two samples, i.e. Samples 1a and 1b, the standard deviation from the mean value will be the same for both samples.

Table 4.7 Standard deviations for the raw water sample

	RAW WATER			
	SAMPLE 1a (50 ml)	**SAMPLE 1b (50 ml)**	**AVERAGE**	**STANDARD DEVIATION**
pH	8.06	8.05	8.055	0.005
TURBIDITY (NTU)	14.87	14.91	14.89	0.02
CHLORINE RESIDUAL (mg/l)	0.45	0.47	0.46	0.01

CLARIFIED WATER

The standard deviation for the clarified water samples are included in Table 4.8.

FILTRATE

The standard deviations for the filtrate water samples are included in Table 4.9.

Table 4.8 Standard deviations for the clarified water sample

	CLARIFIED WATER			
	SAMPLE 3a (50 ml)	SAMPLE 3b (50 ml)	AVERAGE	STANDARD DEVIATION
pH	8.40	8.40	8.40	0.0
TURBIDITY (NTU)	1.68	1.67	1.675	0.005
CHLORINE RESIDUAL (mg/l)	0.89	0.88	0.885	0.005

Table 4.9 Standard deviations for the filtrate water sample

	FILTRATE			
	SAMPLE 5a (50 ml)	SAMPLE 5b (50 ml)	AVERAGE	STANDARD DEVIATION
pH	8.15	8.17	8.16	0.01
TURBIDITY (NTU)	0.55	0.54	0.545	0.005
CHLORINE RESIDUAL (mg/l)	0.98	1.01	0.995	0.015

4.4 DETERMINATION OF FREE AVAILABLE CHLORINE

To determine the amount of chlorine remaining in the test samples after being treated with the $Ca(OCL)_2$ disinfectant, the chlorine photometer was used. The chlorine demand was then calculated using the below equation, with the tabulated results captured in Table 4.10.

Chlorine Demand = (Initial Chlorine Content + Chlorine Added) – Chlorine Residual

Table 4.10 Breakdown of the chlorine usage

TEST SYSTEM		INITIAL CHLORINE CONTENT (mg/l CL)	CHLORINE ADDED (mg/l CL)	CHLORINE RESIDUAL (mg/l CL)	CHLORINE DEMAND (mg/l CL)
RAW WATER	Average	0.19	1.0	0.46	0.73
CLARIFIED WATER	Average	0.05	1.0	0.885	0.165
FILTRATE	Average	0.02	1.0	0.995	0.025

4.5 GRAPHICAL REPRESENTATION AND DISCUSSION OF COMPARISONS IN DATA

4.5.1 TURBIDITY AS A FUNCTION OF CHLORINE

The tables contained in sections 4.1 and 4.2 provide a summary of the results obtained during the laboratory experiments. As a means of deriving a relationship between turbidity and chlorine, i.e. the amount of chlorine disinfectant that is required to produce a corresponding turbidity value, the results of the experimental procedures have been represented by graphical means in Figures 4.1, 4.2 and 4.3.

Table 4.11 Breakdown of the chlorine usage and turbidity change

TEST SYSTEM		CHLORINE RESIDUAL (mg/l)		TURBIDITY (NTU)	
		INITIAL	FINAL	INITIAL	FINAL
RAW WATER	Average	1.19	0.46	16	14.89
CLARIFIED WATER	Average	1.05	0.885	1.97	1.675
FILTRATE	Average	1.02	0.995	0.64	0.545

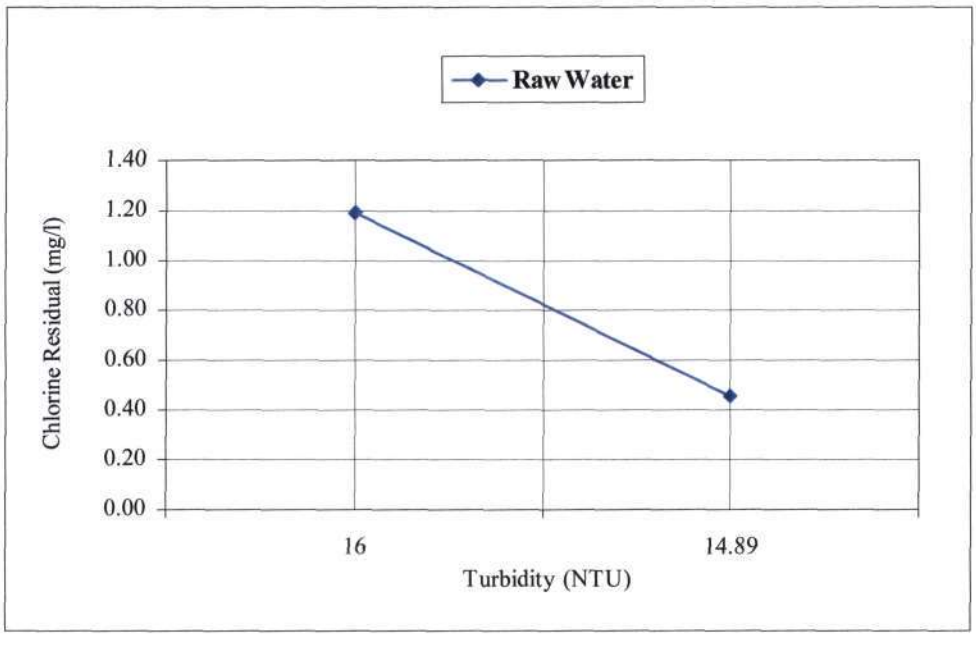

Figure 4.1: Graph illustrating the relationship between chlorine and turbidity in the raw water sample

Gradient = dY / dX = 0.658

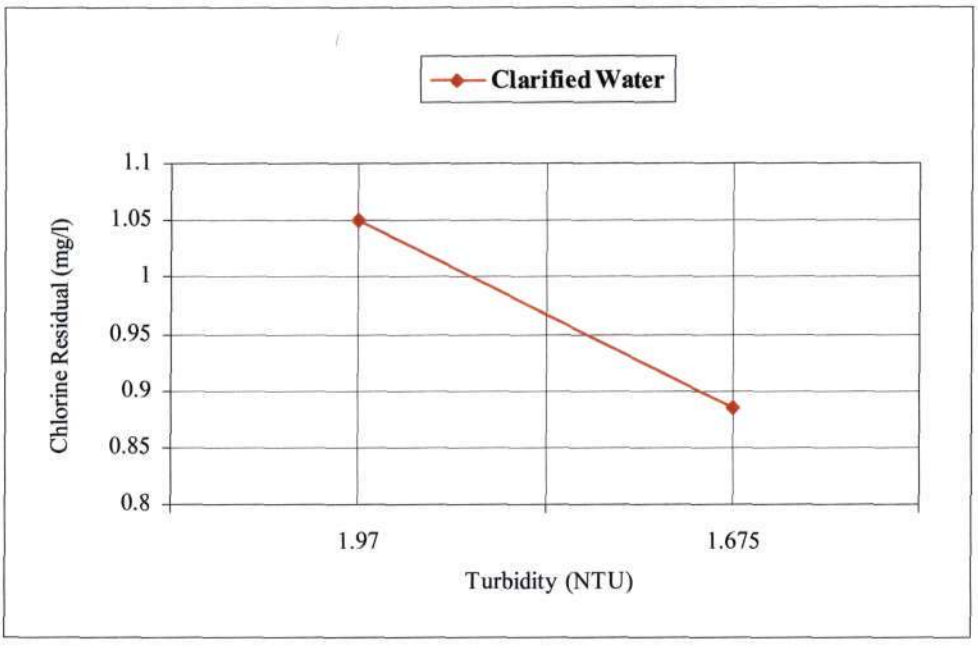

Figure 4.2: Graph illustrating the relationship between chlorine and turbidity in the clarified water sample

Gradient = dY / dX = 0.559

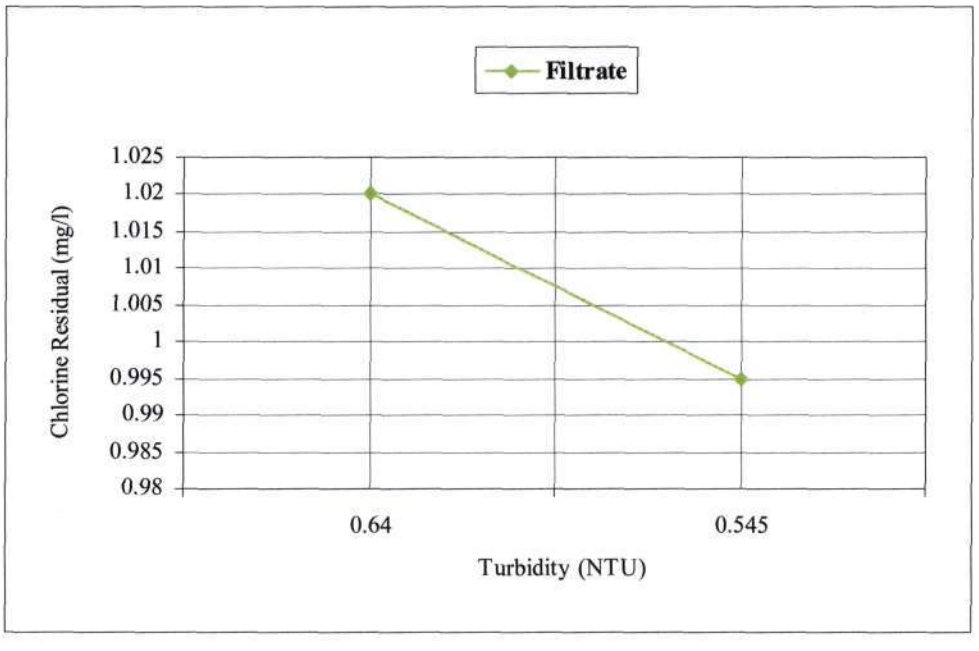

Figure 4.3: Graph illustrating the relationship between chlorine and turbidity in the filtrate water sample

Gradient = dY / dX = 0.263

The gradient (or slope) of each graph has been calculated so that a more distinctive means of comparison can be established. Simply stated with specific reference to the abovementioned graphs, the gradient represents the amount of chlorine that was required for a magnitude of change in the turbidity. The progress/efficiency of the disinfectant is therefore indicated by a decrease in the NTU value, i.e. a decrease in the chlorine residual amount is directly proportional to the decrease in the turbidity value. In this regard, the steeper the gradient of the graph, the greater is the chlorine demand of the sample. If we compare the three graphs while bearing this in mind, the gradient decreases from a maximum in the raw water sample to a minimum in the filtrate.

In light of the above, a guideline disinfection curve can therefore be developed to illustrate the amount of chlorine that is required to obtain a desired turbidity value (Figure 4.4). Although the type of material that constitutes a water's turbidity also plays a significant role in the correctness or usefulness of this graph/curve, it can however, serve as a basis for the development of more specialised graphical guidelines (elaborated upon in the conclusion). Table 4.12 provides the data that is used to formulate the disinfection curve. It should also be noted that this investigation was focused on water that falls within the turbidity range of 0.64 and 16 NTU, and which has been subjected to approximately 30 minutes of contact time with the $Ca(OCL)_2$ disinfectant. This curve should therefore, not be extrapolated for use outside this turbidity range, or in instances where the contact time is longer or shorter than 30 minutes.

Table 4.12 Breakdown of chlorine demand and change in turbidity

TEST SYSTEM		CHLORINE DEMAND (mg/l)	CHANGE IN TURBIDITY (NTU)
FILTRATE	**Average**	0.025	0.64 - 0.545 = **0.095**
CLARIFIED WATER	**Average**	0.165	1.97 - 1.675 = **0.295**
RAW WATER	**Average**	0.73	16 - 14.89 = **1.11**

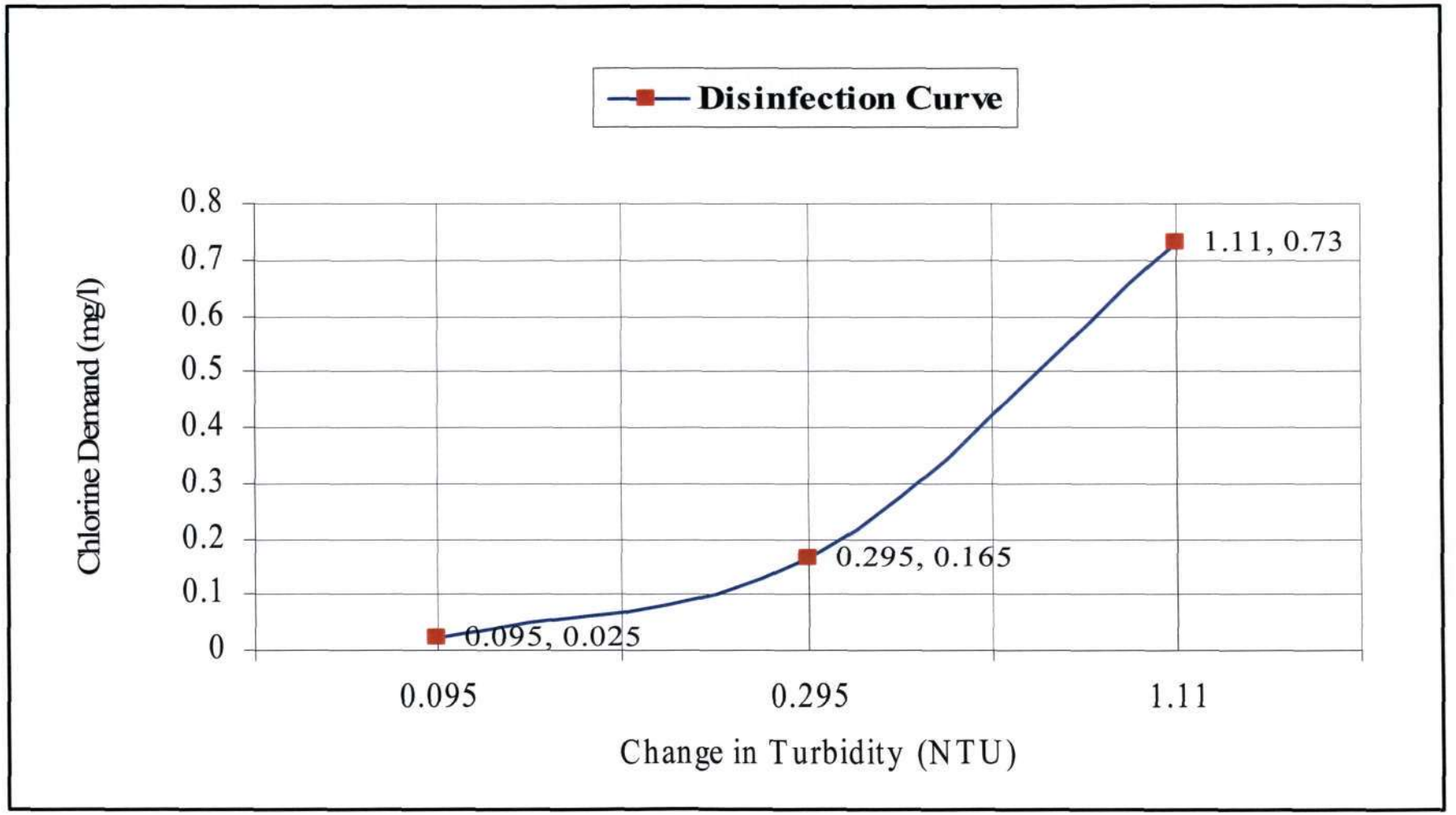

Figure 4.4: Disinfection Curve

4.5.2 pH AS A FUNCTION OF TURBIDITY

Although not being an aim of this experimental investigation, it was however, interesting to also examine the relationships between certain other parameters that were affected during the investigation. The pH value of the test systems were also monitored to ascertain whether the addition of the $Ca(OCL)_2$ disinfectant would also bring about a change in a samples pH, and if so, what is the magnitude of such a change.

It was observed that the pH of the test solutions was also being altered by the addition of the $Ca(OCL)_2$ disinfectant. It was therefore, also possible to represent the relationship between pH and turbidity for each of the test solutions by graphical means. The pH refers to the acidic or basic tendencies of a solution, and in theory, an adjustment in the turbidity of a solution will subsequently result in an alteration to the solution's physical and chemical properties. This will therefore, affect the acidic/basic nature of the solution, and thereby affecting the pH of the same solution.

With this in mind, the chemical characteristics of the substances that bring about changes in a water's turbidity (disinfectant), must also be regarded as one of the critical parameters for determining the subsequent changes in pH. In treatment plant processes, the series of treatment processes that facilitate the removal of unwanted substances from water are performed in a manner that ensures that the pH remains between a specified range at the various steps within the water treatment cycle.

The information that was captured during experimentation is included in Table 4.13, and the relationships between pH and turbidity are represented graphically in Figures 4.5, 4.6 and 4.7.

Table 4.13 Breakdown of the change in pH and turbidity

TEST SYSTEM		pH		TURBIDITY (NTU)	
		INITIAL	FINAL	INITIAL	FINAL
RAW WATER	Average	8	8.055	16	14.89
CLARIFIED WATER	Average	8.38	8.40	1.97	1.675
FILTRATE	Average	8.01	8.16	0.64	0.545

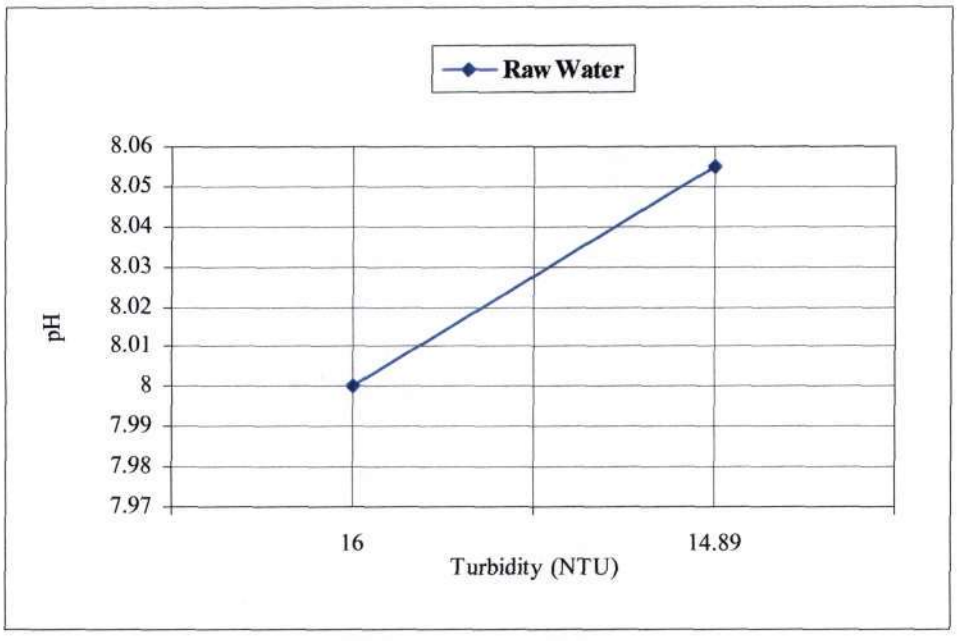

Figure 4.5: Graph illustrating the relationship between pH and turbidity in the raw water sample

Gradient = dY / dX = -0.05

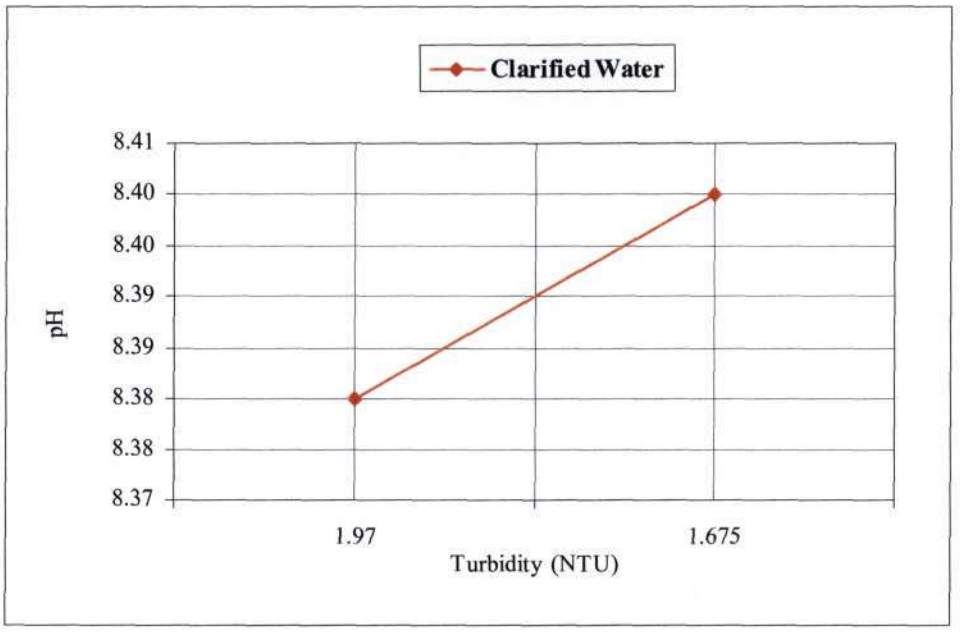

Figure 4.6: Graph illustrating the relationship between pH and turbidity in the clarified water sample

Gradient = dY / dX = -0.068

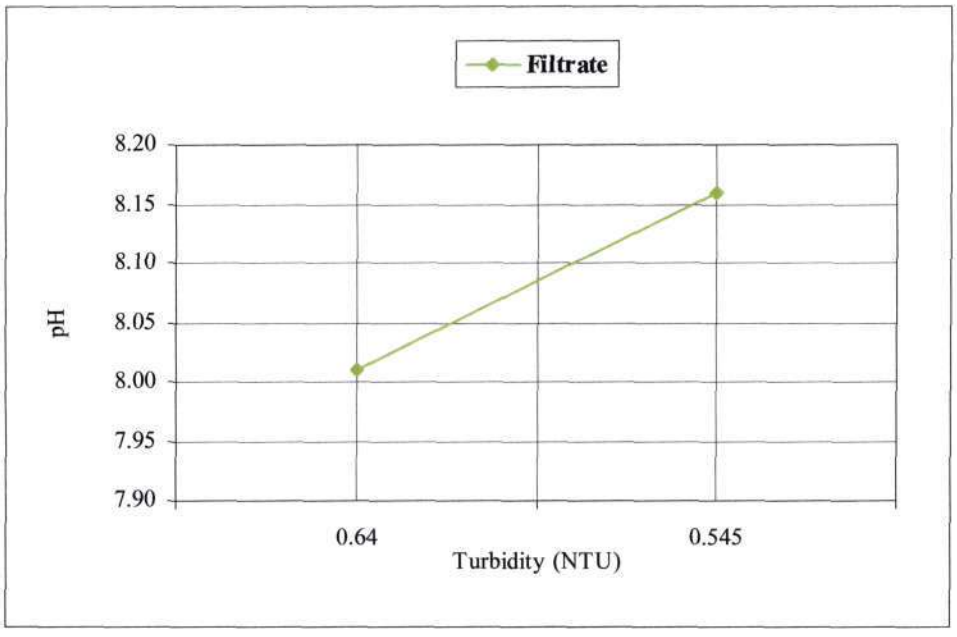

Figure 4.7: Graph illustrating the relationship between pH and turbidity in the filtrate water sample

Gradient = dY / dX = -1.579

The gradients are again utilised to analyse the graphs and to draw a comparison between the three. In this instance, the gradient denotes the changes to the pH of each solution in relation to the turbidity changes. Plainly stated, the steeper the gradient, the greater is the pH change in relation to the turbidity change. The negative sign is merely an indication that one parameter increases as the other decrease, i.e. inverse proportionality.

In the above graphs (Figure 4.5, 4.6 and 4.7), the gradients are at the highest in the filtrate sample, and at the lowest in the raw water sample. This implies that the filtrate sample experienced the largest change in pH in comparison to the subsequent change in the sample's turbidity value. This can be attributed to a number of reasons, but if we concentrate only on the influence of turbidity in this instance, the following can be deduced: the matter that constitutes turbidity in water becomes more prominent, with regard to its effect on the pH of the same water, as the turbidity of the water decrease. However, if we focus on the effect of adding the $Ca(OCL)_2$ disinfectant to the test samples, then the following logic can be applied: due to the filtrate being less turbid than the other two samples, and by using a constant dose of disinfectant, the chemical properties of the filtrate water were more susceptible to change.

4.5.3 PH AS A FUNCTION OF CHLORINE

Similar to section 4.4.2, the relationship between pH and chlorine is also interesting to examine, as the addition of the calcium hypochlorite disinfectant should have an influential role in the altering of the pH value of the test samples. As mentioned in section 4.4.2, pH refers to the acidic or basic nature of water, therefore, the addition of the $Ca(OCL)_2$ disinfectant should stimulate a change in the chemical state of a solution, and will hence, alter the pH of the same solution. The information captured during the laboratory work is indicated in Table 4.14 and the relationships between the pH and chlorine are represented graphically in Figures 4.8, 4.9 and 4.10.

Table 4.14 Breakdown of the change in pH and chlorine usage

TEST SYSTEM		pH		CHLORINE RESIDUAL (mg/l)	
		INITIAL	FINAL	INITIAL	FINAL
RAW WATER	Average	8	8.055	1.19	0.46
CLARIFIED WATER	Average	8.38	8.40	1.05	0.885
FILTRATE	Average	8.01	8.16	1.02	0.995

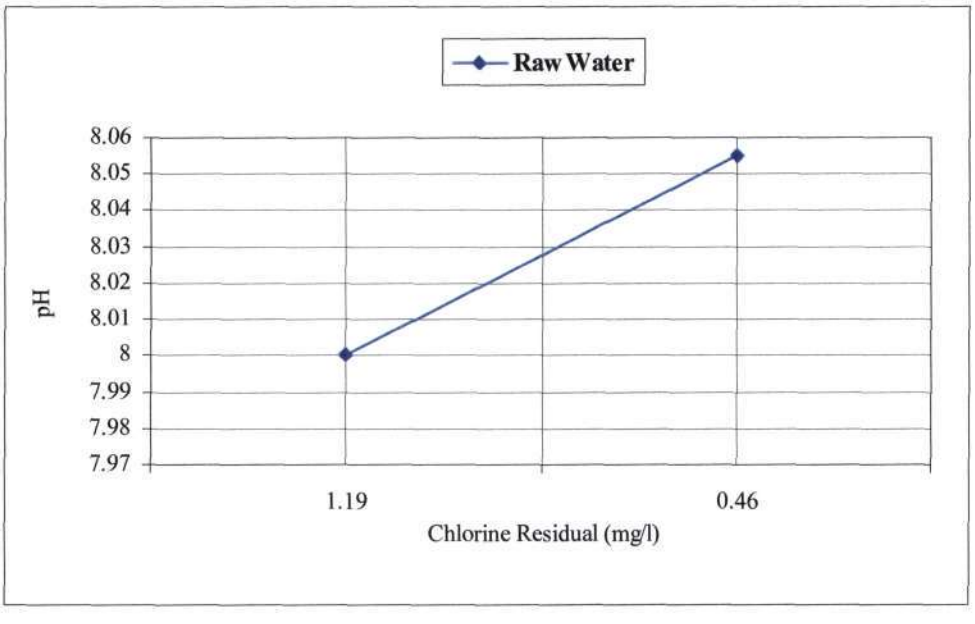

Figure 4.8: Graph illustrating the relationship between pH and chlorine in the raw water sample

Gradient = dY / dX = -0.075

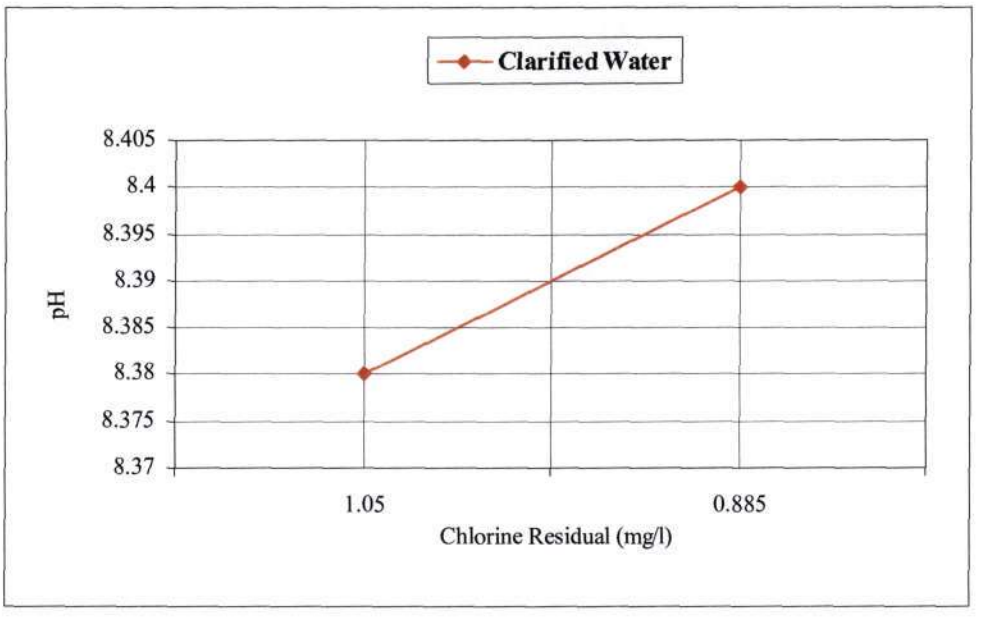

Figure 4.9: Graph illustrating the relationship between pH and chlorine in the clarified water sample

Gradient = dY / dX = -0.121

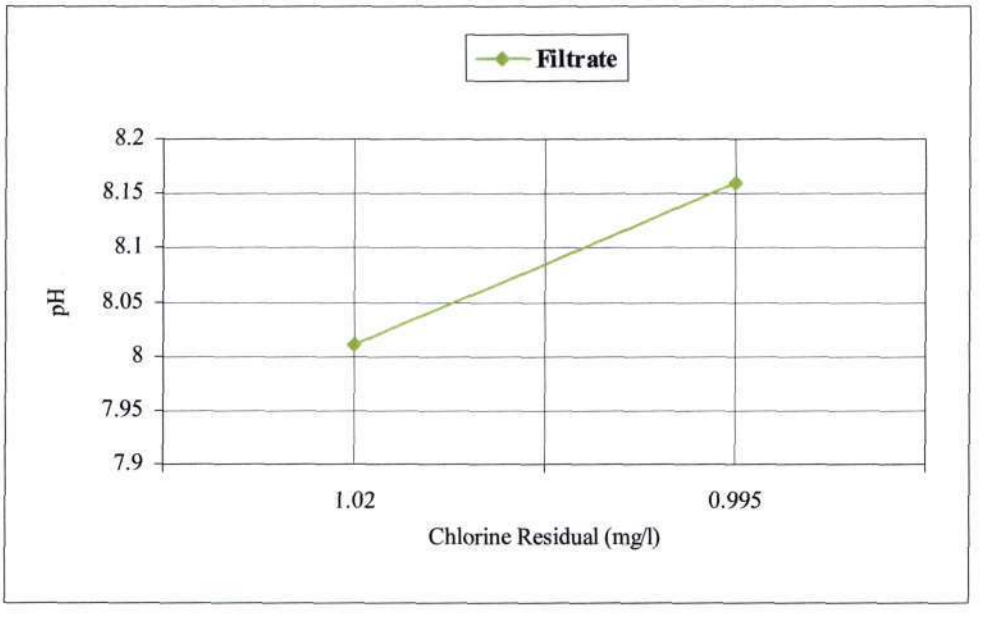

Figure 4.10: Graph illustrating the relationship between pH and chlorine in the filtrate water sample

Gradient = dY / dX = -6.0

Once again, the gradients are used as the parameter for comparison.

The tendencies of gradients are similar to those obtained in the relationship outlined in section 4.4.2, i.e. the dY / dX value is the largest in the filtrate sample, and the least in the raw water sample. The steeper the grade, the larger is the change in pH in relation to chlorine demand of the sample.

SUMMARY OF RESULTS

As established in section 4.4.1, the chlorine demand in the filtrate sample was the least. As a result, the amount of $Ca(OCL)_2$ that was used for the purpose of disinfection was considerably lower than in the raw water and clarified water samples. The implication of this is that the amount of $Ca(OCL)_2$ disinfectant that remained in the filtrate sample was significantly higher than in all the other water samples. The chemical composition of the filtrate sample was therefore altered to a higher degree than the raw water and clarified water samples, and as discussed in section 4.4.2, this subsequently introduced a more significant change in the pH of the filtrate sample.

CHAPTER 5 - GENERAL CONCLUSION

As depicted by literature, the adverse effects on the efficiency of chlorine disinfection posed by high turbidity levels, initiated an experimental investigation to develop a relationship between turbidity and disinfection efficiency, as a means of improving disinfection operations in treatment plants. As outlined in the introduction, the aim of improving disinfection protocol is that those pathogenic substances that contribute to turbidity in water will also be treated by acting directly on the turbidity.

The enmeshment phenomenon, which is facilitated by inorganic substances that often tend to provide a protective environment by allowing micro-organisms to become enmeshed within them, and therefore providing protection from the disinfecting action of chlorine, was of great concern. Upon visiting the Wallmannsthal Bulk Water Treatment Works and the Umgeni Water Treatment Plant, it was learnt that the primary reason for illnesses relating to the consumption of potable drinking water, is the ineffective treatment of water to remove enmeshed pathogenic substances. The treatment processes that constitute effective water treatment in South Africa, has therefore been analysed to ascertain the effect of turbidity at various stages of the water treatment cycle. In this regard, and although the successful functioning of each individual treatment process is dependant on the effectiveness of all preceding processes, the process of coagulation was identified as being primarily responsible for the removal of enmeshed pathogenic substances. The reason for this is that the process of coagulation promotes the formation of flocs with inorganic substances that facilitate this enmeshment phenomenon. These combined floc formations are then removed during the coagulation process. Furthermore, it was also learnt that clays possess the ability to sorb chemical species from water, and can be regarded as useful agents for the cleaning of contaminated water.

Due to the wastage factor that was identified during the disinfection cycle at both of the abovementioned treatment plants, the need for devising a more cost effective solution for disinfection, was considered. The poor operational procedures that were observed with regard to chlorine disinfection practices at both of these treatment plants, initiated the need for experimental analysis to establish a rationale for the effect of turbidity on chlorine disinfection.

A detailed literature review was conducted to identify the characteristics of substances that constitute turbidity in water, with specific emphasis being placed on those substances that possess pathogenic tendencies.

The experimental component of this research revealed the nature of the relationships between turbidity, chlorine and pH. In accordance with the implications of literature, i.e. turbidity poses adverse effects on the efficiency of chlorine disinfection, the outcome of the laboratory procedures were successful in confirming and quantifying this relationship. Upon analysis of the graphs included in Chapter 4 of this study, it was evident that the chlorine demand in proportion to the turbidity value of the test systems, increased together with an increase in the turbidity values of the test systems. It was therefore possible to establish a linear relationship to determine the dosage of chlorine that must be applied to water containing a specific level of turbidity, to achieve a particular amount of disinfection. From this, a turbidity curve was formulated to represent this relationship. This curve however, is merely a guideline, which has been drafted using specific measurement parameters. To expand on such studies, it is recommended that the range of testing should also be expanded upon. In this regard, the turbidity range for the test samples can be increased, while using the same method of testing, or the samples' contact times with the chlorine disinfectant could also be varied. This study focuses on improving operational protocol for water treatment plants and therefore encompasses the treatment of turbid water as a whole. However, it would also be of interest to conduct future investigations to examine a similar relationship using turbid water where the matter that constitutes the water's turbidity was already known. These studies could be useful in understanding the effect of different forms of turbidity on chlorine disinfection.

A further contradiction to the operational policy/procedure employed at the Wallmannsthal Bulk Water Treatment Works and the Umgeni Water Treatment Plant, as noted in the introduction, is the harmful effects of having too much chlorine residual remaining at the end of the disinfection cycle. Upon discussion with a technician employed at the Witbank Municipality, it was also learnt that instances were recorded, where consumers became ill due to the consumption of water that was dosed with too much chlorine, and therefore possessed an unsafe amount of chlorine residual. Although being only a guideline, the utilisation of the disinfection curve will eradicate situations like this, by providing a more accurate means of tabulating the amount of disinfectant that is required in specific instances.

The establishment of the relationships included in this study, i.e. between turbidity and its effect/efficiency on chlorine disinfection, will contribute to the improvement of

operational/analytical procedures currently employed at treatment plants in South Africa and worldwide. This will not only contribute to a more cost effective means of disinfection, but will also prevent the need for constant monitoring of water to ensure suitable disinfection.

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